Textbooks in Contemporary Dentistry

Donald J. Coluzzi
Steven P.A. Parker
Editors

Lasers in Dentistry—Current Concepts

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Donald J. Coluzzi
Steven P.A. Parker
Editors

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Editors
Donald J. Coluzzi
Preventive and Restorative
Dental Sciences
School of Dentistry
University of California
San Francisco, California, USA

Steven P.A. Parker
Department of Surgical Sciences and
Integrated Diagnostics
University of Genoa
Genoa, Italy

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Preface

The first laser specifically designed for dentistry was introduced in 1989 and used a crystal of neodymium-doped yttrium aluminum garnet (Nd:YAG) as its core active medium. Low average power photonic energy produced by this laser was delivered through a small-diameter optic fiber to target oral tissue. Such technology had been developed for use in medicine from 1975, and carbon dioxide (CO_2) lasers were commonly employed during the 1980s for general and oral surgery. Nowadays, approximately 15% of dentists worldwide own lasers, and there are about 30 indications for their use in dental treatment. Whether used in addition to or instead of conventional instrumentation, lasers provide many unique patient benefits.

This textbook is intended to provide information about the basic science and tissue interactions of dental lasers and display the most current examples of clinical use in every dental discipline. The clinical cases were chosen to show the results of proper laser use for a particular procedure, and the accompanying text explains the rationale, advantages, and precautions of that use, documented with numerous citations.

Research studies continue to provide collaborative evidence demonstrating the efficacy of the today's instrumentations. Furthermore, other investigations will enumerate novel clinical applications, and hopefully new laser wavelengths will be explored, developed to deliver highly specific power configurations to optimize laser-tissue interaction.

This book is the product of many highly respected dental clinicians, along with those in academia and involved in research throughout the world, and we are grateful for their efforts and their friendship. Most importantly, we acknowledge the love, understanding, and support of our spouses, Catherine Coluzzi and Penny Parker.

We hope you enjoy the book.

Donald J. Coluzzi
San Francisco, CA, USA

Steven P.A. Parker
Genoa, Italy

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About the Editors

Donald J. Coluzzi, DDS

a 1970 graduate of the University of Southern California School of Dentistry, is a clinical professor in the Department of Preventive and Restorative Dental Sciences at the University of California San Francisco School of Dentistry. He ran his own private practice of general dentistry in Redwood City, CA, and retired from it after 35 years. He is a life member of both the California Dental Association and the American Dental Association. He has served as a past president of the Academy of Laser Dentistry, received its Leon Goldman Award for Clinical Excellence, and is a past editor in chief of the *Journal of Laser Dentistry*. He has used dental lasers since early 1991 and holds advanced proficiency in Nd:YAG and Er:YAG wavelengths. He is a fellow of the American College of Dentists, is a University of California-certified dental laser educator, and is a member of Omicron Kappa Upsilon, the national dental honor society. He serves as a reviewer for several journals and is a founding associate of Laser Education International. He recently received the Outstanding Faculty Member Award from the American College of Dentists. Dr. Coluzzi has presented about lasers worldwide, coauthored two textbooks, and published several peer-reviewed articles and book chapters.

Steven P.A. Parker, BDS, LDS RCS, MFGDP

Dr. Steven Parker studied dentistry at University College Hospital Medical School, University of London, UK, and graduated in 1974. Dr. Parker has been involved in the use of lasers in clinical dentistry since 1990. He is closely involved in the provision of education in laser use in dentistry. He served as president of the Academy of Laser Dentistry in 2005–2006. In addition, Dr. Parker holds advanced proficiency status in multiple laser wavelengths. He was awarded mastership of the Academy of Laser Dentistry in 2008. Awards gained with the Academy of Laser Dentistry have been the Leon Goldman Award for Excellence in Clinical Laser Dentistry (1998) and the Distinguished Service Award (2010). From 2010, he has served an appointment as *professore a contratto* in the Department of Surgical Sciences and Integrated Diagnostics, University of Genoa, Italy. He also acts as international coordinator and lead faculty of the master of science (*Master Livello II*) degree program in laser dentistry at the University of Genoa. Dr. Parker has contributed chapters on aspects of laser use in dentistry in several textbooks and multimedia platforms. Additionally, he has received publication of over 40 peer-reviewed papers on the use of lasers in dentistry, including a series «The Use of Lasers in Dentistry» published in the *British Dental Journal* in 2007 and later as a textbook. He was the dental consultant to the UK Medical Health Regulatory Agency (Dept. of Health) in the 2008 (Revised 2015) publication «Guidance on the Safe Use of Lasers, Intense Light Source Systems and LEDs in Medical, Surgical, Dental and Aesthetic Practices.» He serves as associate editor of the *Journal of Lasers in Medical Science.* In addition, he serves as referee for many peer-reviewed dental journals worldwide. He maintains a private practice in Harrogate, UK.

Contributors

Eugenia Anagnostaki, DDS, MSc
Professor a.c., Department of Laser Surgery and Laser Therapy Faculty of Medicine and Dentistry, University of Genoa, Genoa, Italy

Private Practice, Rethymno, Greece
eanagnostaki@densindente.de

Akira Aoki, DDS, PhD
Associate Professor, Department of Periodontology, Graduate School of Medical and Dental Sciences, Tokyo Medical and Dental University, Tokyo, Japan
aoperi@tmd.ac.jp

Konstantinos Arapostathis , DDS, MSc, PhD
Assistant Professor, Pediatric Dentistry Department, Aristotle University of Thessaloniki, Thessaloniki, Greece
koarap@dent.auth.gr

Ali Borzabadi-Farahani, DDS, MScD, MOrth RCS (Ed)
Fellowship, Craniofacial and Special Care Orthodontics, Children's Hospital Los Angeles, USC, Los Angeles, CA, USA

University of Warwick, Warwick, UK
faraortho@yahoo.com

Adriana Cafaro, DDS, MSc
Department of Oral pathology, Lingotto Dental School, University of Turin, Private Practice, Milan, Italy
ercole.romagnoli@tiscali.it

Nasim Chininforush, DDS, PhD
Laser Research Center of Dentistry, Dentistry Research Institute, Tehran University of Medical Sciences, Tehran, Iran
n-chiniforush@farabi.tums.ac.ir

Donald J. Coluzzi, DDS
Professor, Preventive and Restorative Dental Sciences, School of Dentistry, University of California, San Francisco, CA, USA
doncoluzzi@gmail.com

Mark Cronshaw, BSc, BDS, LDS RCS (Eng), MSc
Professor a.c., Department of Surgical Sciences and Integrated Diagnostics, University of Genoa, Genoa, Italy

Private Practice, Cowes, UK
macron5@hotmail.com

Roy George, BDS, MDS, PhD, ADC, GCHE, MRACDS
Associate Professor / Senior lecturer and the Discipline Lead for Endodontics at the School of Dentistry and Oral Health at Griffith University, Nathan, QLD, Australia
r.george@griffith.edu.au

Kenneth Luk, BDS, DGDP(UK), MGD(HK), MSc
Private Practice, Hong Kong
drkluk@mac.com

Shally Mahajan, BDS, MDS
Professor, Department of Orthodontics and Dentofacial Orthopedics, Saraswati Dental College, Lucknow, India
drshally23@gmail.com

Alex Mathews Muruppel, BDS, MDS, Dipl. LAS. DENT., FPFA
Professor a.c., Department of Laser Surgery and Laser Therapy Faculty of Medicine and Dentistry, University of Genoa, Genoa, Italy

Private Practice, Trivandrum, Kerala, India
alexmuruppel@gmail.com

Claus Neckel, MD, DDS
Private Practice, Maxillofacial Surgery, Bad Neustadt, Germany
cpneckel@t-online.de

Steven P.A. Parker, BDS, LDS RCS, MFGDP
Professor a.c., Department of Surgical Sciences and Integrated Diagnostics, University of Genoa, Genoa, Italy

Private Practice, Harrogate, UK
thewholetooth@easynet.co.uk

Penny J. Parker, DCP, RDN Cert. Dent. Rad.
Private Practice, Harrogate, UK
thewholetooth@gmail.com

Riccardo Poli, DDS, MSc
Professor a.c., Department of Surgical Sciences and Integrated Diagnostics, University of Genoa, Genoa, Italy

Private Practice, Turin, Italy
riccardo.poli.pro@gmail.com

Suchetan Pradhan, MDS, MSc, EMDOLA
Director Laser Dentistry, Manipal University, Manipal, India

Fellowship Program Implant & Laser Dentistry at DY Patil Dental College & Hospital, Pimpri, Pune, India

Private Practice, Mumbai, India
suchetanpradhan@gmail.com

Peter Rechmann, DMD, PhD, Prof. Dr. med. dent.
Professor, Division of Prosthodontics,
Preventive and Restorative Dental Sciences,
School of Dentistry, University of California,
San Francisco, CA, USA
Peter.Rechmann@ucsf.edu

Ercole Romagnoli, DDS
Professor a.c., Department of Surgical Sciences and Integrated Diagnostics, University of Genoa, Genoa, Italy

Private Practice, Milan, Italy
ercole.romagnoli@tiscali.it

Wayne Selting, DDS, BS, MS
Professor a.c., Department of Surgical Sciences and Integrated Diagnostics, University of Genoa, Genoa, Italy

Private Practice, Colorado Springs, CO, Italy
wselting@aol.com

Vipul Srivastava, BDS, MDS
Professor, Department of Conservative Dentistry,
Saraswati Dental College, Lucknow, India
vipul13@gmail.com

Laurence J. Walsh, BDSc, PhD, DDSc, GCEd
Professor, University of Queensland,
St. Lucia, QLD, Australia
l.walsh@uq.edu.au

Concepts of Laser Use

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Lasers in Dentistry: Where to Begin?

Shally Mahajan, Vipul Srivastava, and Donald J. Coluzzi

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Core Message

Lasers have emerged as high-technology instruments and very helpful tools in all aspects of our daily lives. They have been slowly incorporated by dentistry over the last three decades. Our patients have come to expect treatment that is high quality, minimally invasive, comfortable, and patient friendly. Fortunately, a practice that utilizes lasers can fulfill those goals. The purpose of this chapter is to discuss some of the benefits of adopting lasers into a dental practice, what the clinician must know before purchasing a laser, and concepts of revenue generation. Moreover, a practitioner who is apprehensive about adopting the technology should also find helpful information to help in making a decision.

1.1 Introduction

Light has always fascinated mankind for many centuries. There have been innumerable references to light being a source of healing and curing many diseases for ancient cultures. Many Roman homes featured solariums [1], while they and the neighboring Greeks took daily sunbaths. The use of light for photodynamic therapy enabled early civilizations to treat a variety of dermatologic conditions using photosynthesizer chemicals found in plants. Over 200 years ago, physicians in Europe offered similar therapy using both artificial and natural light [2, 3].

At present, laser *technology* has become associated within indispensable and diverse applications such as metrology, science and engineering, medicine, communications, art and entertainment, research work, defense, and astronomy. It is impossible to even imagine state-of-the-art physics, chemistry, biology, and medicine research without the use of radiation from various laser systems.

In 1989 the first laser model specifically designed for the dental profession became available for treating oral soft tissue. Since then, many different wavelengths have been introduced, and the practitioner can easily use them on both hard and soft tissues for both surgery and healing. This new technology greatly expands the scope of procedures while making them easier and more comfortable for patients. Encouraged by an ever-increasing evidence of the safe and effective use of lasers, there are a growing number of practitioners embracing the technology and appreciating how their patients can benefit.

The question in this chapter's title may be properly expanded into «why buy a laser and what do I need to know when I buy it?» The following sections should provide many details for that answer.

1.2 A Buyer's Guide for Choosing a Laser

While investigating a product for our personal use or a piece of equipment for our practice, several aspects should be considered. We check for the features, benefits, assets, and liabilities to help us make sure that we are paying the right value of the product. A well-thought-out decision leads to a better business operation and good management. Hasty decisions can lead to financial distress and instability in career and unnecessary emotional stress. Similarly, before investing in a laser, we can ask the following questions:

? *Is a laser worth the investment; in other words, is there value for the money?*

✓ The first and foremost thing before buying a laser is to identify your practice goals because that will help you optimally understand the demands of your patient and how you would meet their expectations. Thus one response to the posed question is a multipart one: (1) Which procedures would I be able to perform with the laser that would produce beneficial results? (2) Can I achieve a good return on my investment by an additional fee for the procedures that I already perform conventionally? (3) Are there new procedures I can perform? Another section of this chapter will discuss these points in detail. After that analysis, the answer about value should be very straightforward. In any case, and depending upon the various treatment applications, lasers are available in a variety of wavelengths, sizes, and competitive prices.

Where would I put the laser? What should be the room size for the laser unit to fit?

The answers to these questions depend on which wavelength will be used for the procedure you have planned. For example, lasers for hard tissue—tooth preparation and osseous surgery—have a relatively large footprint, approximately the size of a standard dental cart. These lasers have air, water, and main utility requirements similar to that cart so the room should accommodate those. Other lasers such as soft tissue diodes are smaller units and only need small plug in adapters from AC power mains or are battery driven. They can be placed on any available small flat surface. In fact, some of those units are compact to the point of being shaped like a thick pencil and are self-contained. Technological sophistication continues to be developed, but each unit will have its unique space requirements.

What is the laser's portability and ease of setup?

As a corollary to the previous paragraph, all lasers have a degree of portability. The large units all have wheels and the smaller units can be lifted with one hand. Some have a wireless foot control pedal and the others have multiple cables to connect. Nonetheless, any unit can be moved between operatory rooms. Setting up the laser follows prescribed steps. Along with various safety features, the start-up protocol takes very little time. The delivery systems have specific accessories that are simple to attach and the displays on main screen are easily readable. If there are buttons for presetting parameters, they can be customized for a particular procedure. Protective eyewear is essential for the surgical team and for the patient and any observer in the treatment area. These should be stored close at hand. Each of these steps should become routine so that the laser use becomes seamlessly integrated into any patient care where it's needed.

What's the quality of construction?

All of the units are manufactured for patient care with necessary industrial standards that regulate not only electrically powered devices but also dictate infection control requirements. The quality of construction on every laser should be very high, although some components will wear with normal use. A main concern of the practitioner is likely to be how comfortable the delivery system is to handle. Some devices have small flexible optical glass fibers, while other lasers have larger hollow tube assemblies. All terminate in a handpiece and some have small tips or tubes to direct the beam toward the target tissue. Your hand should not fatigue while performing lengthy procedures and the handpiece should be able to reach in all the areas of the mouth. You should be able to perform the range of clinical procedures desired with ease and precision.

What are the safety features?

All dental lasers are well equipped with built-in safety features subject to rigorous rules. Some examples of these features are an emergency stop button, emission port shutters to prevent laser emission until the correct delivery system is attached, covered foot switch to prevent accidental operation, an adjustable control panel to ensure correct emission parameters, audible or visual signs of laser emission, locked unit panels to prevent unauthorized access to internal components, key or password protection, and remote interlocks to minimize the risk of accidental exposure. Clearly, the practitioner must be familiar with these protective items, and a laser safety officer must be appointed to supervise the laser's operation.

What is the cost of operation?

Aside from the initial investment of the device, each procedure will have a cost while performing a procedure. Some items or accessories are single use. An example is a tip for a diode laser; these tips are available in multiple diameters and lengths. One tip can generally be used for one patient visit, although treatment of multiple areas may require more than one tip. Other components are designed as long lasting, but could require replacement. An example is the delivery system itself. Optical fibers can lose some transmissive capability over time; some handpieces have mirrors or other components that degrade. Protective glasses can be scratched or damaged from repeated use. On the other hand, the active medium of the laser and other internal parts generally show little or no wear throughout the life of the laser. While the tip cost is a small percentage of the fee, other items can be a significant economic factor for the practice. In every case, the manufacturer should be able to service the unit and offer replacement parts when necessary.

How are the parts sterilized or disinfected?

It is extremely important to follow the manufacturer's instructions for infection control to prevent any cross contamination from patient to patient. Some components of a laser, especially those that are in direct contact with oral tissues, are either autoclavable or disposable. The handpiece is an example of the former, and the single use tips are disposable. Other areas like the control panel and the delivery system can be protected with barriers and subsequently disinfected with standard spray on liquids. The protective safety glasses can also be disinfected.

1.3 Integrating a Laser into Your Practice

Lasers have provided a new cutting-edge technology to the dental world. It is truly amazing to think about how such an investment like this could have such a huge impact on clinical practice. Incorporating lasers into conventional therapies helps in better prognosis and treatment outcomes. Lasers began as alternatives for soft tissue oral surgery and have expanded into all aspects of dentistry: orthodontics, endodontics, oral and maxillofacial surgery, periodontics, aesthetic dentistry, restorative dentistry, prosthodontics, dental implantology, and pediatric dentistry. In addition, low-level lasers can be used as adjuncts to treat chronic pathologies and within photodynamic therapy to treat infectious disease.

Several factors are presented for consideration about how a laser can be incorporated into a practice:

- *Identify your practice*. The first and perhaps foremost concept before buying a laser is to identify how you practice. Your treatment planning is based on the patient's oral health conditions, and the goals of your care will help improve or maintain that health as well as meet their expectations. Your clinical experience and scope of practice usually determine which procedures you perform, and a list of those should be studied so that you can begin to choose a laser instrument. Likewise, you may have thought about the addition of other newer treatments that will expand your services. Those could affect the type of laser you purchase.
- *Analyze what procedures do you currently perform that can be assisted with laser technology*. A dental laser can help you provide a higher level of care. In restorative dental procedures, management of soft tissue is

simplified because the tedious and painful placement of retraction cord can be eliminated. Better impressions are possible for indirect restorations such as crowns and bridges, and clearer margins near the gingiva are revealed for optical scanning. Class V carious lesions can be prepared at or near the subgingival level with excellent hemostasis. This ensures an improved bond for composite materials and ultimately results in better aesthetics and a longer-lasting restoration. Two minutes of disinfection treatment of an aphthous ulcer brings immediate relief to the patient who may have been suffering for days. Excellent hemostasis can be achieved during minor surgical procedures like an immediate loading implant or second-stage implant uncovering.

- Not only is there a clean dry operating site, but the improved visualization will save time for the other steps of the treatment. All this will save your time. Also, by differentiating your practice, you'll attract a more educated cliental. Patients associate laser procedures as less invasive leading to a better overall dental experience and once treated will refer their families and friends. There is easy return of investment as the procedures are made simpler and easier.
- *Think about which procedures that you do not perform that you would like to provide if you had a laser*. Within your scope of practice, there are procedures that can be accomplished with dental lasers in your office that you previously may have referred to a specialist and/or did not offer to your patients. Of course, proper training is necessary before you begin any procedure and is especially important when you are attempting a new one. However, understanding the fundamentals of the wavelength and watching the interaction as it happens will provide clinical experience and confidence for the clinician to continue offer additional treatment options at chairside. Endodontic therapy can be aided by both laser debridement and pathogen reduction. Examples of laser soft tissue excisions are numerous: a removal of fibrous tissue in an irritation fibroma and epulis in the soft tissues of patients wearing removable prosthodontic appliances, operculectomy treatment of an unerupted tooth, a frenectomy to prevent further adult periodontal problems, releasing a tongue tie in infants, and revising the frenum in a child's diastema to aid proper tooth positioning. Oral surgical procedures such as oral sub-mucositis fibrosis, lichen planus, and leukoplakia can also be performed. Lasers can also be used for aesthetic enhancement of the patient's smile by minor recontouring of gingival tissue, laser tooth whitening, and removal of depigmentation in the soft tissues. Osseous crown lengthening for treatment of altered passive eruption or to obtain adequate tooth structure for a restoration can proceed with the all-tissue lasers [4]. During the initial alignment phase of orthodontic treatment, low-level laser therapy (LLLT) can be given to patient as it has shown to accelerate the tooth movement and also to relieve the discomfort that occurred during the initial arch-wire changes [5]. That same effect, also known as photobiomodulation, can be used in patients with bruxism, temporomandibular joint disease, acute abscess areas, and many more applications [6]. One of the biggest hurdles while taking diagnostic records, impression making, or intraoral radiographs is gag reflex, which can be particularly strong in some patients. Low-level lasers are a boon in such cases; using lower doses of laser energy helps in minimizing the reflex [7]. When all these benefits are explained in detail, there is no doubt the patient will accept the planned treatment. The increased revenue also helps to satisfy a further return on the initial cost of the laser.
- *There are several choices of laser instruments*. There are many lasers available for purchase. Their availability can be dependent on regional regulations of sales and clearances, along with support of service and training. There are worldwide standard and consistent classifications so that basic choices can be made. A generic division describes dental lasers as either surgical or nonsurgical, and they are sometimes termed high level and low level, respectively. ◘ Figure 1.1 shows a simple flowchart of the basic categories of those classifications.

After analyzing your practice's procedures, you can become familiar with how each available laser could be utilized.

- *Prioritize your clinical needs with respect to how a laser's use would be of benefit*.
  - In a modern dental office, a patient has certain expectations: treatment should be less painful, more precise, and less invasive with less bleeding, better healing, and fewer appointments. Fortunately, the practice of dentistry has been revolutionized and modernized so that our procedures have become more patient friendly. With the incorporation of this device, an anxious patient feels more confident, and there is noise-free or no vibration of the drill or smell of conventional dental care, with the fact that much of the treatment can be performed with «no anesthesia» or «needle-free» dentistry. These factors could transform patients who were resistant to conventional treatment into ones who readily accept treatment. Also in the future, we can expect more referrals to the practice, thus, proving lasers to be a safe investment and a true value for the money.

If your practice is focused on oral hygiene maintenance (sulcular debridement), prosthodontic or restorative tissue management (gingival troughing), or aesthetic procedures (crown recontouring, gingivectomy, gingival depigmentation, and laser whitening), a diode or a Nd:YAG laser would be ideal. The small-diameter fiber optic contact delivery can be safely used on soft tissue with minimal interaction with hard tissue. For the restorative practice and conservative dentistry, the erbium family (Er,Cr:YSGG, 2780 nm, and Er:YAG, 2940 nm) and the 9300 nm carbon dioxide lasers offer a wonderful alternative and adjunct to the dental bur. A specialty practice that is mainly focused on oral and maxillofacial surgical

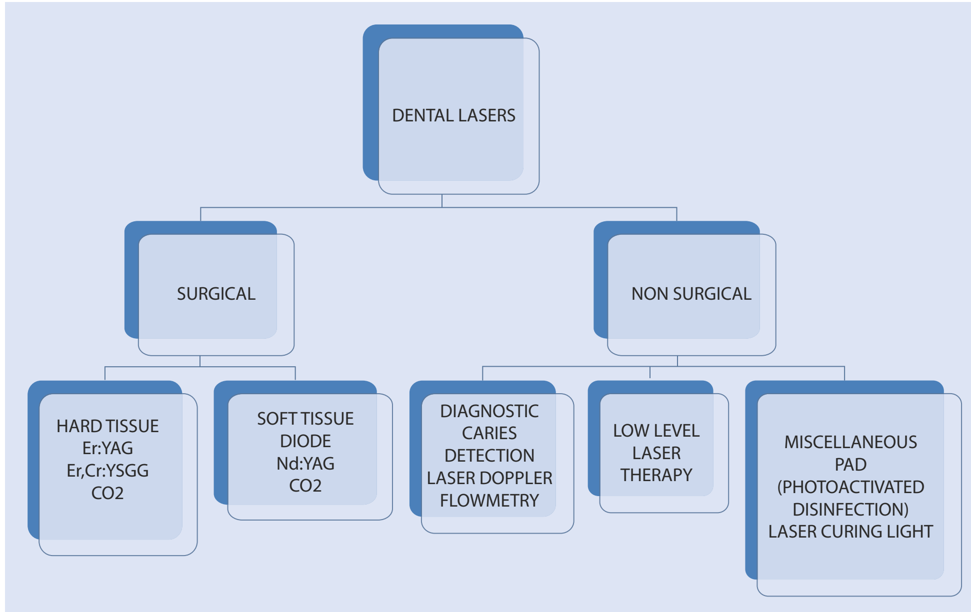


Fig. 1.1 A graphic representation of the type of dental lasers. The surgical lasers have output power sufficient for incision, excision, ablation, and coagulation of dental tissues, whereas the nonsurgical lasers will not perform those procedures. A few surgical devices do have capabilities for low-level laser therapy

procedures, or periodontal surgery, the aforementioned tooth cutting lasers perform osseous surgery safely and rapidly while minimizing potential thermal damage to adjacent tissues and the blood supply. In addition to those instruments, the 10,600 nm carbon dioxide laser is often used for precise and rapid cutting during soft tissue surgery.

The clinician is constantly assessing and assimilating patient's needs and satisfaction while deciding on the proper treatment [8]. When choosing to add a laser to the procedure's protocol, certain wavelengths have advantages over others. To be clear, any of the available laser wavelengths are suitable for soft tissue treatment. But if the dentist treats both soft and hard tissues, only the erbium or the 9300 nm carbon dioxide instruments will provide necessary energy and tissue interaction for those dental procedures.

- *There is no single perfect laser wavelength*. Currently there are over two dozen indications for the use of the various dental wavelengths, as listed in the different manufacturer's operating manuals. There are often many discussions in the profession about which laser is the best, as well as debates about how all lasers are the same. It should be clear that although similarities exist, every laser wavelength has some unique properties compared to another. When asked the question about which laser is best, a proper answer could be the one you know how to use in your practice!

One thing which must not be forgotten is that there is «no perfect laser.» It is simply because the absorption characteristics of the photonic emission by a particular wavelength are different for the same tissues. Although every laser can be used for soft tissue surgery, a very fibrous area will be difficult to cut with a diode laser but will be easily incised with carbon dioxide. On the other hand, a diode can perform aesthetic contouring of gingiva adjacent to a natural tooth without interacting with the healthy enamel, but the carbon dioxide wavelength could damage that same enamel. Erbium lasers are very highly absorbed by water, which allows the easy removal of a carious lesion. However, highly fluoridated enamel can be more challenging to ablate because of the minimal water content. In addition, the laser's output can be a factor during treatment. Some procedures need only minimum energy levels; an example would be when desensitizing an aphthous ulcer. Likewise, photobiomodulation effects are performed at power densities well below any threshold of surgical cutting. In contrast, tooth preparation requires very high peak powers and very short pulses for efficient removal of the mineralized material without thermal damage.

Therefore, before investing, all of the factors just discussed should help the clinician to identify what kind of laser is best suited for one's practice.

1.4 Sales, Training, and Company Support

The laser manufacturer is engaged in a highly competitive business with a limited market of purchasers. The sales team must be transparent and honest about their product's performance and avoid unrealistic assurances about everything from clinical efficacy to availability and shipping time for the device. The company's representatives should have a sound knowledge of the laser's operation so that they can initially demonstrate how the laser is set up along with knowing how to help in case of troubleshooting a problem. Customer support representatives should be available to answer questions and solve problems.

Training and continuing education opportunities must be available. Some companies have formed institutes that provide training for basic and advanced procedures, along with such features as educational resources, a discussion forum, examples of clinical cases, and other digital learning. Others sponsor courses and workshops during larger dental conferences.

It would be useful to know how long the particular device has been commercially available for purchase as well as to learn about the company's track record of efficiency, reliability, and service. Some companies have a global market, but local support in your country or state would be very desirable. Regional dental suppliers can also represent the company to provide sales and service. Since those suppliers already have a relationship with the dental practice, this could facilitate good support.

The operating manual enclosed with the laser is the guidebook for its use and describes the clinical procedures for which the device may be used. This is sometimes termed «indication for use» and simply means that there is solid evidence for safety and effectiveness, as opposed to «off-label» treatment. All sections should be well written. Instructions should include the range of operating parameters for each procedure for the wavelength's use. Those settings are always guidelines and suggestions for modification should be listed. Factors such as beam diameter versus output power, approximate time of exposure, and varying tissue interaction must be considered. The steps necessary for the assembly and disassembly of the delivery system should describe every detail. The care and maintenance of each component of the laser should be illustrated. Warnings, precautions, and troubleshooting procedures should be explained, along with contact information for support.

As previously mentioned, there are various accessories necessary for using a laser. These include delivery system tips, foot control pedals, keys, interlocks, and protective eyewear. The initial and replacement cost of these items as well as any maintenance and availability should be noted. In some cases, accessories are optional and have additional costs. Those can negate an initial attractive initial price of the laser itself. Likewise maintenance can be included for a period of time in the purchase, but a contract for service beyond that may incur a fee.

The warranty period should be clearly stated, and the dentist purchaser should thoroughly understand the terms and conditions. Lasers are designed for precision delivery of photonic energy, and the device is generally well constructed. However, any portion can be damaged with normal use and accidental breakage can occur. Warranty is a promise provided by the manufacturer to repair or replace the instrument if necessary within a specified time. That promise may stipulate what repairs are covered in specific circumstances.

The laser's operation is governed by software control of the internal components. Many companies offer updated versions of their software and may include them in the purchase price. Likewise some of the hardware may undergo modification, and it would be prudent to determine if any retrofitting or upgrades are appropriate and available for the model of laser purchased.

1.5 Education and Knowledge

A prudent question to ask is «how much training and do I need?» The simple answer is that you should continue to acquire knowledge all during your dental career. The elusive secret to success has always been to achieve better quality of patient care. That achievement can only be found with lifelong learning. It starts with the sessions offered by the laser manufacturer after purchase. Unfortunately some of these are simply didactic lectures available on playback media. Hands-on simulated exercises on animal tissue followed by over-the-shoulder supervised patient care are very superior learning methods. Whichever methods of initial training are taken, simple procedures performed with minimum power settings will help to overcome your fears and increase the level of your skills. Observing the rate of tissue interaction and the progress of reaching the treatment objective may appear to be at a slower pace than you first expected. Your patience will be rewarded; in fact, a slow sweeping motion for tissue removal is usually preferred. Moreover, you will avoid unnecessary thermal damage while precisely cutting and contouring tissue; and that will produce a successful outcome. That continuing journey toward mastering how a procedure is performed can bring you a lot of satisfaction. During that time, your range of comfort with all procedures will certainly increase.

For continuing education about the use of lasers in dentistry, a number of opportunities are available. Local study clubs and regional academies have regularly scheduled meetings where members can share information. Many major dental conferences feature presentations and workshop courses. There are university-affiliated programs which both offer information and assess competency. Advanced programs, fellowship, mastership, and MSc programs are offered in many countries. A document entitled «Curriculum Guidelines and Standards for Dental Laser Education» was developed in 1993 and is often used as a reference for these learning opportunities [9].

Finding a mentor would be a bonus for any laser clinician. There's no faster way to improve your skills and knowledge than to have someone to guide you as you work on your goals. That person should have the right attitude about teaching along with the experience to demonstrate the proper way to perform the procedure while correcting any of your deficiencies. Your confidence in delivering care will also increase. In addition, you can gain insights about new techniques and treatments.

Another question that can be asked is «what are the rules for laser use?» The response is that various regulatory agencies exist to ensure safe and efficacious use of lasers for the health and welfare of patients. The practitioner must have knowledge of those regulations and comply with their provisions. A review of those is presented here and will be detailed in ▶ Chap. 5 on laser safety.

- Regional or local bodies issue a license to practice dentistry to a properly qualified dentist. That award allows the dentist to offer dental care according to the scope of practice—i.e., the general or specialty services that are provided. That care is delivered in a manner that is based on the practitioner's training, education, and clinical experience. It should be remembered that «laser dentistry» is not a recognized specialty; in contrast it is a description of using an instrument during a procedure.
- Certain agencies control the manufacturer and their products, but do not control the practice of dentistry. One example is the US Food and Drug Administration through its Center for Devices and Radiological Health that regulates the construction of the laser to ensure compliance with medical device legislation. That same agency awards the manufacturer a marketing clearance for a procedure which states that the treatment where the laser is used will be safe and effective.
- The International Electrotechnical Commission prepares and publishes international standards for all electrical, electronic, and related technologies that include regulations and conformity assessment for lasers in a similar manner to the Food and Drug Administration.
- Both of these organizations strongly influence regulatory agencies in other countries.
- Currently there is no common agreement about what defines a proper credential for a dental laser practitioner. Some local licensing jurisdictions have a course requirement. A small number of dental schools have introduced laser care into the predoctoral curriculum.

Evidence-based dental practice comprises an equal combination of the integration of clinically relevant scientific evidence, the clinician's experience, and the patient's treatment needs and experience. Regarding dental lasers, the peer-reviewed literature offers an abundance of studies, clinical cases, and meta-analysis. Some reviews proclaim controversies that exist with regard to superiority of incorporating lasers into the treatment protocol. However, many manuscripts using controlled clinical studies do show effectiveness of these instruments. The laser practitioner should be familiar with as much of the literature, published articles, case reports, and scientific reviews that are readily available online or offline. Less reliable blogs and forums can offer information and networking about personal experiences. All of those resources contribute to evidence that has a place in the hierarchy of learning. The knowledge of how a particular wavelength would serve the purpose will be very beneficial to the success of your practice.

1.6 Investing in Your Team

Nurturing your employees is an important part of creating an engaged workforce. Invest in their personal and professional development and it will pay handsome dividends down the line by giving you a happy, capable, and productive team in an optimized practice. Your patients will immediately notice the professional and friendly atmosphere where you have created a healthy working environment with a caring and holistic approach toward their treatment.

Everyone on your staff from the receptionist and administrators at the front desk to the clinical team of assistants, hygienists, and other associated doctors must be educated about dental lasers.

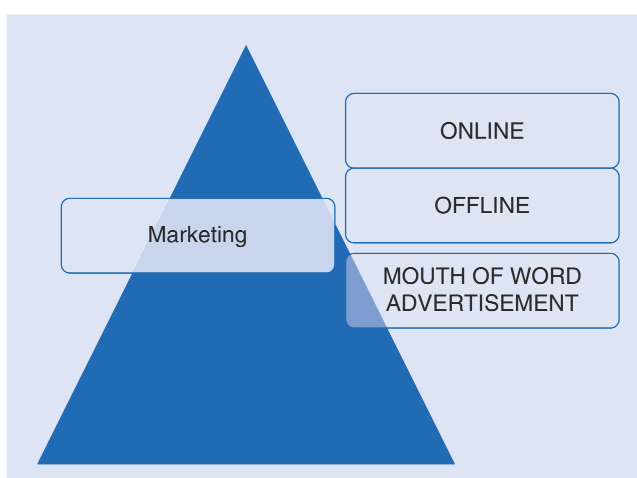
With proper training and experience, they can answer any of the patient inquiries about how a laser might be used for treatment. They can increase the patients' awareness of the advantages and limitations of the technology. They can also address any apprehension about a procedure. Interestingly, many people are familiar with lasers because of previous medical procedures; and a few have expressed a misunderstanding about the word radiation as it represents the last letter in the laser acronym. Regarding the latter, a well-informed staff member can clarify the fact that dental lasers do indeed emit radiation in the thermal portion of the electromagnetic spectrum and not in the ionizing portion used for radiographs. The entire team would benefit by attending an introductory course about the use of lasers in dentistry as well as being actively interested in other continuing education offerings.

1.7 Marketing

One of the secrets to a successful practice lies in its marketing. Marketing is a process by which a product or service is introduced and promoted to potential customers [10]. It is the best means to make people aware of the quality of service being provided. The overall marketing umbrella covers advertising, public relations, promotions, and sales.

There are mainly three methods of marketing, namely, online, offline, and word of mouth. The latter is sometimes termed «internal marketing.» Online marketing uses the Internet, e-mail, social networking websites, and blogs as online channels for delivering marketing content to the public. Offline marketing is disseminated through the «conventional» media: radio, television, and print ads. Word-of-mouth marketing is the best of the three approaches for any dental office. The starting point is that the staff or team must have knowledge of the practice. A written strategic plan composed of a vision, mission statement, goals, and objectives will certainly provide a framework for that knowledge. Each employee should be able to articulate the fact that the entire office constantly stays updated with current innovations and procures the latest technology to ensure the best treatment, care, in a comfortable environment. That in turn will clearly influence how the patient will speak about the practice, encouraging friends, neighbors, and relatives to seek dental care there.

For the best results, all three modalities should be incorporated in a marketing plan. For the first two portions, you also may consider promoters, publicists, and professional marketing outlets to support any of your large-scale promotion efforts. Obviously, a budget must be prepared so that the dollars necessary for any of the above are well spent. However, word-of-mouth marketing usually just involves spending some time inside the office to ensure a consistent and high standard of delivery of dental care.



Lasers can be an excellent marketing tool. In a surgical case, the dentist who utilizes a laser is no longer bound by conventional treatment that always involves injectable anesthesia, along with bleeding, and sutures. Instead the patient can be treated with the alternate laser technique that may require minimal or no anesthesia, with no bleeding, and minimal to no suturing. Similarly, for restorative dentistry, the traditional cavity preparation with rotary high- and low-speed drills and burs can give way to laser ablation of the carious lesion and preparation of the preparation margins. As an additional benefit, some of the treatment can be also performed with less anesthesia and more patient comfort.

Patients are becoming more techno-savvy these days, and because of that, they can spend an inordinate amount of time researching dental treatment options on various online portals with varying degrees of opinion and education. Nonetheless, they gain knowledge about their options; and they rarely oppose treatments with laser if given a choice. They know and understand that the technology is up to date and it can provide faster, more comfortable dental care while achieving those better results in less time.

1.8 Why Lasers in Dentistry

Lasers are in common use in every aspect of our lives, be it military, industrial, or medical. Now in its third decade, laser dentistry is no exception. The term laser itself evokes a positive response in patient's mind. Possibly because of prior experience with other medical procedures, the patient will associate the treatment performed with the instrument as very beneficial. Laser dental care can be quicker and more efficient along with markedly reduced pain, lack of bleeding, minimal need of anesthesia, and last but not the least minimal postoperative discomfort. The patients can resume their daily activities shortly after the treatment is rendered [11].

? *Why should I buy a laser?*

✓ The dental laser should become part of the practitioner's armamentarium. The photonic energy, with its unique properties of monochromatism and coherency, transmitted through an ergonomic delivery system, becomes a novel instrument for dental care. When used with proper knowledge, understanding, and correct training, it can function as an integral part of any dental treatment appointment. The clinician can have assurance that each laser procedure is being safely and easily performed without some of the disadvantages that were present when the scalpel or electrosurgery was used. Two examples can be listed: disinfection during a laser incision versus a bleeding scalpel cut and safe removal of tissue during laser implant fixture exposure versus certain damage with an electrosurgical tip. In addition, for those who challenge themselves to constantly better their skills, a laser is a must «have» for them—not as a «gadget,» but as a surgical instrument.

? *What difference will it make for my patients and myself?*

✓ The incorporation of technology in dentistry has improved the way we serve our patients. Digitized radiographs are replacing traditional radiographs, diagnosis is done on 3D model of teeth and bone (CBCT) and single sitting root canals, and CAD/CAM technology is gaining popularity. All these advancements including lasers are being incorporated to improving the dental care provided to the patients on daily basis [12]. Dental pain is scored among the world's first ten phobias. In some patients, just the sight of dental chair, the whining noise of air rotor, or the white coat of a dentist can create panic attacks. Dental lasers make a huge difference in the life of such patients since they can reduce the level of stress and anxiety [13] and help a clinician to deliver the best of dentistry. As an added benefit, it has been shown that lasers can help to provide neural blockage leading to analgesic effect and anti-inflammatory effects [14].

? *Will it be income generating?*

✓ Dental lasers can help the practitioner to formulate treatment plans for the benefit of the patients. As mentioned previously, the existing procedures will be improved and new or previously referred treatments can be offered. The dentist may necessarily increase the fee schedule to reflect the additional cost of the laser purchase, but that adjustment should be explained by simply enumerating the benefits of using the instrument.

✓ The surgical procedures are generally shorter than traditional surgeries and are usually performed on an outpatient basis. Patients usually have less pain, swelling, and scarring than with traditional surgeries. This makes a huge difference in the quality of life of patient since there is usually no long recovery period. Just as important, the practitioner can be more efficient because the surgical appointment and necessary pre- and post-procedure protocol is less complex and time consuming. Thus there could be more time available for other patients which will in turn generate more revenue and help to grow the practice. An additional advantage is that multiple procedures may be performed during one visit, thus increasing production. It naturally follows that more patient's acceptance of a proposed treatment, coupled with a positive, comfortable, and healthy outcome, will result in confident referrals of new patients to the practice.

When should a laser be used?

The clinician should know the indications for the use of the laser. This textbook will describe all of those in detail. Continuing education will certainly provide suggested techniques and protocols. When reviewing the steps necessary for a procedure, there should be an analysis of how the laser could be used either as an adjunct or as monotherapy. Equally importantly, the instrument and all of the needed accessories should be easily obtained—within reach or stored close by—so that it can be inserted into the procedure. As the clinician continues to utilize the laser, it will become essential in the armamentarium. For some treatments, it can be substituted for other instruments; in other procedures, it can be used adjunctively. Likewise, the experience of repeated use will result in confidence in delivering excellent patient care. Indeed, the laser will become the smart investment that was hoped for during purchase. Figure 1.2 shows a small sampling of clinical procedures where a laser can be used. In every case depicted, the laser was used instead of conventional instrumentation.

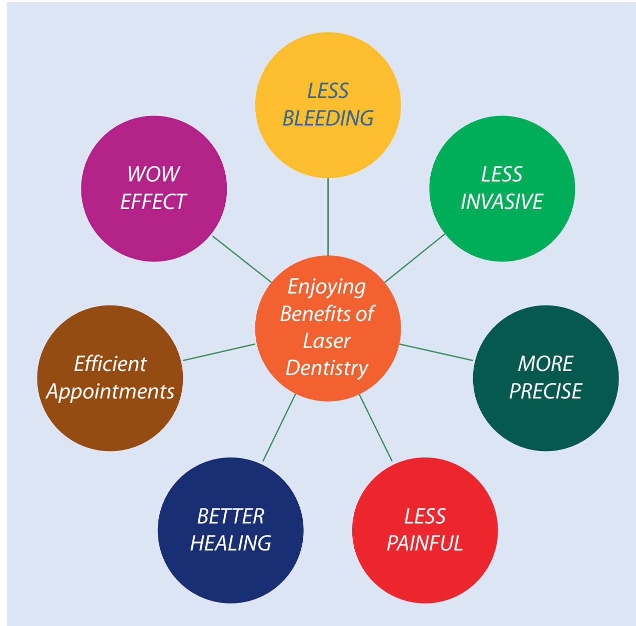
Fig. 1.2 **a** Preoperative view of hyperplastic tissue present during orthodontic therapy. **b** Postoperative view showing tissue removal, with more normal periodontium. **c** A preoperative view of a wide maxillary diastema with frenum involvement. **d** Photo depicting the healed frenum revision, gingivectomy, and good progression of orthodontic alignment. **e** A low-level laser is used for treatment of temporomandibular joint inflammation. **f** Preoperative view of interproximal carious lesions. **g** Immediate postoperative view of the new restorations. Both teeth were prepared with the laser instead of the dental handpiece. **h** Preoperative view of pigmentation on the mucosa. **i** Postoperative view showing the pigment removed. **j** Preoperative view of a benign irritation fibroma. **k** Postoperative view showing healed area

1.9 Limitations of Laser Dentistry

If you are a proficient clinician using a laser, then you can see the almost limitless and enormous possibilities of using them for treatment. However, as with any instrumentation, certain considerations apply. The clinician should be very well trained to judge the disease to be treated. After proper selection of the case, an appropriate decision is to be made on what wavelength, power, or energy density will be used and will be dependent on the absorptive pattern of the target tissue. This of course implies a very thorough understanding of the fundamentals of laser physics, tissue interactions, and the safe use of the device.

There are some disadvantages to the currently available dental laser instruments. They are relatively high cost and require training. Most of the laser emission tips are end-cutting, although there are some radial firing ones available. Nonetheless, a majority of dental instruments are both side- and end-cutting. The laser practitioner will be necessarily required to employ a modification of clinical technique. A laser incision is by definition not as sharp edged as the one made with a scalpel. Furthermore, since sutures are seldom used compared to the one from a surgical blade, a laser wound heals by secondary intention. The patient must be given the appropriate postoperative instructions to correctly care for the area during healing. As mentioned, no single wavelength will optimally treat all dental disease. Accessibility to the surgical area can sometimes be a problem with some current delivery systems, and the clinician must prevent overheating the tissue while attempting to complete a procedure. One additional drawback of the erbium family and 9300 nm carbon dioxide lasers is the inability to remove defective metallic and cast porcelain restorations. Of course, this limitation in some cases could be quite beneficial when treating small areas of recurrent decay around otherwise sound restorations. Sometimes the slower pace of laser soft tissue surgery can lead to tissue charring or carbonization during any surgical procedure. This can be due to a combination of too much average power or moving the laser beam too slowly. Both of those can be corrected with experience. One aspect that should not be ignored is the production of the laser plume which is a by-product of vaporized water (steam), carbon and other harmful molecular particles, and possibly infectious cellular products, which combine to produce a malodorous scent. Maintaining the suction wand within 4 cm of the surgical site to remove as much of the plume as possible is recommended [15, 16].

1.10 Enjoying Benefits of Laser Dentistry



Over the time, the developments in the art and science of dentistry have provided us with the ability to allow the clinician to provide minimally invasive solutions to the patient’s disease. From the incorporation of less invasive treatment of periodontitis to comprehensive cosmetic restorative treatment, the current standard is to conserve as much of the dentition and surrounding structure as possible. With the advancements in innovative materials and new and improved clinical techniques, that goal can be achieved. The rapid use of laser technology has gained popularity in various dental specialties and disciplines including endodontics, prosthodontics, oral and maxillofacial surgery, orthodontics, dental implantology, pediatric dentistry, aesthetic dentistry, and periodontics. It has revolutionized some treatment protocols and is certainly a practice-building tool.

The benefits enumerated above can transform a patient who was previously resistant to conventional treatment plans into a more relaxed and certainly cooperative one. Moreover, the fact is that dental practice can be very physically demanding and stressful during normal patient care. For more special needs patients such as those who are mentally and physically challenged, it is possible for the laser clinician to perform more procedures with efficiency and confidence, while conserving time and respecting the patient's tolerance. Lasers are especially helpful in geriatric patients as it makes the procedure more tolerable and help them overcome some of the barriers in providing dental care to them including severe dental complexity, multiple medical conditions, and diminished functional status. Similarly, laser-assisted pediatric dental treatment can result in a happy, healthy, and trusting child whose parents will appreciate the gentle and efficient care.

In today's digital world, patients interact almost instantly with their multimedia friends, share their experiences and concerns, and better understand diagnoses and treatment options. They are more likely to accept recommendations for treatment, and they certainly are willing to invest in a procedure that they value and that is as comfortable as possible. If a patient's experiences with the laser are positive, then it will invite more referrals. In short, lasers can enable the dentist to render better quality dentistry [17].

Conclusion

We live in a fast-paced world. The practice of dentistry is constantly evolving and there are mainly two main reasons we change: one is that we want to strive to deliver the optimum treatment available for our patients; the other is that we want to keep abreast with the latest and best method to achieve that. Never stop learning or else we shall stop growing. In the present era, it is always important to improve your skills and abilities, and we should continue to learn so that we can continue to grow in knowledge as a lifelong pursuit. Willingness and openness to learn new things is the key to success. Whenever we think we are good, we can be even better.

The first step toward laser dentistry is to seek objective information on all aspects of the instrument and its uses. Eventually, the decision to purchase a laser should be based on sound scientific evidence; your own experience, knowledge, and training; and upon the patient's preference for treatment options.

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Laser and Light Fundamentals

Donald J. Coluzzi

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2

Core Message

The word LASER is an acronym for light amplification by stimulated emission of radiation. The theory was postulated by Albert Einstein in 1916. A brief description of each of those five words will begin to explain the unique qualities of a laser instrument.

Once the laser beam is created, it is delivered to the target tissue. Furthermore, each device has certain controls that the clinician can operate during the procedure.

An understanding of these fundamentals will become the foundation for further elaboration of the basic concepts of how lasers are used in dentistry.

2.1 Light

2.1.1 Origins and Curiosities of Light

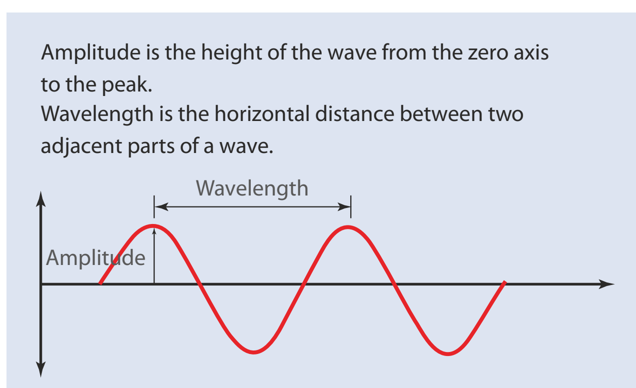
The word light has been used for many centuries, including biblical references such as in the beginning sentences of the Book of Genesis. Early civilization seemed to understand that the cycle of day and night with the sun, the moon, and the stars produced differences in ambient brightness. Historical investigations into the nature of light produced interesting and sometimes conflicting studies. Ancient peoples were curious about this brightness: the Greek philosopher, Pythagoras, began to develop wave equations about 400 B.C. Over a century later, the Greek mathematician Euclid claimed that light is emitted in rays from the eye; he then proclaimed the law of reflection of those waves. It took until 1021 for a mathematician from Basra, Ibn al-Haytham, to correct the concept and prove that light enters rather than emanates from the eye. In addition, al-Haytham postulated that there are tiny particles of energy coming from the Sun that produce light. In 1672, British physicist Isaac Newton was studying the laws of reflection and refraction and concluded that light was made of particles, which he called «corpuscles» [1]. He concluded that light is a combination of seven colored particles—violet, indigo, blue, green, yellow, orange, and red (in keeping with the belief that seven is a mystical number.) Those particles combine to produce white light [2]. A few years later in 1678, the Dutch physicist Christiaan Huygens insisted that light was made up only of waves and published the «Huygens» Principle [3]. As history would have it, both Newton and Huygens were at best half correct.

Over a hundred years later, new discoveries of light emerged. In 1800, William Herschel, a German-born musician and astronomer, moved to England and investigated individual temperatures of the visible colors. From those experiments, he discovered infrared light [4]. Johann Ritter, from a region of Eastern Europe now known as Poland, discovered ultraviolet light in 1801, by observing how the common chemical silver chloride changes color when exposed to sunlight [5]. The British physicist Michael Faraday produced evidence that light and electromagnetism were related [6]. In 1865 his Scottish colleague James Maxwell then explained electromagnetic radiation: that is, electricity, magnetism, and light are in fact interrelated in the same phenomenon [7]. His discovery quantified the different wavelengths of radiation and thus helped to explain our current understanding of the existence of light in more than just the visible spectrum of Newton's colors. In 1895 Wilhelm Roentgen, a German professor of physics, added X-radiation to the electromagnetic spectrum, after studying many experiments from colleagues such as Philipp Lenard and Nikola Tesla [8]. He used the terminology of X to signify an unknown quantity. A theoretical physicist Max Planck, also from Germany, proposed that light energy is emitted in packets he termed quanta in 1900 [9]. He formulated an equation that gave a relationship between energy and wavelength or frequency. In 1905 the German scientist Albert Einstein discovered what he termed the photoelectric effect. He observed that shining light on many metals causes them to emit electrons, and he termed them photoelectrons. He then deduced that the beam of light is not just a wave traveling through space but must also be composed of discrete packets of energy, as described by Planck. Einstein called these tiny particles photons [10], thus crystallizing the particle-wave dual nature of light.

2.1.2 The Duality of Light

Based on the discoveries and arguments over the last three millennia, it can now be stated that light is a form of electromagnetic energy with a dual nature. It behaves as a particle and travels in waves at a constant velocity. The basic packet or quantum of this particle of radiant energy is called a photon [11]; a photon is a stable particle that only exists when moving at the speed of light in a vacuum. By implication of the theory of relativity, it has no mass. When decelerated, it no longer exists, and its energy is transformed.

The wave of photons which travels at the speed of light can be defined by two basic properties, as shown in ◘ Fig. 2.1. The first is amplitude, which is defined the vertical height of the wave oscillation from the zero axis to its peak. This



◘ **Fig. 2.1** A depiction of electromagnetic waves showing the two important quantities of amplitude and wavelength correlates to the amount of energy carried in the wave: the larger the amplitude, the greater the amount of energy available that can do useful work. The second property of a wave is wavelength, which is the horizontal distance between any two corresponding points on the wave. This measurement is very important both in respect to how the laser energy is delivered to the tissue and what the interaction will be. Wavelength is measured in meters, and dental lasers have wavelengths on the order of much smaller units using terminology of either nanometers (10^{-9} m) or microns (10^{-6} m.) As waves travel, they oscillate several times per second, which is termed frequency. Frequency is inversely proportional to wavelength: the shorter the wavelength, the higher the frequency and vice versa.

2.1.3 Properties of Light and Laser Energy

Ordinary light produced by a table lamp, as an example, is usually a white glow. The white color seen by the human eye is really a sum of the many colors of the visible spectrum—for example: red, orange, yellow, green, blue, and violet, as first described by Isaac Newton. The light is usually diffuse, and not well focused.

Laser energy is distinguished from ordinary light by two properties. One is *monochromaticity* which means the generated light wave is a single specific color. For dental instruments, that color is usually invisible to our eyes. Secondly, each wave has *coherency*, identical in physical size and shape along its axis, producing a specific form of electromagnetic energy. This wave is characterized by spatial coherency—that is, the beam can be well defined; the beam's intensity and amplitude follow the Gaussian beam's bell curve in that most of the energy is in the center, with rapid drop-off at the edges. There is also temporal coherency, meaning that the single wavelength's emission has identical oscillations over a time period. The final laser beam begins in collimated form and can be emitted over a long distance in that fashion. However, beams emanating from optical fibers usually diverge at the tip. By using lenses, all the beams can be precisely focused, and this monochromatic, coherent beam of light energy can accomplish the treatment objective.

Using a household fixture as an example, a 100-watt lamp will produce a moderate amount of light and proportionally more heat in a room. On the other hand, two watts of laser power can be used for a precise excision of an irritation fibroma, providing adequate hemostasis on the surgical site without disturbing the surrounding tissue.

2.2 Emission

2.2.1 Spontaneous Emission

In 1913, Niels Bohr, a Danish physicist, developed his model of an atom, applying the quantum principle of Planck. He proposed distinct energy orbits or levels of energy around the nucleus of that atom. Bohr found that an electron could «jump» to a higher (and unstable) level by absorbing a photon and then the electron would return to a lower (more stable) level while releasing a photon [12]. He termed this spontaneous emission. The nuance to this emission is that, since there are several possible orbital levels in the atom, the wavelength of the photonic emission would be determined by the energy of the emitted photon, according to Planck's equation. It should also be noted that the emitted photon will likely have a random direction and phase. In more simple terms, spontaneous emission can be demonstrated when a conventional electric light bulb is switched on. The filament glows brightly emitting light and heat as the electrons are excited to higher energy states and then return to their ground conditions. Different broad groups of wavelengths (e.g., white light) will be produced during emission from the higher energy levels. A light-emitting diode also produces spontaneous emitted light by using a flow of energized electrons recombining on the positive side of the wafer to produce luminescence. The color (wavelength) of the emitted light will depend on the chemical composition of the diode wafer [13].

2.2.2 Stimulated Emission

In 1916 Albert Einstein postulated the theory of lasers [14]. Using Bohr's model, he postulated that during the process of spontaneous emission, an additional photon, if present in the field of the already excited atom with the same excitation level, would stimulate a release of two quanta. These would be identical in phase, direction, and wavelength. In addition, these emission photons would share monochromatic and coherent properties—thus a laser is born.

2.3 Amplification

Amplification is part of a process that occurs inside the laser. Once stimulated emission occurs, the process should theoretically continue as more photons enter the field both to excite the atoms and to interact with the excited photons returning to their ground state. One could imagine a geometric progression of the number of emitted photons, and, at some point, a population inversion occurs, meaning that a majority of atoms are in the elevated rather than the resting state. As Bohr implied, there can be several potential levels of energy available in most atoms. Having multiple levels (more than two) would aid in maintaining a population inversion because there would be no possibility of equal rates of absorption back into the ground state and stimulated emission. This amplification effect can only occur if there is a constant and sufficient source of energy, which is supplied by a pumping mechanism.

2.4 Radiation

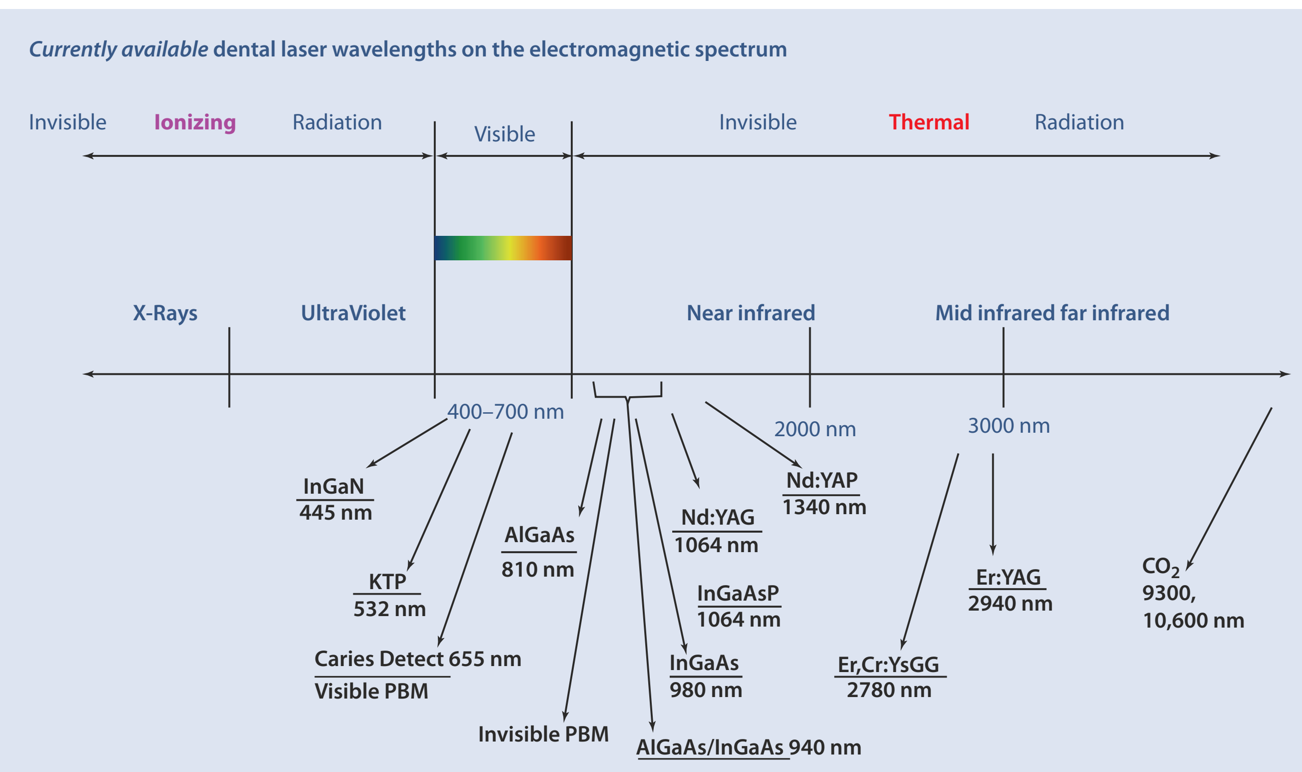
The basic properties of a wave were discussed in ▶ Sect. 2.1.2. The entire array of wave energy is described by the electromagnetic spectrum (ES)—in other words, all frequencies and wavelengths of radiation [15]. The ES has several regions with rough boundaries of wavelength or frequency. There are seven general classes, with increasing order of wavelength to describe the radiation: gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, microwaves, and radiofrequency waves. These wavelengths range in size: gamma rays measure about 10^{-12} m; on the other end of the spectrum, radio waves have wavelengths up to thousands of meters. The ES can be more broadly divided into two divisions with gamma rays, X-rays, and ultraviolet light in a group termed ionizing radiation, while all the other wavelengths are termed nonionizing. Ionizing simply means that the radiant wave has enough photon energy to remove an electron from an atom, and those wavelengths can cause mutagenic changes in cellular DNA. The human eye responds to wavelengths from approximately 380–750 nm, with those two numbers representing deep violet and dark red, respectively. That range is termed the visible spectrum. The term thermal radiation can be applied to many wavelengths. For example, an infrared lamp generates heat; the sun provides both light and heat; and the ionization present in plasma can also produce high temperatures.

The energy of a photon can be calculated using the equation from Max Planck. It states that the energy is directly related to the frequency of wave or inversely proportional to the wavelength. Thus, gamma or X-radiation with very short wavelengths (ranging from 10^{-12} to 10^{-10} m) has very high energy, while radio waves (approximately 3 m to 1 km) have significantly lower energy by comparison.

2.5 Components of a Laser

Identifying the components of a laser instrument is useful in understanding how the energy is produced. For dentistry, there are two basic types of lasers: (1) one that operates as a semiconductor and is compact in size and (2) one that has distinct components that, when assembled, occupy a larger footprint. The first type is generally known as a diode laser; the second type encompasses all other lasers. Both of these types share common features—an active medium, a pumping mechanism, and a resonator. In addition, a cooling system, controls, and a delivery system complete the laser device.

All available dental laser devices have emission wavelengths of approximately 0.45 microns, or 450 nanometers to 10.6 microns or 10,600 nanometers. That places them in either the visible or the invisible nonionizing portion of the electromagnetic spectrum. ◘ Figure 2.2 is a graphic depiction of those lasers on a portion of the electromagnetic spectrum.



◘ **Fig. 2.2** A graphic showing the currently available dental wavelengths' position on the visible and invisible nonionizing portion of the electromagnetic spectrum. Note that most of the wavelengths also include the composition of the active medium which produces that wavelength. PBM is an abbreviation for photobiomodulation, and those instruments use various active media

2.5.1 Active Medium

Lasers are generically named for the material that is being stimulated; such material is called the active medium. As mentioned above, the atoms (or molecules) of that material absorb photonic energy and then begin to spontaneously emit. Subsequently under the right conditions, the process of stimulated emission will begin. Common materials for dental lasers can be broadly designated as one of three types: a container of gas, a solid-state crystal, or a semiconductor. The active medium is at the center or core of the laser, termed the optical cavity.

Gas Lasers

The most common gas dental laser is carbon dioxide, which contains a gas mixture of carbon dioxide, helium, and nitrogen. Helium is not directly involved in the lasing process, but nitrogen does interact with the excitation process and ultimately transfers that energy to the carbon dioxide molecules.

A second gaseous laser is the argon ion instrument. A tube of this noble gas when excited can produce several radiant emissions, the most common being a visible blue and blue-green beam of collimated light. The physical demands of power and cooling have rendered this laser to a very limited application in dentistry.

One of the first lasers developed was the helium-neon gas laser, which has a visible red color emission.

Solid-State Crystal Lasers

Various solid-state crystals are used in dental lasers. The host material is composed of yttrium aluminum garnet (YAG), yttrium aluminum perovskite (YAP), or yttrium scandium gallium garnet (YSGG.) Any of these can then be «doped» with ions of neodymium, erbium, and chromium. The resulting designation would be written as Nd:YAG, for example, which would be a neodymium-doped yttrium aluminum garnet crystal.

Semiconductor Dental Lasers

A semiconductor laser utilizes the basic positive-negative (p-n) junction of everyday electronic circuits—the diode: that is, a two pole oppositely charged wafer. The flow of negatively charged electrons into the positively charged holes diffuses across the junction. The lasing action takes place between the charged layers, called the depletion region. This small rectangle will emit coherent and monochromatic light, but collimation must be performed by an external lens. Current diode lasers consist of various atomic elements in binary, ternary, or quaternary form arranged in a wafer-like structure. Examples would be gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), indium gallium arsenide (AlGaAs), and indium gallium arsenide phosphate (InGaAsP.) These elements provide a checkerboard-like crystalline structure to allow lasing to occur; the usual silicon-based semiconductor is not used because of its symmetry. The single diode wafer just described is then arranged in a linear array for cooling, and the number of wafers determines the power output.

2.5.2 Pumping Mechanism

Surrounding this optical cavity with its active medium is an excitation source, known as the pumping mechanism. Pumping is used to transfer energy into the optical cavity, and that energy must be of sufficient quantity and duration so that the occupation of a higher energy level exceeds that of a lower level. This condition is called a population inversion and it allows amplification to occur.

Although the above-described process occurs rapidly, it still takes some time. Most lasers are described as three-level or four-level. A three-level system describes the basic concept: level one would be the stable, ground state, sometimes designated as energy level zero, a pumped level (energy level 2), and a lasing level (energy level.) Despite rapid decay from level 2, with enough pumped energy, there will be a population inversion between level 1 and 2. A four-level system is similar with the pumped level designated as 3, the upper lasing level as 2, and the lower lasing level as 1. The difference between these two lasing levels will aid in producing a population inversion. Certain active media operate as either three- or four-level systems.

In the laser industry, there are a wide variety of pumping mechanisms. The pumping of dental lasers is usually performed with optical devices—high-power lamps or lasers or by electricity—either with direct current mains or with electronic modulation of alternating current. Currently diode lasers are electronically pumped; solid-state crystal lasers use high-powered strobes (flash lamps); and carbon dioxide lasers can be operated with AC or DC current or radiofrequency (RF) pumping methods. As a variation in pumping, one form of carbon dioxide technology uses very high pressure gas and many electrodes along the length of the gas tube. This is known as a transversely excited atmosphere (TEA) laser.

2.5.3 Resonator

The resonator, sometimes known as the optical cavity or optical resonator, is the laser component surrounding the active medium. In most lasers, there are two mirrors one at each end of the optical cavity, placed parallel to each other, or in the case of a semiconductor, either a cleaved and polished surface exists at the end of the wafer or there is reflection within the wafer. In all cases, these mirrored surfaces then produce constructive interference of the waves: that is, the incident wave and the reflected wave can superimpose on each other producing an increase in their combined amplitude. Clearly some waves will not combine and will soon lose their intensity, but others will continue to be amplified in this resonator. With the mirror system, this continued effect will help to collimate the developing beam. As mentioned previously, a diode laser collimation occurs externally.

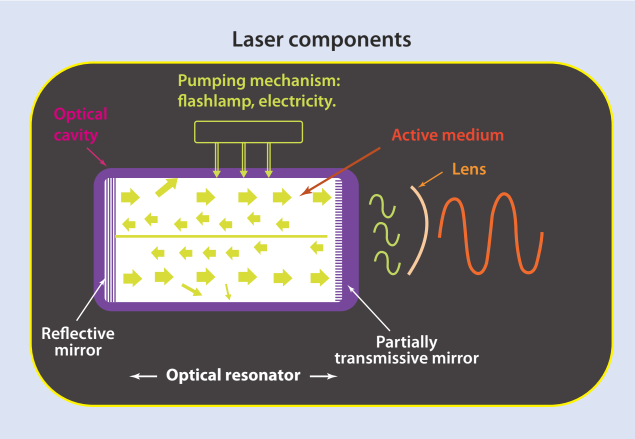


Fig. 2.3 General schematic of a laser. The active medium can be solid state (like Nd:YAG) or a gas (like carbon dioxide.) The pumping mechanism provides the initial energy, and the resonator consists of the active medium and axial mirrors. One mirror is totally reflective and the opposite one is partially transmissive. When a sufficient population inversion is present, laser photonic energy is produced and focused by lenses

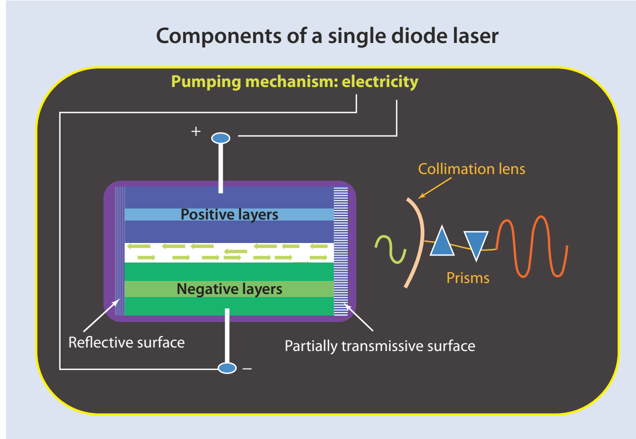


Fig. 2.4 Schematic of a single (individual) diode laser wafer. There are layers of positively and negatively charged compounds, pumped by electricity. The white layer with the yellow arrows represents the active layer where stimulated emission takes place. In this example, a reflective coating is applied to opposite ends of the wafer. In the right area are examples of lenses and prisms that would be placed at the emission end of an array of wafers to produce useful powers of diode laser photonic energy

2.5.4 Other Mechanical Components

A cooling system is necessary for all lasers, and higher output power requires increasing dissipation of the heat produced by pumping and stimulated emission. Air circulation around the active medium can control the heat, especially with diode lasers; the sold state crystal lasers and some gaseous lasers require additional circulating water cooling.

Focusing lenses are employed for each beam, and in the case of diode lasers, for collimation. The delivery system will ultimately determine the diameter of the emitted wavelength.

The laser control panel allows the user to adjust the parameters of energy emission, along with a foot or finger switch for «on-off» or variable output operation on some devices.

2.5.5 Components Assembled

Laser energy is produced because the active medium is energized by the pumping mechanism. That energy in the form of photons is absorbed into the active medium, raising its atomic electrons to higher orbital levels. As the electrons return to their stable ground state, photons are emitted while other entering photons can produce stimulated emission. The resonator allows more numbers of these photonic interactions and will continue the amplification process.

The operation is temperature controlled, the beam is focused, and the clinician can control the laser used. Figure 2.3 shows a graphic of a solid-state laser such as an Nd:YAG or a gas laser such as carbon dioxide, and Fig. 2.4 depicts a schematic of a single semiconductor laser wafer. Tables 2.1 and 2.2 provide details of the currently available dental lasers with their active medium, common usage, and emission wavelength.

Table 2.1 Currently available visible spectrum dental lasers

Type of laser and emission spectrum	General uses	Active medium	Wavelength	Emission mode
Semiconductor diode, visible blue	Soft tissue procedures, tooth whitening	Indium gallium nitride	445 nm	CW, GP
KTP solid-state visible light emission	Soft tissue procedures, tooth whitening	Neodymium-doped yttrium aluminum garnet (Nd:YAG) and potassium titanyl phosphate (KTP)	532 nm	CW, GP
Low-level lasers, visible red light emission semiconductor or gas lasers	Photobiomodulation therapy (PBM), photodynamic therapy (PDT), or carious lesion detection.	Variations of gallium arsenide or indium gallium arsenide phosphorus diodes Helium-neon gas	600–670 nm 632 nm	CW, GP

The type of laser and its emission spectrum is listed in column 1; column 2 indicates the general usage in dentistry; column 3 describes the active medium; column 4 shows the emission mode with the following abbreviations: *CW* continuous wave, *GP* acquired pulse

Table 2.2 Currently available invisible infrared dental lasers

Type of laser and emission spectrum	General uses	Active medium	Wavelength	Emission mode
Low-level lasers, (invisible) near infrared	Photobiomodulation therapy (PBM) , photodynamic therapy (PDT)	Variations of aluminum gallium arsenide diodes	800–900 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Aluminum gallium arsenide	800–830 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Aluminum/indium gallium arsenide	940 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Indium gallium arsenide	980 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Indium gallium arsenide phosphorus	1064 nm	CW, GP
Solid state, near infrared	Soft tissue procedures	Neodymium-doped yttrium aluminum garnet (Nd:YAG)	1064 nm	FRP
Solid state, near infrared	Soft tissue procedures, endoscopic procedures	Neodymium-doped yttrium aluminum perovskite (Nd:YAP)	1340 nm	FRP
Solid state, mid infrared	Soft tissue procedures, hard tissue procedures	Erbium, chromium-doped yttrium scandium gallium garnet (Er,Cr:YSGG)	2780 nm	FRP
Solid state, mid infrared	Soft tissue procedures, hard tissue procedures	Erbium-doped yttrium aluminum garnet (Er:YAG)	2940 nm	FRP
Gas, far infrared	Soft tissue procedures, hard tissue procedures	Carbon dioxide (CO_2) laser, with an active medium isotopic gas	9300 nm	FRP
Gas, far infrared	Soft tissue procedures	Carbon dioxide (CO_2) laser with an active medium of a mixture of gases	10,600 nm	CW, GP, FRP

The type of laser and its emission spectrum is listed in column 1; column 2 indicates the general usage in dentistry; column 3 describes the active medium; column 4 shows the emission mode with the following abbreviations: *CW* continuous wave, *GP* acquired pulse, *FRP* free-running pulse

2.6 History of Laser Development

After Einstein's laser theory was published, experiments to build a device didn't appear until the 1950s. Charles Townes of Columbia University in New York began working with a microwave amplification in 1951. In 1957 another Columbia graduate student Gordon Gould described in his laboratory notebook the basic idea of how to build a laser. That was considered the first time the term was used. The first laser was built by Dr. Theodore Maiman in 1960 at Hughes laboratory [16]. He used a 1 × 2 cm synthetic ruby cylinder for the active medium and photographic flash lamps for the pumping mechanism and produced a brilliant red light pulsed emission. At the end of that year, three other scientists at Bell labs developed the helium-neon gas laser with a continuous output of red light. Other wavelength instruments were rapidly developed during that decade. Notable is the 1964 invention of the carbon dioxide laser, with a 10.6 micron wavelength, by Kumar Patel, and, in the same year, the Nd:YAG laser was built by Joseph Geusic and Richard Smith, all at Bell labs. In the spring of 1970, a team of Russian and American scientists independently developed a continuous wave room temperature semiconductor laser [17]. The first laser specifically designed for dentistry was marketed in 1989 [18].

2.7 Laser Delivery Systems

Laser energy can be delivered to the surgical site by various means that should be ergonomic and precise. There are three general modalities:

- **An optical fiber**
- **A hollow waveguide**
- **An articulated arm**

■ Fig. 2.5 An optical fiber assembly

■ Fig. 2.6 A hollow waveguide assembly

2.7.1 Optical Fiber

An optical glass fiber usually made of quartz-silica. This glass core conducts the laser beam along its length. A thin polyamide coating surrounds the core to contain the light, and a pliable thicker jacket covers both to protect the integrity of the system. A specific connector couples the fiber to the laser instrument; a handpiece and tip are added to the operative end. ■ Figure 2.5 shows a typical optical fiber assembly.

2.7.2 Hollow Waveguide

A hollow waveguide is a jacketed flexible tube. The internal surface has a reflective coating like silver iodide to allow the beam's transmission. A series of protective jackets complete the system. The waveguide is connected to the emission port on the laser, and a handpiece and optional tip are connected to the operative end. ■ Figure 2.6 shows a typical hollow waveguide assembly.

2.7.3 Articulated Arm

An articulated arm consists of a series of reflective hollow tubes with pivoting internally mirrored joints along its length. The arm has a counterweight to provide ease in movement. The laser emission port is coupled with the first tube, and a handpiece and optional tip are added to the operative end of the distal tube. ■ Figure 2.7 shows the basic arm assembly.

Shorter wavelength instruments, such as KTP, diode, and Nd:YAG lasers, have small, flexible fiber-optic systems with bare glass fibers or disposable tips that deliver the laser energy to the target tissue. A few low-powered diode lasers are offered as handheld units with disposable glass tips.

■ Fig. 2.7 An articulated arm delivery system

Erbium devices are constructed with more rigid glass fibers, semiflexible hollow waveguides, or articulated arms. Carbon dioxide lasers use waveguides or articulated arms. Some of the erbium systems employ small quartz or sapphire tips, and carbon dioxide instruments employ metal cylinders that attach to the handpiece. All of the tips are used for contact with target tissue, although they can direct the beam toward the tissue when not directly touching it. Other lasers in these wavelengths use tip less (and therefore noncontact) delivery systems. In addition, some procedures demand that a clinician not directly contact the tissue. In addition, the erbium lasers and the 9.3 micron carbon dioxide laser employ a water spray for cooling hard tissue.

2.7.4 Contact and Noncontact Procedures

All conventional dental instrumentation, either hand or rotary, must physically touch the tissue being treated, giving the operator instant feedback. As mentioned, dental lasers can be used either in contact or out of contact. Clinically, a laser used in contact can provide easy access to otherwise difficult-to-reach areas of tissue. The fiber tip can easily be inserted into a periodontal pocket to remove small amounts of granulation tissue, for example. In noncontact, the beam is aimed at the target at some distance away from it. This modality is useful for following various tissue contours, but the loss of tactile sensation demands that the surgeon pays close attention to the tissue interaction with the laser energy.

The active beam is focused by lenses. With the hollow waveguide or articulated arm, there will be a precise spot at the focal point where the energy is the greatest, and that spot should be used for incisional and excisional surgery. For the optic fiber, the focal point is at or near the tip of the fiber, which again has the greatest energy. When the handpiece is moved away from the tissue and away from the focal point, the beam is defocused and becomes more divergent. At a small divergent distance, the beam can cover a wider area, which would be useful in achieving hemostasis. At a greater distance away, the beam will lose its effectiveness because the energy will dissipate. This concept will be further discussed in ► Sect. 2.8.

2.7.5 Aiming Beam

All the invisible dental lasers are equipped with a separate aiming beam, which can either be laser or conventional light. The aiming beam is delivered coaxially along the fiber or waveguide and shows the operator the exact spot where the laser energy will be focused.

2.8 Emission Modes

There are two natural modes of wavelength emission for dental lasers, based on the excitation source: continuous wave and free-running pulse. A subset of continuous wave mode is a gated pulsed emission, where there is some means of modification performed after the beam is initially generated.

2.8.1 Continuous Wave

Continuous wave emission means that laser energy is emitted continuously when the laser is switched on and produces constant tissue interaction. These lasers are pumped with a constant direct current electrical field source. KTP, diode, and older model CO_2 lasers operate in this manner. The energy and/or power have a level output.

2.8.2 Free-Running Pulse

Free-running pulse emission occurs with very short bursts of laser energy due to a very rapid on-off pumping mechanism. Two examples are a high-powered strobing lamp or a radiofrequency electronic field. The usual pulse durations of energy can be measured in microseconds, and there is a relatively long interval between pulses. The power produced has a high peak and low average level, which will be discussed in ► Sect. 2.9. Nd:YAG, Nd:YAP, Er:YAG, and Er,Cr:YSGG and some carbon dioxide devices operate as free-running, direct pulsed lasers.

2.8.3 Gated Pulsed Mode

Some laser instruments are equipped with a mechanical shutter with a time circuit or a digital mechanism to produce pulsed energy. Pulse durations can range from tenths of a second to several hundred microseconds. Some diode and carbon dioxide lasers have these gated pulses from their continuous wave emission. There can be high peak and low average power levels produced.

Another method to produce very short pulses is called Q switching (the Q indicates the quality factor of the optical resonator.) An attenuating mechanism modulates the rate of stimulated emission, while the pumping mechanism continues to provide energy into the resonator. When the Q switch is turned off (opened), the result is a very short pulse of light, on the order of tens of nanoseconds. Peak powers can be very high.

Alternatively, an acousto-optic modulator can be placed in the laser cavity to ensure that the phases of emission all constructively interfere with each other. This is called mode-locking and can produce pico- or femtosecond pulse durations with resulting extremely high peak powers.

Current dental lasers do not utilize Q switching or mode-locking emission modes.

2.9 Terminology

The laser instrument's wavelength has a unique and unchangeable photon energy emission. However, the clinician can adjust various parameters of that emission from both the control panel and the handpiece's position on the target tissue. Throughout the remainder of this book, various terms will be used to describe the laser procedures. The Glossary at the end of this chapter contains many of the terms and definitions that are standard for lasers.

2

Table 2.3 Important terminology for laser use

Term	Definition	Abbreviation
Energy	The ability to do work	J (joule) or mJ (millijoule)
Fluence	Energy per area	J/cm^2
Power	Work performed over time	W (watt)
Power density	Power per area	W/cm^2
Beam size	The area of the projected laser beam on the tissue	(Usually measured in microns or millimeters)

Table 2.3 describes the fundamental terms that are common notations found in clinical procedures. A few of those terms will be described in more detail in this section.

2.9.1 Energy and Fluence

Energy is a fundamental physics term defined as the ability to do work. This energy is usually delivered in a pulse. A joule (J) is a unit of energy; a useful quantity for dentistry is a millijoule (mJ), which is one-one thousandth of a joule. Pulse energy is therefore the amount of energy in one pulse.

Fluence is a measurement of energy per area and is expressed as J/cm^2. This is also known as energy density. Procedures on different dental tissues will require various fluences for both efficiency and safety.

2.9.2 Power and Power Density

Power is the measurement of work completed over a period of time and is measured in watts (W.) One watt equals 1 joule delivered for 1 s.

Power density is the measurement of power used per unit of area and is expressed as W/cm^2. Alternate terms are intensity or radiance.

2.9.3 Pulses

Except for continuous wave operation, all lasers can produce pulsed emission; that is, several bursts of energy can occur in a second. The number of pulses per second (pps) is the usual term applied, and an alternate word is hertz. That word could be confused with the description of the number of cycles per second of alternating electrical current.

Pulse Duration, Pulse Interval, and Emission Cycle

The length of each pulse is called the pulse duration or sometimes pulse width and can be as short as one microsecond (10^{-6} s.) The pulse interval is that time period between the pulses, when no laser energy is emitted. The emission cycle is the ratio, usually expressed as a percentage of the individual pulse duration to the total time of that pulse duration plus the subsequent pulse interval. In other words, if the pulse duration is 0.5 s and the pulse interval is 0.5 s, that is one pulse per second and the emission cycle is 50%. The emission cycle is sometimes referred to as the duty cycle. Similar to hertz, that similarity is unfortunate since the phrase duty cycle actually refers to how long on a device can remain on and working before it must be switched off for cooling.

2.9.4 Average and Peak Power

Average power is what the tissue experiences during the duration of the procedure. Peak power is the power of each pulse. Obviously, with continuous wave lasers, there is really no peak power. For any pulsed laser, the average power will be less than the peak power.

The calculation of peak power is the result of dividing the pulse energy by the pulse duration. For example, a 100 mJ pulse with a duration of 100 μs would have a peak power of 1000 W. This a common peak power achieved in free-running pulsed dental lasers. However, those same lasers are generally used with a low pulses per second parameter, which means that the pulse interval is relatively large. This results in a correspondingly low percentage emission cycle. Using the above example of a pulse duration of 100 μs at 50 pulses per second, the total emission time is 5/1000 of a second, which means the total pulse interval is 995/1000 of a second. The duty cycle is then calculated at approximately 1%. Figure 2.8 shows a graphic depicting the relationship between peak and average power with basic laser parameters.

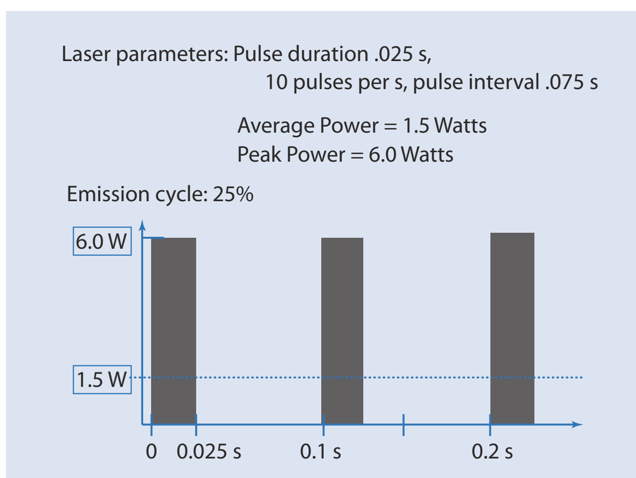


Fig. 2.8 This graphic shows the relationship between peak and average power along with the emission cycle. The pulses of laser energy are depicted in *dark gray* bars. The individual pulse duration is 0.025 s and the pulse interval is 0.075 s. Each pulse has a peak power of 6 watts, but the average power is 1.5 watts, due to the emission cycle of 25%

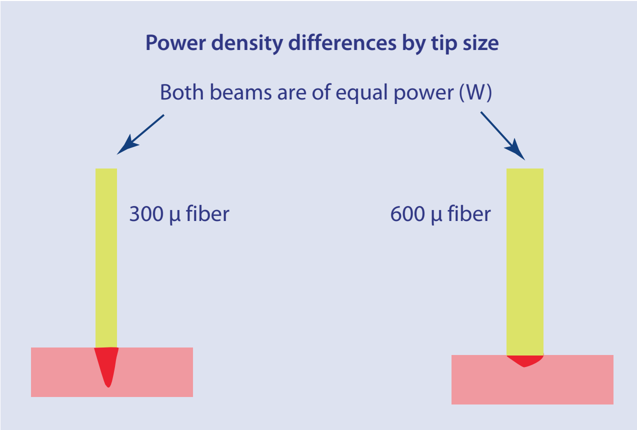


Fig. 2.9 This graphic shows the difference between power density areas using a 300 micron tip/beam size and a 600 micron tip/beam size. The smaller fiber has a larger area of interaction because of the larger power density calculation

2.9.5 Beam Size

This is the area of the photonic emission that will interact with the target tissue. Lasers that employ tips have their nominal size indicated on the tip, and noncontact lasers also have an area of focus. Laser tips are available in several diameters; typical sizes are 200, 300, 400, and 600 microns. Other tip less lasers can produce beam sizes with similar measurements. Clearly, the fluence and power density measurements will be based on that beam size. As mentioned previously, the laser beam will diverge at a prescribed angle from a quartz or sapphire tip, increasing its area. Likewise a focused beam from a tip less delivery system will have a larger area when the beam is defocused. If the average power remains the same, both the fluence and the power density will be reduced.

Conversely, choosing a smaller diameter tip or producing a smaller focused area would increase the fluence or power density with the same laser output setting. This could affect the tissue interaction. Figure 2.9 is a graphic showing how the difference in tip sizes would affect the power density.

2.9.6 Hand Speed

In addition to the above parameter adjustments, an important principle of laser use is the speed at which the beam moves on the target tissue. A slower speed will increase the power density because of the longer time the energy remains in the tissue and could result in a larger area of interaction. This may or may not be a desirable effect, especially if the treatment objective is a minimally invasive procedure. Figure 2.10 shows a laboratory comparison of hand speed for soft tissue incision.

Fig. 2.10 An 810 nm diode laser with a 400 micron contact fiber was used at 1.0 W continuous wave for both incisions on a porcine maxilla specimen. The left incision was made with a faster vertical movement than the right incision. The left incision is narrower; the right incision is wider and more ragged and produced a higher temperature in the tissue. Thus, the power density was larger for that incision

Summary
This chapter provided details of light and lasers. From basic experiments with light to the sophisticated development of different instruments, it should be clear that laser photonic energy can be precisely produced and controlled to be used for dental procedures.

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Laser–Tissue Interaction

Steven P.A. Parker

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3

Core Message

The potential for laser–tissue interaction forms the basis of the usefulness of predictable employment of laser photonic energy as an adjunct to clinical dental and oral therapy. Appreciation of the underlying mechanisms together with acknowledgement of limitations will help the clinician to provide laser therapy and minimize collateral damage.

There is an often-cited belief that in order to obtain benefit from laser photonic energy irradiation of target tissue, there must be absorption of the energy. Such understanding has merit but not entire truth. Owing to the multistructural nature of oral hard and soft tissue, the possibility of incident photonic energy reacting in a definite, predictable and exclusive manner with target tissue molecules is flawed through the very nature of the varying structures. Interaction may be a combination of surface, deeper, scattered and refracted energy distribution, and true absorption of power values predicated through laser control panel selection may be impossible to achieve because of the varying interactive phenomena that may occur.

All oral tissues are receptive to laser treatment, but the biophysics governing laser–tissue interaction demands a knowledge of all factors involved in the delivery of this modality. Through this knowledge, correct and appropriate treatment can be delivered in a predictable manner.

This chapter looks at the concepts of electromagnetic energy distribution within oral hard and soft tissue and examines the potential for true photonic energy ablation of target molecules. Prime concepts of photothermal action as a pathway to tissue change are explained, and adjunctive spatial and temporal components of the incident beam and the effects of such variance are explored.

The inconsistencies of laser–tissue interaction continue to pose some difficulty for the dental clinician; however, the development of many laser machines, amounting to a facility to produce laser photonic energy at several wavelengths between the visible and far-infrared areas of the electromagnetic spectrum, addresses many of the inconsistencies.

3.1 Introduction

Our understanding of the concepts of color helps to define the interaction of an incident beam of multiwavelength (λ) electromagnetic (EM) energy – the so-called white light – with a target structure. Human interpretation of «light» as a concept is limited to the ability of the retina to respond to this energy and the visual cortex to correlate stimulation in terms of a very limited range of the EM spectrum (λ 350–750 nm), termed the «visible spectrum.» White light is seen in nature as the consequence of solar energy that filters through the many layers of the earth's atmosphere or the emission of a man-made incandescent light source. «Light waves» that arise from such sources are multidirectional (not in phase – incoherent) and of multiple energy values.

The fundamental theories on light of the latter nineteenth and early twentieth centuries – notably work of Maxwell, Planck, Hertz, Einstein and Bohr – provided a coalescence of the prevailing opinions of light being composed of either particles or waves. Newton, through his «Corpuscular» theorem [1], in which light traveled as discrete packets («corpuscles»), was at variance with earlier work of Huygens. Popular acceptance of a predominant belief in light propagation by waves reemerged in the early eighteenth century England with the slit experiments of Thomas Young [2]. The confirmation that light energy was a form of electromagnetic (EM) radiation, capable of causing a photoelectric effect with certain metals, proposed a duality of existence for «packets» of light energy. Einstein is attributed [3] with providing the annotation «photon» (one quantum – smallest unit – of electromagnetic energy is called a photon (origin Greek «φως», meaning «light»)) and, with others listed before, provided an understanding that photonic energy is a form of energized EM radiation, with each photon traveling at the speed of light (approx. 300×10^6 m/s) in a sinusoidal wave pattern. From this it is fundamental to our understanding of the so-called laser–tissue interaction that EM energy in its many forms is interrelated and the energy contained therein is capable of conversion to thermal and sonic equivalent within target tissue, through the law of conservation of energy (sic energy cannot be created or destroyed, just transformed from one form to another).

In determining a prescribed level of energy-derived physical change in target oral tissue, it is necessary to appreciate the quantity of incident energy, the degree of positive interaction and the potential for energy conversion. Inherent in every incident laser beam is the photonic energy.

Laser «light» is considered unique in that, unlike other forms of light (sunlight, incandescent, LED irradiation), there are two inherent properties – monochromaticity and coherence. The single wavelength concept is founded in the physics of laser EM propagation, and using the Einstein/Bohr postulations, the delivery of laser irradiation is in sinusoidal waveform with successive waves in phase – the so-called wave coherence. Additional man-made configuration of the photonic energy produced can provide high-density beam spatial density over distance – this is termed «collimation.» In terms of the benefits of laser–tissue interaction due to these properties, the monochromatic absorption of a chosen laser, together with the coherence of the beam, will offer selective tissue interaction of high quality; the collimation and ability to focus the beam will define a degree of accuracy and power density (PD).

Figure 3.1 provides examples of predictable laser–tissue interaction.

3.2 Photonic Energy

The emission of a single photon from an atom is the result of a shift in the energy status of that origin. Plank proposed all matter existed in a state of energy relative to extremes of a lower (ground) state and a higher (energized) state, commensurate with entropic physical form [4]. Boltzmann, through his theories on thermodynamics [5], readily

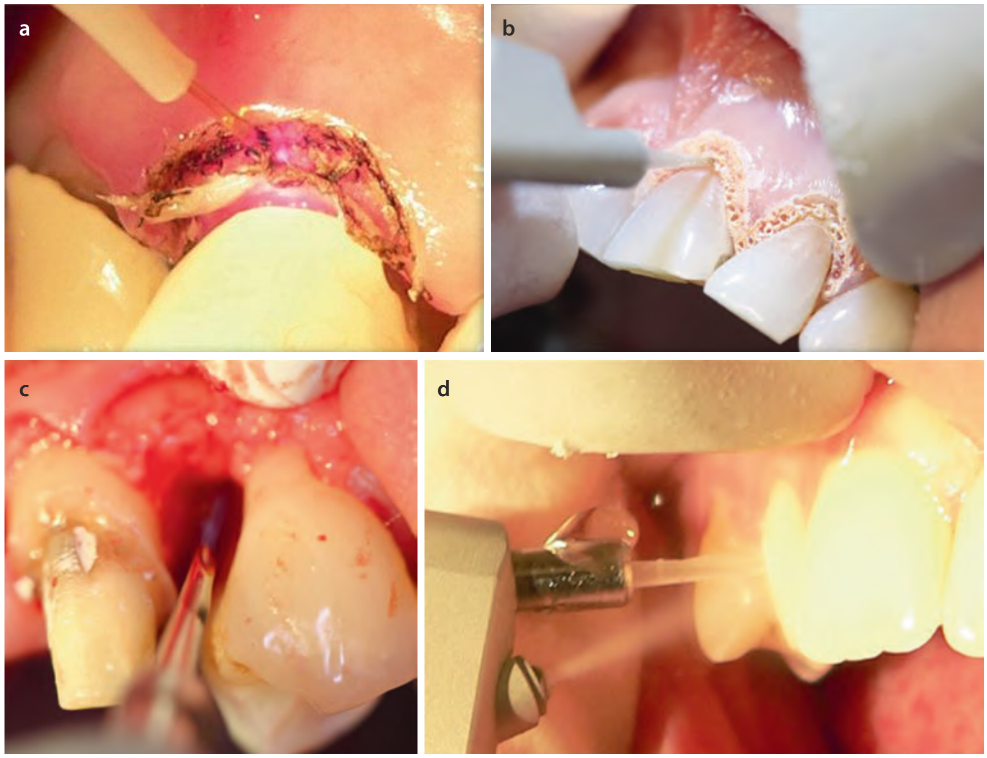

Fig. 3.1 Laser-assisted oral tissue surgery is photothermal in nature. Incident (photonic) energy is absorbed by target tissue elements (chromophores), relative to the laser wavelength. This leads to rapid temperature rise, protein denaturation, and water vaporization. This constitutes an example of photoablation

accounted a direct relationship between matter, energy and temperature. Put simply, an electric light filament at room temperature is a dull, inert wire but rapidly heats when energized by an electric circuit. The resistance of the wire leads to thermal conversion of the electrical (EM) energy. At this induced higher energy state of the light filament, the volatility of constituent electrons gives rise to higher thermal energy and the emission of such energy as light.

Laser photonic energy assumes the production of high-energy photons from an energized source, whereby each photon scribes an identical waveform and each photon has identical energy value. Plank and Einstein had established an inverse relation between wavelength and photonic energy, a direct proportional relationship between photonic energy and frequency, and Niels Bohr paved a way for the «quantum» (amount) nature of emitted photons to be calculated; thus, it provided a predictable base for the development of the MASER and optical-MASER or LASER.

The energy of emitted photons is expressed in Joules or, more conveniently, eV (energy derived by acceleration through a PD of 1 volt). Since photonic energy is related to wavelength (λ), photons emitted from different sources will have differing energy values. Basic calculation can be derived through:

$\lambda = hc/E$,

where h = Plank's constant, c = speed of light and E = photon energy in eV.

1 eV = 1.602×10^{-19} J and it is possible to evaluate energy-equivalent values for the many laser wavelengths; for example, photons of wavelength 1240 nm (near infrared) equate to an eV value of 1.0, whereas an eV value of 2.0 is 621 nm (visible red) and eV 0.13 equates to 9600 nm.

Table 3.1 Commonly used laser wavelengths associated with dental treatment

(eV)	Laser	λ (nm)
2.4	KTP	532
2.0	He-Ne	633
1.6	Diode	810
1.2	Nd:YAG	1064
0.4	Er:YAG	2940
0.1	CO_2	10,600

Photonic energy and wavelength are inversely proportional.
With ascending numerical value of wavelength, the corresponding photonic energy (expressed in electron volt – eV) is reduced
With ascending numerical value of wavelength, the corresponding photonic energy (expressed in electron volt – eV) is reduced

Table 3.1 provides an overview of laser wavelengths commonly used in dentistry with corresponding photonic values:

3.3 Photonic Energy and Target Molecular Structures

A simplistic look at one of the many graphic representations of the relationship of target tissue elements, incident laser wavelengths and relative absorption potential, would suggest

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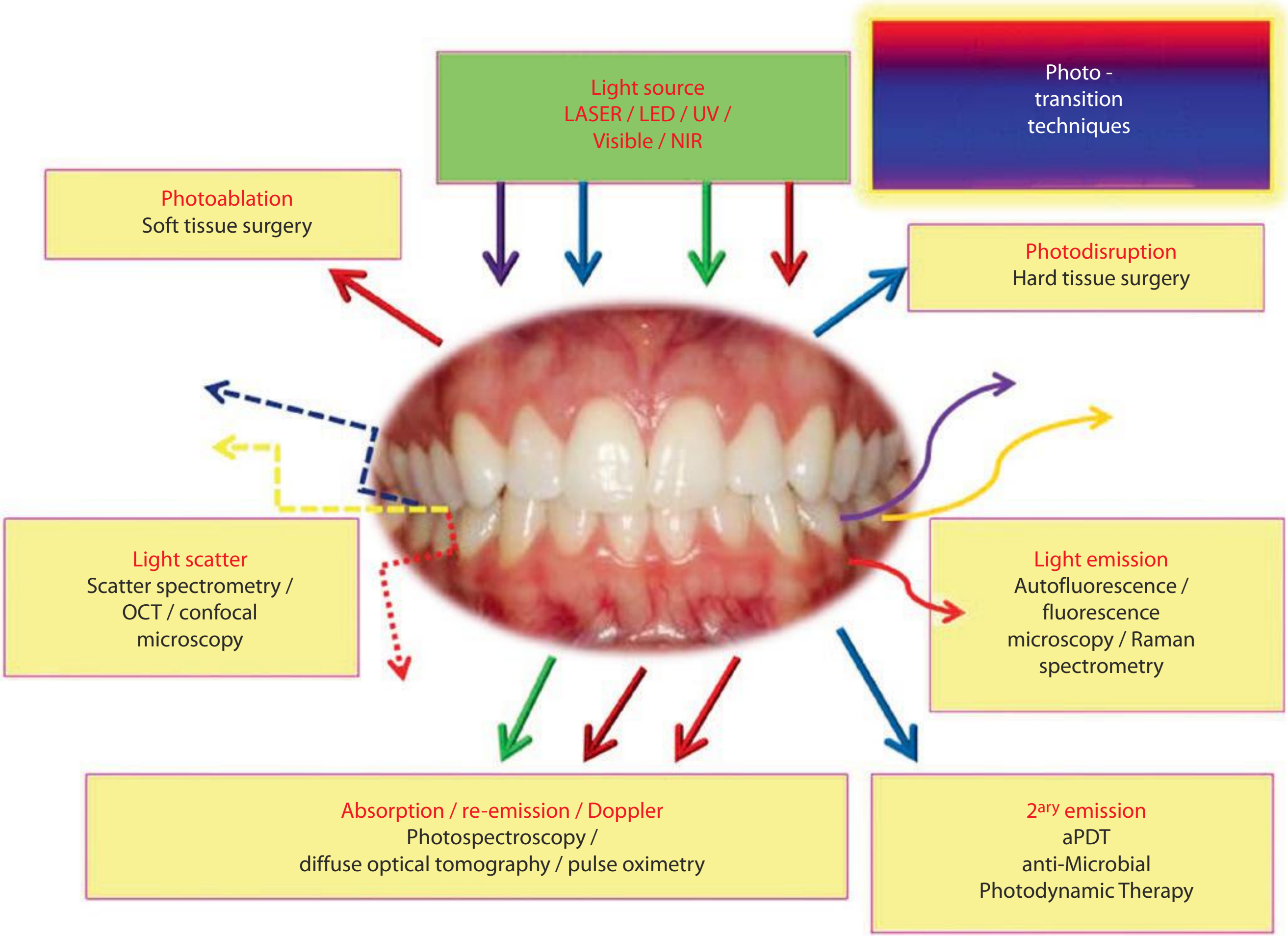


Fig. 3.2 An overview of the manipulation of incident photonic energy, such as laser light as an adjunct to screening, diagnostic and therapeutic clinical activity

that laser photonic energy is capable of ablative interaction with target tissue elements (chromophores). A chromophore is defined as «a chemical group capable of selective light absorption resulting in the coloration of certain organic compounds» [6]. For those compounds whose color is discernible within the visible spectrum, the definition may be sustained; however, given the concept that the chemical group confers a preferential ability to absorb (to a greater or lesser degree) photonic (EM) energy, the wavelength of that energy may fall within a spectrum of ultraviolet to far infrared, a narrow component of which may be visible to the human eye.

It must be stressed that laser–tissue interaction may occur within one of two basic scenarios, an interaction that is sufficiently powerful to cause direct and irreversible change in the target (usually achieved through thermal rise) – a process termed photothermolysis – and a second, less-powerful interaction that results in nondamaging, predominately (but not exclusively) stimulatory and biochemically mediated change, termed photobiomodulation (PBM).

According to the first law of thermodynamics, the energy delivered to the tissue must be conserved, and three possible pathways exist to account for what happens to the delivered light energy when laser photonic energy is delivered into tissue (Fig. 3.2):

1. The commonest pathway that occurs when light is absorbed by living tissue is called internal conversion. The energy of the electronically excited state gives rise to an increase in the vibrational modes of the molecule; in other words, the excitation energy is transformed into heat [7]. In many instances, the thermal rise is near instantaneous and substantial and quickly leads to conductive thermal energy into surrounding tissue. In the case of oral soft tissue and visible/near-IR laser wavelengths, the absorption by tissue chromophores gives rise to protein denaturation and secondary vaporization of interstitial water. The result is a visible ablation and vaporization of target tissue [8].

   With longer laser wavelengths, mid-IR and far IR, the prime chromophore in both soft and hard oral tissue is water. Ablation of tissue is achieved through the near-instantaneous vaporization of interstitial water, leading to an explosive fragmentation of tissue structure. With hard oral/dental tissue, this interaction can be quite dramatic [8].

2. With incident laser photonic energy values that fall below target tissue ablation, a second pathway can occur as fluorescence. Fluorescence is a luminescence or reemission of light in which the molecular absorption of a photon triggers the emission of another photon with a longer wavelength. Such action provides the basis for optical scanning techniques used in caries detection in enamel and dentine and tomographic techniques in the scanning of soft tissue for neoplastic change.
3. The third pathway is broadly termed photochemistry [9]. Because of the energy of the photons involved, covalent bonds cannot be broken. However, the energy is sufficient for the first excited singlet state to be formed, and this can undergo intersystem crossing to the long-lived triplet state of the chromophore. The long life of this species allows reactions to occur, such as energy transfer to ground state molecular oxygen to form the reactive species, singlet oxygen. Singlet or nascent oxygen is an ultrashort-lived form of the parent molecule that can cause cell apoptosis through oxidative stress. Such action can be commonly seen in photodynamic therapies where an intermediary chemical – photosensitiser – is employed to direct energy transfer to target tissue sites [10, 11].

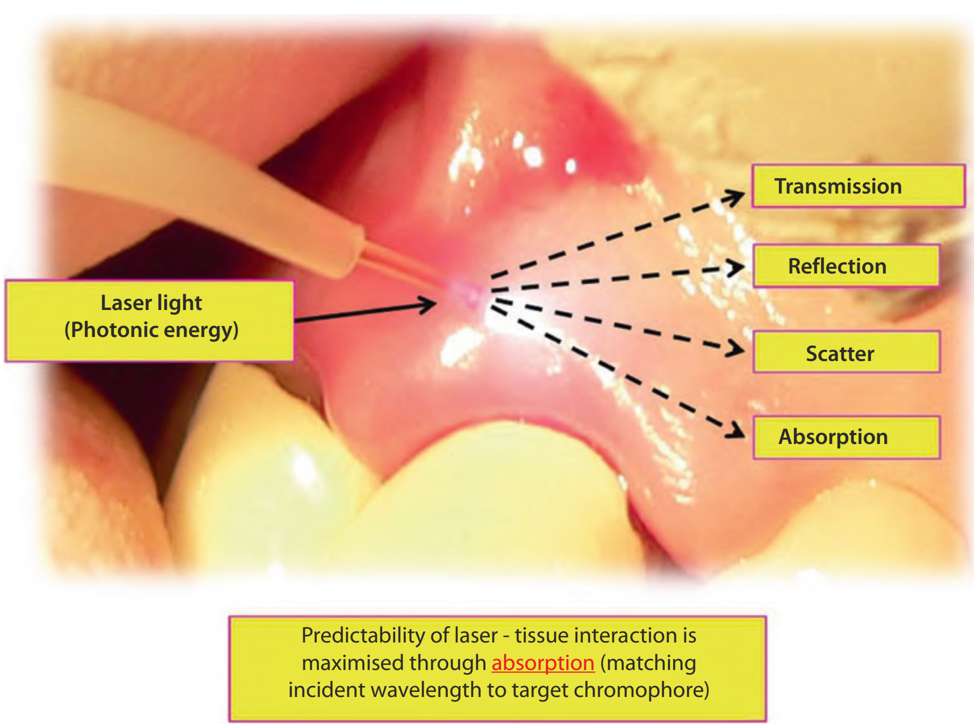
   Electron transfer reactions are highly important in the host cell mitochondrial respiratory chain [12], where the principal chromophores involved in laser therapy are thought to be situated. An additional photochemistry pathway that can occur after the absorption of a red or NIR photon within a host cell is the dissociation of a noncovalent bound ligand from a binding site on a metal containing cofactor in an enzyme. The most likely candidate for this pathway is the binding of nitric oxide to the iron-containing and copper-containing redox centers in unit IV of the mitochondrial respiratory chain, known as cytochrome-c-oxidase. Such action may induce an increase in cell pH and production of ATP and has been cited as basic cellular theory in photobiomodulation with low-level lasers.

3.4 Basics of Photothermolysis

Incident photonic irradiation directed onto target tissue will behave in one of four ways: transmission, reflection, scatter, and absorption. The defining criteria can be simply summarized as dependent on the nature of the target tissue and wavelength of the incident beam (hence the predictability of absorption or transmission), the nature of the tissue and its heterogeneity (hence the scope for scatter) and angle of the beam incident to the tissue surface (incident beam angle < total reflective angle) wherein reflection may have predominant effects (Fig. 3.3).

Oral hard and soft tissue is complex and heterogenous, anisotropic and of varying degrees of thickness. Within such tissue, component elements may be found that represent key molecules capable of selective absorption of photonic energy and termed chromophores. Examples are protein/amino acid based, such as collagen, keratin and nonstructural proteins such as melanin and hemoglobin in both its oxygenated and nonoxygenated (HbO_2 and Hb) forms. Dental and osseous chromophores are based upon the calcium phosphate complex referred to as hydroxyapatite (HA) found as a structural crystal in bone and the carbonated lattice crystal as a mineral component of enamel and dentine (CHA). Water – as the intracellular medium

Fig. 3.3 Summary of the basic interactive phenomena of incident laser energy and target tissue. Such is the variance in tissue structure and heterogeneity commonly found in oral hard and soft tissue; there may be multiple and complex degrees of each interactive phenomena



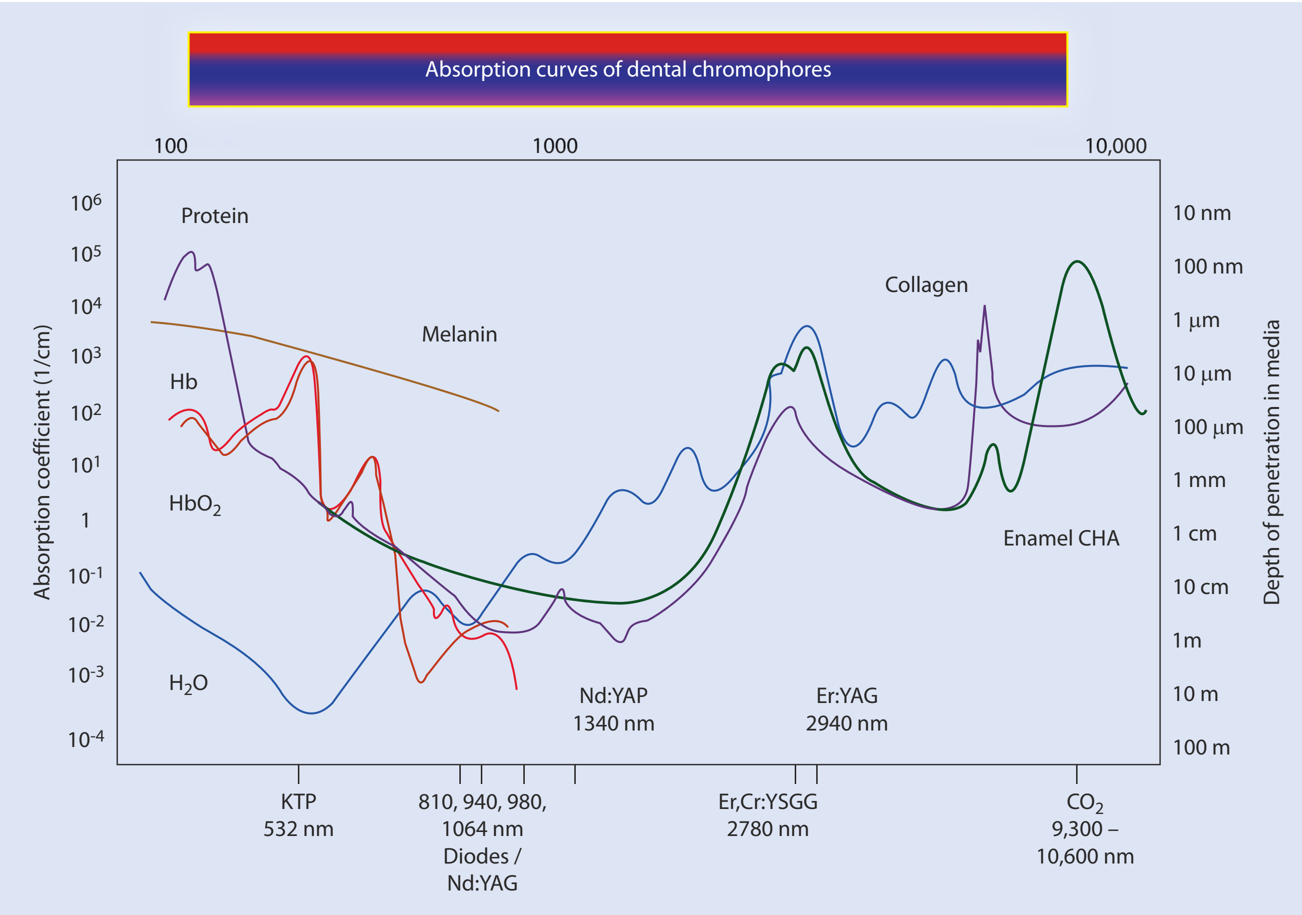


Fig. 3.4 Absorption coefficient curves for commonly found chromophores, relative to incident photonic wavelength

base of cell cytoplasm, a component of circulating blood and plasma, a free molecule in interstitial tissue structure or as a hydroxyl (OH-) radical as part of the hydroxyapatite molecule – represents a major ubiquitous chromophore of varying degrees of absorptive potential relative to incident photonic wavelength. Figure 3.4 demonstrates a graphical interpretation of the interaction of ascending photonic wavelengths with each of the major tissue chromophores that are found in oral and dental tissues. The term adopted as a measurement of the level of energy absorption by a chromophore is absorption coefficient – considered as a measure of the rate of decrease in the intensity of electromagnetic radiation (as light) as it passes through a given substance. The optical properties of tissue will determine the penetration into tissue of the radiant energy from a laser source. Absorption coefficient is inversely proportional to transmittance and the depth of penetration of photons within a given chromophore will reduce as the absorption coefficient increases.

Each chromosome has molecular structure, and for each there is a «ground state» which defines the structure, atomic configuration and interatomic binding energy at body temperature [13]. If external energy is applied, a point may be reached when molecular vibration is sufficient to overcome the forces binding atoms or molecules together. Examples include protein dissociation and water vaporization. True photonic ablation of a target molecule therefore represents incident energy sufficient to break interatomic binding forces and is termed dissociation energy. Table 3.2 provides examples of commonly found chromophore molecules and the dissociation energy value required to break the interatomic bond.

As is evident from data in Table 3.1, almost none of the popular laser photonic energies is capable of direct intramolecular bond cleavage, and one may be forgiven for concluding that dental lasers cannot ablate target oral tissue through the use of empirical-state photonic energy. Certainly, when the binding (ionic) lattice energies of crystalline carbonated hydroxyapatite are exposed to the mid-IR laser wavelengths (Er,Cr:YSGG, Er:YAG), the photonic energy value is pitiful compared to the dissociation energy of hard dental tissue [14].

Something else must be happening:

Figure 3.5 offers a summary of the interaction between a photon and target chromophore molecule, through successive stages of absorption, excitation and dissociation. Such predictive events might account for why certain laser wavelengths interact (are absorbed) with certain oral tissues

Table 3.2 Dissociation energy, expressed in eV values, required to break the bonds (covalent, ionic, etc.) that bind atoms of common chromophores

General concepts	
Dissociation energy of selected chemical bonds*	
Type of bond	Dissociation energy (eV)
C=O	7.1
C=C	6.4
O-H	4.8
N-H	4.1
C-C	3.6
C-N	3.0
C-S	2.7
Fe-OH	0.35
HA Lattice	310

Data taken from Mó et al. [13]
*Examples represent component molecules within tissue water, protein, blood and ionic forces within the crystal lattice of hydroxyapatite

Although individual photons possess insufficient energy to break apart target molecules, with each successive photon absorbed, the energy causes increasing molecular vibration up to a point where sufficiently high power density (energy density within ultrashort time) drives molecular fragmentation, or – more commonly seen with current dental lasers – molecular vibration, converted into thermal rise, leads to protein denaturation and water vaporization.

3.5 Problems Associated with Delivery of Photonic Radiation Versus Laser Wavelength

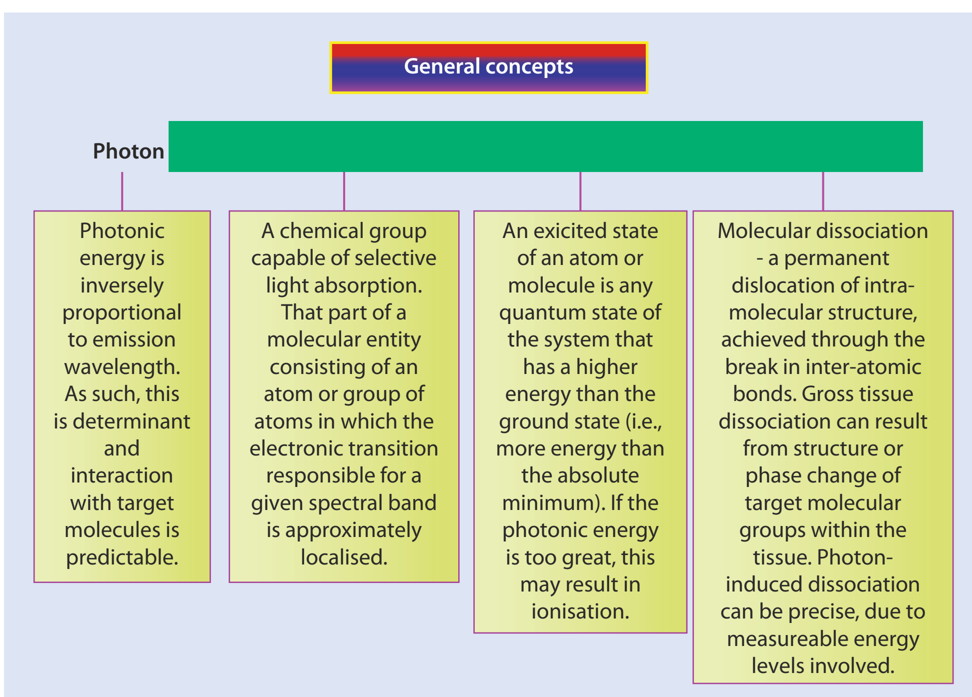
Considering a clinical application of high-intensity lasers, parameters such as wavelength, energy density, intensity, peak power, average power, repetition rate, and pulse length are extremely important to heat generation due to irradiation on any biological tissue. The amount of heat inside the tissue is highly dependent of its optical properties, such as absorption and scattering coefficients [15].

The complex nature of oral soft tissue structure can pose some problems in delivering predictive laser–tissue interaction. For some wavelengths in the visible and near-infrared regions of the EM spectrum, the prime pigmented chromophores may be at some depth within the oral epithelium and covered with a thick keratinized layer. During photothermolysis, photonic energy may be delivered to the target and theoretically transferred (and undergo conversion) in one of three [16] ways:

Radiation

Noncontact laser waves are emitted from the delivery tip and absorbed by the target. Energy conversion occurs. This is referred to as the «real» laser effect. High photonic energy wavelengths such as the KTP (532 nm) may be delivered through a «noncontact» technique, and direct photoablation may occur.

Fig. 3.5 Photonic energy interaction with target chromophore molecules



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Conduction

At slightly longer wavelengths (810–1064 nm), the need arises to both hold the delivery fiber in contact with the tissue and to «initiate» the fiber tip with suitable absorbent material. A proportion of the incident laser energy is absorbed and gives rise to a «hot-tip» effect, whereby thermal energy is conducted to the tissue and aids the ablation of the tissue.

Some concern is expressed as to possible disadvantages of this technique in that the effect of the hot tip on tissue is independent of the wavelength of laser radiation and that the heated fiber (sic) transmits only thermal energy, no direct radiation energy [17].

Convection

Heat moves within large volumes of liquid or gas either toward or away from the target. A similar effect of cooling may be seen through the effect of using a water spray, high-volume suction or air.

3.6 Concepts of "Power Density"

Figure 3.6 provides an example of simple manipulation of sunlight, using a magnification device such as a simple lens. Multiwavelength cosmic radiation from the sun, although powerful and capable of tissue damage over time, can be brought to a focal area, and with the power in the beam concentrated to a small spot, the effects are much more dramatic. The use of a magnifying glass to concentrate the sun's rays is a simple example of power density. Power (energy per second) is an expression of a laser's ability to do work, and when measured over the area exposed to the beam, it will be readily acknowledged that the greater the concentration of photons, the greater the level of potential

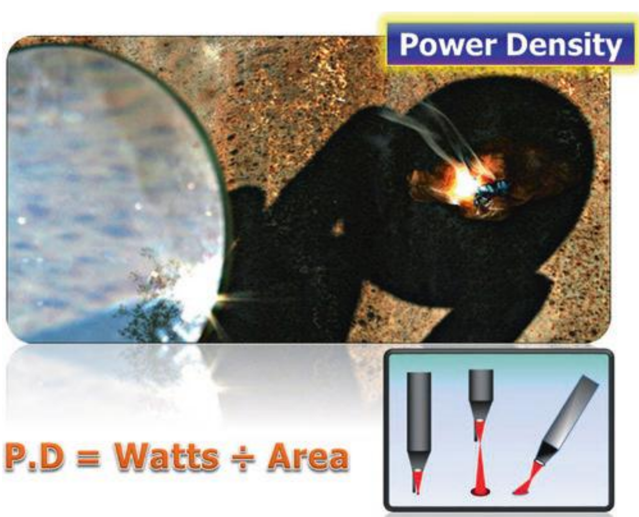


Fig. 3.6 Manipulation of incident beam power over area to enable the power density effect to be a major factor in delivering predictable and powerful laser–tissue interaction

interaction. Consequently, for any given laser delivery system, reduce the spot size of the beam and one can expect to speed up the interaction – assuming all other parameters are constant [18].

> «Power density» (PD) is the delivery of energy through time divided by the area of the exposed tissue; it is expressed in watts/Sq.cm.

The output of any laser over time is expressed as average power and equates to the total number of watts delivered per second. For a continuous wave (CW) emission laser, the average power will equal the maximum output; for a micro-pulsed free-running emission, the average power output may be of the order of a few watts, but due to the active photonic emission only lasting a possible 20% of each second, there will be peaks of energy. A typical free-running emission laser, such as Nd:YAG or Er:YAG, may deliver an average power value of 3.0 watts, but due to the pulse width of 150 µs, there will be peak power bursts of 1000+ watts [19].

As has been seen elsewhere, the predominant temporal emission mode is a Gaussian distribution, and this lends itself readily to being brought to a focal spot. With control over the area of irradiation, the concept of power density as a prime factor in laser–tissue interaction becomes valid. Even in those conditions where there is little if any direct absorption, the concentration of laser power in ever-higher values over ever-shorter time periods gives rise to power density of such magnitude that photodisruption and photoionization of target molecules can occur.

Technology has much to deliver in terms of future developments, but already it is possible to see predictable laser–tissue interaction involving PD of values of 10^6 + watts/Sq.cm for microsecond periods and even shorter, enabling photovaporization of interstitial water in tooth tissue and consequent disruption of the crystalline solids.

Nowhere within this discussion does the influence of laser wavelength occur. Of course, the harmonization of incident wavelength, its inherent energy value and selective absorption within a suitable target chromosome will remain as empirical in our understanding of interaction concepts; but as we have already seen the continuous bombardment of a target tissue with photons of a suitably absorbed wavelength will lead to thermal rise and eventually sufficient heat to effect physical change in the tissue. Such processes take time and the risk of collateral thermal damage becomes an ever-present threat. To deliver sufficient energy in a form of concentration of both area of exposure and time must be seen as a distinct advantage.

As our understanding develops, there evolves the interaction of three components to predictive laser–tissue interaction: firstly, the absorptive potential of the target tissue, relative to

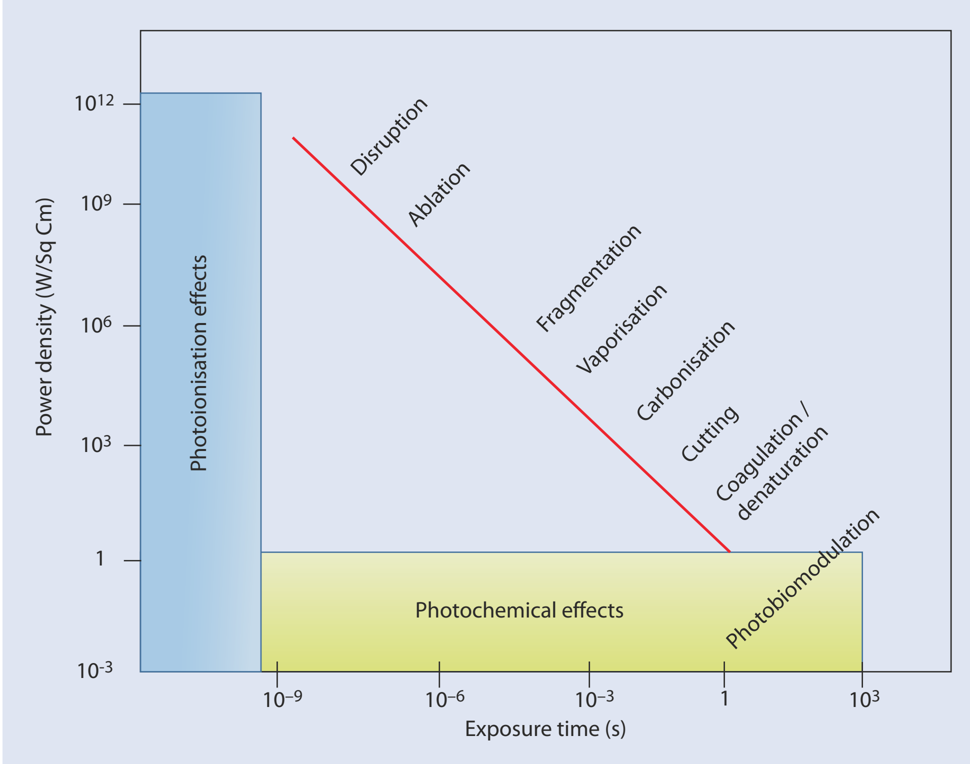


Fig. 3.7 Relationship of incident photonic power density and exposure time (Graphics S. Parker Source: Boulnois [21])

the incident laser wavelength; secondly, the transfer of energy, from initial photonic energy and the delivery (emission) mode of the laser, together with power density and time of exposure; and thirdly, the availability of thermal relaxation to enable the target tissue to avoid progressive overheating. Thermal relaxation is inherent with free-running pulsed (FRP) emission modes and impossible to deliver with continuous wave emission modes. The clinician would therefore need to be aware of the potential for thermal damage and allow sufficient time and respite periods to enable the tissue to recover.

In Fig. 3.7. the relationship between PD and exposure time is represented with reference to an ascending physical change in the target tissue. Very low irradiance over extended periods may give rise to subtle stimulation of biochemical pathways associated with tissue heath and reparative capabilities and is the core of understanding of photobiomodulation. With ever-shortening time and an ascending level of power density, not only do irreversible physical changes occur in tissue but, with exposure times of micro- and nanoseconds, even with relatively low average power values, the effects on the target can be spectacularly rapid and without leaving a «thermal thumbprint.»

For any given laser–tissue interaction, assuming absorption can occur, the equation of power density with exposure time may enable the clinician to influence the type of interaction that occurs. It has already been established that at everyday levels of power delivery in dentistry, the predominant effect is tissue ablation through thermal rise – photothermolysis. By reducing the exposure time to milliseconds and microseconds, successively higher peak power density above 10^8 watts/Sq.cm can be obtained. At such powerful levels, the intensity of energy is so great that electromagnetic fields developed around the interaction are sufficient to tear target molecules apart – photoplasmolysis [20]. Reference to the work of Boulnois and the graphic representation of laser–tissue interaction can be seen as an ascending phenomenon and product of ultrashort exposure time and megawatt peak power [21].

3.7 Thermal Rise and Thermal Relaxation

In considering the broadest concepts of photothermal action and regardless of the laser system used for a soft tissue surgical application, the effects may be broadly classified as follows:

Tissue heating

To a nondestructive level, the warming of tissue may be a desired total effect (as part of a biomodulation therapy) or may occur at some distance from an ablation site, along a thermal gradient within the tissue. This latter example is covered in greater detail later.

Tissue coagulation

Over a period of time, the temperature rise in soft tissue at or above 45 °C will constitute «destructive heating,» i.e., amounting to progressive irreversible change. At about 50 °C bacteria can be demonstrated to achieve a state of deactivation, with tissue protein denaturation occurring at around

60 °C. Within this zone of thermal rise, the walls of small-diameter vessels (arterioles, venules and lymphatics) within the irradiated area will undergo structural change of vessel walls and lead to progressive blood and lymph coagulation. Dependant on the wavelength of the laser used and concentration of chromophores specific to that wavelength, a concept of «selective photothermolysis» can be considered, such as in the ablation of melanin in diode laser-assisted gingival depigmentation.

Vaporization

At normal atmospheric pressure (1 Bar), vaporization of water occurs at 100 °C. Within soft tissue the vaporization of water will accompany existing protein denaturation that may have occurred at a lower temperature. The phenomenon of water vaporization is accompanied by volumetric change and expansion in the ratio of 1:1600 as the liquid is vaporized to steam. With short wavelengths (visible and near IR), the structural change in soft tissue collagen scaffolding would allow water vaporization to occur as part of the overall ablation process. With mid-IR erbium family wavelengths, the scenario is often very different owing to the poor absorption of these wavelengths in pigmented tissue, the limitation of thermal rise in the tissue when a coaxial water spray is being used and the FRP emission mode of the lasers with associated high peak power values and with the extremely high absorption of these wavelength in water, and the vaporization is often more dynamic and accompanied by audible «popping.»

When erbium lasers are used on soft tissue without water spray, or when CO_2 laser wavelengths are used (often without water spray), the vaporization is reflective of a more «thermal» exchange, where the heating of the tissue as well as the absorption of the photons in water occurs. Often, the result of such vaporization leads to visible signs of tissue desiccation, structural shrinkage and predisposition to rapid heating and carbonization.

Carbonization

As laser-assisted surgery proceeds, the risk remains the potential for tissue heating that leads to the production of end-stage molecular destruction and residual carbon. It is generally considered to be at temperatures around 200 °C, although the actual rise may be considerably higher. Carbonization would only occur as a result of either an inappropriate high dose, relative to the parameters consistent with a desired surgical outcome, or the application of laser photonic energy over excessive time, resulting in opportunity for destructive collateral effects. The characteristic visual sign is the development of black residue associated with the soft tissue incision.

By far the consequence of such development is the preferential absorption in carbon residue of (in effect) all incident EM photonic wavelengths. This is the basis of the «black body» concepts of preferential absorption and characterized by the reemission of multiwavelength, incandescent near-IR thermal radiation; in consequence, the carbonized tissue continues to absorb incident laser energy and becomes the source of thermal conductive energy that significantly contributes to collateral damage during soft tissue surgery.

Photoacoustic phenomena

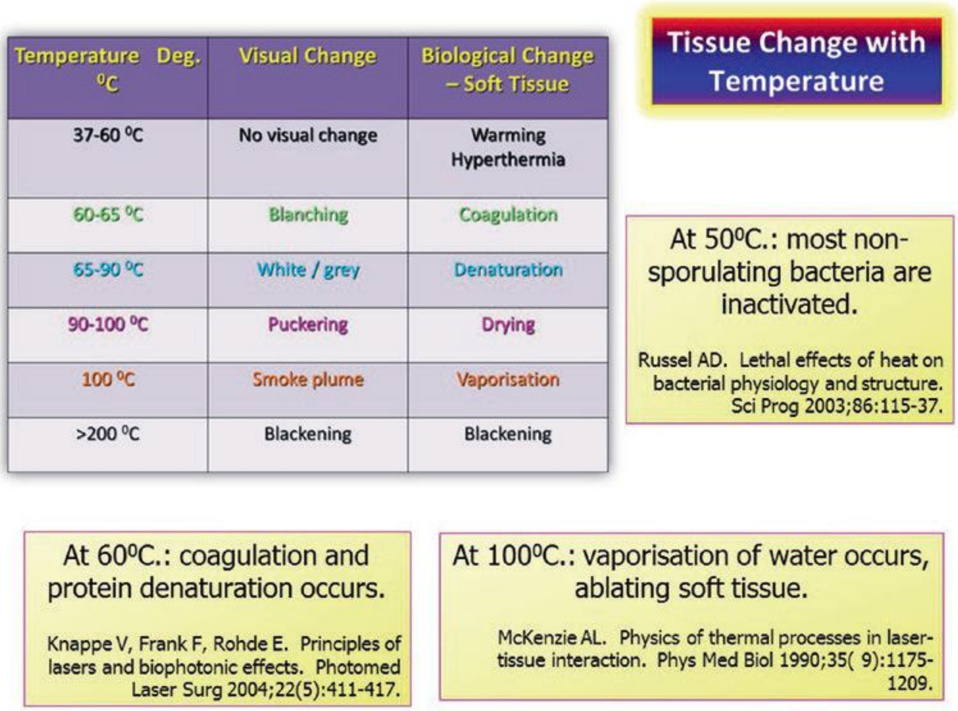
As has been seen already, incident coherent photonic energy can be subject to conversion into other forms of energy, notably thermal in the dominant effect of photothermolysis. With the instantaneous phase change of water from stable liquid to vapor, the volume change can give rise to a cavitation phenomenon and consequent shock wave. Additionally, the energy may be changed to sound, and this may be witnessed with mid-IR interaction with tissue and the «popping» sound often heard. True photoacoustic effects are used elsewhere in medicine and surgery in procedures such as lithotripsy where the kidney and gallstones are fragmented using indirect shock waves; in maxillofacial surgery a similar approach has been reported to assist in the fragmentation and subsequent safe passage of sialoliths within the submandibular gland [22, 23].

Given current limitations of laser emission parameters and the consequence that by far the greater consequence of laser–tissue interaction is photothermal shift and temperature rise, the ablation of target tissue can be severely compromised by excessive thermal rise and a build-up of the ablation residue that may rapidly overheat.

The effects of thermal rise can be both subtle and dramatic – depending on the rate of warming. ◘ Figure 3.8 provides a tabulated outline of the effects that temperature rise may have, relative to both the visual change and the biological change (the latter as may be applied to soft tissue). In addition, the varying stages of thermal rise have been investigated and provide opportunity to influence the structural changes in the tissue and the effect of heat on associated bacterial cells. Irradiated tissue should not be regarded as sterile, although there will be significant pathogen reduction at the site of maximum laser–tissue interaction.

Two concepts of ablation may be considered: a zone of tissue removal/permanent change preceded by an «ablation» front and a second advancing line denoting the permanent effect of change rendered by thermal rise – a «thermal» front. In an ideal situation, the «ablation» front will denote the predicted volume of ablated tissue, and through the correct management of heat rise and debridement, the risk of unwanted thermal damage can be avoided. In hard tissue management, the concepts of ablation and thermal zones will be discussed with specific reference to tooth cavity preparation.

Thermal relaxation time can be deduced mathematically [24] as the time taken for the irradiated tissue to dissipate about 63% of the incident thermal energy. It is related to the



Temperature Deg. °C	Visual Change	Biological Change – Soft Tissue
37-60 °C	No visual change	Warming Hyperthermia
60-65 °C	Blanching	Coagulation
65-90 °C	White / grey	Denaturation
90-100 °C	Puckering	Drying
100 °C	Smoke plume	Vaporisation
>200 °C	Blackening	Blackening

Fig. 3.8 Effects of thermal rise on (soft) tissue

area of the irradiated tissue and thermal diffusivity and bulk of the tissue.

Thermal damage time is the time required, for the entire target, including the primary chromophore (e.g., melanin) and the surrounding target (e.g., gingiva), to cool by about 63%. It includes cooling of the primary chromophore as well as the entire target.

Extinction length is the thickness of material necessary to absorb 98% of incident energy.

3.8 Laser Photonic Energy and Target Soft Tissue

Various laser wavelengths are available for clinical use with target oral soft tissue and span the visible (blue) EM spectrum through to the far infrared. Examples of laser wavelength currently available to the clinician are shown in Fig. 3.9.

With current configurations of emission modes, power limits and commercial technology application, all soft tissue ablation achievable in clinical dentistry is primarily and almost exclusively due to photothermolysis [25]; in general, chromophore absorption is by pigmented molecules (heme, melanin) with short wavelengths (532–1064 nm), whereas longer wavelengths experience greater interaction with tissue water components (H_2O and OH^- radicals), with peak absorption occurring at approximately 3000 and 10,600 nm. The emergence of commercially available laser units with wavelength emissions at 450–490 nm offers the opportunity of utilizing absorption in water with a diode-source active medium. Protein as a structural component of oral soft tissue appears to have moderate absorption of ultraviolet wavelengths, together with peaks at 3.0 and 7.0 µm. Visible and near-IR wavelengths have limited absorption in protein, but as has been discussed above, secondary thermal rise consequent upon time-related photonic energy exposure will give rise to conductive heat changes in proteinaceous material.

As such, oral soft tissue, high in water and protein with varying degrees of pigment and blood perfusion, remains a straightforward target tissue wherein low-dose irradiation can be configured to deliver predictable laser–tissue interaction with limited collateral damage.

Of practical interest to the clinician, the following factors (Table 3.3) will each and collectively affect the absorption of laser light by a chosen target tissue [26]:

Shorter wavelengths tend to penetrate soft tissue to depths of 2–6 mm [27] and scatter is a significant event, both backscatter of photons as well as forward scatter into the tissue. Longer wavelengths are attenuated at or near the tissue surface, due to water content of cellular tissue. As tissue ablation proceeds, short wavelength photonic energy causes protein denaturation and conductive effects as the tissue is heated. A typical soft tissue zone of near-IR laser ablation is surrounded by a zone of reversible edema and little evidence of acute inflammatory response. Classically the progression of near-IR laser ablation of soft tissue is through a crater-shaped zone where depth and volume removed appear proportional [28].

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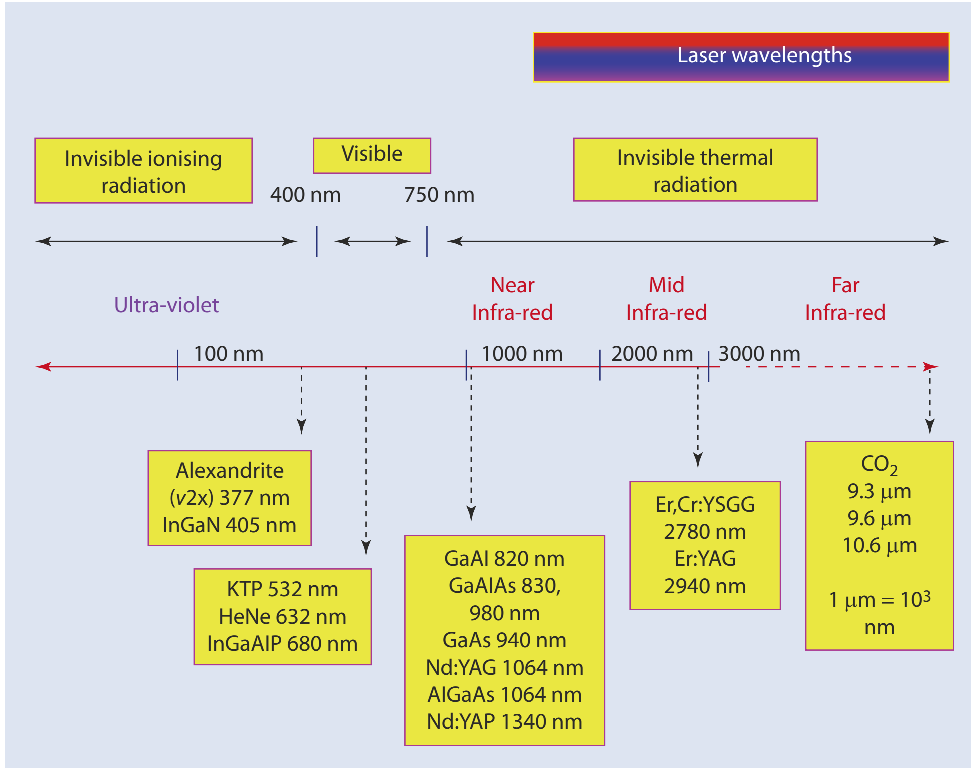

Fig. 3.9 Laser wavelengths commonly available for use in dentistry

Table 3.3 Individual factors associated with laser–tissue interaction that may affect the predictability of clinical use of a chosen laser

Factor	Comment
Laser wavelength	Individual wavelengths (visible extending to far-infrared nonionizing radiation) and inversely proportional to the photonic energy
Laser emission mode	Inherently continuous wave (CW) or free-running pulsed (FRP), due to the excitation source or additionally modified by the manufacturer to deliver gated CW and mode-locked CW or modification in pulse width (>10 µs) with FRP
Laser power value	With increasing power delivery, there is potential for thermal rise. Below the ablation threshold, this may be reversible (tissue warming/PBM)
Exposure time	Together with laser power, «spot size» and emission mode, this will affect power density and thermal relaxation
Tissue type (composition)	All oral tissue is heterogenous and the proportions of common chromophore content will alter the potential for individual laser wavelength absorption
Tissue thickness	Thicker tissue will take longer to incise/ablate. Additional factor may be thermal diffusivity and longer thermal relaxation times
Tissue surface wetness	Due to water or saliva – of note with longer wavelengths >approx. 1500 nm. – wetness will affect tissue reflection (below)
Incident angle of the laser beam	Incident angle of beam to tissue of 90° will define maximum potential for interaction. As angle approaches the reflection limit (TIR), this reduces potential for interaction to zero
Contact vs. noncontact modes	Employed between laser delivery tip and the tissue. With visible and near-IR wavelengths, contact technique may be essential to allow a «hot-tip» technique. Noncontact may have a focused beam, and distance of tip/hand-piece to tissue may be crucial to maximize laser–tissue interaction
Thermal relaxation factors	Exogenous (water spray, tissue pre-cooling, high-speed suction, pulsing/gating laser emission) Endogenous (tissue type and density, blood supply)

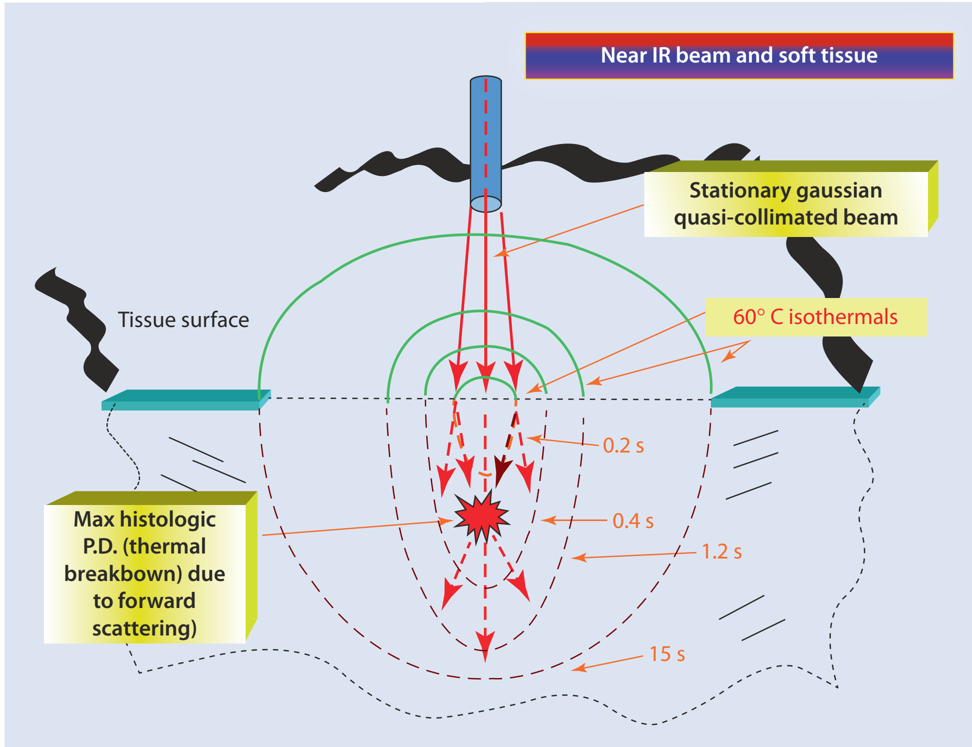

Fig. 3.10 Graphic representation of visible and near-IR laser photonic energy interaction with oral soft tissue (Graphics: S. Parker after Fisher J.C. (1993))

In Fig. 3.10, the interaction and progression of near-IR irradiation in soft tissue is graphically represented. In an ideal fashion, the zone of ablation and conductive temperature spread occurs over time. The predominant scatter phenomenon of these wavelengths gives rise to a complex pattern of photon penetration wherein there may be indeterminate tissue effects, giving rise to the acronym of WYDSCHY – «What You Don't See Can Harm You,» coined by Fisher in his 1993 paper [29]. In essence, visible and near-IR laser wavelengths have deeper-penetrating effects on oral soft tissue and demand that optimal and nonexcessive operating parameters are used in order to avoid unwanted tissue damage.

Clinically, such interaction can be seen in Fig. 3.11, during the removal of a fibroma from the lateral tongue, using an 810 nm diode laser.

Certainly, even incisions will have a «U»-shaped cross-sectional appearance, and this is due in part to progression of photonic energy through scatter as well as some direct conductive thermal spread [29]. A simple in vitro example using pig mucosa with short and longer wavelengths provides an excellent example of the structure of the incision and difference in laser–tissue interaction between the two wavelengths (Fig. 3.12).

Fig. 3.11 Following removal of a fibroma lateral tongue, using an 810 nm diode laser. The central ablation zone is surrounded by an area of edema. The lack of carbon residue indicates a correct choice of laser power parameters

With longer laser wavelengths (mid-IR approx. 3.0 µm – Er,Cr:YSGG, Er:YAG – and far IR approx. 10 µm – CO_2), a more «V»-shaped cross-sectional appearance prevails

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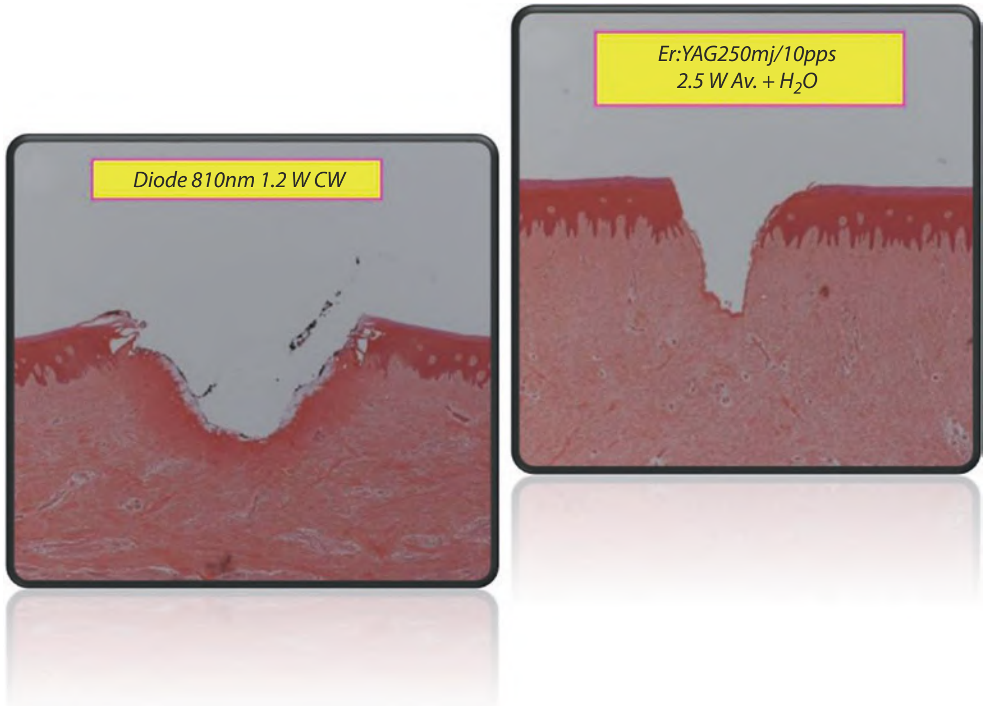


Fig. 3.12 Histological representation of two laser wavelengths (diode 810 nm and Er:YAG 2940 nm) interaction with pig mucosa in vitro. This demonstrates the progressive crater-shaped incision with shorter wavelengths and a «V»-shaped incision with longer wavelengths

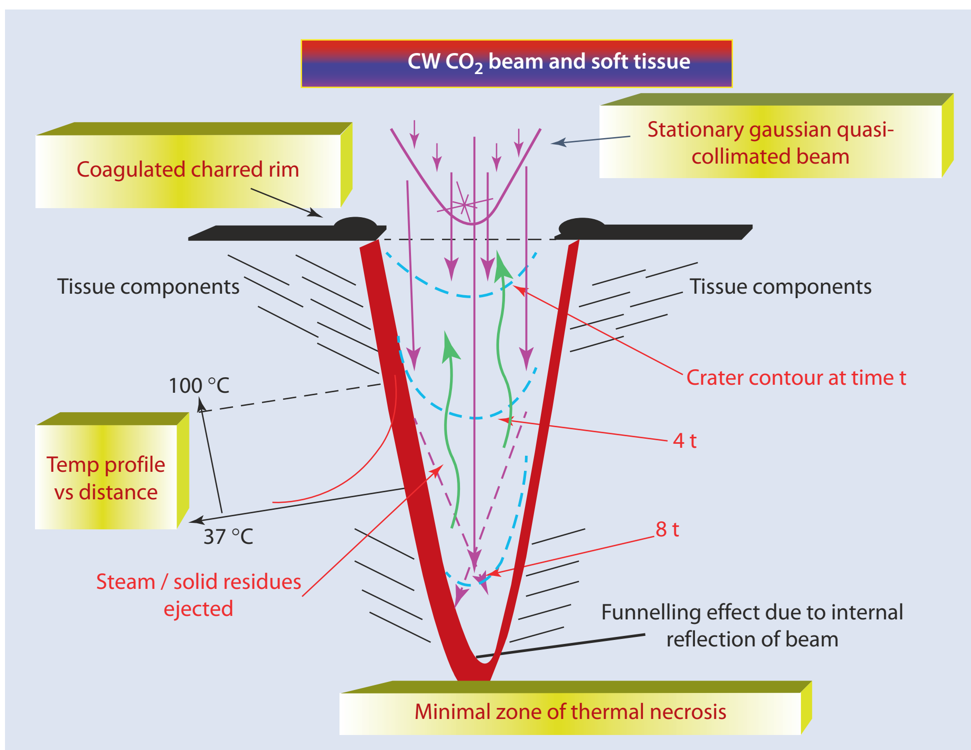


Fig. 3.13 Graphic representation of far-IR (and potentially mid-IR) laser photonic energy interaction with oral soft tissue (Graphics: S. Parker after Fisher J.C. (1993))

(Figs. 3.13 and 3.14). The bulk of laser–tissue interaction occurs at or within the confines of the tissue surface, and as an incision is developed, the majority of excess energy (thermal) is released through the escape of vaporized tissue water [29]. This predominant effect reduces the conductive thermal rise into adjacent tissue. A risk exists with soft tissue in that desiccation of target tissue can predispose to the formation of carbonized tissue elements (surface char – termed eschar) and the preferential absorption of this material leading to very high temperatures that might cause conductive collateral tissue damage and postoperative pain. Various techniques have been developed to address this risk; the eschar is loosely adherent and can be easily wiped away with a damp gauze to allow fresh tissue exposure (this technique forms part of the so-called «laser peel» techniques associated with surgical treatment of surface pathology). Parameter manipulation may include the choice of short-gated CW or pulsed laser emission modes or coaxial water spray that may enhance tissue thermal relaxation.

Broad consensus would suggest that although laser soft tissue incisions do not heal any faster than scalpel, there is evidence that, with appropriate operating parameters, these wounds appear to heal less eventually [30–32].

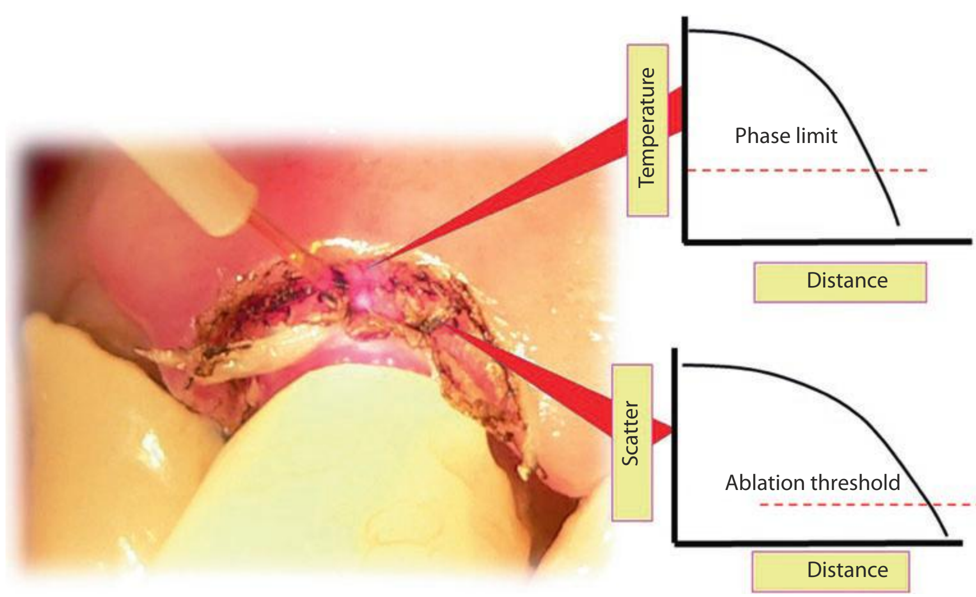
In terms of laser–tissue interaction and disregarding any reduction in bacterial contamination, there will be a point at some distance from the wound where both temperature and photon scatter are reduced to a point of containment within the tissue. By this, the temperature gradient reduces to a level of tissue stimulation, tissue molecular energizing, and increased local blood flow [33]. In addition, a scatter gradient exists where the energy delivered is reduced to that point where biomodulation effects predominate [34]. For these reasons, it may be seen that laser-assisted surgical wounds respond in a positive and supportive framework that deliver less-eventful healing (Fig. 3.15).

Fig. 3.14 Clinical example of a mucosal incision using a CO_2 laser. In the absence of a water spray, note the build-up of eschar which can be easily removed with damp gauze to minimize thermal damage

Fisher [35] defines a comprehensive understanding of photon scattering into deeper soft tissue areas that is seen with the use of visible and near-IR lasers. With successive interaction and as photons are absorbed, the possibility exists for a scenario whereby the ablation threshold of the host tissue at deeper sites is greater than the photonic energy. This «energy gradient» phenomenon might provide explanation as to how distant effects of (surgical) laser use may mimic essentially low-level (photobiomodulation) stimulation of cells and host tissue. Standard textbooks [36] provide authoritative and evidence-based explanations of how the host tissue may respond positively to low-level photonic energy, and the reader is directed to such references for further information.

Positive healing effects following laser surgery: One of the often-cited side effects of laser-assisted surgery is the lack of postoperative inflammation and uneventful healing. Inasmuch as many claims are anecdotal, often if not always, the need for dressings or sutures can be avoided, and irrespective of the laser wavelength employed, all soft tissue healing will be by secondary intention in that it will be impossible to oppose the cut tissue edges to their original alignment. Of note, however, is the phenomenon of lack of postincisional contamination by bacteria, due to a possible sterility of the cut surface [37] but certainly through the protective layer of coagulum of plasma and blood products – a tenacious film that allows early healing to take place underneath [38]. Additionally, studies with longer wavelengths show that there is a lack of fibroblast alignment associated with the incision line and consequent reduced tissue shrinkage through scarring [39]. Such findings are often borne out in the clinical setting.

Fig. 3.15 At the point of surgical ablation of tissue, two intra-tissue gradients predominate. One is a thermal gradient, and with distance a reduction in temperature will define a point where the temperature provides tissue stimulation. The other gradient – scatter – can produce a similar point-at-distance stimulation wherein biomodulation effects predominate



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3.9 Laser Photonic Energy and Target Oral Hard Tissue

Oral hard tissue includes the cortical and trabecular (cancellous) bone and components of deciduous and permanent teeth (enamel, dentine, cementum). Within this group it acknowledges the association of dental caries, being the predominant reason why teeth are subject to surgical intervention.

In common with laser–tissue interaction mechanisms described above, the current limitations of operating parameters of those lasers that are commercially available in dentistry centers on the targeting of chromophores within the host tissue.

From the development of early lasers to ablate dental hard tissue, the predominant chromophore has been water – both interstitial «whole molecular» water and OH^- radicals forming part of the carbonated hydroxyapatite molecule ($[Ca_{10}(PO_4)_{6\text{-}Y}(CO_3)_Z(OH)_2] + H_20$). Prime tissue groupings of oral hard tissue are listed by percentage of constituent structural elements [40, 41] in Table 3.4.

Absorption curves for both water and carbonated hydroxyapatite between wavelengths of approximately 3.0 and 10 μm is graphically listed in Fig. 3.16. The carbonated hydroxymolecule (CHA) is a relatively complex inorganic molecule with a parent calcium chain supporting radicals of phosphate, carbonate and hydroxyl subgroups. Additionally, within clinical specimens, there is whole-molecule free water; each radical is capable of preferential absorption and peaks occur to indicate that laser interaction is possible, assuming correct spatial and temporal operating parameters are used [42].

Table 3.4 Oral and dental hard tissues have structural components that may be viewed as potential chromophores – mineral, protein and water

Tissue	Component (chromophore) as percentage		
	Mineral (HA/CHA) (%)	Protein (collagen I and II) (%)	Water (%)
Cortical bone	65	25	10
Cancellous (trabecular bone)	55	28	17
Tooth enamel	85–90	1–3	4–12
Tooth dentine	47	33	20
Tooth cementum	50	40	10
Dental caries	>5	70	25

For each tissue, the percentage of each of these chromophores will differ and define a level of laser–tissue interaction with a suitable laser wavelength

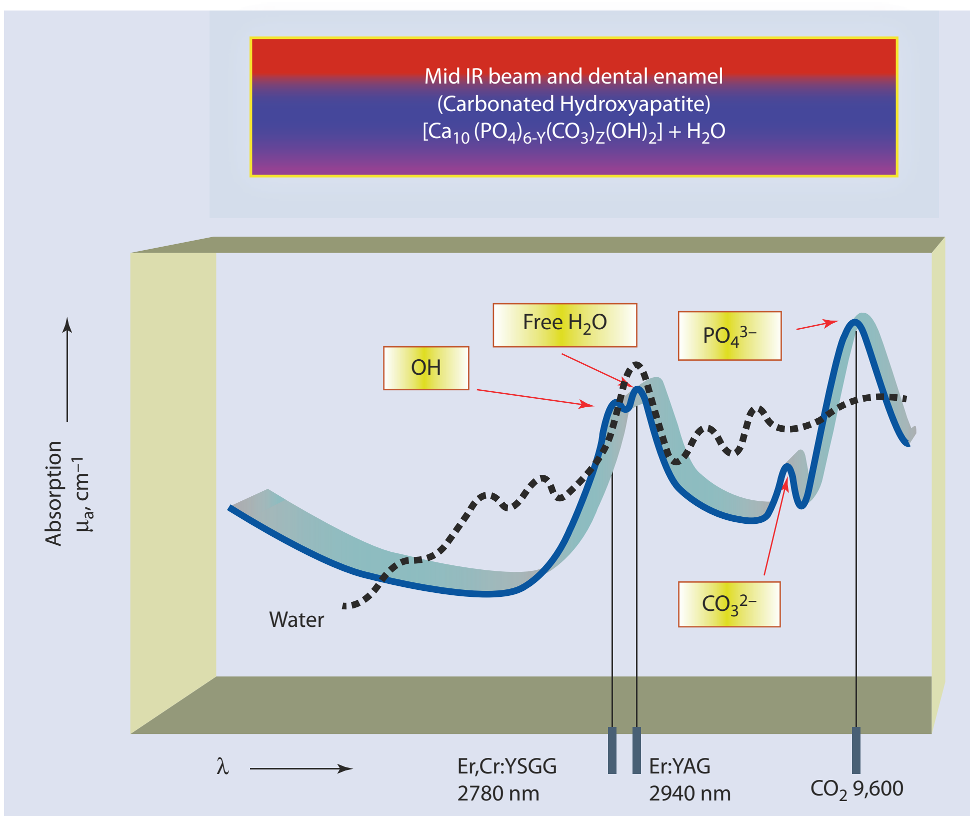


Fig. 3.16 Absorption peaks for water and CHA exist coincident for both Er,Cr:YSGG and Er:YAG wavelengths. High absorption exists in the phosphate group of CHA, coincident with CO_2 at 9300 and 9600 nm (Source Parker S. BDJ. 2007;202(8);445–54.)

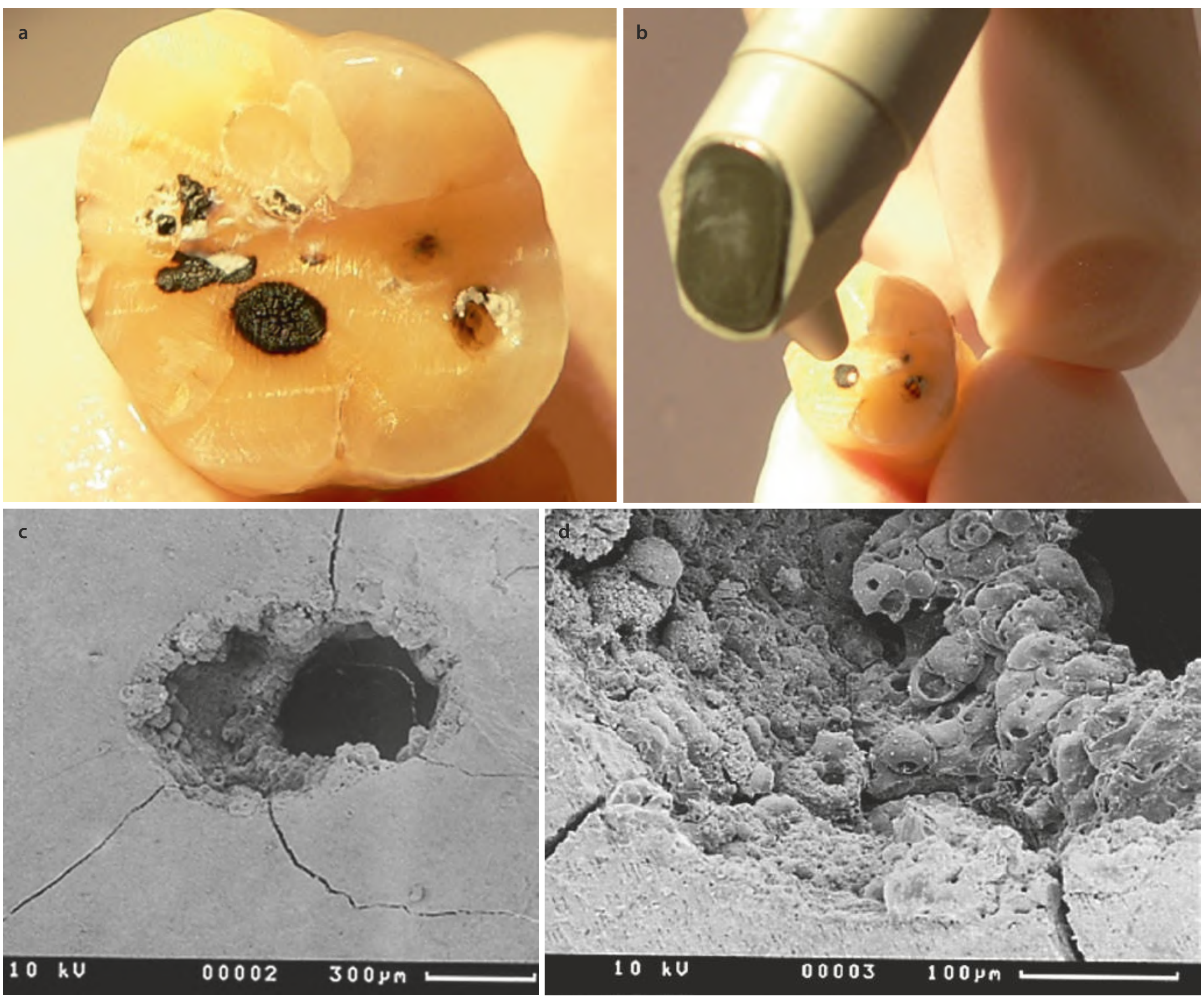
As was seen in the earlier table (◘ Table 3.2), there is insufficient energy associated with an incident photon of erbium YAG (2940 nm) whose value is 0.42 eV, to break the atomic bond of a hydroxyl radical (value – 4.8 eV). By the same measure, the dissociation energy within the crystal lattice of hydroxyapatite, at 310 eV, is two orders of magnitude greater [14]. Given that successive photons within a stream of irradiance will lead to progressive molecular vibration in the target structure, it follows that the chief goal of laser ablation of oral hard tissue would be the induced phase transition of water to vapor (steam), leading to the dislocation and explosive derangement of the surrounding crystal lattice. Both erbium (erbium YAG, erbium chromium YSGG) laser wavelengths have free-running pulsed emission modes (pulse width 50–150 µs), which give rise to high peak power levels (>1000 watts). Such power levels result in an instantaneous, explosive vaporization of the water content of enamel and dentine which leads to dissociation of the tissue and ejection of micro-fragments [43].

The increased water content of caries results in rapid and preferential ablation of such material compared to normal enamel and dentine; to some extent this may allow cavity preparation to be accomplished with a more-conservative preservation of intact dental tissue.

Sustained exposure of hydroxyapatite and carbonated hydroxyapatite to laser irradiance will quickly render the structure to overheating, first to drive off any residual water and then to rapidly melt the mineral and produce signs of carbonization (◘ Fig. 3.17). It is evident that sufficient heat may be produced to cause the melting of hydroxyapatite (several hundred degrees Celsius) and associated thermal cracking. Of course, such temperatures would lead to direct pulpal damage through heat conduction.

In consequence, the interactions of high-intensity laser irradiation with bone and dental hard tissues are the result of a photothermal action [44] targeting both molecular and interstitial water.

With an appropriate laser wavelength such as the Er,Cr:YSGG (2780 nm) and Er:YAG (2940 nm) and operating parameters configured to maximize interaction, together with adequate coaxial water spray, the outcome is completely



◘ **Fig. 3.17** In vitro exposure of molar tooth to CO_2 laser irradiation and SEM examination. Globules of melted and resolidified (amorphous) hydroxyapatite are present, with large voids and gross disruption of structure. Average power 1.5 watts CW with no water spray

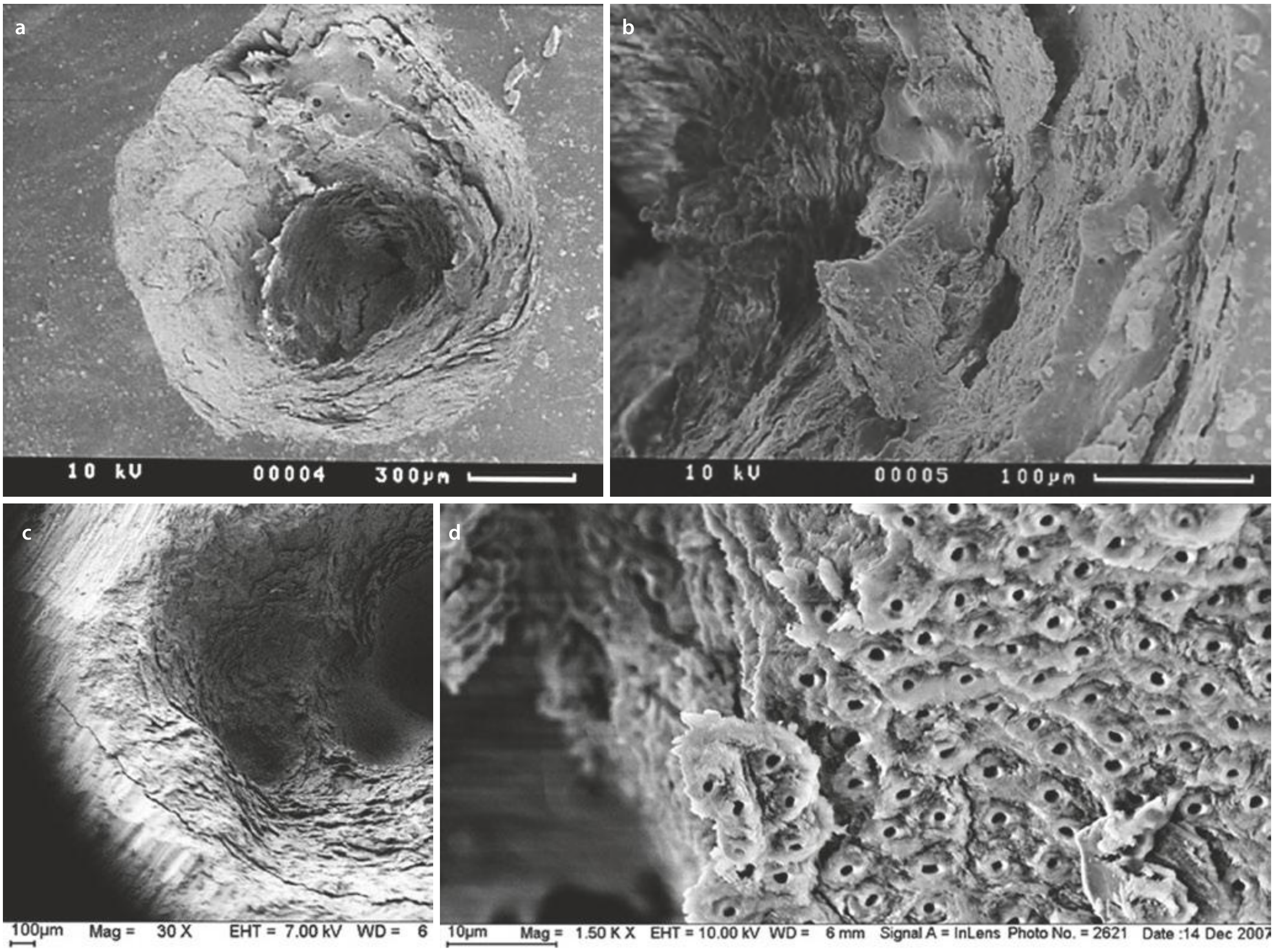


Fig. 3.18 SEM examination of tooth structure exposed to Er:YAG laser irradiation. Top images L and R – enamel structure showing evidence of dislocation and some fragmentation of the cut surface. Lower images L and R similar cut surface of dentine, showing the absence of smear layer and open tubules

different. With both enamel and dentine, the outcome of the «explosive» vaporization and ejection of tooth fragments results in a clean cut surface, without smear layer often associated with rotary instrumentation. Due to the outward dissipation of energy, there is minimal thermal rise within the structure of the tooth and conduction to the pulp.

The fragmented appearance of cut enamel (Fig. 3.18) especially was historically thought to enhance the facility for bonding of restorative resins and composites without the need for acid etching. However, many studies have highlighted the fragility of the cut margin in enamel and subsequent failure of the restoration margin as weakened tooth fragments gave way under tensile stress, with resulting failure and secondary caries risk [45, 46].

Mid-IR laser beam interaction with enamel (and to some extent also with dentine and bone) is a combination of temperature and pressure [47]. Both of which can be seen to rise rapidly during the pulse train of a clinical ablation procedure. The increase in volume as water vaporizes (1:1600) is significant and will give rise to significant rise in pressure just prior to the explosive dislocation of the enamel structure. As pressure rises, the continued vaporization leads to increase in temperature, resulting within the micro-confines of the interaction in «superheating» of the water and temperatures of several hundred degrees Celsius.

Furthermore, there are additional characteristics of laser ablation of hard tissue, surrounding the use of coaxial water, a necessary component to aid both excessive temperature rise and also to help wash away debris as a result of ablation. In addition, commercial models of both lasers use coaxial water spray to aid dispersal of ablated tissue and to cool the target [48], in a process called «water augmentation» [49]. According to this study, when dental hard tissues are irradiated with Er,Cr:YSGG and Er:YAG emission wavelengths with an additional thin water layer, the cutting efficiency increases at the same time that the pulp temperature decreases. However, the thickness of water layer should be well controlled to avoid a compromise in cutting efficiency and the blurring of the visual field.

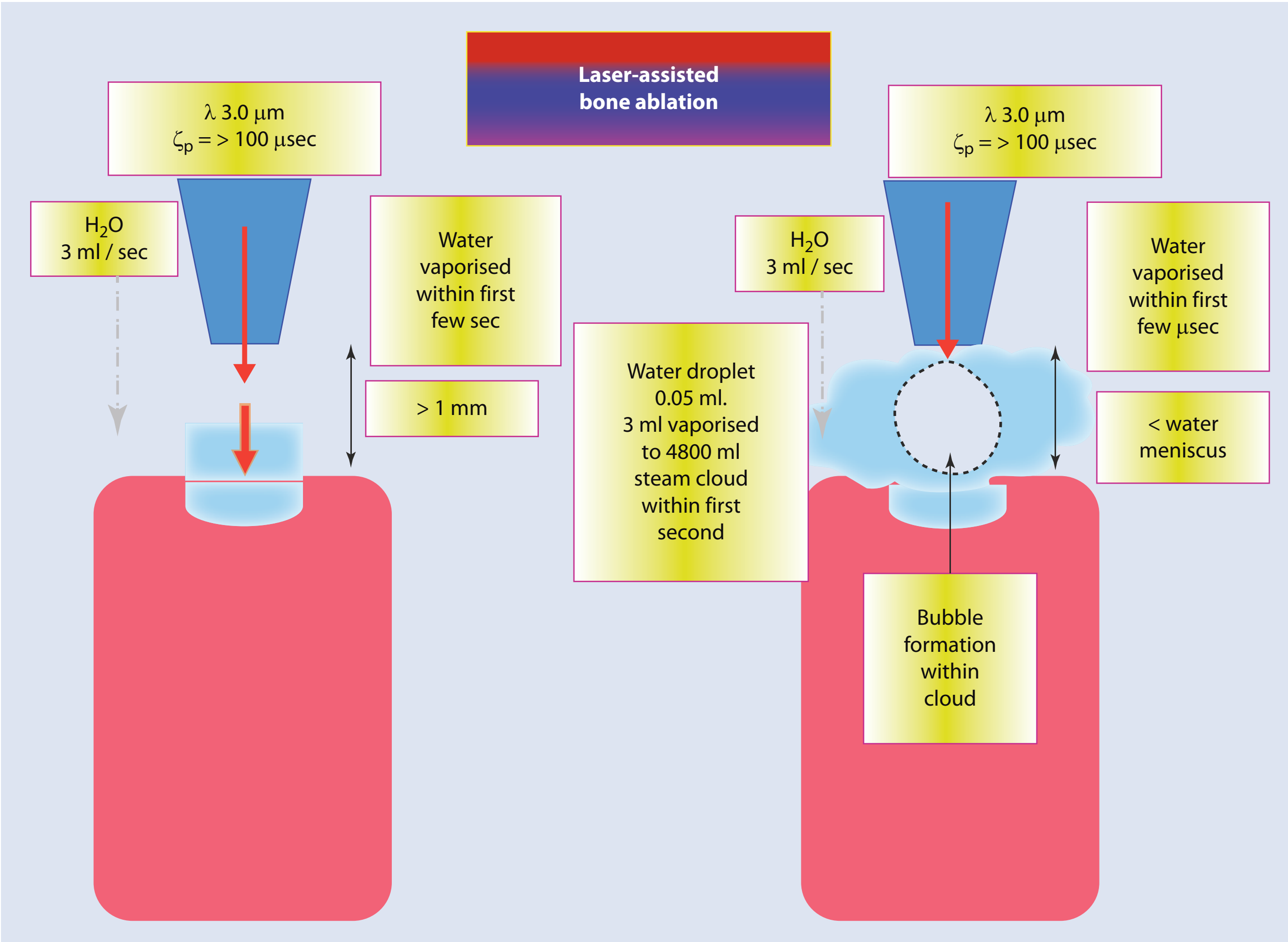


Fig. 3.19 Diagrammatic influence of the tip-to-tissue distance and influence of a contiguous water film, facilitating laser-induced cavitation phenomena (Adapted graphics S. Parker from Mir et al. [50])

As a liquid, water has a moderately high surface tension (72.8 millinewton per meter at 20 °C), and this accounts for the intact film that may surround the tooth surface during water-augmented laser irradiation. In a further study [50], the influence of the water thickness was investigated.

During ablation, the stream of photons is emitted in a free-running train of microsecond pulses (>100 μs), and any water between the laser delivery tip and the target would be vaporized during the first >30 μs of each pulse, allowing successive photons to interact with the target. If the tip-to-target distance is greater than the distance wherein the integrity of the water meniscus is maintained, the photon stream will pass through air before interacting with water at the surface of the tissue.

However, in circumstances where the delivery tip is close enough to the tissue surface and due to the surface tension of the water a continuous envelopment of that distance occurs, the vaporization of the water film happens as before, but the vapor is contained within a rapidly expanding bubble; as it collapses it gives rise to a cavitation phenomenon, and associated pressure waves may be sufficient (50–100 MPa) to initiate laser-induced «tripsy» (disintegration) of the tooth surface (Fig. 3.19).

This concept is exciting and in common with the similar phenomena of laser-induced cavitation in water using wavelengths at 3.0 microns that may occur in endodontic and laser-assisted osteotomy procedures. With reference to the study by Mir et al. above, the staging can be summarized as follows:

Staging of laser-induced cavitation phenomenon

- Energy intensity in the first pulses leads to absorption in the first μm layers of water opposite to the tip.
- Bubble formation with higher output energy density bubble dimensions was not clear, and a cloud-shaped appearance of laser–water interactions was recorded.
- In, for example, 140 μs pulses, after approximately 20–30 μs of the start of the pulse curve, a plume of vapor (comparable with a cloud) covers the tissue surface.
- The suction force exerted by the collapsing bubble and by the impact of the high-velocity jet generated during bubble collapse results in tissue ablation.

It remains to be seen to what extent this contributes to the «classic» understanding of 3.0 µm-mediated hard tissue ablation, but it is worthy of note that superheating of the vapor and hyperbaric pressure phenomena play a part.

In consideration of the ever-changing nature of available technology and its incorporation into laser wavelength choice, a precise irradiation parameter must be chosen in order to avoid collateral damage. This has importance no more than in terms of hard dental morphological damage, such as surface carbonization or cracking, which could produce structural and esthetic damage and postoperative complications such as transient pulpitis. Moreover, the energy densities used must be safe with regard to pulp and periodontal tissue vitality [51]. Studies have indicated that temperature increments above 5.6 °C can be considered potentially threatening to the vitality of the pulp [52] and increments in excess of 16 °C can result in complete pulpal necrosis [53]. In comparison with rotary instrumentation, pulpal temperature rise is minimal when erbium laser wavelengths are employed in cavity preparation [54].

Until recently, the commercially available CO_2 laser has been predominately a soft tissue ablation tool. The CW and gated CW emission modes of the 10,600 nm wavelength, together with an absence of coaxial water to aid tissue cooling and disperse ablation debris, give rise to rapid overheating of tooth tissue, cracking, carbonization and melting which has made its use in restorative dentistry impossible [55–57].

However, due to the «four-level» nature of photon generation within the laser cavity, three major wavelength emissions occur – at 9300, 9600 and 10,600 nm. The longer wavelength is easier to manipulate from a technical point of view and has predominated the availability of the CO_2 laser in clinical therapy. Absorption in water is a strong feature at this far-IR range, but the shorter 9300 and 9600 wavelengths are also strongly absorbed in the phosphate radical of the hydroxyapatite molecule. Investigation into this laser–tissue interaction has spanned almost 20 years [58], and in consequence, with a shorter CO_2 wavelength and manipulation of the emission to allow microsecond bursts together with a coaxial water spray to minimize heat generation, the interaction is both more positive and clinically acceptable [59].

If pulse durations in the range of 5–20 µs are used, efficient ablation occurs with minimal peripheral thermal damage [60, 61], and this has now resulted in a, for instance, commercially available laser unit emitting at 9300 nm with a specimen pulse duration of 10–15 µs and repetition rate of 300 Hz, demonstrating that enamel and dentine surfaces can be rapidly ablated by such lasers with minimal peripheral thermal and mechanical damage and without excessive heat accumulation [62, 63].

Commercial pressures may dictate the direction and speed of investigation into laser–tissue interaction with dental hard tissue that is based upon concepts of power density and pulse width as predominant factors to minimize collateral thermal damage, as opposed to the pure selection of chromophore-related laser wavelengths. By way of an example, in a most recent published investigation, a diode-pumped, thin-disc femtosecond laser (wavelength 1025 nm, pulse width 400 fs) was used for the ablation of enamel and dentine. Laser fluence, scanning line spacing and ablation depth all significantly affected femtosecond laser ablation efficiency and were predominant in comparison with the intuitively inappropriate choice of a near-IR laser wavelength of 1025 nm [64].

As may be seen with the erbium family of lasers at 3.0 µm, there is also the potential for easy disruption and ablation of composite restorative materials, and this has been the subject of published data [65, 66].

3.10 Laser Interaction with Dental Caries

Key to the efficient and safe laser-assisted removal of caries would be the facility to selectively ablate decayed dental tissue without causing injury to surrounding tooth tissue or the pulp. Caries removal should be within the desired outcome of complementary esthetic restoration of the tooth.

Prior to the development of the erbium family of lasers, the limited laser wavelengths and technology available within dental application meant that only visible and near-IR lasers (diode and Nd:YAG), together with CO_2 10,600 nm wavelength, could be investigated. Due to the rapid heat build-up with the available laser delivery parameters, attempts to remove (pigmented) dental caries received only limited success [67–69].

With the use of 3.0 µm wavelengths, the high absorption in water has transformed interaction. Caries as a demineralized residue of bacteriogenic acid action on enamel and dentine has varied structure but predominately a much higher water content than normal tooth structure. Interaction of laser photonic energy with this material will allow some selective ablation relative to the tooth tissue and this remains a major advantage of lasers over more conventional rotary instrumentation [70, 71]. Additional positive indications support the development of the new generation of micro-pulsed CO_2 lasers and the ability to utilize the absorption on water at this wavelength. This has been the subject of intense research and investigation by the group at UCSF in San Francisco, USA [72, 73].

3.11 Caries Prevention

Laser–tissue interaction with hard dental tissue may pose difficult challenges relative to the wavelength and operating parameters, and this has been outlined above. Peripheral to the blunt outcome of thermal damage potential has been the careful application of several wavelengths to achieve a thermally mediated change in the carbonated hydroxyapatite

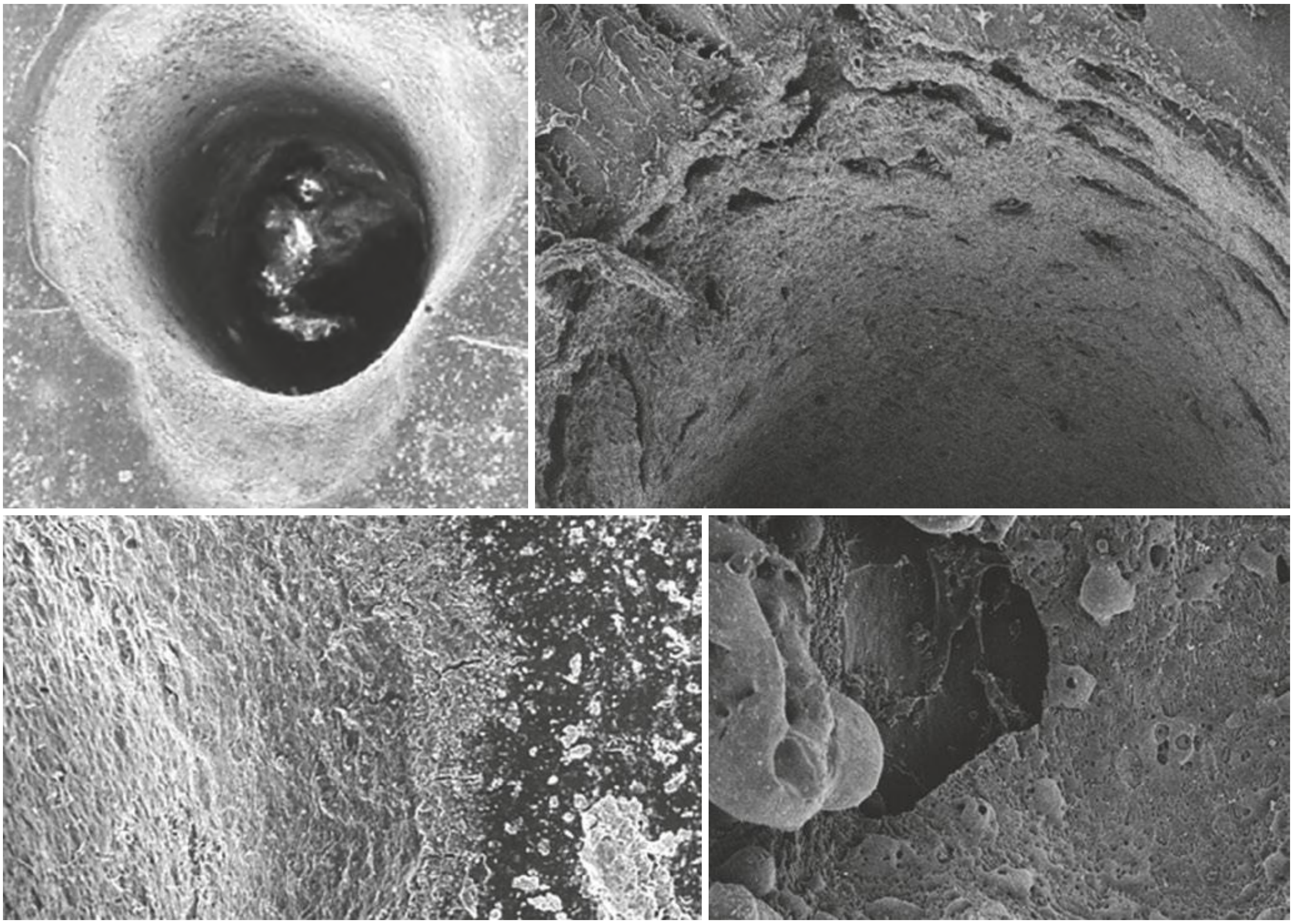


Fig. 3.20 SEM representation of laser interaction with osseous tissue. Top left, right and lower left images relate to ascending magnification of Er:YAG (2940 nm) with porcine rib bone in vitro. The cut is clean with minimal evidence of tissue disruption and thermal damage beyond the cut margin. Compare this to the image at lower right, using Nd:YAG (1064 nm), where apatite melting and large thermally induced voids are visible

structure of enamel to change the crystal lattice to a more acid-resistant amorphous «glass-like» state. This change has been shown to occur with injudicious laser use on hard tissue, but with care a number of studies [74–78] have proposed that many laser wavelengths may be manipulated to provide caries resistance in nondiseased teeth.

3.12 Laser–Tissue Interaction with Bone

The structure of osseous tissue of the maxilla and mandible resembles that of dentine in terms of proportional ratios of mineral, protein and water (Table 3.4). The bone is a much more dynamic tissue with reference to cell activity and turnover, compared to tooth tissue, and care must be observed to respect the potential for disruptive consequences of using inappropriate laser parameters. Although early reports of supportive use of CO_2 (10,600 nm) laser wavelength in surgical bone management are recorded [79], the potential for photothermolysis and collateral damage remains high. Laser ablation of bone with erbium laser wavelengths (2780 nm and 2940 nm) with high absorption in water defines a level of selective ablation through the vaporization of water and tissue structure disruption, and in this way, laser ablation of the bone proceeds in a similar fashion to that seen in laser-mediated tooth tissue ablation. The higher water content and lower density of bone compared to enamel allows faster cutting, through dislocation of hydroxyapatite and cleavage of the collagen matrix (Fig. 3.20). This ease of cutting places the use of Er:YAG and Er,Cr:YSGG laser wavelengths as the preferred choice for laser bone ablation when compared to other wavelengths [80].

3.13 Laser–Tissue Photofluorescence

In an earlier section of this chapter, it was defined that fluorescence, as a form of sub-ablative laser–tissue interaction, is a luminescence or reemission of light in which the molecular absorption of a photon triggers the emission of another

3

Table 3.5 Common fluorophores found within the oral cavity and dentistry

Autofluorescence – wavelength?			
Fluorophore	**Excitation nm**	**Fluorescence peak**	**Comments**
Tryptophan	275	350	Protein
Collagen	335	390	Connective tissue (CT)
Elastin	360	410	CT
Keratin	370	505	Surface analysis
Porphyrins	405, 630	590, 625, 635, 705	Cell mitochondria/metallo-, copro-, proto-porphyrins
Healthy enamel	405	533	
Caries	405, 488, 655	580–700	
Inorganic composites	655	Mean fluorescence intensity closely matched to healthy enamel	
GI composites	655	Mean fluorescence intensity closely matched to carious enamel	

Source: Kim et al. [81]
Each fluorophore is capable of excitation at specific light wavelength and corresponding reemission measurement can prove helpful in differential diagnosis of tissue change

photon with a longer wavelength. Please change to "In absorbing incident photonic energy, some of that energy is expended, and the difference between the absorbed and re-emitted photonic energy may be seen as molecular vibrations or heat. With consequent energy loss, the re-emitted photons have a longer wavelength". This event is governed by the biophysical nature of tissue molecules involved (*termed fluorophores*) and as such can be the basis for optical scanning techniques used in caries detection in enamel and dentine and tomographic techniques in the scanning of soft tissue for neoplastic change.

The oral cavity provides substantial opportunity for scanning and fluorescence techniques, due to the ease of access of oral structures and the database of the excitation and emission wavelengths of individual tissue elements as well as non-biologic materials that may have use in dentistry [81]. In Table 3.5 it may be seen that through the choice of precise monochromatic laser wavelengths, predominately in the visible spectral range, the resultant reemission would help to provide analysis of the target composition. A specific example might be that whereas healthy enamel exposed to a blue incident irradiation reemits as a green color, the presence of porphyrin (pigment component of dental caries) reemits at a longer red-brown color and would allow differentiation diagnosis of dental caries to be made.

Fluorescent and photodynamic diagnosis may provide screening facility or part of a hierarchical series of tissue investigation and must be regarded as an adjunct to a range of investigations – direct visual, microscopic and histologic examination, genetic analysis – to provide support to the clinician especially within the field of soft tissue health screening [82].

In oral soft tissue structure, disease changes the concentration of the fluorophores as well as the light scattering and absorption properties of the tissue, due to changes in blood concentration, collagen content and epithelial thickness. Such effects may be seen as:

- Recorded fluorescence signal will be lower in the case of hyperplasia – the epithelial layer shields the strongly fluorescent collagen layer.
- Excessive keratin production by lesions may produce an increase in autofluorescence intensity.
- Cell metabolism may increase with malignant changes, which changes the balance between fluorescent NADH (increase) and nonfluorescent NAD+ (decrease).

Many studies have been performed to investigate photodynamic diagnosis and fluorescence techniques in the oral cavity. These studies may be grouped in an attempt to address specific criteria of relevance in clinical assessment of neoplastic soft tissue change:

1. Whether autofluorescence imaging is capable of providing a higher contrast between a lesion and healthy tissue than white light or tactile and visual inspection. This is certainly the case for flat, early lesions [83, 84].
2. Whether autofluorescence imaging is helpful in differentiating between different lesion types, in particular between benign, dysplastic and malignant lesions. Overall, the specificity of autofluorescence imaging for distinguishing (pre)malignant from benign lesions does not seem to be very promising [85, 86].
3. The detection of unknown lesions and unknown extensions of known lesions, which would be useful for tumor demarcation. Indications have indeed been found that autofluorescence imaging is capable of detecting invisible lesions or invisible tumor extensions [87, 88].

Autofluorescence imaging might be appropriate as an easy-to-use, sensitive and inexpensive method for lesion detection, although further research is still necessary. In general, autofluorescence imaging may give good results for the distinction of lesions from normal mucosa. However, suspect lesions of the oral mucosa must be subjected to biopsy and other investigations, and certainly, it is inappropriate to place autofluorescence investigation in any role other than as an adjunctive scanning technique. If possible, autofluorescence spectroscopy could be used to find the optimal, most dysplastic location for biopsy, although the literature shows that autofluorescence is not specific enough for this purpose.

An allied area of laser–tissue interaction and spectroscopic analysis of reemission is Raman scattering. This is a special, very weak form of light scattering in which energy is lost or gained to a molecule through a phenomenon known as inelastic scattering, where the frequency of photons in monochromatic light changes upon interaction with a tissue sample under investigation. The frequency (frequency and photon energy are inversely proportional) of the reemitted photons is shifted up or down in comparison with original monochromatic frequency, and this is called the Raman effect. This shift provides information about vibrational, rotational and other low-frequency transitions in molecules.

Raman spectroscopy can be used to study solid, liquid, and gaseous samples. Vibrational information is specific to the chemical bonds and symmetry of molecules. Therefore, it provides a fingerprint by which the molecule can be identified and has an important role within the area of tissue photo-analysis as it impacts on disease versus health.

3.14 Laser–Tissue Interaction and Photobiomodulation

Photobiomodulation (PBM) is the manipulation of cellular behavior using low-intensity light sources and the delivery of laser therapy (application of photonic energy at specific wavelengths) to induce a biological response through energy transfer. Sub-ablative photonic energy delivered into the tissue modulates biological processes within that tissue and within the biological system of which that tissue is a part. Key to the limits of benefit is the restriction of laser operating parameters to ensure that PBM has no appreciable thermal effect in irradiated tissue.

Phototherapy is characterized by its ability to induce photobiological processes in cells [89]. This conforms to the first law of photobiology (light absorption by specific molecular chromophores). There is a so-called optical window in tissue (approx. 650 nm–1100 nm), where the effective tissue penetration of light is maximized. The use of LLLT in patients almost exclusively involves red and near-infrared light (600–1100 nm) [90].

The absorption and scattering of light in tissue are both much higher in the blue region of the spectrum than the red. The principal tissue chromophores (hemoglobin and melanin) have high absorption bands at shorter wavelengths, tissue scattering of light is higher at shorter wavelengths and water strongly absorbs infrared light at wavelengths >1100 nm.

Wavelengths in the 600–700 nm range are chosen for treating superficial tissue, and those between 780 and 950 nm are chosen for deeper-seated tissues, due to longer optical penetration distances through tissue with the latter group. Beam coherence is maintained as the laser beam penetrates the tissue and along with polarization may be an important factor in allowing the laser to effectively treat deeper tissues

Incident photons of wavelengths as referenced above are absorbed into mitochondria and cell membranes of the target cells. Photonic energy is incorporated into a molecule to increase kinetic energy, activate or deactivate enzymes or alter physical or chemical properties of main macromolecules.

Growth factor response within cells and tissue may be seen as a result of increased ATP and protein synthesis [91], change in cell membrane permeability to Ca++ uptake and cell proliferation, and overall a cascade of metabolic effects results in physiological changes resulting in improved tissue repair, faster resolution of the inflammatory response and a reduction in pain [92].

In summary, the results of laser–tissue interaction that promote PBM may be seen within three clinical areas of benefit – anti-inflammatory effects [93], analgesic and pain suppression effects [94] and effects that promote healing in the irradiated tissue [95].

Investigation into pain response during surgical laser use has revealed findings that are inconsistent with many anecdotal reports and may provide an opportunity for the essential subjective aspects of patient receptiveness to be accepted. Pain is a defense mechanism and pain perception is innate and subjective. Equally, all stimuli applied to excess will result in pain.

Factors affecting the perception of pain

Pain perception is multifactorial and may be influenced through the following, either singularly or in combination:

- *Emotion*: fear, anxiety, stress syndrome, excitement
- *Awareness*: trust, previous experience, conditioning, e.g., hypnosis, activity subordination
- *Threshold potential*: age, infirmity, drugs, alcohol, social factors

The avoidance of pain during restorative and dental surgical procedures remains a strong factor in promoting patient acceptance of treatment, and many studies have been carried out to evaluate this in terms of laser–tissue interaction [96–98]. The use of the Nd:YAG (1064 nm) laser in developing pulpal analgesia, possibly through interference with the «gate theory» of neural stimulus propagation, was an early mainstay benefit of this laser following its launch into dental

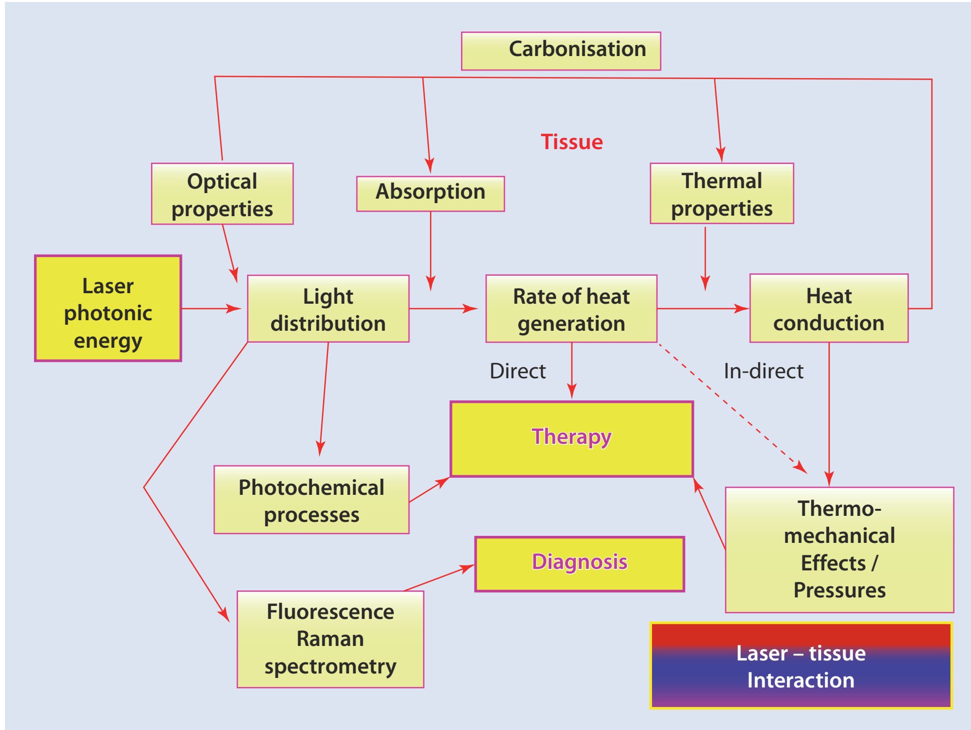


Fig. 3.21 Summary of laser–tissue interaction to demonstrate the breadth of application, relative to photon delivery

practice in 1990. However, investigation into the subjectivity or placebo effect has rendered its application inconsistent [99–101]. Chaiyavej et al. found that Er:YAG laser use, similar to rotary bur cutting of tooth tissue, caused neural response in both A and C intradental fibers [102].

Perhaps of greater significance in exploring this area may be the lack of tactile and thermal stimulation compared to rotary instrumentation during laser-assisted restorative dentistry. In seeking to understand the essentially anecdotal reports of soft tissue surgery using laser photonic energy in what is a thermally based interchange, there is the patient-centered factor of trust in the operator, together with a possible harmonization of micro-pulsed free-running emissions with regeneration potential of acetylcholine at synaptic junctions within the sensory neurone.

It is without question that, when used correctly and with recommended operating parameters to maximize laser–tissue interaction, laser-assisted surgical procedures on soft and hard tissue are less physically injurious when compared to both scalpel and rotary bur. Patient acceptance, peer pressure and a general acceptance of «hi-tech» approach to treatment may all propose an enhancement of tolerance of sensory stimulation.

Conclusion

An overview has been presented to explore the physical and biological aspects of interaction of laser photonic energy with target oral hard and soft tissue. Any inconsistency may be viewed in terms of the precise mechanisms governing molecular energy dynamics but also the great diversity in tissue types and their close approximation within the oral cavity. The clinician is faced with technical challenges in manipulating any given laser wavelength to employ it as broadly as possible during clinical procedures; the additional facility of power density phenomena in helping to initiate an essentially photothermal event may help to deliver predictable and precise surgical outcomes. In Fig. 3.21 it is possible to appreciate the complex yet interconnected relationship that exists between incident laser choice and operating parameters, the consequent gradient of effects that result from such choice and how the laser–tissue effects so produced can represent a breadth of clinical application – both in terms of therapy and diagnosis. The photon distribution and concentration (fluence) delivered will influence the degree of (essentially) photothermal effect and consequent reaction of the target tissue. At low fluences, the benefits can be seen as diagnostic value and PBM (photochemical) effects; at higher fluences (with the same laser wavelength or another), the photothermal interaction predominates with ablative and permanent structural tissue change. The overload of fluence values may give rise to destructive collateral effects such as carbonization and consequent changes in tissue optical properties and absorption potential.

In summary, laser photonic energy offers a degree of «purity» through empirical properties – wave coherence and single (mono)wavelength. Unique wavelength value confers predictable photonic EM energy value through an inverse proportional relationship.

All matter has constituent atomic and molecular energy, consistent with intra-, inter- and extra-atomic and molecular binding forces. For any system, the «resting» gross energy value determines a ground state physical form (solid, gas, liquid) relative to temperature.

Predictable («pure») interaction with tissue can only occur if incident energy is absorbed by the tissue, although levels of laser photonic energy may be viewed as being largely insufficient to overcome interatomic covalent or intra-lattice ionic binding forces within target tissue.

A better explanation might emerge, based on chromophore absorption of photonic energy leading to temperature rise within the system and based on such assumption, laser photothermolytic interaction with tissue is mainly due to the indirect consequences of the conversion of EM photonic energy into thermal energy.

Photoacoustic and photochemical effects may be viewed as further consequential effects of primary photothermolysis.

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Laser Operating Parameters for Hard and Soft Tissue, Surgical and PBM Management

Wayne Selting

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Core Message

New technologies introduced into clinical dentistry in recent years have added immeasurably to the quality of care that may be provided. Lasers, dental implants, CAD/CAM, and motorized endodontics have all improved clinical outcomes but require a significant investment in hardware and, most importantly, education to understand concepts and protocols. As with all medical instrumentation, it is not enough to follow basic guidelines or «preset» parameters in approaching each patient situation. A deep understanding of the technology, how it interacts with the patient's tissues and what variables are important to consider is necessary for a successful clinical outcome.

Of the four technologies mentioned above, lasers are, perhaps, the easiest to abuse. Without basic education, it is nearly impossible for a clinician to accomplish the first successful case of implant placement, CAM/CAD crown fabrication or motorized endodontic treatment. However, with a manufacturer provided user's manual, a dentist with a new laser may push a button that says «gingivectomy» and attempt a procedure.

The purpose of this chapter is to explore the parameters that are important, and in some cases critical, to successful laser therapy. This discussion then leads to insights into specific lasers and tissues.

As has been presented, various lasers can be used for surgical treatment of both hard and soft tissues. In addition, photonic energy can be injected into tissue to affect cellular metabolism beneficially. In each of these therapies, applied energy density, its wavelength, and the time over which it is applied represent critical factors affecting the outcome.

4.1 Intrinsic Properties

A number of parameters are dictated by design decisions during the manufacture of any clinical laser. They cannot be chosen or controlled by the operator and must be accepted with their benefits and shortcomings.

4.1.1 The Photon

A photon is a quantum of electromagnetic energy and has been discussed extensively in previous chapters. All photons are certainly not alike. The amount of energy in each photon is determined by the wavelength, or more precisely, the wavelength is determined by the photonic energy released.

The number of photons generated by a laser is mindboggling. If an 810 nm diode laser is set to deliver 1 watt of output power, 4.08 quintillion photons are produced every second. That is, 4,080,000,000,000,000,000, photons are released each second. On the other hand, an Er:YAG laser at 2940 nm must produce 14.799 quintillion photons in a second [1]. Photons exert their influence on tissue through absorption by cellular elements and that absorption is highly dependent on wavelength.

4.1.2 Wavelength

As an electron drops from one orbital to one of lower energy, a precise amount of photonic energy is released producing a specific wavelength. Every laser is capable of and does generate several wavelengths. The resonant cavity is designed to dampen unwanted wavelengths through destructive interference leaving only the desired output to be amplified and emitted.

4.1.3 The Laser

Every laser produces only one predominant wavelength of photons. The laser is usually identified by its active medium and host material. The active medium is a material that can absorb photons of energy and then release them when stimulated further by more photons. Many different materials have been shown to produce this unique «stimulated emission.» Lasers are designated therefore as solid state, gas, semiconductor, and liquid, based on the material used.

Solid-state lasers are most commonly trivalent rare earth ions such as neodymium (Nd) and erbium(Er). The host material suspends the active ions and comprises the majority of the laser crystal. They are most commonly grown crystal structures such as yttrium aluminum garnet abbreviated as YAG [2]. This combination of elements accounts for the naming convention of Er:YAG, Nd:YAG, etc.

Gas lasers consist of a combination of gases. Carbon dioxide lasers are actually a mixture of approximately one part carbon dioxide combined with four parts nitrogen as the active medium distributed in approximately five parts helium as the host material.

Liquid or, so-called, dye lasers use fluorescein, malachite green, coumarin, or rhodamine as the active medium suspended in water, alcohol, or glycol as a host material. They have the great advantage of being «tunable» from approximately 365 nm to 1000 nm and, because of the inherent cooling provided by the liquid medium, can produce as much as 20 watts of continuous wave output and 1.4 kilowatts of pulsed output. Unfortunately, they are bulky, complex, and expensive and are not currently used in dental applications [3].

Finally, semiconductor lasers, represented by the diode laser, are the most common laser available in dentistry today. They are small, simple, and relatively inexpensive making them very attractive. Most diode lasers are based on combining group III and group V compounds from the periodic table. Those fabricated from gallium arsenide and its derivatives typically lase at wavelengths between 660 and 900 nm while those utilizing indium phosphide-based compounds produce wavelengths between 1300 and 1550 nm [4]. Recent advances in technology allow laser emission at wavelengths ranging from as little as 370 nm to an amazing 15,000 nm. Only a few of these have practical application in dentistry and are limited to approximately 808 nm to 1064 nm [5].

All photons produced at a particular wavelength are the same. While a laser manufacturer would like you to believe that their photons are different and better than those of their

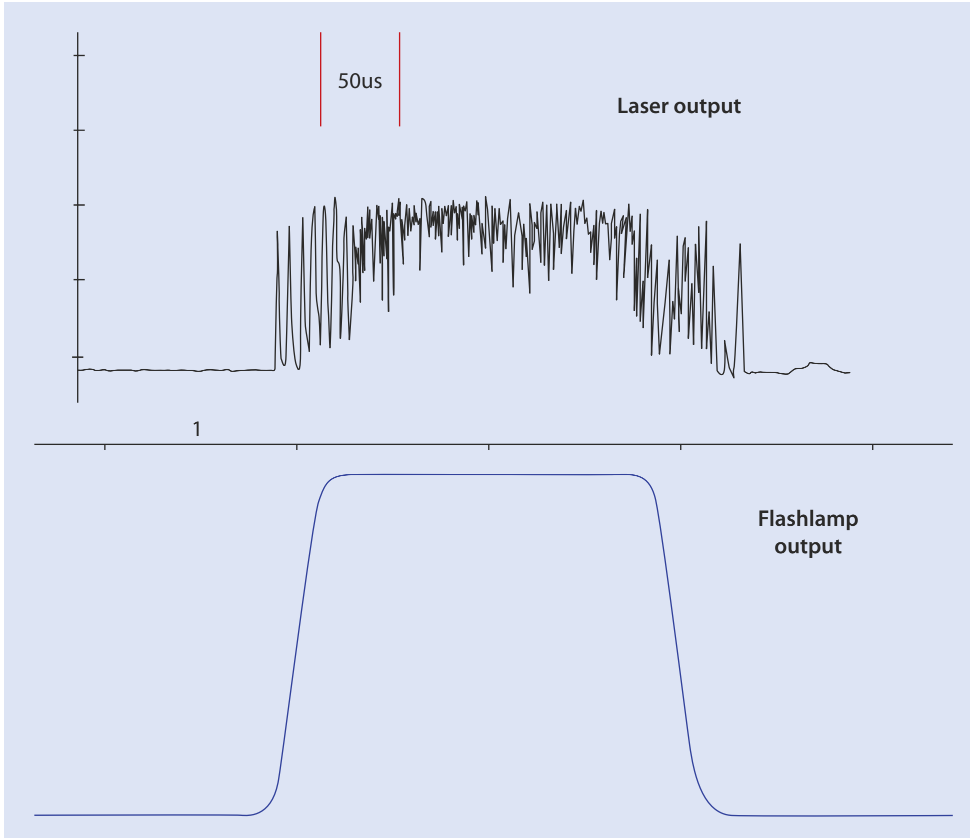

Fig. 4.1 As long as photons are injected into a resonator by a flashlamp or other source, stimulated coherent photons will be emitted. The amount of lasing activity changes throughout the pulse

competitor, it simply is not true. How they deliver those photons to the tissue and how you are able to control that process is unique to each product and could be a factor in your decision to purchase that particular laser.

Free-Running Pulse Laser

Free-running pulse is a term applied to a laser, meaning that the laser emission lasts as long as the pumping process is sufficient to sustain lasing conditions. Lasers such as Nd:YAG, Er,Cr:YSGG, and Er:YAG release photons as a train of pulses. Most commonly, a flashlamp similar to a photographic flash injects a large number of photons into the active medium. This begins a cascade of events that has been described previously. As long as the flashlamp is injecting photons, lasing will continue. Therefore, the pulse width or length of time that photons will be emitted is controlled by how long the flash lasts. Usually the duration of the flash in dental lasers and, therefore, the laser output of photons is in the range of 50 microseconds to 1000 microseconds. Complex control electronics usually allow the operator to select this vital parameter through a touch screen.

The amount of energy in each of these pulses is controlled by the intensity of the flashlamp. If the flash-lamp injects twice as many photons to stimulate the active medium, approximately twice as many coherent laser photons will be produced in the resonant cavity and be emitted within the same selected time frame or pulse width.

Lasing is not a continuous activity during the duration of the pulse. It takes some time measured in microseconds for the process to build. As energy is released, the number of stimulated photons is depleted and drops below the state of population inversion. As more photons continue to be injected by the flashlamp, the critical level is again exceeded, and laser photon production again occurs. This process repeats itself about every five microseconds. Figure 4.1 is a representation of actual laser activity.

Continuous Wave Lasers

Lasers such as the KTP, diode, and many CO_2 emit photons on a continuous basis rather than in pulses. The flashlamp is replaced by an electric current which injects electrical energy instead of photons into the active medium. However, the result is still the release of photons in the familiar stimulated emission mode. As long as the laser is energized, a continuous stream of photons will be emitted. An LED (light emitting diode) is not capable of laser activity but is a common example of electrical energy being converted to photonic energy. All diode lasers rely on this direct energy conversion.

The CO_2 laser is a bit different. Electrons are passed through a gas starting the lasing process using a high-voltage transformer that can operate continuously. As long as the gas is energized, lasing will occur. Using control circuits, the output can be continuous wave, variable gated continuous wave, pulsed, super-pulsed, gain-switched, or Q-switched.

In super-pulsed mode, the pulse peak power driving the laser discharge can be several times the average continuous wave power. A super-pulsed CO_2 laser is gated «on» for about one-third of the time. This allows it to be driven three times as hard when «on» to produce the same average power while still avoiding overheating. The pulse width is usually in the 5–1000 us range with peak power reaching triple that of its continuous wave counterpart [6]. Super-pulsed lasers available in dentistry usually operate at a wavelength of 9.3 or 10.6 um.

Gain-switched CO_2 lasers can produce megawatts of peak power, while Q-switched lasers with pulse widths in the nanosecond range can produce peak powers that are several 100 times the average output. These lasers are not currently applied in dentistry.

Variable Gated Continuous Wave Lasers

Continuous wave lasers may be turned on and off repeatedly by an electronic circuit generating what is commonly called a variable gated continuous wave. The term «variable» suggests that the ratio of on-time to off-time is not fixed but each parameter can be varied independently. Currently, on-times and off-times can be selected in the range of approximately 10 ms to 1000 ms. One laser manufacturer has developed a unique system that allows on-times of as little as 18 microseconds with pulse repetition rates of up to 20,000 pulses per second.

Clarification of Pulsed Laser Concept

Confusion continues regarding very important differences in the nature of laser photon emission. Continuous wave output is inherently different than pulsed output.

Variable gated continuous wave lasers are often incorrectly designated as «pulsed lasers.» Continuous wave lasers produce the same number of photons in each microsecond whether they are gated or not. Gating simply represents an on-off switch. If the on-time is twice as long, twice as many photons will be emitted. Of course, no photons are delivered to the target tissue during the off-time. This concept is illustrated in ◘ Fig. 4.8 below.

The most important characteristic of a pulsed laser is the ability to store and release energy very rapidly. This creates very high peak powers. Pulsed lasers, as described in ▶ Sect. 4.1.3.1, emit a predetermined amount of energy during the pulse. If a pulse is half as long, the same total number of photons will be emitted but all must be emitted in half the time. Therefore, twice as many photons will be emitted in each microsecond during the pulse. It should be evident that, if the pulse width is made very short, very high peak powers will result – a very large number of photons will be emitted in each microsecond. This concept is illustrated in ◘ Fig. 4.9 below.

The best way to illustrate this dramatic difference between pulsed and continuous wave emission is to compare two lasers that, on the surface, appear to be nearly the same. ◘ Table 4.1 shows the large difference in actual output.

◘ **Table 4.1** Comparison of pulsed Nd:YAG and variable gated continuous wave lasers adjusted to what appear to be identical settings. The resulting pulse energy, average power, peak power and peak power density are calculated to be dramatically different

Laser type	Nd:YAG	Diode
Wavelength	1064 nm	1064 nm
Mode	Pulsed	Variable gated continuous wave
Delivery fiber diameter	600 um	600 um
Power displayed on screen	5 watts	5 watts
Pulse width	100 us	100 us
Pulse repetition rate	50 pps	50 pps
Pulse energy	100 mj	0.5 mj
Average power	5 watts	0.025 watts
Peak power	1000 watts	5 watts
Peak power density	353,678 w/cm^2	1,768 w/cm^2

4.1.4 The Photon Beam

As photons leave the resonating chamber through the partially reflective mirror, they are gathered by a series of lenses. These lenses collimate the photons making them all travel parallel to each other in a common direction or they focus the beam to the correct spot size to be fed into the delivery device.

Beam Profile

The spatial profile of the laser beam is often, erroneously, assumed to be homogeneous with energy output uniform across the entire beam. Most lasers emit in the «fundamental transverse mode» also called the «TEM_{00} mode.» This output is Gaussian in cross-section as it leaves the resonator as depicted in ◘ Fig. 4.2.

The density of the photons is significantly higher at the center of the beam. Cells directly on the beam axis are irradiated at a very high fluence, while those cells on the periphery of the incident beam receive insufficient cellular energy to produce any surgical effect. Laboratory measurement of the actual output from a diode laser reveals that the power density at the beam center is more than twice the average calculated from the applied power, while power density on the periphery is as low as 5% of applied power. Significant amounts of sub-ablative energy are deposited into tissue on the fringes causing heating and dehydration instead of the desired ablation.

By the time the light is emitted, imperfections in the laser tip and the fiber optic bundle can cause further variation from this theoretical output as shown in ◘ Fig. 4.2c.

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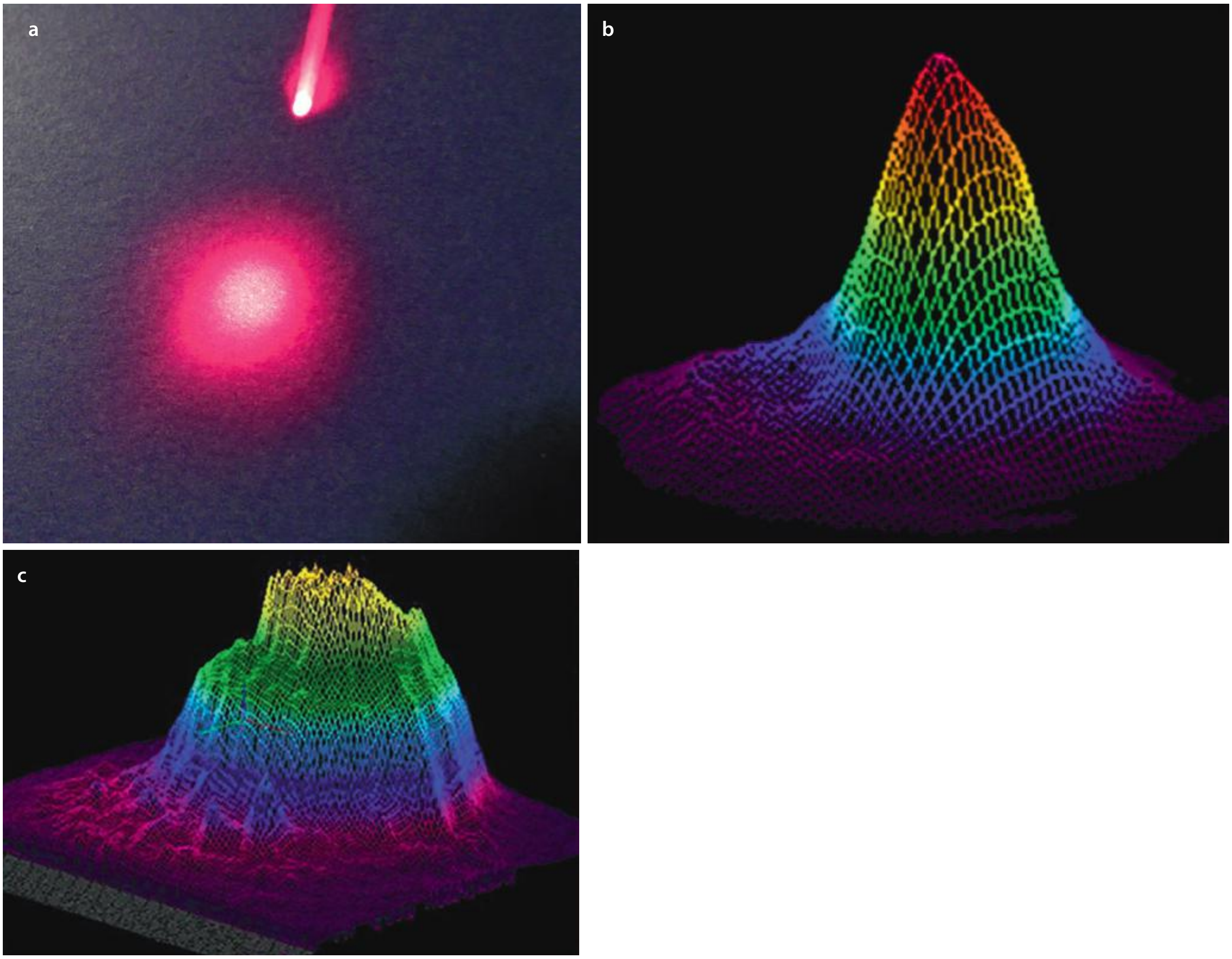

Fig. 4.2 The output from the laser fiber in **a** is obviously nonuniform. The plot in **b** depicts power density at different points across the beam and is approximately Gaussian in cross section. Figure 4.2c depicts the output profile of an Er:YAG quartz. The vertical axis indicates relative energy density (Photo courtesy of Frank Yung DDS)

4.1.5 Delivery System

Laser energy exiting the resonant chamber and passing through collimating and sizing lenses is delivered to one of three devices for transportation to the tissue: optical fiber, semiflexible waveguide, or articulated arm.

Optical Fiber

The propagation of light in fibers depends on the principle of total internal reflection [7]. The core layer of the fiber, made of fused silica, has a larger refractive index than the outer cladding layer. The incident laser energy is reflected off of this boundary layer and is trapped inside the core. The core and cladding are coated with a buffer material, such as polyamide which has a refractive index slightly greater than that of the cladding and has the additional advantage of mechanically protecting the fiber.

Optical fibers are exceptionally flexible as shown in Fig. 4.3a, b. Even with a severe bend, they continue to reflect photons off the boundary and continue to travel inside the fiber. Figure 4.3b illustrates this phenomenon. However, even a slight nick in the fiber will result in an instantaneous fracture. The polyamide plastic coating surrounds the entire fiber to prevent damage from accidental contact.

For dental use, these fibers are produced in diameters from 100 microns to more than 1200 microns. The significance of selecting a particular size will be discussed later in this chapter. These optical fibers are very attractive to use since their flexibility and light weight make them easy to maneuver when accessing challenging areas in the oral cavity. However, they are only able to be used with short wavelength lasers such as diode and Nd:YAG. Longer wavelength photons are strongly absorbed in all optical fibers.

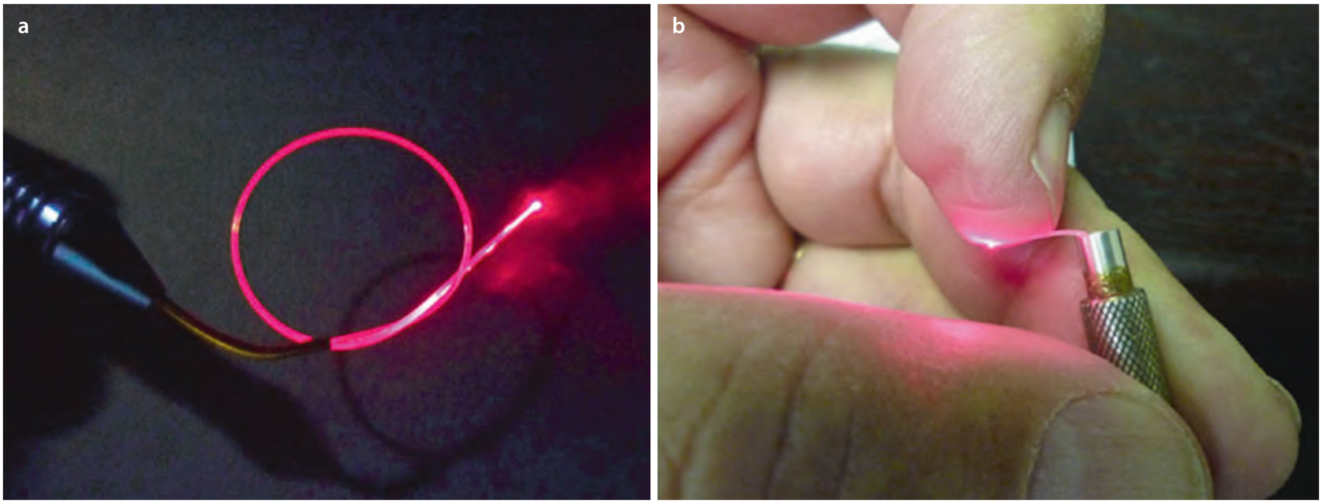

Fig. 4.3 **a** A 400 um diameter optical fiber can be tied in a knot and still transmit most of the laser energy. The red color visible in the knot indicates a small number of photons are escaping. **b** As long as the protective polyamide coating is present, the same fiber can be bent at nearly a 90° angle without breaking

Semi-Rigid Hollow Waveguides

Photons of longer wavelength travel easily through an air medium. Most erbium wavelengths deliver energy through a hollow, semirigid waveguide with inner diameters of typically 300–1000 µm. The inner surface is coated with a silver mirror finish and then with silver halide, creating a very efficient dielectric reflector for infrared wavelengths.

Photons traveling down the lumen of this tube reflect off the sides and continue to the exit portal. However, while bouncing back and forth, photons lose any semblance of collimation and, also, assume a Gaussian distribution. Therefore, lenses are again needed to collimate the output and direct it into the final delivery handpiece. From there it is delivered to the tissue, using a variety of end attachments, such as a tipless handpiece, a sapphire or quartz tip, and metal or ceramic «guides.»

These waveguides have very limited flexibility and a large diameter making them somewhat unwieldy to maneuver within the oral cavity. There are also some limitations on the power level that may pass through without damaging the silver coating.

Articulated Arm Waveguides

For even longer wavelengths such as CO_2, rigid, hollow waveguides are used. Light is redirected using articulated arms and reflective mirrors. These usually consist of seven segments connected with joints containing carefully aligned mirrors. The mirrors move in such a fashion that the beam is always directed down the center, no matter how the joint is turned. Photons entering each segment are transmitted in a straight line down the center of the tube. When they reach the end, they strike a mirror and are reflected precisely down the center of the next segment.

At the end of the last segment, the photons are presented to mirrors in the handpiece and then on to the delivery tip. In many cases, they are delivered, instead, to a final lens to be focused at some distance away from the handpiece for delivery to the tissue. The distance is usually 6–10 mm to allow vision around the handpiece to the underlying hard or soft tissue. This distance creates some difficulty in precise application of the laser energy although aiming beams provide considerable guidance.

Semirigid hollow waveguides and articulated arm waveguides are used almost exclusively for longer wavelength lasers such as Er:YAG, Er,Cr:YSGG, and CO_2. While bulkier and more difficult to maneuver than optical fibers, they overcome the problem of transmission through a solid medium.

4.1.6 Emitting Device

The final tip or lens through which the laser energy passes has a very significant impact on interaction with target tissues. An optical fiber has a flat end and will emit in the pattern shown in Fig. 4.4a. The beam immediately diverges as will be discussed in ▶ Sect. 4.1.7 below. This pattern also applies when using a removable flat-ended tip with an Er:YAG or Er,Cr:YSGG laser. These tips are constructed of either quartz or sapphire.

Erbium and CO_2 lasers using a tipless delivery will emit as shown in Fig. 4.4b. A lens is the last element in the path of the beam and focuses it. The normal distance between the lens and the focal point is 6-10 mm.

Maximum power density is achieved by positioning the handpiece so that the tissue surface is at the system focal point. In practical terms, the most efficient ablation occurs at

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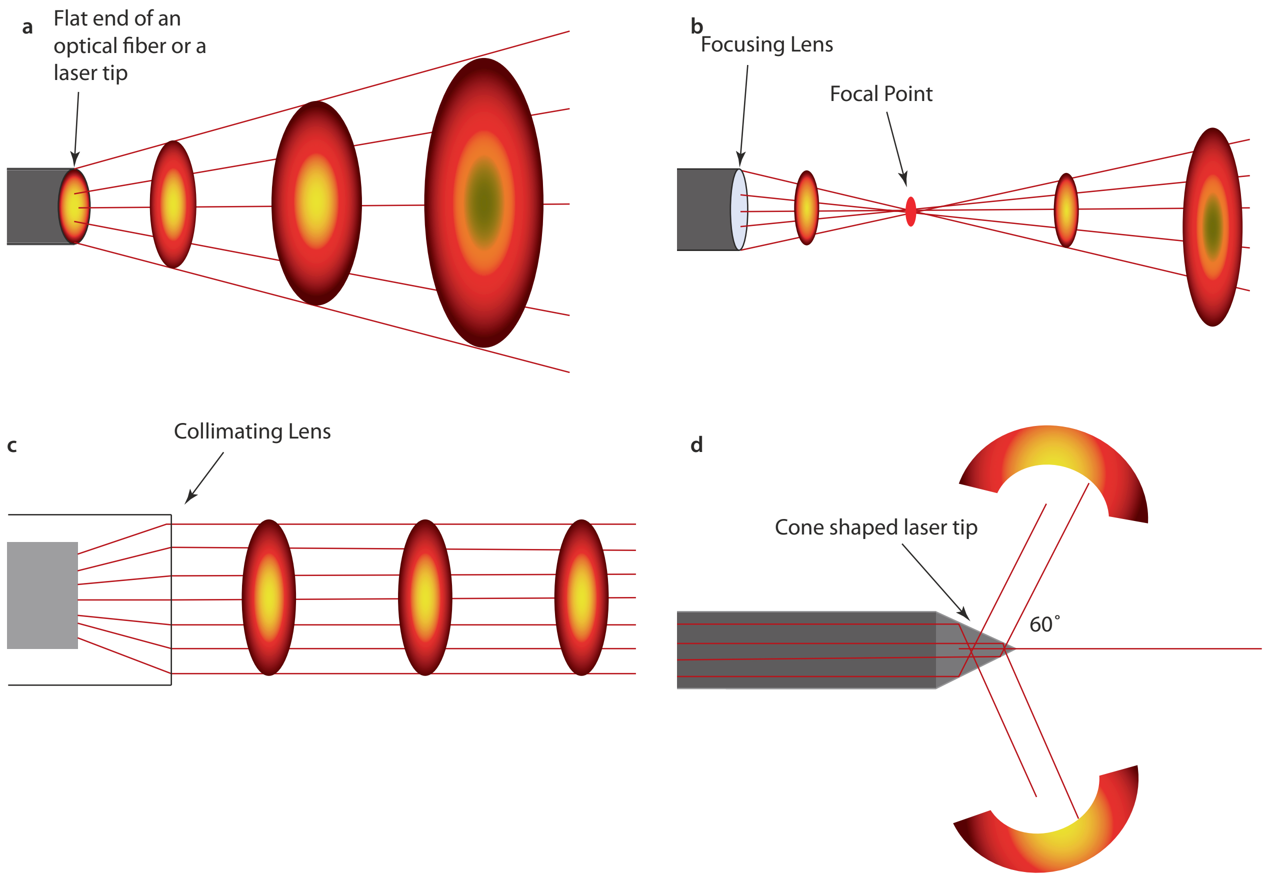


Fig. 4.4 The output from different laser devices is not the same. **a** Optical fiber or laser tip, **b** Tip-less delivery system **c** laser pointer or flat-top hand-piece, **d** radial-firing laser tip

this distance. A significant advantage of this system is that, as the tip is moved either nearer or further away than this distance, the beam diverges, spot diameter increases, and power density decreases. This technique is often referred to as «defocusing» the beam and is of value when the aim is to inject energy into the tissue without the consequences of high power density such as ablation. This point is further discussed in ▶ Sect. 4.2.7.

Laser pointers use a collimating lens as shown in Fig.4.4c. This allows the beam to have a consistent diameter at a large range of distances. This system is not used in surgical lasers for safety reasons since a misaimed beam could accidently interact with a distant tissue with the same power density as at the intended target. Also, if the beam were to reflect off of a mirror, it could ablate other tissues in random locations. Instead, by using the patterns in Fig. 4.4a or Fig. 4.4b, the beam safely loses its power density and, consequently, its surgical ability with distance.

The exception to this rule is seen in the newly developed «flattop» handpiece used in photobiomodulation. In this application, a predictable power density that is independent of tip-to-tissue distance is extremely desirable and important. However, the power levels used are very low, thus mitigating the risk of inadvertent tissue damage.

There are many instances when it is desirable to direct the laser energy laterally. Examples would be when irradiating into dentinal tubules or the threads of a failing implant. A tip has been developed by several manufacturers with a conical terminal end. Energy is internally reflected from this surface and then passes through the opposite side. Practical considerations allow redirection up to approximately 60° from the original forward axis as shown in Fig. 4.4d.

4.1.7 Beam Divergence

As laser energy exits any optical fiber or flat-ended handpiece tip, the beam diverges at a predictable angle. In practical applications this is usually on the order of 8–15° per side angle. While this may seem to be a small amount, the area on which the delivered photons impact increases rapidly with distance. The influence of this divergence on power density is of great significance and will be discussed in detail later in this chapter.

4.2 Adjustable Parameters

The parameters discussed above are all intrinsic to the particular laser being used. They are determined by the laser manufacturer and begin the process of optimally matching the photon delivery to the tissue of interest. The operator has control of a number of parameters that profoundly affect the interaction and, therefore, the outcome of laser therapy. Fluence, irradiance, and peak power are parameters critical to effective laser treatment. However, determining and controlling these parameters is not as straightforward as it would at first seem.

In order to discuss the scientific basis of parameters, it is necessary to have an understanding of definitions:

- *Power* (measured in joules per second or watts) is the measure of how much energy is delivered in 1 s of time. 1 watt is an abbreviation and equivalent of 1 joule per second.
- *Power density* (measured in W/cm^2) is the power delivered to a unit area of target tissue, usually here 1 cm^2.
- *Irradiance* is another term for power density.
- *Energy density* (measured in J/cm^2) is calculated as the power density in W/cm^2 multiplied by the total time of illumination.
- *Fluence* is another term for energy density.

Each laser manufacturer displays a different group of parameters on the control interface. In addition, some manufacturers do not provide direct control of every variable. Figures 4.5, 4.6, and 4.7 are representative of dental lasers currently produced by different manufacturers. Throughout the remainder of this chapter, these three lasers will be used as the basis for discussion and calculation. The parameters available to be directly controlled are different in each case. Therefore, a unique set of equations must be used in each instance to determine the critical parameters. Examples of all appropriate calculations will be provided in ▶ Sect. 4.7 of this book.

Fig. 4.5 This 810 nm diode laser has a limited number of variables that may be controlled directly

Fig. 4.6 This 2780 nm Er,Cr:YSGG laser has a choice of two pulse widths. It allows control of average power but energy per pulse and peak power must be calculated. Levels of auxiliary air and water are set as percentage of arbitrary values determined by supply to the individual dental suite

4.2.1 Average Power

Power and energy are often confused. Energy is, classically, a measure of the ability to do work. It is a «quantity» and is measured in joules. It is important to remember that a joule of energy is produced by a variable number of photons since each photon contains a different amount of energy based on its wavelength.

Power is the rate of producing energy. It is the number of joules created in each second of time and is designated in joules per second. A watt is simply an abbreviated word to mean «Joule per second.» If 1 joule per second or watt is produced and continues to be produced for 10 s, then 10 joules of total energy will have been produced. If energy continues to be produced at this rate for 60 s, 60 joules of total energy will have been produced. If instead, the power (the rate of doing work) is increased to 6 joules per second (watts) and is applied for just 10 s, the same 60 Joules of total energy will have been produced.

Since average power, peak power, energy per pulse, pulse width, and pulse frequency are so interrelated, they will be discussed as a parameter group interspersed with examples.

Average power represents the total energy produced in 1 s, no matter how uniformly that happens within that length of time. A continuous wave laser produces a constant number of photons for each time increment that it is activated, while a pulsed laser produces photons in short bursts ranging from femtoseconds to milliseconds.

The average power would seem to be provided on two of the three laser control displays in Figs. 4.5, 4.6, and 4.7, but a very important distinction must be made. With a diode laser, the power displayed is usually (but not always) the peak power. The diode laser in Fig. 4.5 allows direct control of the output power, but the power displayed is the «continuous

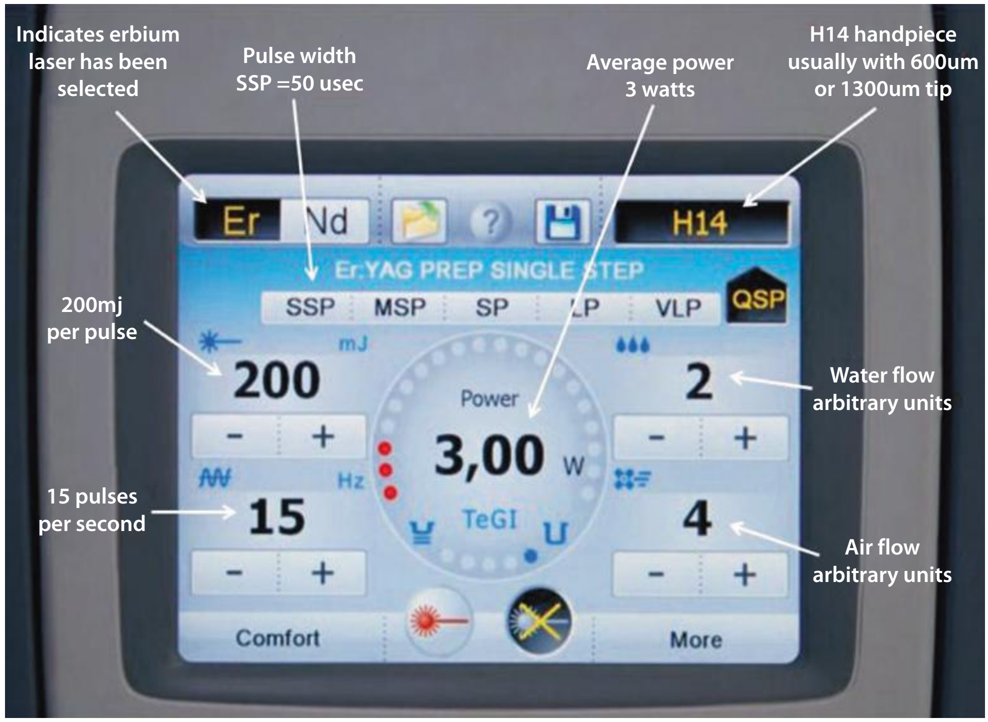


Fig. 4.7 This laser contains both a 2940 nm Er:YAG laser and a 1064 nm Nd:YAG laser. In erbium mode, it allows selection of six different pulse widths. However, the operator must refer to a manual to find the value. It allows control of pulse energy and pulse frequency. The resulting average power is displayed but not directly selectable

wave» output rather than the average power. Any time that this laser is emitting photons, it is emitting 2 watts of peak power.

In *variable gated mode*, independent selection of off-time and on-time is provided and results in vastly different average power for a given indicated power. If the laser is «on» for 20 ms and «off» for 80 ms, then it is on for 20 percent of the time:

$$\begin{aligned}\text{Percentage of “on} - \text{time”} &= 20\text{ms} / (20\text{ms} + 80\text{ms}) \\ &= 20\text{ms} / 100\text{ms} = 0.2 = 20\%\end{aligned}$$

Average power is then calculated as

$$\begin{aligned}\text{Power}_{\text{avg}} &= \text{power}_{\text{indicated}} \times \text{percentage of “on} - \text{time”} \\ &= 2\text{ Watts} \times 20\% = 0.4\text{ Watts}\end{aligned}$$

If the length of the on and off periods are changed but stay in the same ratio, average power will be the same. Figure 4.8 illustrates these concepts.

Peak power will always be the same as that indicated on this display, no matter what magnitude or ratio of «on» and «off» times are selected.

While Figs. 4.6 and 4.7 are both erbium lasers, their control features are distinctly different. The Er,Cr:YSGG laser shown in Fig. 4.6 allows control of average power. The pulse width is selected as «H» for hard tissue and represents a pulse width of 60 us. The laser displays the pulse repetition rate (15 pulses per second). The peak power is adjusted by the laser to provide this output although it cannot be directly controlled. There is no indication of the energy produced in each pulse.

The Er:YAG laser in Fig. 4.7 allows control of energy per pulse and pulse frequency. While average power is indicated on the display, it is not directly controllable. If the amount of energy contained in each pulse and the number of pulses in each second are known, the average power is calculated as the total of all of these pulses in 1 second.

$$\begin{aligned}\text{Power}_{\text{avg}} &= \text{energy } \textit{per} \text{ pulse} \times \\ &\quad \text{number of pulses } \textit{per} \text{ second}\end{aligned}$$

4.2.2 Peak Power

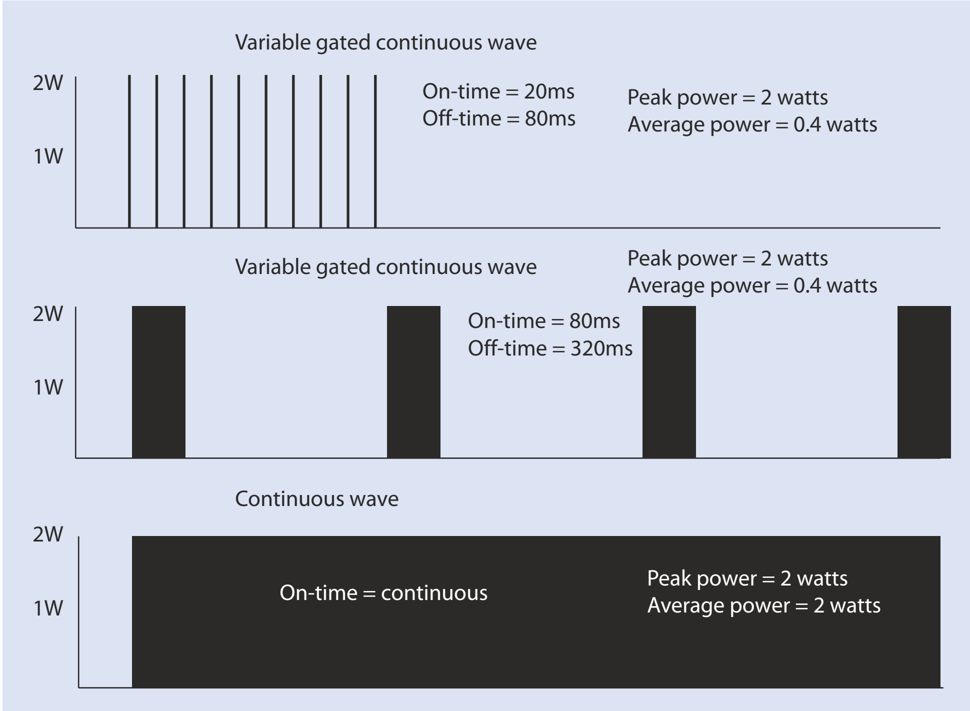
Peak power represents the maximum instantaneous power that the laser produces at any single time. In a continuous wave laser, the peak power does not change from that selected on the user interface, no matter what other parameters are changed. As has been discussed, it is the value displayed by the diode laser in Fig. 4.5.

With pulsed lasers such as all dental erbium and Nd:YAG lasers, peak power is dramatically affected by the interrelated control of average power, energy per pulse, pulse width, and pulse frequency. If these parameters are not known, they can be calculated.

Peak power can be calculated as:

$$\text{Power}_{\text{peak}} = \text{energy } \textit{per} \text{ pulse} / \text{pulse width}$$

Fig. 4.8 Calculated peak and average power produced at the settings with the diode laser shown in Fig. 4.5



4.2.3 Pulse Energy

Some manufacturers allow direct control of the total amount of energy in each pulse instead of controlling the average power. By necessity, if the pulse energy is held constant, altering the pulse width will change the peak power. Figure 4.9 illustrates this concept. It is based on the Er:YAG laser shown in Fig. 4.7. In each case, the energy per pulse is the same. If that energy is delivered in one-half the time, the peak power or rate of delivery must be doubled.

Some pulsed lasers do not allow direct control of pulse energy but, instead, provide selection of average output power. This output results in vastly different pulse energy and peak power as illustrated in the following example.

In Fig. 4.6, if average power is set to 4 watts and there are 15 pulses per second:

$$\text{Energy / pulse} = \text{total energy } \textit{per} \text{ second / number of pulses containing that energy}$$

$$\text{Energy / pulse} = 4\,\text{Joules } \textit{per} \text{ second / } 15\,\text{pulses } \textit{per} \text{ second} = 0.267\,\text{J / pulse} = 267\,\text{mj / pulse}$$

At the same time, if average power were to be set to 8 watts and there were 30 pulsed per second:

$$\text{Energy / pulse} = 8\,\text{Joules } \textit{per} \text{ second / } 30\,\text{pulses } \textit{per} \text{ second} = 0.267\,\text{J / pulse} = 267\,\text{mj / pulse}$$

The energy per pulse is the same even though the average power is doubled.

4.2.4 Pulse Width

In most pulsed lasers, selection of several different pulse widths is provided. As an example:

For the control panel shown in Fig. 4.6,
- «H» = «hard tissue» = 60 us
- «S» = «soft tissue» = 700 us

- For the control panel shown in Fig. 4.7,
- «SSP» = «super short pulse» = 50 us
- «MSP» = «medium short pulse» = 100 us
- «SP» = «short pulse» = 300 us
- «LP» = «long pulse» = 600 us
- «VLP» = «very long pulse» = 1000 us
- «QSP» = «quantum square pulse» = a unique pulse train not relevant to this discussion.

4.2.5 Pulse Repetition Rate

Doubling the number of pulses that are delivered in a second will double the total amount of energy delivered to the target tissue. If the pulse width and energy per pulse are left unchanged, the peak power will be unchanged. Since there are twice as many pulses applied in a second, the average power will double.

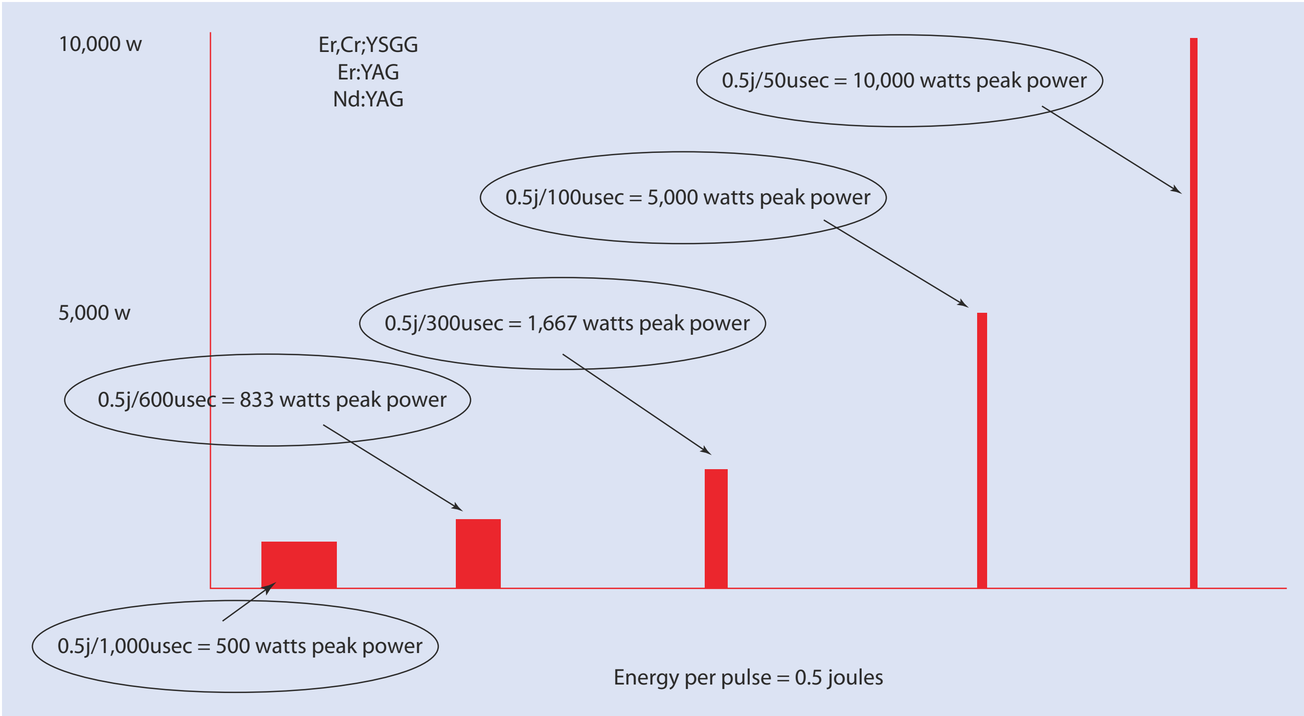


Fig. 4.9 The peak power emitted by a laser changes with changes in pulse width if the energy per pulse is constant. This graph shows examples of free-running pulsed lasers, but some variable gated pulsed laser use a similar concept

In the Er:YAG laser example of Fig. 4.7:

$$\begin{aligned}\text{Power}_{\text{avg}} &= 0.200\,\text{Joules / pulse} \times 15\,\text{pulses / s}\\ &= 3.0\,\text{Watts}\left(\text{joules } per \text{ second}\right)\end{aligned}$$

If the pulse repetition rate were doubled to 30 pulses per second:

$$\begin{aligned}\text{Power}_{\text{avg}} &= 0.200\,\text{Joules / pulse} \times 30\,\text{pulses / s}\\ &= 6.0\,\text{Watts}\left(\text{joules } per \text{ second}\right)\end{aligned}$$

In each case, the peak power would be 4000 watts, if the laser were set to SSP mode.

4.2.6 Diameter of the Final Emitting Device

The number of photons that strike an individual cell and their associated energy is one of the primary determinants of tissue effect. Power density or fluence is a critical factor in determining laser-tissue interaction.

Power density is, by definition, the number of photons passing through a specific area in each second of time. A 400 micron laser fiber has a cross-sectional area of:

$$\text{Area} = \pi \times r^2 = 3.14159 \times (0.02\,\text{cm})^2 = 0.0013\,\text{cm}^2$$

A seemingly small output of 1 watt, if passed through this fiber, results in a power density striking an individual cell of 796 watts/cm^2.

$$\begin{aligned}\text{Power density} &= \text{Power / area} = 1\text{ Watt} / 0.0013\,\text{cm}^2\\ &= 796\,\text{W / cm}^2\end{aligned}$$

The same 1 watt passing through a 200 um diameter fiber would have a power density of 3185 Watts/cm^2.

Each of these outputs will have a profoundly different effect on a target cell. Table 4.2 shows the dramatic range of power densities that occur with different optical fiber diameters at average power outputs routinely available in dentistry. It is evident that the choice of fiber diameter has a critical effect on the delivered power density. Simply choosing a 200 um diameter fiber instead of a 1200 um fiber makes a 36-fold difference.

The combined influence of pulse width and fiber or tip diameter looms as an overwhelming determinant of laser-tissue interaction. In the example of the Er:YAG laser in Fig. 4.7, using an 800 um diameter tip, producing 1000 mj of energy per pulse with a pulse width of 50 us and 50 pps will deposit a mind-boggling peak power density of 4,000,000 W/cm^2 into the target tissue with an average power density of 10,000 watts/cm^2. These calculations are illustrated in ► Sect. 4.7.

Table 4.2 Average power density in watts/cm^2 with different fiber size and power setting

Power density (watts/cm^2)						
Fiber diameter		200 um	400 um	800 um	1200 um	1.15 cm
	0.5	1591	397	99	44	0.5
Power (watts)	1	3185	795	198	88	1
	2	6370	1591	397	176	2

4.2.7 Tip-To-Tissue or Focus-to-Tissue Distance

Under many circumstances, the optical fiber tip, quartz tip or sapphire tip is held at some distance away from the tissue. In addition, there are a number of erbium and carbon dioxide lasers that are routinely used without a tip but rely on focused laser energy as discussed in ▶ Sect. 4.1.6 above. With a tipless system, the smallest spot diameter and, consequently, highest power density, exists at the point of focus. All measurements of distance are referenced to that point.

Tip-to-tissue distance, or the comparable focus-to-tissue distance, provides yet another parameter that dramatically affects the density of photons striking an individual target cell. As laser energy exits an optical fiber or a quartz or sapphire tip, it diverges quite significantly.

The applied energy is distributed over an increasing area as the tip-to-tissue distance increases, dramatically affecting power density at a cellular level as shown in Fig. 4.10. Power density can be diminished by 95 percent with only 5 mm of tip-to-tissue distance. This is further demonstrated in Fig. 4.11. When using this standard delivery system, the repeatable application of an appropriate energy density is extremely technique-sensitive and operator-sensitive.

Table 4.3 illustrates how significantly the power density changes with just minor changes in the tip-to-tissue distance. It is also apparent that the effect of beam divergence is far greater with smaller diameter emitting devices. A collimated beam eliminates this destructive divergence but is only possible to produce if a lens is the final element in the path of the laser energy as it is emitted.

All concepts associated with beam divergence from a flat-ended tip apply to tipless systems with distances being measured from the focal point as demonstrated in Fig. 4.12.

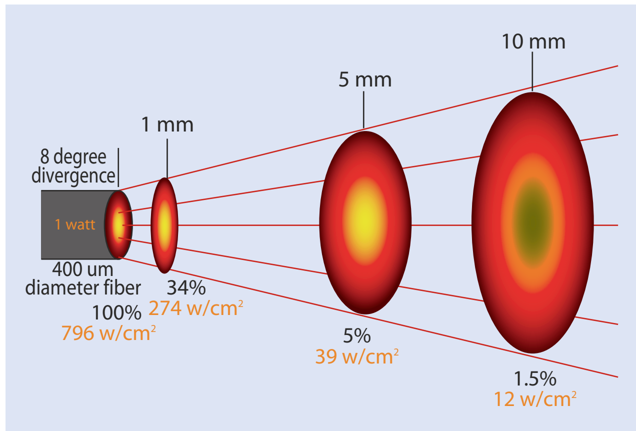


Fig. 4.10 The effect of tip-to-tissue distance on spot diameter and, therefore, on power density. These calculations are based on a beam divergence of 8° per side angle

4.2.8 Auxiliary Water

All erbium lasers, together with the 9300 nm CO_2 laser, have the ability to spray water on the tissue during treatment. In the case of hard tissue, this spray is used to cool the tooth or bone and remove debris from the ablation site. Without extrinsic water, the tooth will overheat under repeated pulses and ablation may cease.

Er:YAG laser energy is absorbed in approximately 0.8 microns of water [8–10]. Logic suggests that, if auxiliary water is used, all energy will be absorbed by overlying water before it can reach the tissue surface and no ablation will occur. On the other hand, without extrinsic water, charring will rapidly occur and ablation will cease with significant damage to the tooth.

In practice, other principles resolve this issue [11]. When laser energy strikes the surface of a water film, it is rapidly absorbed causing vaporization. This rapid phase change occurring in a few microseconds creates a shock wave of very significant magnitude generating pressures of a few hundred atmospheres. This shock wave displaces water at the point of contact creating an open channel to the underlying tooth surface [12] as shown in Fig. 4.13.

If the laser tip is completely submerged, water is evacuated from the laser path by a slightly different phenomenon. When laser energy strikes the water directly in front of the tip, it once again causes vaporization. An air bubble is created, as shown in Fig. 4.14, which pushes the water out of the way allowing energy from the remainder of the pulse to strike the tooth surface and cause ablation.

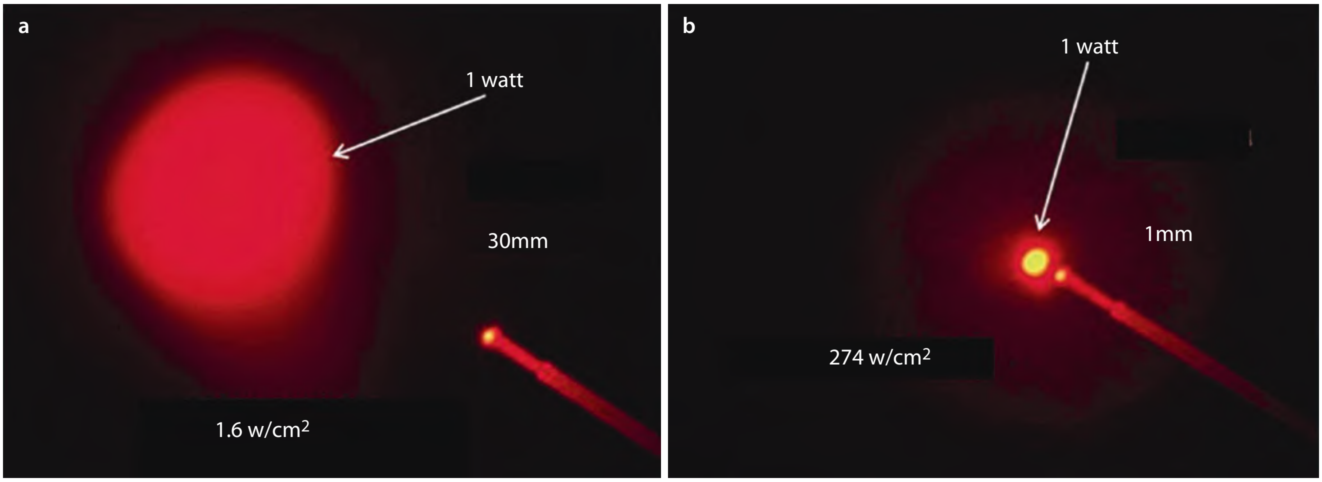
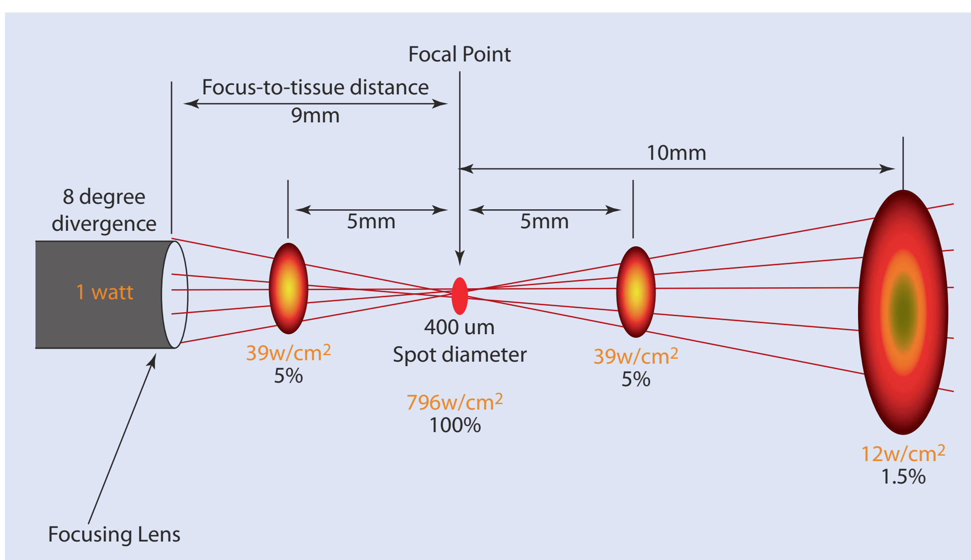


Fig. 4.11 Power density at tip-to-tissue distances of 30 mm **a** and 1 mm **b** with an identical 1 watt of applied diode laser power

Table 4.3 Average power density at 1 watt laser output for different tip diameters and tip-to-tissue distances assuming an 8° per side beam divergence

Power density (W/cm^2)						
T-T distance		**Contact**	**1 mm**	**2 mm**	**5 mm**	**10 mm**
	400 um	796	275	138	39	12
Tip diameter	800 um	199	109	69	26	10
	8 mm	2	1.9	1.7	1.4	1.1
	1.15 cm	1	0.92	0.88	0.76	0.62
	1.15 cm (collimated)	1	1	1	1	1

Fig. 4.12 The effect of focus-to-tissue distance on spot diameter and, therefore, on power density. These calculations are based on a beam divergence of 8° per side angle. It is evident that all of the distances from the focus point are the same as those from the tip in Fig. 4.10. Consequently, the calculated values are identical



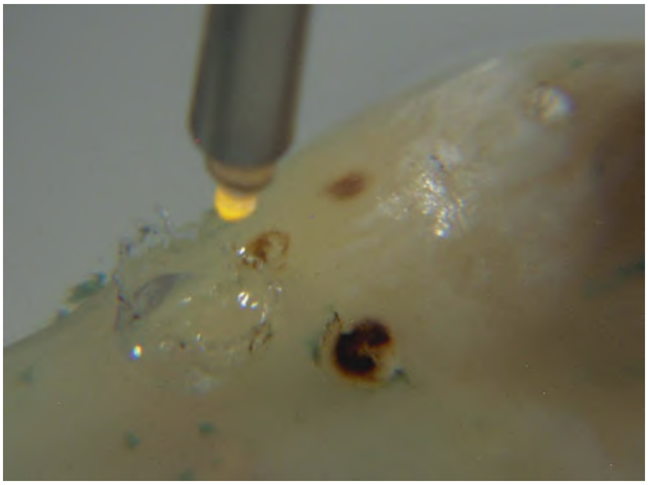


Fig. 4.13 Ultra-speed macrophotograph of Er:YAG laser energy interaction with a superficial water layer. The shock wave generated by the laser pulse displaces the water on the tooth surface

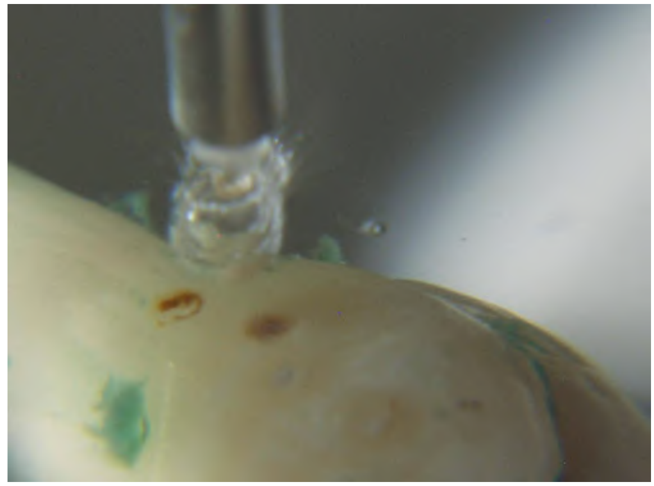


Fig. 4.14 Ultra-speed macrophotography of Er:YAG laser energy interaction when the tip is completely submerged in water. Vaporization of the water in front of the tip creates a bubble forming a channel for ablation

Nahen and Vogel [13] showed that such a bubble forms in the first 10–20 microseconds of the laser pulse. The balance of the pulse energy is then able to ablate as though no water is even present. Nearly all of the laser energy strikes the tooth surface unimpeded allowing excellent ablation. As the bubble collapses between each pulse, the newly ablated surface is bathed in water thus cooling, cleaning and rehydrating the structure.

Within limits, the thickness of the water layer is of little consequence. The bubble formed has a finite size estimated by the author from ultra-speed photographs, such as Fig. 4.15, to be approximately 3 mm in length.

When only a water mist is used, any droplets in the path of the laser energy are rapidly vaporized allowing passage of subsequent energy.

In an experiment to verify the theoretical concepts discussed above, the flow rate of irrigation water was controlled at 1, 2, 4, 8, 16, and 24 ml/min, while the tip-to-tissue distance was held at 0.5 mm. Other samples were ablated completely submerged in water at the same controlled distance [11].

Figure 4.16 shows that Er:YAG ablation efficiency is essentially independent of irrigation water flow rate. In addition, applying energy with the tip completely submerged in water has no detrimental effects on ablation efficiency as long as the laser tip is within about 2 mm of the tissue surface.

At low irrigation water flow rates, the possibility of dehydration and charring is significant. Without water coolant, residual heat quickly dehydrates the enamel making further ablation inefficient or impossible. At the same time, a layer of exploded hydroxyapatite particles covers the enamel surface and absorbs some of the energy

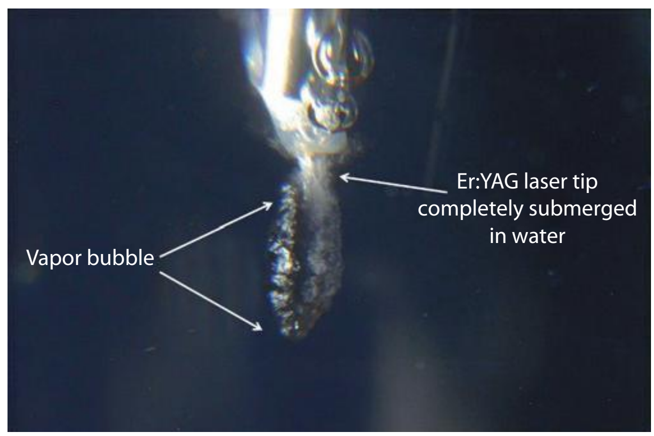


Fig. 4.15 Ultra-speed macrophotography of the bubble formed surrounding an Er:YAG laser tip when it is completely submerged in water. The vaporization bubble in this picture has a diameter of approximately 1.5 mm and a length of more than 3 mm beyond the tip

of the next energy pulse heating this unwanted layer significantly.

Figure 4.17 shows enamel ablated without water. Thermal damage results in carbonization, cracking, and a loss of laser ablation effectiveness. Water spray both cools the tooth and washes away the debris. Irrigation also serves to enhance ablation rate and efficiency, improve surface morphology, alter chemical composition, and enhance adhesion to restorative materials.

A flow of at least 8 ml/min is needed to minimize adverse effects. Since flows of up to 24 ml/min have been shown to have no negative effect on laser ablation efficiency, it is prudent to use 8–24 ml/min to ensure adequate hydration.

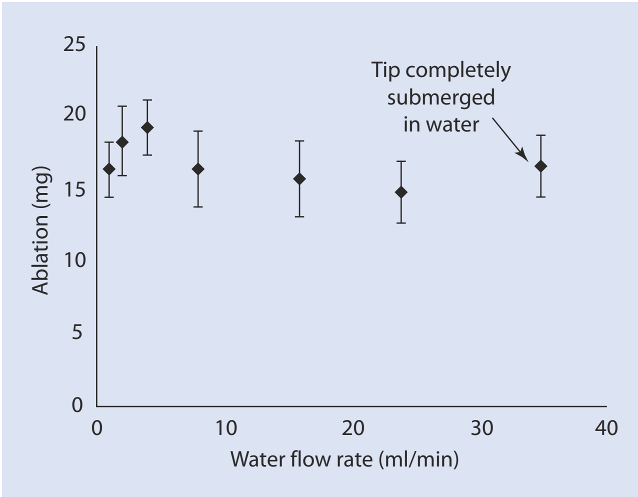


Fig. 4.16 Effect of irrigation water flow rate on Er:YAG laser ablation of enamel. Tip-to-tissue distance was constant at 0.5 mm. The volume of irrigation water has a minimal effect on ablation efficiency

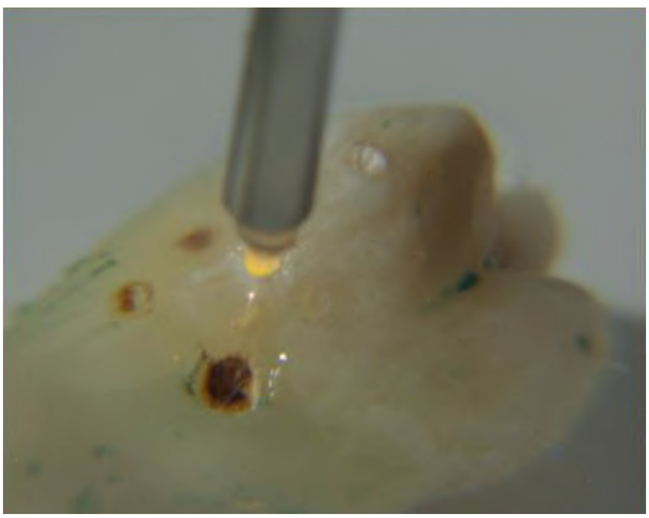


Fig. 4.17 Effect of irrigation water flow rate on Er:YAG laser ablation of enamel. Without irrigation, hydroxyapatite absorbs laser energy causing progressive desiccation, overheating and carbonization

In fact, it can be argued that using the maximum amount of water possible is an appropriate strategy. However, ultimately, site visibility by the dentist as well as patient tolerance for large water volumes will dictate the water flow rate used.

Super-pulsed CO_2 lasers also use auxiliary water to cool the tooth or bone and remove debris from the ablation site and it is vital to effective use of this modality. Water is not used with continuous wave CO_2 lasers since it would absorb all the energy in the scenario discussed in the second paragraph of this section.

4.2.9 Auxiliary Air

Auxiliary air is also provided by all erbium lasers. However, its value and effect are not as well understood. Certainly, air may help dissipate accumulated thermal energy but its primary function is to remove debris from the path of the laser energy.

4.2.10 Speed of Movement

Energy is being dispensed as long as the laser is activated. The speed which with the tip is moved across the target tissue will dictate how much energy strikes each individual cell. Moving too quickly will not allow sufficient energy absorption to initiate ablation and the tissue will be detrimentally heated. Moving too slowly or maintaining the tip in one position will, ablate the tissue but also cause overheating. A method of calculating energy density with movement is illustrated in Fig. 4.18.

4.3 Further Calculated Parameters

Having adjusted laser parameters in accordance with an established protocol, it is instructive to understand the nature of the resulting energy applied to the target. Average power, peak power, fluence (energy density), and irradiance (power density) all have a very significant effect on the target tissue. Further parameters are also important.

4.3.1 Spot Area at the Tissue

The spot area at the tissue surface must be determined before fluence and irradiance can be calculated. Incorporating the effect of beam divergence and tip-to-tissue distance can often make this a confusing calculation. Further confusion arises regarding even the definition of spot size.

In physics and engineering, spot size refers very specifically to the radius of the laser beam [14], while in many medical publications, it is used to describe the beam diameter or even the area. While the exact definition is of minor importance, knowledge of the author's intent is critical. It is preferable to use the more specific terms of «spot diameter at tissue» and «spot area at tissue.»

4.3.2 Average Power Density

Average power density is determined by dividing the average power by the spot area at the tissue surface. Since spot area is generally very small as shown in ► Sect. 4.2.6 above, average power densities can be surprisingly large.

4.3.3 Peak Power Density

Peak power density is simply determined by dividing the peak power by the spot area at the tissue surface. Once again

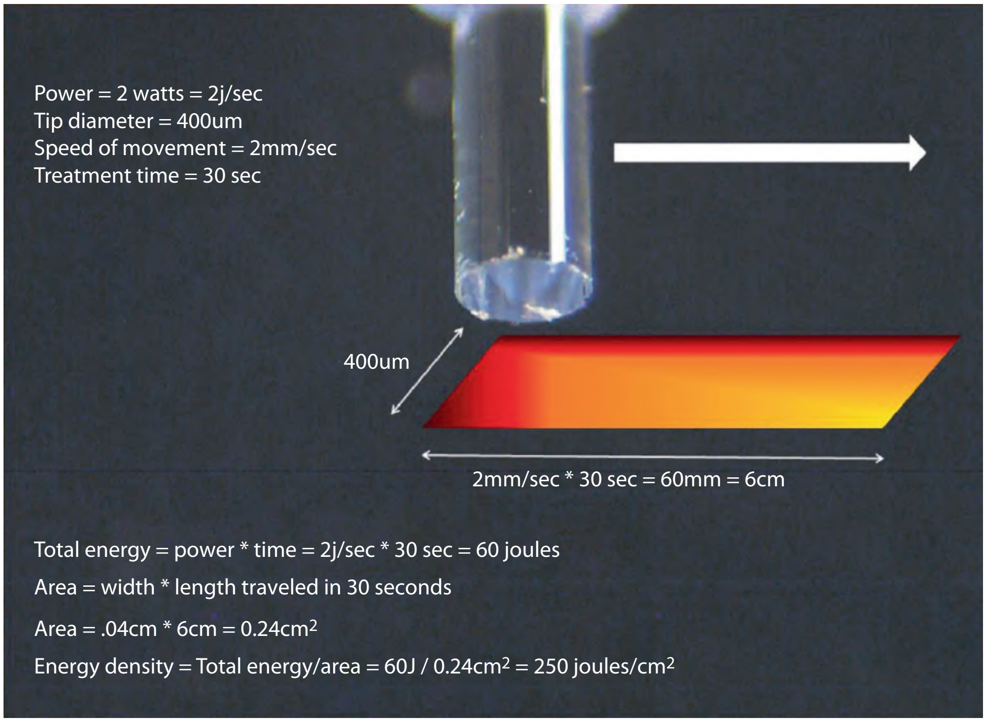


Fig. 4.18 The energy density striking individual cells is calculated by dividing the total energy delivered by the total area irradiated

with a small spot area, it is possible to get a stunning 4,000,000 W/cm^2 as shown in ► Sect. 4.2.6.

4.3.4 Total Energy Applied

The total energy applied to the tissue is simply the average power multiplied by the total number of seconds of treatment.

The discussion in this chapter highlights the importance of understanding and controlling the exact nature of the parameters selected in any clinical protocol in order to effectively interact with either hard or soft tissue. While the necessary calculations are not complicated, they need to be precise. ► Section 4.7 assembles all relevant information and provides calculations based on the settings shown in Figs. 4.5, 4.6, and 4.7.

4.4 Hard Tissue Considerations

4.4.1 Most Appropriate Laser for Hard Tissue Procedures

In the past, erbium lasers were the only devices appropriate for ablation of hard tissues. In recent years, super-pulsed carbon dioxide lasers have been developed that are capable of ablating dentin, enamel, and bone effectively and safely. In addition, research has shown that almost any wavelength of laser energy can be used if the pulse width is short enough and the peak power high enough. The next decade will, no doubt, see the development of practical nanosecond and femtosecond pulsed devices.

4.4.2 Mechanism of Hard Tissue Ablation

Mechanism of Ablation for Erbium Lasers

While a hydrokinetic theory was originally proposed to explain tissue interaction with Er,Cr:YSGG laser energy, a different mechanism is now most widely accepted [15–17]. All erbium lasers interact with tissue in a similar fashion. Ablation of enamel, dentin, and bone occurs through the explosive removal of tissue in a thermo-mechanical event. Because laser energy at erbium wavelengths is very highly absorbed by water, molecules in the target tissue are rapidly superheated [18]. When the steam pressure within the tissue exceeds the structural strength of the overlying material, micro-explosions occur, ejecting particles of fractured material as shown in Fig. 4.19. This explosive phenomenon is initiated long before melting of the carbonated hydroxyapatite occurs.

Considerable pressure is needed to fracture enamel and dentin so temperatures much higher than the intuitive 100 °C must be generated. A study suggests that ablation actually occurs at superheated temperatures of approximately 600 °C for enamel and 500 °C for dentin [19].

Mechanism of Ablation for Carbon Dioxide Lasers

Ablation at CO_2 wavelengths is predominantly a photothermal phenomenon [19]. Laser energy is directly absorbed by the carbonated hydroxyapatite. Melting of the mineral is nearly instantaneous, occurring in less than a picosecond, and is followed rapidly, with increased temperature, by vaporization and the expulsion of molten

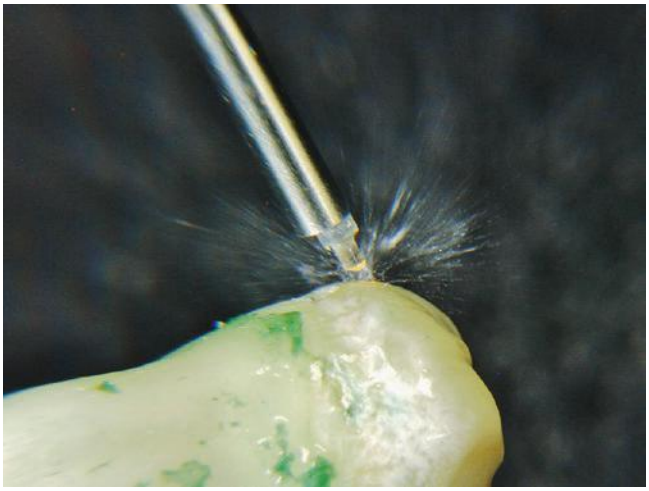


Fig. 4.19 Ultra-speed microphotography of Er:YAG laser energy interaction with an enamel surface

mineral droplets [20]. This liquid mineral quickly resolidifies into characteristic globules routinely seen in SEMs. Lesser absorption by water and protein at these wavelengths only has a minor effect on the ablation process.

If laser energy at CO_2 wavelengths is applied in a continuous wave mode, the principal interaction consists of melting of carbonated hydroxyapatite and massive transfer of thermal energy to the surrounding tooth structure. Charring and pulp death are the inevitable outcome. However, applying this energy in super-pulsed mode with very short pulses, ablation as described above still occurs but most of the thermal energy is ejected with the molten carbonated hydroxyapatite. Water spray directly removes further amounts of diffused energy.

Mechanism of Ablation for Femtosecond Lasers

Femtosecond lasers emit energy in extremely short pulses with durations of less than a nanosecond. Even with pulse energy as low as 20 microjoules per pulse, a 400 fs pulse width produces peak power of 50 million watts. This is sufficient to ionize carbonated hydroxyapatite directly to plasma. The plasma then quickly dissipates, carrying virtually all energy away and transferring almost none to surrounding tissues. Residual thermal energy and collateral damage are almost nonexistent. The wavelength of the applied laser energy is of little consequence as a study of efficient enamel ablation using a 1025 nm laser shows [21]. Ablation simply relies on plasma formation. It should be noted that this wavelength is nearly identical to that of the Nd:YAG laser (1064 nm). Peak ablation efficiency occurs at approximately 5 j/cm^2. Clinical femtosecond lasers are not currently available in dentistry but show great promise.

4.4.3 Role of Hydroxyapatite in Ablation

To further clarify the discussion above, carbonated hydroxyapatite is a major absorber of carbon dioxide laser energy and is the primary vehicle of ablation. It absorbs energy, injecting heat into the enamel or dentin promoting dehydration and structural change. If sufficient energy is absorbed to raise the temperature to about 1280 °C, melting followed by vaporization of the enamel will occur. Melting is a short-lived change in physical state and there is a new solid created upon cooling. This new solid has a modified structure and composition and will interact with subsequent laser energy differently.

This is a completely different phenomenon than that seen with erbium lasers where water is the primary vehicle of ablation. With these lasers, ablation is the explosive removal of tissue using thermal energy to vaporize internal water. In either case, if the enamel temperature is sufficiently elevated, some of the thermal energy will diffuse into the interior of the tooth compromising pulp vitality. Femtosecond lasers have the potential to nearly eliminate this problem.

A simple experiment illustrates this point. Directing erbium laser energy at a dried extracted tooth with no water spray using 240 mj at 25 pps (commonly recommended parameters for enamel ablation) from a distance of 10 mm results in sub-ablative irradiation. After about 10 s the tooth becomes too hot to hold having reached about 200 °C. No ablation has occurred but a significant amount of energy has been absorbed [18]. Moving even closer (5 mm) causes melting, charring, and overheating of the enamel as depicted in Fig. 4.16 above. No true explosive ablation occurs under these conditions.

4.4.4 Cautionary Considerations

Interaction with Non-biological Materials in the Oral Cavity

In the course of applying clinical lasers to intraoral structures, a number of non-biological restorative materials will be encountered. Each of these may lead to reflection, absorption, scattering, refraction or transmission of energy. Research on the potential negative results of accidental or intentional interaction has been sparse.

Many publications have asserted that laser energy is reflected off of the surface of metal restorations and so is of little consequence except to use caution with reflective surfaces. In fact, laser energy of most wavelengths is absorbed by metals. Lasers are routinely used in industrial situations to both cut and weld steel, copper and aluminum.

Figure 4.20a illustrates the interaction with existing amalgam restorations. Some might suggest that the interaction is due to adsorbed water, but Fig. 4.20b shows the interaction with dental amalgam powder in the absence of water and Figure 4.20c displays the destructive effects of the interaction on the laser tip. Figure 4.21 shows the interaction of energy from different lasers with composite and acrylic dental materials.

All of these photographs represent the effect at commonly used laser parameters. This suggests that these negative side effects will likely occur any time restorative materials are inadvertently exposed to laser irradiation.

Laser tips and fibers can become coated with exploded or melted debris making them ineffective for future use. Techniques have been developed to alleviate this problem [21].

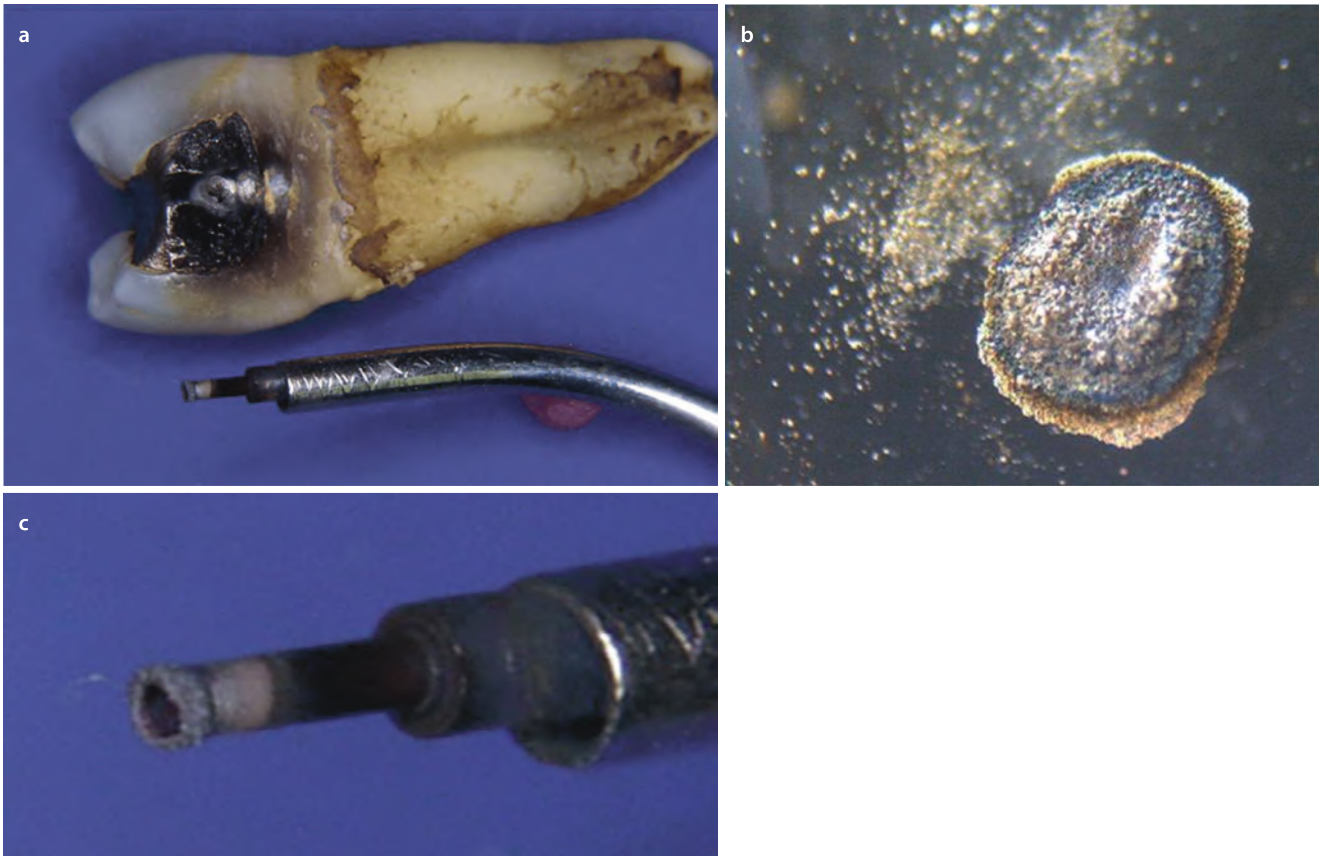


Fig. 4.20 **a** The erbium laser energy produces a significant interaction with amalgam restorations. **b** Interaction with amalgam powder suggests that it is not interaction with adsorbed water. Any such interaction will severely damage the laser tip. **c** An erbium laser was applied at 240 mj and 25 pulses per second

Other Considerations

As discussed earlier in this chapter, applying erbium energy to enamel, dentin, or bone without adequate irrigation will almost always be disastrous. The significant thermal energy absorbed by the target will cause irreversible changes. A minimum of 8 ml/min is the recommended level.

Marjaron [23] showed that maintaining a gap of 0.3–0.7 mm between the tip and tissue increased enamel ablation significantly. Theoretically, this would allow more water in to flush accumulated debris, allow debris to exit the gap, and remove thermal energy that had been absorbed by the hydroxyapatite. As the distance exceeds 1 mm, decreases in energy density as well as absorption and refraction from interposed water will minimize these advantages.

4.5 Soft Tissue Surgery Considerations

4.5.1 Most Appropriate Laser for Soft Tissue Procedures

All of the existing dental lasers can surgically incise soft tissue.

The diode laser is the most popular dental laser with thousands in use in dental offices around the world. They are attractive because they are small, lightweight, low maintenance, durable, and relatively inexpensive.

While a valuable tool, these devices are plagued by a very significant shortcoming. They are very poorly absorbed in soft tissue. With diode lasers ranging from approximately 808 to 1064 nm, melanin, hemoglobin, and protein are the primary chromophores. However, water which makes up more than 70% of most tissues is not a chromophore and produces almost no interaction at diode wavelengths. This suggests that the diode is a poor laser for incising soft tissue.

Since the laser energy spreads through a large area of tissue, the risk of significant collateral damage is high. On the other hand, this energy is highly absorbed in blood and causes excellent coagulation and hemostasis.

The Nd:YAG laser at 1064 nm suffers from the same poor absorption as all diode lasers, again suggesting that this is not a good laser for incising soft tissue. Its advantage lies in its very high peak power with short pulse width providing thermal containment and moderate ablation with very good hemostasis. Nd:YAG lasers are more complex and considerably more expensive than diode lasers.

Erbium lasers have a primary chromophore of water which is the most abundant constituent of biological tissue making them an excellent choice to perform surgical soft tissue procedures. Both the Er:YAG and the Er,Cr:YSGG lasers are absorbed efficiently in a few of microns of tissue. Since little energy is transferred to the surrounding area, little

Fig. 4.21 Energy from both erbium lasers **a** and **b** and diode lasers **c** interacts with composite resins and dental acrylic materials at commonly used power levels

collateral tissue damage occurs. Because of this same property, these lasers do not produce significant hemostasis from thermal absorption at the incision margins.

Finally, the CO_2 laser has primary chromophores of water and collagen making it a useful soft tissue laser. Its action is very superficial but produces melting of collagen as well as explosion of tissue through steam generation. Since this energy is delivered via a noncontact hand-piece, precision is more difficult to achieve.

4.5.2 Fiber Initiation Consideration

While diode lasers are poor soft tissue lasers, they are small and relatively inexpensive. The optical fiber delivery system is flexible and very maneuverable allowing access to hard-to-reach areas of the oral cavity. Fiber initiation provides a technique to circumvent this laser's shortcomings.

An energy absorbing material is applied to the end of the fiber as shown in Fig. 4.22 in a process called initiation or activation. Material is transferred to the fiber end creating a thin layer that absorbs subsequent laser energy.

When the laser is activated, this thin layer absorbs the emitted photons and is rapidly heated to several hundred degrees. This «hot tip» is used to melt proteins thus separating the tissue. The argument is often made that this technique is similar to electrosurgery or applying a heated instrument. However, because only the thin layer of absorbent material is heated, the thermal energy is concentrated, and there is significantly less collateral thermal damage than with these other modalities.

While each laser manufacturer has suggestions for proper fiber initiation, the following technique has been shown to provide superior results:

- Adjust the laser to a very low power setting of less than 0.5 watts.
- Touch the fiber tip to articulating paper without activating the laser.
- Activate the laser momentarily until a perforation is seen in the articulating paper.
- Repeat at least 8 times.
- Observe the aiming beam against a surface. If it is still clearly visible, repeat more times.

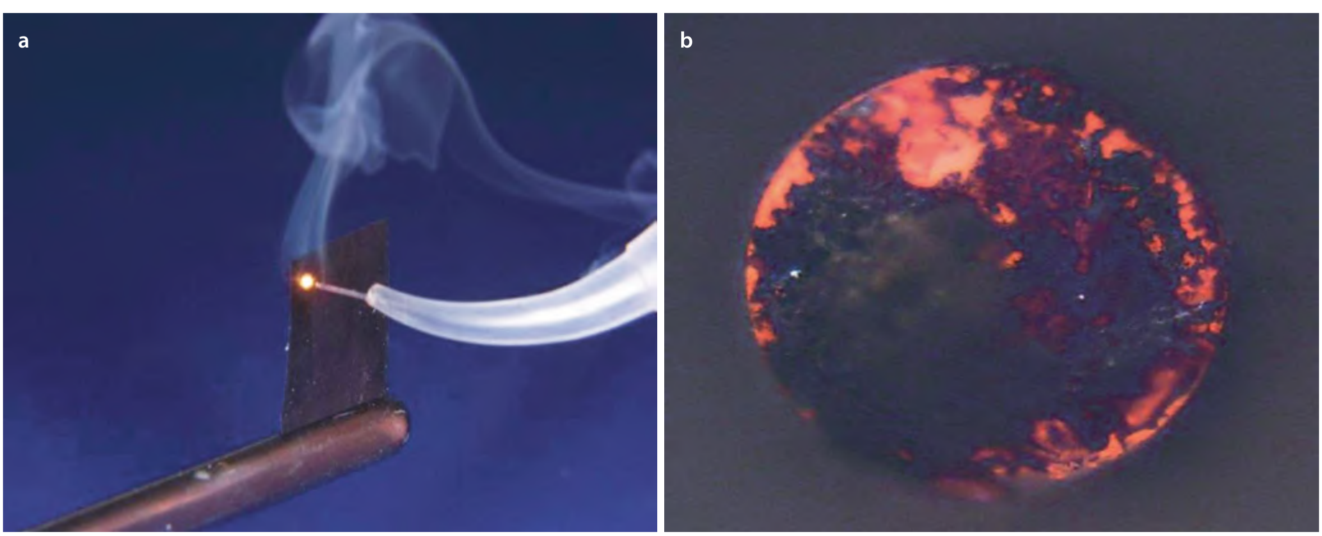


Fig. 4.22 The technical process of initiation is shown in **a**, while the resulting coat on the fiber end is shown in **b**

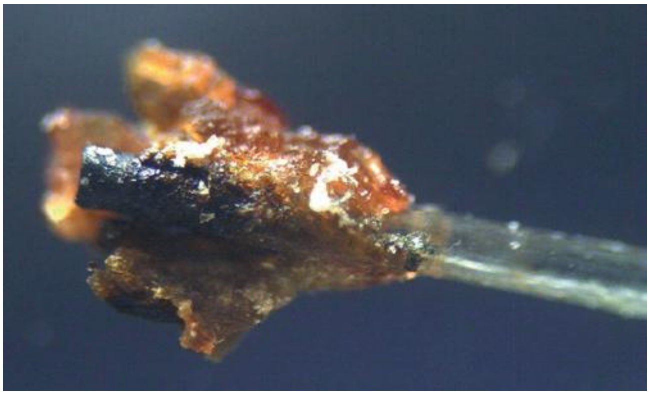


Fig. 4.23 During clinical application, tissue adheres to the fiber tip. It, in turn, is heated causing collateral tissue damage

4.5.3 Effect of Fiber Size

As has been discussed in ▶ Sect. 4.2.6 above and Table 4.2, smaller fiber diameters significantly increase power density and positively affect the ability of the laser to incise tissue. However, fibers with a diameter smaller than 400 um are very flexible affecting the ability to cut precisely and are at higher risk of spontaneous fracture.

4.5.4 Effect of Debris Accumulation

In the course of clinical treatment, cellular debris adheres to the warm fiber tip as shown in Fig. 4.23 This material absorbs laser energy and is progressively heated increasing the risk of collateral thermal damage. It is prudent to remove this debris repeatedly during a surgical procedure. This is best accomplished with wet gauze.

4.5.5 Precooling of Tissue

Collateral damage occurs through the prolonged heating of cells. A study by Simanovskii et al. [23] asserted that mammalian cells can survive a temperature increase to 42–47 °C for prolonged periods of time. Above this point, the length of time at higher temperatures becomes a critical variable. Cells can only survive 70 °C for about 1 s and 130 °C for 300 microseconds. Since optical fiber tip temperature can exceed 800 °C, it becomes apparent that this is the source of damage.

The margins of a surgical excision will be rapidly heated although not to this level. It has been shown that approximately 350 um of collateral tissue death may occur [25]. Precooling the tissue with an air/water spray can reduce but, certainly, not eliminate collateral damage. Frequent cooling during procedures is also considered to be of benefit. However, using a constant flow of water during surgery is not recommended. Vision will be compromised, and, more importantly, thermal energy will be diffused over the

Fig. 4.24 Three cuts all performed with a 940 nm diode laser at 1 watt, CW. The bottom cut is done with no precooling, air, or water irrigation. Note the significant collateral damage. The middle cut was performed with air directed over the surface. Speed of cut was slower but as effective with much less collateral damage. Applying an air/water spray during treatment in the top cut caused significant surface cell death (Courtesy of Dr. Mark Cronshaw)

tissue surface scalding a superficial layer as shown in Fig. 4.24.

4.5.6 Cautionary Considerations

The preceding discussions illustrate the need for careful attention to tissue response during even the most rudimentary procedure.

4.6 Photobiomodulation Considerations

It is well established that, in general, photobiomodulation can have a positive effect on tissue [26–28]. However, photonic energy must reach target cells at the appropriate intensity to be effective. This energy density is widely accepted to be between 3 and 10 J/cm^2, relative to the individual cell surface, in accordance with the Arndt-Schultz law [29, 30]. At less than 3 J/cm^2, there is insufficient energy absorbed by the cell to increase its metabolism, while densities of more than 10 J/cm^2 appear to inhibit cellular function.

While energy is applied on a macroscopic level, the interaction with tissue occurs on a subcellular level [31]. Ideally, each individual cell in the path of the applied energy should be illuminated with the same number of photons within this range. The positive effects of photobiomodulation are very strongly associated with the density of photons striking the cells. Unfortunately, a method of delivering photons to a group of individual cells, often deep within a tissue mass, in a uniform and predictable manner has been lacking.

4.6.1 Most Appropriate Laser for Photobiomodulation

Between approximately 600 nm and 1200 nm, very few absorbing chromophores exist allowing laser energy to penetrate deeply into the tissue mass. This range of wavelengths has labeled the «optical window» and is exploited in most photobiomodulation protocols. In general, diode lasers are the most appropriate laser for this application.

4.6.2 Recommended Parameters

Further chapters will explore the intricacies of dosage in photobiomodulation. The energy density at the cellular level is a key determinant of biostimulation and appears to be between 3–10 J/cm^2 depending on the cell type and should be applied at a rate of approximately 100 mW/ cm^2.

For lesions on the surface of tissue, calculation of the appropriate dose is rudimentary. However, as energy enters tissue, it is moderately absorbed and highly scattered reducing the effective dose.

4.6.3 Distribution of Applied Energy in a Tissue Volume

As energy penetrates a tissue mass, it is absorbed and widely scattered. Bashkatov [32] asserted that photons are 100 times more likely to be scattered than to be absorbed. When treating a muscle or a temporomandibular joint, energy reaching the target cells is predictably and drastically reduced. ▫ Figure 4.25 is a presentation of energy reaching cells deep within the tissue.

4.6.4 Effect of Lesion Depth and Tissue Type on Parameter Calculations

Many of the anatomic structures that are purported to benefit from low level laser therapy such as the TMJ or joint bursa are located at some distance within the surrounding tissue. ▫ Figure 4.26 suggests that, at 5 mm into representative tissue ranging from beef muscle (similar to human muscle) to beef liver (similar to highly vascularized tissue), energy density has decreased to about 10% of its surface value.

4.6.5 Cautionary Considerations

Arany et al. [33] state that a skin temperature increase to greater than 45 °C is phototoxic. While it is tempting to apply large amounts of energy in a short period of time in order to stimulate deep structures and to speed treatment, very negative unintended consequences may occur in overlying tissues.

Of all the protocols for laser use in dentistry, photobiomodulation is at the greatest risk of misunderstood technique and unintended consequences. Unfortunately, there is no direct visual feedback of effectiveness leaving the clinician to rely on an understanding of parameters.

While not settled science, the currently accepted guidelines recommend applying a fluence of 100 mw/cm^2 and a total cellular dose of 3–10 j/cm^2.

There are several unique devices available for applying therapeutic doses including large diameter (8 mm to 10 mm) optical fibers, rectangular therapy /bleaching handpieces, and flattop hand-pieces. Many clinicians use the expedient of a surgical optical fiber held at a distance from the tissue surface as a perceived equivalent. However, these devices can produce very different tissue exposure.

If 1 watt of power is applied through a 400 μm fiber from a distance of 10 mm for 30 s as it is moved over a tissue area of 2 cm^2, the result is:

$$\text{Fluence} = 1\text{w} / 2\,\text{cm}^2 = 0.5\text{w} / \text{cm}^2 = 500\text{mw} / \text{cm}^2$$

$$\text{Irradiance} = 0.5\text{w} / \text{cm}^2 * 30\,\text{s} = 15\text{J} / \text{cm}^2$$

Applying the same parameters through an 8 mm diameter PBM hand-piece in contact without movement results in:

$$\text{Fluence} = 1\text{w} / 0.5\,\text{cm}^2 = 2\text{w} / \text{cm}^2 = 2{,}000\text{mw} / \text{cm}^2$$

$$\text{Irradiance} = 2\text{w} / \text{cm}^2 * 30\,\text{s} = 60\text{J} / \text{cm}^2$$

Finally, applying the same parameters through a rectangular therapy/bleaching handpiece with dimensions of 8 mm by 35 mm results in:

$$\text{Fluence} = 1\text{w} / 2.8\,\text{cm}^2 = 0.36\text{w} / \text{cm}^2 = 360\text{mw} / \text{cm}^2$$

$$\text{Irradiance} = 0.36\text{w} / \text{cm}^2 * 30\,\text{seconds} = 10.7\text{J} / \text{cm}^2$$

It is easy to understand that, while using identical laser parameters, each of these common delivery systems will have a vastly different effect on the target tissue.

Whichever means of energy delivery is chosen, it is incumbent on the clinician to carefully calculate the tissue dose and to adjust parameters appropriately. To achieve the recommended protocol:

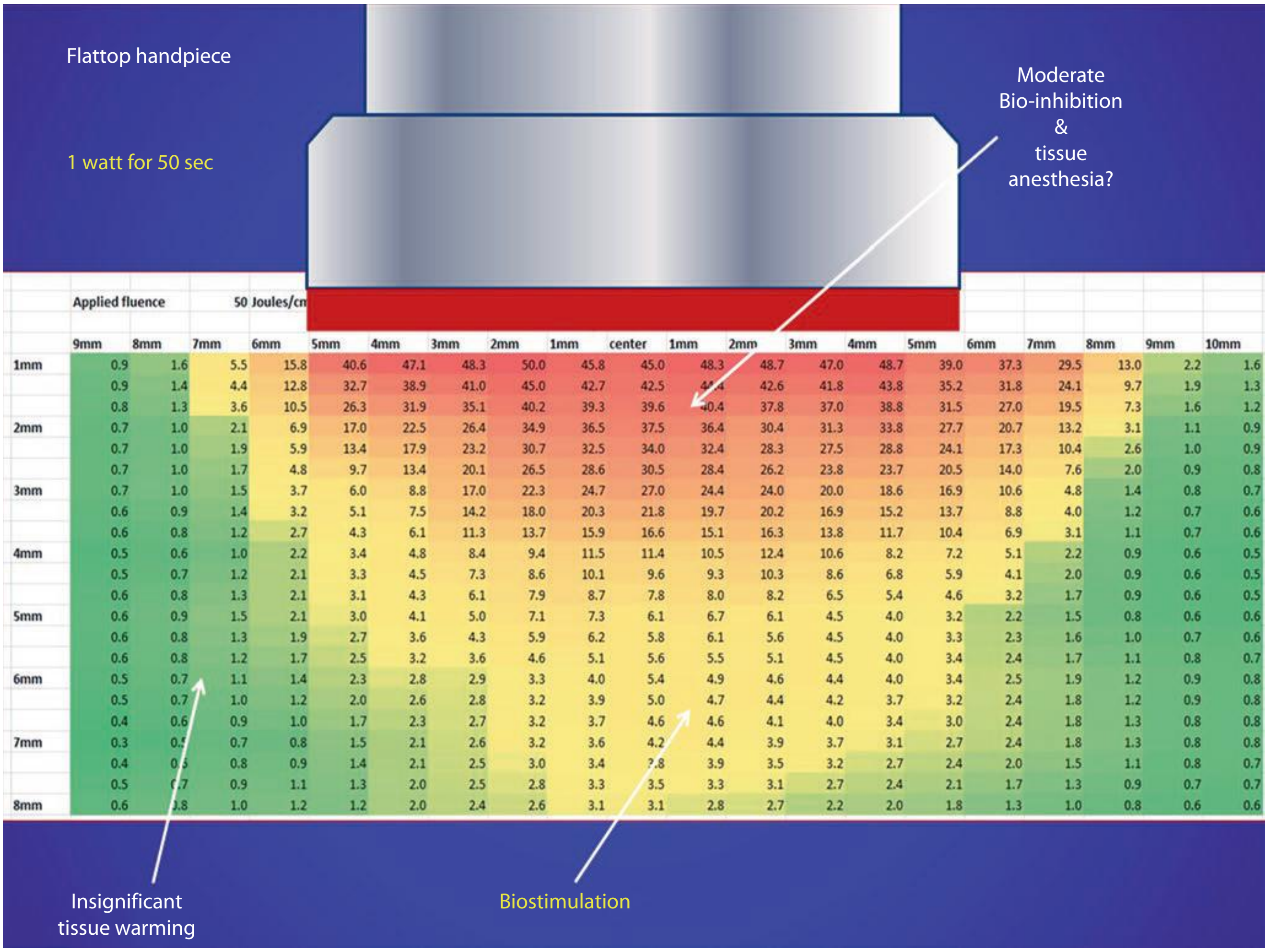
The 400 μm fiber should be applied at 0.2 watt for 50 s from a distance of 10 mm

The PBM hand-piece should be applied at 0.05 watt (an impossibility) for 100 s

The therapy hand-piece should be applied at 0.3 watt for 90 s.

Summary

Knowledge of actual laser energy being applied to the target tissue with any laser is vital to achieving positive results. This chapter has focused on understanding the meaning and the effect of each of the variable parameters available to the clinician when making a decision to apply laser technology for the benefit of a patient.



	9mm	8mm	7mm	6mm	5mm	4mm	3mm	2mm	1mm	center	1mm	2mm	3mm	4mm	5mm	6mm	7mm	8mm	9mm	10mm
1mm	0.9	1.6	5.5	15.8	40.6	47.1	48.3	50.0	45.8	45.0	48.3	48.7	47.0	48.7	39.0	37.3	29.5	13.0	2.2	1.6
	0.9	1.4	4.4	12.8	32.7	38.9	41.0	45.0	42.7	42.5	44.4	42.6	41.8	43.8	35.2	31.8	24.1	9.7	1.9	1.3
	0.8	1.3	3.6	10.5	26.3	31.9	35.1	40.2	39.3	39.6	40.4	37.8	37.0	38.8	31.5	27.0	19.5	7.3	1.6	1.2
2mm	0.7	1.0	2.1	6.9	17.0	22.5	26.4	34.9	36.5	37.5	36.4	30.4	31.3	33.8	27.7	20.7	13.2	3.1	1.1	0.9
	0.7	1.0	1.9	5.9	13.4	17.9	23.2	30.7	32.5	34.0	32.4	28.3	27.5	28.8	24.1	17.3	10.4	2.6	1.0	0.9
	0.7	1.0	1.7	4.8	9.7	13.4	20.1	26.5	28.6	30.5	28.4	26.2	23.8	23.7	20.5	14.0	7.6	2.0	0.9	0.8
3mm	0.7	1.0	1.5	3.7	6.0	8.8	17.0	22.3	24.7	27.0	24.4	24.0	20.0	18.6	16.9	10.6	4.8	1.4	0.8	0.7
	0.6	0.9	1.4	3.2	5.1	7.5	14.2	18.0	20.3	21.8	19.7	20.2	16.9	15.2	13.7	8.8	4.0	1.2	0.7	0.6
	0.6	0.8	1.2	2.7	4.3	6.1	11.3	13.7	15.9	16.6	15.1	16.3	13.8	11.7	10.4	6.9	3.1	1.1	0.7	0.6
4mm	0.5	0.6	1.0	2.2	3.4	4.8	8.4	9.4	11.5	11.4	10.5	12.4	10.6	8.2	7.2	5.1	2.2	0.9	0.6	0.5
	0.5	0.7	1.2	2.1	3.3	4.5	7.3	8.6	10.1	9.6	9.3	10.3	8.6	6.8	5.9	4.1	2.0	0.9	0.6	0.5
	0.6	0.8	1.3	2.1	3.1	4.3	6.1	7.9	8.7	7.8	8.0	8.2	6.5	5.4	4.6	3.2	1.7	0.9	0.6	0.5
5mm	0.6	0.9	1.5	2.1	3.0	4.1	5.0	7.1	7.3	6.1	6.7	6.1	4.5	4.0	3.2	2.2	1.5	0.8	0.6	0.6
	0.6	0.8	1.3	1.9	2.7	3.6	4.3	5.9	6.2	5.8	6.1	5.6	4.5	4.0	3.3	2.3	1.6	1.0	0.7	0.6
	0.6	0.8	1.2	1.7	2.5	3.2	3.6	4.6	5.1	5.6	5.5	5.1	4.5	4.0	3.4	2.4	1.7	1.1	0.8	0.7
6mm	0.5	0.7	1.1	1.4	2.3	2.8	2.9	3.3	4.0	5.4	4.9	4.6	4.4	4.0	3.4	2.5	1.9	1.2	0.9	0.8
	0.5	0.7	1.0	1.2	2.0	2.6	2.8	3.2	3.9	5.0	4.7	4.4	4.2	3.7	3.2	2.4	1.8	1.2	0.9	0.8
	0.4	0.6	0.9	1.0	1.7	2.3	2.7	3.2	3.7	4.6	4.6	4.1	4.0	3.4	3.0	2.4	1.8	1.3	0.8	0.8
7mm	0.3	0.5	0.7	0.8	1.5	2.1	2.6	3.2	3.6	4.2	4.4	3.9	3.7	3.1	2.7	2.4	1.8	1.3	0.8	0.8
	0.4	0.5	0.8	0.9	1.4	2.1	2.5	3.0	3.4	3.8	3.9	3.5	3.2	2.7	2.4	2.0	1.5	1.1	0.8	0.7
	0.5	0.7	0.9	1.1	1.3	2.0	2.5	2.8	3.3	3.5	3.3	3.1	2.7	2.4	2.1	1.7	1.3	0.9	0.7	0.7
8mm	0.6	0.8	1.0	1.2	1.2	2.0	2.4	2.6	3.1	3.1	2.8	2.7	2.2	2.0	1.8	1.3	1.0	0.8	0.6	0.6

Fig. 4.25 All tissue areas in red exceed the optimal range and experiences bioinhibition and perhaps even irreversible cellular damage. This zone extends about 3.5 mm into the tissue. Biostimulation would occur from 10 J/cm² to about 3 J/cm² as depicted in yellow. This semicircular band about 4 mm wide directly in front of the hand-piece tapers down to about 1 mm wide on the periphery. Beyond that band, the tissue cells would be perhaps warmed a little bit with no discernable photobiomodulation effect

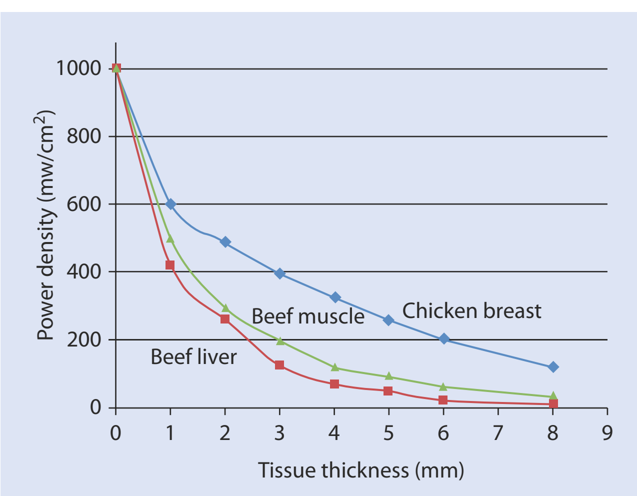


Fig. 4.26 Power density diminishes rapidly as the laser energy penetrates the tissue. Beef muscle and liver are representative of the range of tissues seen in the oral cavity

4.7 Laser Photonic Energy – Examples of Mathematical Quantification and Calculation

Calculation of parameters is provided for each of the lasers shown below. While some readers may find this rudimentary, others will appreciate the review of physics and mathematical calculations.

Please note that, for calculations to be valid, it is necessary to convert all dimensions to centimeters, all times to seconds, all energies to joule, and all powers to watts before computation. This standardized system allows the statement of parameters as watts/cm², joules/cm² and joules/second.

Because of basic differences in variable gated continuous wave and true pulsed lasers, each needs a different set of equations to calculate the same set of variables.

4.7.1 Variable Gated Continuous Wave Laser

Figure 4.27, below, shows the graphic user interface for a variable gated continuous laser.

Fig. 4.27 This 810 nm diode laser has limited variables that may be controlled directly. It is used here with a 400 um diameter optical fiber

Emission Cycle

If the laser is «on» for 20 ms and «off» for 80 ms, then it is on for 20% of the time:

$$\begin{aligned}\text{Percentage of «on-time»} &= 20\,\text{ms} / (20\,\text{ms} + 80\,\text{ms}) \\ &= 20\,\text{ms} / 100\,\text{ms} \\ &= 0.2 = 20\%\end{aligned}$$

Average Power

This diode laser allows direct control of the output power, but the power displayed is the «continuous wave» output rather than the average power. Any time that this laser is emitting photons, it is emitting 2 w. Average power is calculated as:

$$\begin{aligned}\text{Power}_{\text{avg}} &= \text{power}_{\text{indicated}} \times \text{percentage of «on-time»} \\ &= 2\,\text{w} \times (20\,\text{ms} / (20\,\text{ms} + 80\,\text{ms})) = 0.4\,\text{W}\end{aligned}$$

If the length of the on and off periods are changed but stay in the same ratio, average power will be the same.

$$\begin{aligned}\text{Power}_{\text{avg}} &= \text{power}_{\text{indicated}} \times \text{percentage of «on-time»} \\ &= 2\,\text{w} \times (80\,\text{ms} / (80\,\text{ms} + 320\,\text{ms})) = 0.4\,\text{w}\end{aligned}$$

Peak Power

For this diode laser, peak power will always be the same as that indicated on the display, no matter what magnitude or ratio of «on» and «off» times are selected.

$$\text{Power}_{\text{peak}} = \text{power}_{\text{indicated}} = 2\,\text{W}$$

Pulse Width

Pulse width, in this case, is simply the «on» time:

$$\text{Pulse width} = 20\,\text{ms}$$

Pulse Repetition Rate

One repetition is the same as one emission cycle or the sum of one «on» time and one «off» time. So:

$$\begin{aligned}\text{Emission cycle} &= 20\,\text{ms}(\text{«on»}) + 80\,\text{ms}(\text{«off»}) \\ &= 100\,\text{ms}\end{aligned}$$

Then, the number of these events that occur in 1 s represents the pulse repetition rate.

$$\begin{aligned}\text{Pulse repetition rate} &= 1\,\text{s} / 100\,\text{ms} \\ &= 10\,\text{pulses per second}\end{aligned}$$

Beam Divergence

Beam divergence is a function of the fiber construction and the numerical aperture. For optical fibers used with diode and Nd:YAG lasers, the numerical aperture is commonly 0.22. This results in a divergence of 12.7° per side angle.

Tip Area

Tip area is the radius of the tip squared multiplied by pi:

$$\begin{aligned}\text{Tip area} &= 200\,\text{um} * 200\,\text{um} * 3.14159 \\ &= 0.02\,\text{cm} * 0.02\,\text{cm} * 3.14159 = 0.00126\,\text{cm}^2\end{aligned}$$

Spot Diameter at Tissue

Diode lasers are used in contact for surgical procedures. Therefore, the spot diameter at the tissue surface is the same as the tip diameter:

$$\text{Spot diameter at tissue} = 400\,\text{um} = 0.04\,\text{cm}$$

Spot Area at Tissue

Similarly, the spot area at the tissue surface is the same as the area of the optical fiber tip.

$$\text{Spot area at tissue} = 0.00126\,\text{cm}^2$$

Power Density

Power density is the total energy, in joules passing through a specific area in 1 s of time. With the attached 400 μ laser fiber, this diode laser produces:

$$\begin{aligned}\text{Power density}_{\text{avg}} &= \text{power}_{\text{avg}} / \text{area} \\ &= 0.4\,\text{Watt}/0.00126\,\text{cm}^2 \\ &= 318\,\text{w/cm}^2\end{aligned}$$

$$\begin{aligned}\text{Power density}_{\text{peak}} &= \text{power}_{\text{peak}} / \text{area} \\ &= 2\,\text{Watt}/0.00126\,\text{cm}^2 \\ &= 1587\,\text{w/cm}^2\end{aligned}$$

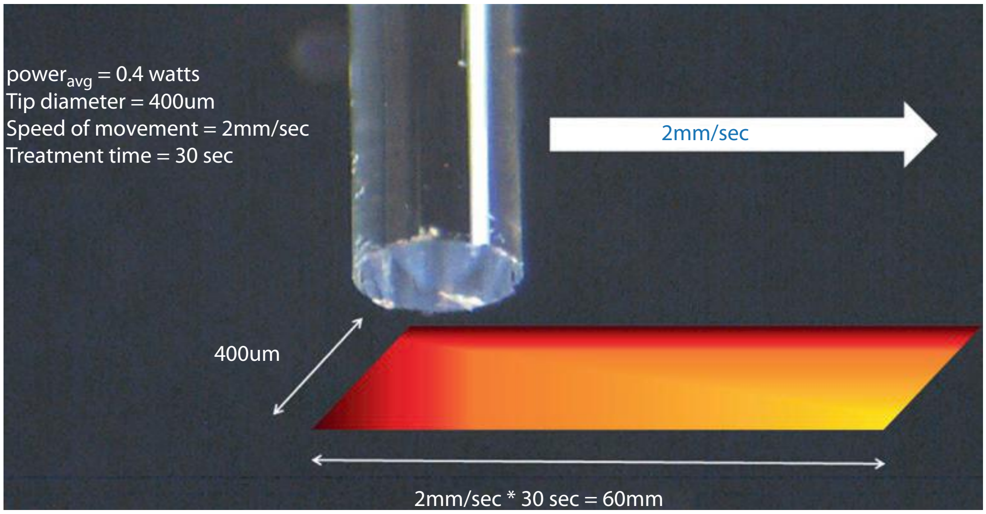


Fig. 4.28 When the optical fiber or emitting tip is moved across the tissue during treatment, the energy produced is distributed over a larger area based on the speed of movement. When determining energy density received by an individual group of cells, it is necessary to calculate the entire area that is irradiated

Total Energy

The total amount of energy delivered to the tissue during a 30 s treatment is:

$$\text{Total energy} = \text{power}_{avg} * \text{time} = 0.4\,\text{W} * 30\,\text{s} = 12\,\text{J}$$

Energy Density

If the fiber tip is held stationary in one location, the energy density is calculated as:

$$\begin{aligned}\text{Energy density}_{avg} &= \text{power}_{avg} * \text{time/area}\\ &= 0.4\,\text{W} * 30\,\text{s}/0.00126\,\text{cm}^2\\ &= 9{,}540\,\text{J/cm}^2\end{aligned}$$

$$\begin{aligned}\text{Energy density}_{peak} &= \text{power}_{peak} * \text{time/area}\\ &= 2\,\text{W} * 30\,\text{s}/0.00126\,\text{cm}^2\\ &= 47{,}610\,\text{j/cm}^2\end{aligned}$$

Movement of the Tip

If the fiber tip is moved through the tissue at a speed of 2 mm/s, the applied energy is distributed over a much larger area affecting energy density. This may be calculated as shown below Fig. 4.28:

Energy Density with Movement

$$\text{Area} = \text{width} * \text{length traveled in } 30\,\text{s}$$
$$\text{Area} = .04\,\text{cm} * 6\,\text{cm} = 0.24\,\text{cm}^2$$
$$\text{Energy density} = 0.4\,\text{W} * 30\,\text{s} / 0.24\,\text{cm}^2 = 50\,\text{J/cm}^2$$

4.7.2 True Pulsed Laser with Control of Average Power

Figure 4.29, below, shows the graphic user interface for a true pulsed laser with control of average power.

Fig. 4.29 This 2,780 nm Er,Cr:YSGG laser has a choice of two pulse widths. It allows control of average power, but energy per pulse and peak power must be calculated. Levels of auxiliary air and water are set as percentage of an arbitrary value (Courtesy Waterlase MD Biolase, Irvine California)

Average Power

This erbium laser allows direct control of the average output power. In this case, it has been adjusted to 4 w.

Pulse Width

Pulse width is established by choosing one of the two values available – «H» = «hard tissue» = 60 usec or «S» = «soft tissue» = 700 usec. In this case, 60 usec has been selected.

Pulse Repetition Rate

Pulse repetition rate is selected as 15 pulses per second (pps).

Emission Cycle

The emission cycle indicates the percentage of time that the laser is actually emitting energy. With any true pulsed laser, this is a very small amount. It is calculated as the length of time that the laser is emitting during each second or the sum of the width of all pulses:

$$\text{Emission cycle} = (\text{pps} * \text{pulse width}/1\,\text{sec}) * 100\%$$
$$\text{Emission cycle} = (15 * 0.00006\,\text{s}) * 100\%$$
$$\text{Emission cycle} = 0.09\%$$

Energy per Pulse

If 4 w is produced in 1 s, then 4 J/s are produced. If this energy is divided equally between 15 pulses, then:

$$\begin{aligned}\text{Energy per pulse} &= \text{energy per second}/\\ &\quad\ \text{number of pulses per second}\\ \text{Energy per pulse} &= 4\,\text{J/s}/15\,\text{pps}\\ &= 0.267\,\text{J per pulse}\\ &= 267\,\text{mj/pulse}\end{aligned}$$

Note: A key point must be considered here. With any pulsed laser that allows control of average power, the energy per pulse changes if the pulse repetition rate changes. As an example, if the laser in Fig. 4.29 has the pulse repetition rate changed to 5 pulses/s, while the average power is unchanged, the energy per pulse changes to:

$$\begin{aligned}\text{Energy per pulse} &= 4\,\text{J/s}/5\,\text{pps}\\ &= 0.8\ \text{Joules per pulse}\\ &= 800\,\text{mj/pulse}\end{aligned}$$

This concept applies to any Er:YAG, Er, Cr:YSGG, or Nd:YAG laser that provides control of average power instead of energy per pulse.

Peak Power

Peak power represents the maximum instantaneous power that the laser produces.

Peak power can be calculated as:

$$\text{Power}_{\text{peak}} = \text{energy per pulse/pulse width}$$
$$\text{Power}_{\text{peak}} = 0.267\,\text{J}/0.00006\,\text{s} = 4{,}444\,\text{W}$$

Tip Area

Commonly available tips for this laser are cylindrical, tapered, and chisel shaped. While calculating the area, divergence, and spot area for chisel tips is beyond this discussion, the diameter of the output end of a tapered tip can be treated the same as a cylindrical tip as calculated below.

Assuming use of a 600 um diameter cylindrical tip allows the following calculations:

Tip area is the radius of the tip squared multiplied by pi:

$$\begin{aligned}\text{Tip area} &= 300\,\text{um} * 300\,\text{um} * 3.14159\\ &= 0.03\,\text{cm} * 0.03\,\text{cm} * 3.14159\\ &= 0.00283\,\text{cm}^2\end{aligned}$$

A tip that tapers from 1200 to 600 um at the output end would have the same tip area of 0.00283 cm^2.

Spot Diameter at Tissue

Erbium lasers are usually used in contact for soft tissue surgical procedures. Therefore, the spot diameter at the tissue surface is the same as the tip diameter:

$$\text{Spot diameter at tissue} = 600\,\text{um} = 0.06\,\text{cm}$$

Spot Area at Tissue

For this scenario, the spot area at the tissue surface is the same as the area of the optical fiber tip.

$$\text{Spot area at tissue} = 0.00283\,\text{cm}^2$$

Beam Divergence

When this or any laser is used out of contact, the effect of beam divergence has a critical effect on spot diameter at the tissue surface and, therefore, energy and power density.

Beam divergence is a function of the particular tip chosen. For tips used with this laser, it is commonly 12° per side angle. For a tip-to-tissue distance (A) of 2 mm and an angle (x), from geometry as shown in Fig. 4.30:

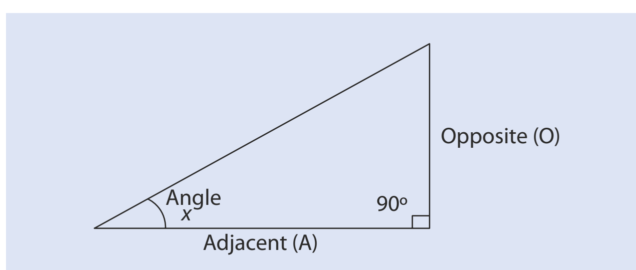


Fig. 4.30 Basic geometry establishes the relationship between different variables in a right triangle

$$O = A * \tan(x)$$
$$O = 2\,\text{mm} * \tan(12^0)$$
$$O = 2\,\text{mm} * 0.2126 = 0.425\,\text{mm}$$
$$\text{Spot radius at tissue} = \text{tip radius} + \text{Opposite}$$
$$= 0.03 + 0.0425 = 0.0725\,\text{cm}$$
$$\text{Spot diameter at tissue} = 0.145\,\text{cm}$$

As shown Fig. 4.31, at a tip-to-tissue distance of 2 mm with a 12^0 beam divergence per side angle:

$$\text{Spot area at tissue} = \text{pi} * r^2$$
$$= 3.14159 * 0.0725\,\text{cm} * 0.0725\,\text{cm}$$
$$= 0.0165\,\text{cm}^2$$

The effect of divergence on parameters is similar to that with an optical fiber.

Power Density

Power density is the total energy, in joules passing through a specific area in 1 second of time. With the attached 600 µ laser fiber and a tip-to-tissue distance of 2 mm, this erbium laser produces:

$$\text{Power density}_{avg} = \text{power}_{avg} / \text{area}$$
$$= 4\,\text{W} / 0.0165\,\text{cm}^2 = 242\ \text{w/cm}^2$$

$$\text{Power density}_{peak} = \text{power}_{peak} / \text{area}$$
$$= 4,444\,\text{W}/0.0165\text{cm}^2$$
$$= 269,333\,\text{w/cm}^2$$

This peak power calculation should make it clear how a pulsed laser can ablate enamel.

Total Energy

The total amount of energy delivered to the tissue during a 30 second treatment is:

$$\text{Total energy} = \text{power}_{avg} * \text{time} = 4\,\text{W} * 30\,\text{s} = 120\,\text{J}$$

Energy Density

If the fiber tip is held stationary in one location, the energy density is calculated as:

$$\text{Energy density}_{avg} = \text{power}_{avg} * \text{time} / \text{area}$$
$$= 4\,\text{W} * 30\,\text{s} / 0.0165\,\text{cm}^2$$
$$= 7,273\,\text{J} / \text{cm}^2$$

$$\text{Energy density}_{peak} = \text{power}_{peak} * \text{time/area}$$
$$= 4,444\,\text{W} * 30\,\text{s}/0.0165\,\text{cm}^2$$
$$= 8,080,000\ \text{J/cm}^2$$

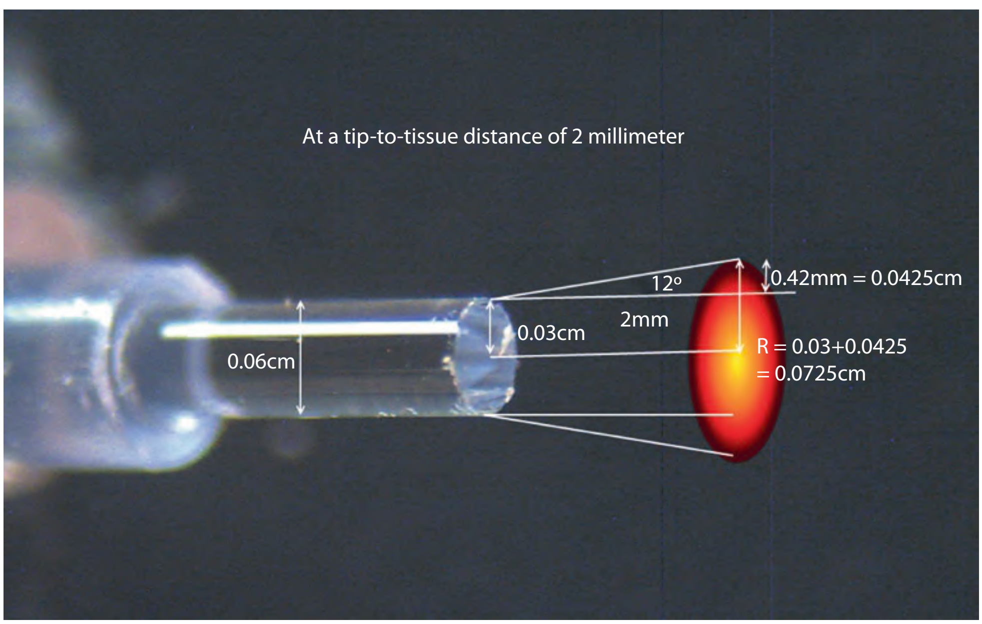


Fig. 4.31 This is a depiction of the various values calculated to determine the spot area at the tissue with a divergent beam

4.7.3 True Pulsed Laser with Control of Pulse Energy

Figure 4.32, below, shows the graphic user interface for a true pulsed laser with control of pulse energy.

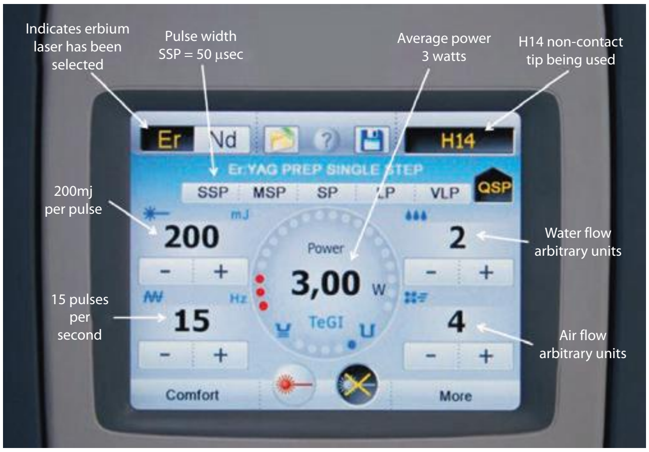


Fig. 4.32 This laser contains both a 2,940 nm Er:YAG laser and a 1,064 nm Nd:YAG laser. In erbium mode, it allows selection of six different pulse widths. However, the operator must refer to a manual to find the value. It allows control of pulse energy and pulse frequency. The resulting average power is displayed but not directly selectable

Pulse Width

Pulse width is established by choosing one of the six values available – choosing the SSP mode selects a pulse width of 50 usec.

Pulse Repetition Rate

Pulse repetition rate is selected as 15 pulses per second (pps).

Emission Cycle

The emission cycle indicates the percentage of time that the laser is actually emitting energy. With any true pulsed laser, this is a very small amount. It is calculated as the length of time that the laser is emitting during each second or the sum of the width of all pulses:

$$\text{Emission cycle} = \left(\begin{array}{l}\text{number of pulses per second} * \\ \text{width of each pulse/1s}\end{array}\right) * 100\%$$

$$\begin{aligned}\text{Emission cycle} &= 15\text{pps} * 0.00005\text{s/1s} \\ &= 0.00075 * 100 = 0.075\%\end{aligned}$$

Energy per Pulse

The energy per pulse is directly selected as 200 mj.

Average Power

This erbium laser indicates an average output power of 3 w. In this case, it is not directly adjustable but is internally calculated by the laser. It can be calculated as shown below:

$$\begin{aligned}\text{power}_{\text{avg}} &= \text{energy per pulse} * \text{number of pulses per second} \\ \text{power}_{\text{avg}} &= 0.2\ \text{Joules per pulse} * 15\ \text{pulses per second} = 3.0\,\text{W}\end{aligned}$$

Peak Power

Peak power represents the maximum instantaneous power that the laser produces.

Peak power can be calculated as:

$$\begin{aligned}\text{Power}_{\text{peak}} &= \text{energy per pulse/pulse width} \\ \text{Power}_{\text{peak}} &= 0.200\,\text{j} / 0.00005\,\text{sec} = 4,000\,\text{W}\end{aligned}$$

Tip Area

As with the Er,Cr:YSGG laser discussed above, commonly available tips for this laser are cylindrical, tapered, and chisel shaped. All calculations below are based on use of a 600 mm diameter tip at a tip-to-tissue distance of 2 mm. The resulting calculations will be identical as those above.

Assuming use of a 600 um diameter cylindrical tip allows the following calculations:

Tip area is the radius of the tip squared multiplied by pi:

$$\begin{aligned}\text{Tip area} &= 300\,\text{um} * 300\,\text{um} * 3.14159 \\ &= 0.03\,\text{cm} * 0.03\,\text{cm} * 3.14159 = 0.00283\,\text{cm}^2\end{aligned}$$

A tip that tapers from 1200 to 600 um at the output end would have the same tip area of 0.00283 cm^2.

As before, at a tip-to-tissue distance of 2 mm with a 12^0 beam divergence per side angle:

$$\begin{aligned}\text{Spot area at tissue} &= \text{pi} * \text{r}^2 \\ &= 3.14159 * 0.0725\,\text{cm} * 0.0725\,\text{cm} \\ &= 0.0165\,\text{cm}^2\end{aligned}$$

Power Density

Power density is the total energy, in joules passing through a specific area in 1 s of time. With the attached 600 µ laser fiber and a tip-to-tissue distance of 2 mm, this erbium laser produces:

$$\begin{aligned}\text{Power density}_{\text{avg}} &= \text{power}_{\text{avg}} / \text{area} \\ &= 3\,\text{W} / 0.0165\,\text{cm}^2 = 182\,\text{w} / \text{cm}^2\end{aligned}$$

$$\begin{aligned}\text{Power density}_{\text{peak}} &= \text{power}_{\text{peak}} / \text{area} \\ &= 4,000\,\text{W}/0.0165\,\text{cm}^2 \\ &= 242,424\,\text{w/cm}^2\end{aligned}$$

Total Energy

The total amount of energy delivered to the tissue during a 30 s treatment is:

$$\text{Total energy} = \text{power}_{\text{avg}} * \text{time} = 3\,\text{W} * 30\,\text{s} = 90\,\text{J}$$

Energy Density

If the fiber tip is held stationary in one location, the energy density is calculated as:

$$\begin{aligned} \text{Energy density}_{\text{avg}} &= \text{power}_{\text{avg}} * \text{time/area} \\ &= 3\,\text{W} * 30\,\text{s}/0.0165\,\text{cm}^2 \\ &= 5{,}455\,\text{J/cm}^2 \\ \text{Energy density}_{\text{peak}} &= \text{power}_{\text{peak}} * \text{time/area} \\ &= 4{,}000\,\text{W} * 30\,\text{s}/0.0165\,\text{cm}^2 \\ &= 7{,}272{,}727\,\text{J/cm}^2 \end{aligned}$$

Assumptions

Several assumptions are made in these calculations:

- Output is assumed to be uniform over the radiated area. In practice, this is rarely true since a Gaussian output is normally produced.
- Output is assumed to be uniform over time. That is, each pulse is assumed to rise instantaneously from zero to the peak power being produced. Again, this is rarely true.
- Output is assumed to be constant over the duration of the pulse. In fact, as shown in ► Chap. 4, ◘ Fig. 4.1, of this text, the true output varies significantly and must be averaged for these calculations.
- The output is assumed to be the same as that displayed on the interface screen. Laser manufacturers as careful to point out in their technical specifications that most parameters are only guaranteed to be within about 20% of the stated value.
- Actual spot diameter is as calculated. Because of the Gaussian nature of the beam cross section, a portion of the photons will strike tissue outside of the calculated area.

Summary

The calculations presented here are based on representative values as shown on actual dental lasers for all parameters. By substituting actual known values for the laser being used into the equations, it is possible to determine appropriate parameters. In general, all continuous wave lasers can be assessed using the set of calculations in ► Sect. 4.7.1, while true pulsed lasers can be analyzed using calculations in ► Sects. 4.7.2 and 4.7.3 depending on which parameters are displayed or can be selected.

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Laser Safety

Penny J. Parker and Steven P.A. Parker

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5

Core Message

Laser use in general dental practice has grown considerably over the past 25 years, both in numbers of machines and the scope of usage. General and specific measures must be employed to ensure the safe use of lasers in dentistry. Regulations – specific to lasers or within the licenced scope of practice – apply a duty of care to all dental healthcare professionals in the application of lasers in clinical practice. Such laser regulations may exist through international standards and/or through national or regional legislation. The duty of care extends to all staff as well as patients. The registered laser owner or lead clinician is responsible for ensuring that all staff personnel have a thorough knowledge of laser safety. Additional devolved responsibility may be applied to the laser safety officer.

Laser safety is applicable according to the class of laser being used. Within the classification of lasers, there is a range from Class I to Class IV, with subclasses relevant to laser operation using optical magnification (loupes, microscope, etc.). Specific risks apply to the unprotected eye and skin, according to the laser class and wavelength. Nonbeam risks exist, including those posed by the laser plume.

It is mandatory therefore that those personnel involved in the delivery of laser photonic energy that is capable of risk to unprotected ocular and nontarget tissue should undergo training sufficient to alert them to their responsibility. Prime amongst this responsibility is to any patient receiving such therapy.

5.1 Introduction

LASER – coherent nonionizing electromagnetic radiation is an intense form of energy and a potential may exist for such energy, directed at the biological tissue to be absorbed, in part or totally, and give rise to structural change within the tissue. Lasers used in dentistry are configured to deliver photonic energy that would mostly convert to thermal energy within the tissue, and it is this thermal rise that may be sufficient to progress through tissue warming to a level and above, where irreversible change such as protein denaturation and water vaporization may occur.

To deliver controlled, predictable, and positive laser-assisted change represents the ideal of the dental clinician in providing treatment. However, inappropriate energy levels and/or delivery of laser photonic beam to nontarget tissue can represent a risk, sufficient to cause irreparable and permanent damage. This may occur within the oral cavity, to circumoral and facial skin structure or most importantly to the structures of the unprotected eye.

As the purchase and use of lasers in dentistry continues to grow, so must concern for laser safety. Failing to wear available eye protection is one of the most frequent contributing factors to laser injuries [1]. Within such risk and pertinent to the use of lasers in general, laser safety measures are delineated for interpretation and application in the workplace, such as the dental operatory.

In a systematic review of papers relevant to beam and nonbeam medical laser hazards, together with access to the Rockwell Laser Industries Laser Accident Database, it was concluded that occupational hazards associated with medical laser applications remain poorly understood and uncharacterized. There are relatively few published accounts of laser accidents; they tend to suffer from the problem of reliance on self-reporting. Eye injuries, skin burns, injuries related to the onset of fires, and electric shock have been reported in relation to medical laser use. It is probable that both acute and chronic health effects have been experienced by medical personnel as the result of exposure to laser-generated air contaminants (plume) [2].

A more substantial study of laser-related injuries reported on risk factors, but was not limited to medical laser application [3]. Four database sources within the USA – Center for Devices and Radiological Health of the US Food and Drug Administration (FDA), Rockwell Laser Industries (RLI), the US Army's Laser Accident and Incident Registry (LAIR) and the Federal Aviation Administration (FAA) safety reporting system – revealed a total of 869 injuries and deaths. Of these where injury or death occurred, a total of 663 (52%) were located in some type of medical facility.

It may seem innocuous to the dental professional new laser user that safety is a key objective to protect the patient and clinical team. Useful lessons can often be learned from studying laser accidents, and although most countries require such accidents to be reported to the relevant authority, often such information is not accessible to laser users. The risk of such accidents may be reduced by performing a risk assessment and this is often a legal requirement, such as in the countries of the European Union [4, 5].

In a paper that reported laser-associated accidents within medical practice [6], 12 incidents were reported. Simple errors relating to the operation of laser equipment accounted for five of the reported incidents; in four incidents there was temporary or permanent damage to the operator's eye, but of greater significance was the reporting of three incidents where the laser emission caused either direct inflammation of gauze and drapes or damage to endotracheal tubing that led to potentially fatal airway fires in an anesthetized patient. The paper suggested that operator error was at fault in 67% of the incidents reported and that equipment fault (25%), laser-induced fire (25%) and broken delivery fiber (17%) constituted the (avoidable) risks in these unfortunate accidents.

It is only when viewed in the context of permanent and possibly life-threatening risk to the clinician and attendant staff but more so the patient that the importance of knowledge and appreciation of laser safety issues must be acknowledged. Table 5.1 provides a glossary of terminology associated with aspects of laser safety.

Table 5.1 Glossary of terminology associated with aspects of laser safety

Laser safety term	Explanation
Laser classifications I–IV	Laser/LED unit capability of ascending laser beam emission power, relative to the safety risk posed. I, low; IV, high
Aversion response	Blinking of the eye or movement of the head to avoid exposure to a bright light, approximately 0.25 s
Accessible emission limits (AEL)	Maximum accessible level of laser radiation permitted within a particular laser class
Maximum permissible exposure (MPE)	The level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin
Nominal hazard zone (NHZ)	Aka nominal ocular hazard zone. Area within which the level of the direct, reflected or scattered radiation during normal operation exceeds the applicable MPE
Controlled area	Area within which occupancy and activity are subject to control and supervision for the purpose of protection from laser radiation hazards
Intrabeam viewing	Exposure of the eye to all or part of a laser beam
Specular reflection	A mirror-like reflection of a laser beam, with or without loss of beam fluence
Diffuse reflection	Change in the spatial (area) distribution of a laser beam when it is reflected in multiple directions by a rough or matt surface
American National Standards Institute (ANSI) ANSI Z 136.1, 2, 3, 4, 7.)	US regulations governing areas of laser safety pertinent to clinical laser dentistry Z 136.1 – Safe Use of Lasers Z 136.2 – Safe Use of Optical Fiber Communication Systems Utilizing Laser Diode and LED Sources Z 136.3 – Safe Use of Lasers in Healthcare Z 136.4 – Recommended Practice for Laser Safety Measurements for Hazard Evaluation Z 136.7 – Testing and Labeling of Laser Protective Equipment
International Electrotechnical Commission (IEC) IEC 60825 + updates	Broad range specifications relating to laser manufacture and use

5.2 Regulatory Framework

The regulatory framework governing the safe use of lasers may be seen as a hierarchical devolvement, most referenced through the IEC (International Electrotechnical Commission) and ANSI (American National Standards Institute). From these organizations and their representation, national regulations may apply – either as specific statutory instruments or more often as part of laws and regulations that might apply within the workplace [7, 8, 9].

IEC, formed in 1906, is responsible for the development of world standards for the electrical and electronics area and is composed of the national committees from countries around the world. In 1930 the IEC established electrical units under a system commonly known as the «Système International», or SI for short. In 1974, the IEC created Technical Committee 76, to address standards relating to lasers, with a particular focus on safety. This committee developed a four-class system for lasers that was the global reference, later modified in 2002.

The American National Standards Institute (ANSI) developed in parallel, although initially unconnected, to the IEC. ANSI was originally established in 1919 as the American Engineering Standards Committee and created the International Standards Association (ISA), an organization that would eventually become the International Organization for Standardization (ISO). In 1969 ANSI adopted its present name.

The ANSI Federation also initiated what has now become an annual series of discussions with the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI).

The USA has always had its own regulation on lasers (known as FDA CFR 21 1040.10). This is a US government regulation and is written into US law. As an interpretation of recommendations, the ANSI Z136 series is recognized by the Occupational Safety and Health Administration (OSHA) as the authoritative series of laser safety in the USA.

An important ANSI Federation member and accredited standards developer, the Laser Institute of America (LIA) is the professional society dedicated to fostering lasers, laser applications and laser safety worldwide. In 2005, the LIA published ANSI Z136.4 – Recommended Practice for Laser Safety Measurements for Hazard Evaluation. This provides guidance for optical measurements associated with laser safety requirements.

In addition, the US Food and Drug Administration (FDA) informed laser product manufacturers that the US FDA would henceforth accept IEC classification and labeling [10].

In addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PASs) and Guides. Most pertinent to laser and (some aspects of) light-emitting diode (LED) safety is the publication IEC 60825 (European variant EN 60825) which has been published in several formats with revisions from 1994 to 2014 [11].

The Standard IEC (EN) 60825-1 «Safety of laser products, Part 1: Equipment classification, requirements and user's guide» sets out regulation governing the following:

- To introduce a system of classification of lasers and laser products emitting radiation in the wavelength range 180 nm to 1 mm according to their degree of optical radiation hazard in order to aid hazard evaluation and to aid the determination of user control measures
- To establish requirements for the manufacturer to supply information so that proper precautions can be adopted
- To ensure, through labels and instructions, adequate warning to individuals of hazards associated with accessible radiation from laser products
- To reduce the possibility of injury by minimizing unnecessary accessible radiation and to give improved control of the laser radiation hazards through protective features

From such broad regulation, safety and risk assessment when using lasers and LED equipment in clinical dental surgery can be devolved to include [12]:

- Suitability for use and clinical parameters
- Administrative code and record-keeping
- Safety features of laser and laser maintenance
- Environment safety and patient safety
- Laser safety officer and laser protection advisor

5.3 Laser Classification

Lasers and laser systems are divided into four major classifications according to their potential to cause biological damage to the eye or skin. The purpose of these classifications is to warn users of the hazards associated with the laser and LED relative to accessible emission limits (AEL). These limits are based on laser output energy or power, radiation wavelengths, exposure duration and cross-sectional area of the laser beam at the point of interest.

Prior to 2002, the classification of lasers ran from I to IV, with Class IV to include surgical lasers.

Class I: Laser products are generally exempt from radiation hazard controls during operation and as such do not pose any specific risk in normal usage.

Class II: Low-powered visible lasers that emit above Class I levels but at a radiant power not above 1 mW. The concept is that the human aversion reaction (blink response) to bright light will protect a person. Only limited controls are specified.

Class IIIA: Intermediate-powered lasers. Some limited controls are usually recommended.

Class IIIB: Moderate-powered lasers. In general Class IIIB lasers will not be a fire hazard, nor are they generally capable of producing a hazardous diffuse reflection. However, specific controls are recommended.

Class IV: High-powered lasers are hazardous to view under any condition (directly or diffusely scattered) and are a potential fire hazard and a skin hazard. Significant controls are required of Class IV laser facilities.

From 2002, this classification has been refined and adopted by the IEC. The revision was prompted by increasing sophistication in laser technology, together with the increased adoption of magnification devices as adjuncts to operative medicine and dentistry – operating microscopes, loupes, etc. In general, LEDs would be in the lower classes (1, 1M, 2, 2M, 3R), but very exceptionally may be Class 3B. As such, this classification will be examined in greater detail.

The IEC laser classifications are summarized as follows:

Class 1: Class 1 lasers are safe under all operating conditions. There is no risk to the eyes or skin. This means the maximum permissible exposure (MPE) cannot be exceeded when viewing a laser with the naked eye or with the aid of typical magnifying optics (e.g., telescope or microscope). To verify compliance, the standard specifies the aperture and distance corresponding to the naked eye, a typical telescope viewing a collimated beam and a typical microscope viewing a divergent beam. Class 1 lasers may consist of a higher-powered laser housed within an enclosure.

Class 1M: Class 1M lasers are not capable of producing hazardous exposure under normal operating conditions, but may be hazardous if viewed with the aid of optical instruments – magnifying optics such as microscopes and telescopes.

Class 1M lasers produce large-diameter beams, or beams that are divergent. The MPE for a Class 1M laser cannot normally be exceeded unless focusing or imaging optics are used to narrow the beam.

Class 1C: Under IEC 60825:2014, a new Class 1C is defined where C stands for «contact» but in some interpretations also stands for «conditional» [13]. Currently the class is limited to products intended for treatment of the skin or internal tissue in contact or close to the skin where the product is designed to be safe for the eye.

Class 2: Class 2 lasers are limited to 1 mW continuous wave or more if the emission time is less than 0.25 s or if the light is not spatially coherent. A Class 2 laser is safe because the blink reflex will limit the exposure to no more than 0.25 s. It only applies to visible-light lasers (400–700 nm). Intentional suppression of the blink reflex could lead to eye injury. Many laser pointers and measuring instruments are Class 2. There is no hazard from exposure to diffuse radiation.

Class 2M: Low-powered lasers (CW up to 1 mW) in visible wavelength range (400–700 nm). Class 2M lasers are not hazardous under normal operating conditions because of the aversion reaction (blink reflex). Class 2M lasers may be hazardous if viewed with the aid of optical instruments. As with Class 1M, this applies to laser beams with a large diameter or large divergence, for which the amount of light passing through the pupil cannot exceed the limits for Class 2.

Class 3R: Moderate-powered lasers (CW up to 5 mW) for visible wavelengths (400–700 nm) up to a factor of five over maximum allowable exposure of Class 2 lasers for other wavelengths. A Class 3R laser is considered safe if handled carefully, with restricted beam viewing. With a Class 3R laser, the MPE can be exceeded, but with a low risk of injury. Visible continuous lasers in Class 3R are limited to 5 mW. For other wavelengths and for pulsed lasers, other limits apply.

Since the exposure limits (MPEs) for the eye are the direct basis for the AEL (accessible emission limits) for the laser product safety classes Class 1, 1M, 2, 2M, and 3R, any changes in the MPE will also result in equivalent changes of the AEL values and thus in the permitted output powers for these classes [14].

Class 3B: Moderate-powered lasers (CW up to 500 mW, pulsed up to 30 mJ) in wavelength range of 300 nm to far infrared. Direct eye exposure to Class 3B lasers is hazardous; however, diffusely scattered radiation is generally safe. Direct exposure to skin is a potential hazard.

The AEL for continuous lasers in the wavelength range is from 300 nm to 500 mW far infrared. For pulsed lasers between 400 and 700 nm, the limit is 30 mJ. Other limits apply to other wavelengths and to ultrashort-pulsed lasers. Protective eyewear is typically required where direct viewing of a Class 3B laser beam may occur. Class 3B lasers must be equipped with a key switch and a safety interlock.

Class 4: High-powered lasers (CW above 500 mW). Class 4 is the highest and most dangerous class of laser, including all lasers that exceed the Class 3B AEL. By definition, a Class 4 laser can burn the skin or cause devastating and permanent eye damage as a result of direct, diffuse or indirect beam viewing. Class 4 lasers are also a potential fire hazard.

These hazards may also apply to indirect or nonspecular reflections of the beam, even from apparently matt surfaces, and therefore, great care must be taken to control the beam path. Class 4 lasers must be equipped with a key switch and a safety interlock.

A summary of laser classes commonly used in clinical dentistry is shown in ◘ Table 5.2.

5.4 Hazards of Laser Beams

A laser injury can be defined as an event causing (a) physical harm or damage; (b) physiological dysfunction; (c) an adverse surgical outcome, resulting directly from the laser energy, or a consequence of the device's inherent technology; or (d) a second treatment procedure to correct the first procedure.

The risk posed by coherent light irradiation may be assessed with regard to the following:

- The laser wavelength
- The power intensity of the incident laser irradiation
- Optical risks
- Nontarget oral tissue
- Nontarget skin
- Inhalation and laser plume risks
- Other associated risks: hazards – mechanical, chemical, fire, sterilization

1. *The laser wavelength:* In clinical dentistry, the range of laser wavelengths falls within 370 nm and 10,600 nm, i.e., from the blue visible limit to the far infrared, nonionizing spectrum. All laser–tissue interaction may be viewed as photothermal in that incident photonic energy is absorbed by chromophore molecules, raising the molecular energy level and leading to disruption. With regard to laser safety, it must be appreciated that absorption is but one of the basic physical phenomena associated with laser–tissue interaction. Absorption confers the maximal interaction, with scatter as an associated, quantitatively less precise energy transfer. Additional phenomena not associated with energy transfer to the exposed tissue are laser beam reflection and transmission. All four interactions may occur simultaneously in the nonhomogenized tissue and pose a mixture of threats that must be nullified through adequate safety measures.
2. *The power of the irradiation:* This will be related to the amount of energy delivered over time, together with consideration of the area of tissue that is exposed to the beam. In consequence, the power density of the beam may represent a threshold above which irreversible change may occur in the tissue exposed to the beam. As

◘ **Table 5.2** A summary of laser classes commonly used in clinical dentistry

Laser class	Maximum output	Use in dentistry	Possible hazard	Safety measures
Class I Class IM	40 µW (blue) 400 µW (red)	Integral scanning, laser caries detector	No implicit risk Possible risk with magnified beam	Blink response Laser safety labels
Class II Class IIM	1.0 milliWatt (mW)	Laser caries detection, aiming beams	Possible risk with direct viewing, significant risk with magnified beam (Class IIM)	Sight aversion response Laser safety labels
Class IIIR Class III	Visible 5.0 mW Invisible 2.0 mW 500 mW (0.5 W)	Some low-level lasers, aiming beams Low-level lasers	Eye damage Eye damage – direct or specular, maximum output may pose slight fire/skin risk	Safety eyewear, safety personnel, training for Class IIIR and IIIB lasers
Class IV	No upper limit	All surgical lasers	Eye/skin damage, nontarget tissue fire hazard, plume hazard, possible ionizing effects with UV lasers	Safety eyewear, safety personnel, training/local rules, possible registration with national regulations

was seen in Table 5.2, the classification of lasers sets out the upper limit of power delivered. In addition, the potential for the laser to deliver pulsed irradiation may influence the maximum power achievable (peak power).
3. *Optical risks:* The unprotected eye is generally regarded as the organ at greatest risk from accidental laser exposure. Several cases of laser-induced eye injuries have been documented [15–18]. For any given laser beam that exceeds an output value in excess of the MPE of ocular tissue, a risk pertains that must be anticipated and safety protocols of eye protection employed.

An important natural reflex in limiting the potential for contact and injury to the eye is blinking. The eyelid response time is of the order of 0.2 and 0.25 seconds and is cited as a significant natural aversion response to visible lasers within Class I and II. Of course, key to this protective mechanism is the word «visible». It will have no beneficial effect with beams of wavelengths outside the visible spectrum, and in addition, some laser beam intensities are so great that injury can occur faster than the protective action of the lid reflex [19].

Laser hazards to the eye depend most predominantly upon wavelength [20, 21] as shown in Fig. 5.1.

As described above, laser photonic energy cannot damage the tissue unless the light energy is absorbed within that structure. Visible and near-infrared wavelengths which can be transmitted through clear ocular media can, subject to MPE levels, be absorbed in the retina and cause significant damage. Lasers operating between 400 and 1400 nm are particularly dangerous; the high collimation of the incident beam permits the rays to be focused to an extremely small spot on the retina with most of the light being absorbed by melanin pigments in the pigment epithelium just behind the photoreceptors [22], causing burns in the retina. This spectral band of wavelengths is often referred to as the retinal hazard region, since the increased concentration of light after entering the eye and falling on the retina is of the order of 100,000 times. Hence, a collimated beam of 1 W/cm^2 at the cornea will focus to an area on the retina with an irradiance of 100 kW/cm^2.

Due to the action of the lens, incident beams will be focused on the macula and its fovea; if these areas are damaged by laser radiation, substantial loss of vision can result.

Laser wavelengths outside the retinal hazard region (1400–10,600 nm) may give rise to injury to the anterior region of the unprotected eye. Injury to the cornea is normally very superficial, involving only the corneal epithelium, and with the cornea's high metabolic rate, repair occurs within a day or two and total recovery of vision will occur. However, if significant injury occurs in deeper corneal layers, in the stroma or endothelium, corneal scars can result, leading to possible permanent loss of vision.

The types of damage sustained by nonprotected ocular structures exposed to laser beams of varying wavelengths are listed in Table 5.3.

Optical risks therefore assume a «worst-case» scenario, and the choice of maximum permitted exposure values defines objective quantifiable levels of risk, expressed in irradiance terms (W/cm^2) that would be measured at the cornea [23]. Table 5.4 provides a range of values by wavelength. In order to provide perspective, the values are expressed within three possible time-related scenarios that may be applicable to laser use in dentistry:

0.25 s: The human aversion time for bright-light stimuli (the blink reflex).

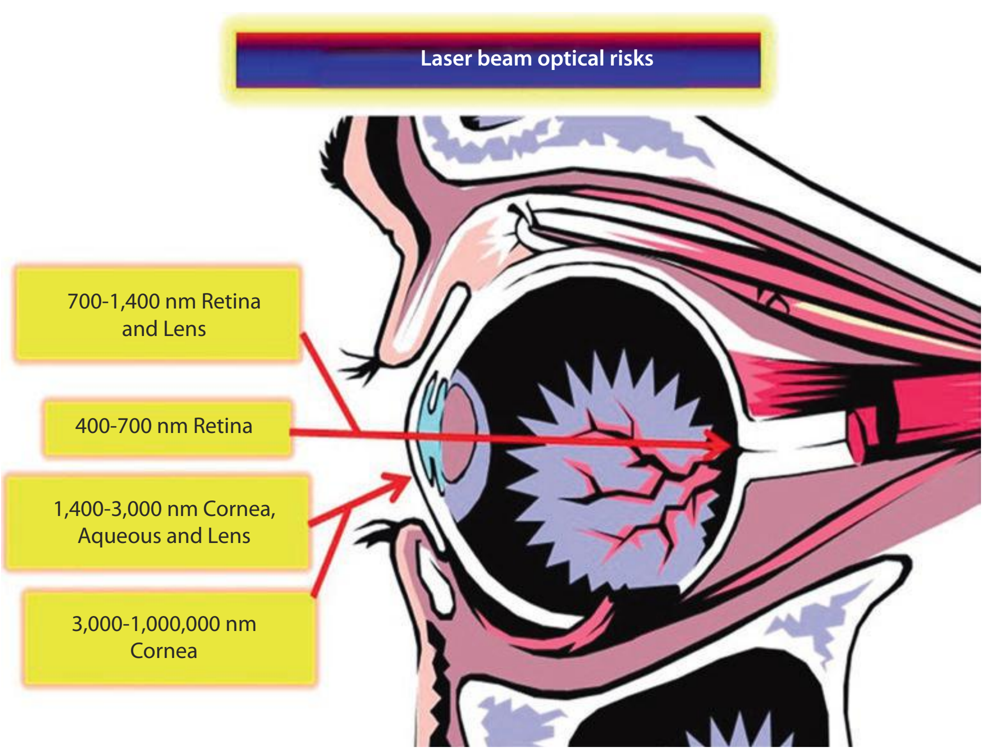


Fig. 5.1 Risk associated with varying laser wavelengths in anterior and posterior structures of the unprotected eye

10 s: The time period chosen by the ANSI Z 136.1 committees represents the optimum «worst-case» time period for ocular exposures to infrared (principally near-infrared) laser sources.

30,000 s: The time period that represents a full 1-day (8 h) occupational exposure.

According to regulations, for lasers operating in a pulsed emission mode, the MPE value was calculated by considering the most restrictive amongst the following conditions: (a) the MPE from a single pulse within a train of pulses does not exceed the MPE for a single pulse; (b) the average exposure for a complete pulse train (of constant amplitude) during a time interval shall not exceed the MPE values for a single pulse as given in the standard [24].

Of particular note is the substantially higher value of MPE in the region of 3.0 μm – Er:YAG laser. This may be accounted for through the intensely high absorption of this wavelength in water – <1.0 microns in corneal surface depth [25].

In summary, coherent laser photonic beams pose significant risk to the unprotected eye and to some extent the non-target tissue and skin. The length of exposure may be instantaneous or may be cumulative over a period of time. Direct exposure to the laser beam would maximize the risk, but of concern would be those instances where the beam may be reflected. Table 5.5 provides an overview of risk in these events.

4. *Nontarget oral tissue:* The oral cavity may present significant challenge in terms of access and nonintentional/function-related movements of structural components in the conscious dental patient. Often the visualization and access for treatment of individual teeth and areas of supporting tissues is compromised by restriction in space together with involuntary movement of the cheeks, lips, and tongue. Care should always be taken to ensure free and easy identification of and access to the treatment site, together with planned manipulation of the laser delivery handpiece and tip prior to operation and firing of the laser.

The oral tissue is nonhomogeneous and this may impact the absorption characteristics when using a laser and certainly may pose a risk where adjacent nontarget oral tissue has a higher absorption coefficient than the target tissue. Examples are high-peak-powered mid-IR irradiation of a cervical tooth cavity encroaching and causing collateral damage to the adjacent gingival tissue and unintentional transmission of near-IR and visible wavelengths through the tooth tissue to the pulp.

Additional risk may be posed to nontarget oral tissue through reflection phenomena. Many instruments used in dentistry are metal and in many instances the clinician will operate using a mouth mirror. Direct reflection or specular (diffuse) reflection of the incident laser beam may expose nontarget oral tissue to ablative beam fluences and may not be detected at the time of the treatment. Moist oral tissue may lead to specular reflection.

Care should be taken when using hollow metal delivery tips where such may come to lie against nontarget structures such as the lips or tongue. It is likely that such tips may become extremely hot when no coaxial water spray is used and may cause direct thermal burns to the tissue being retracted.

Table 5.3 Types of damage sustained by nonprotected ocular structures exposed to laser beams of varying incident wavelengths

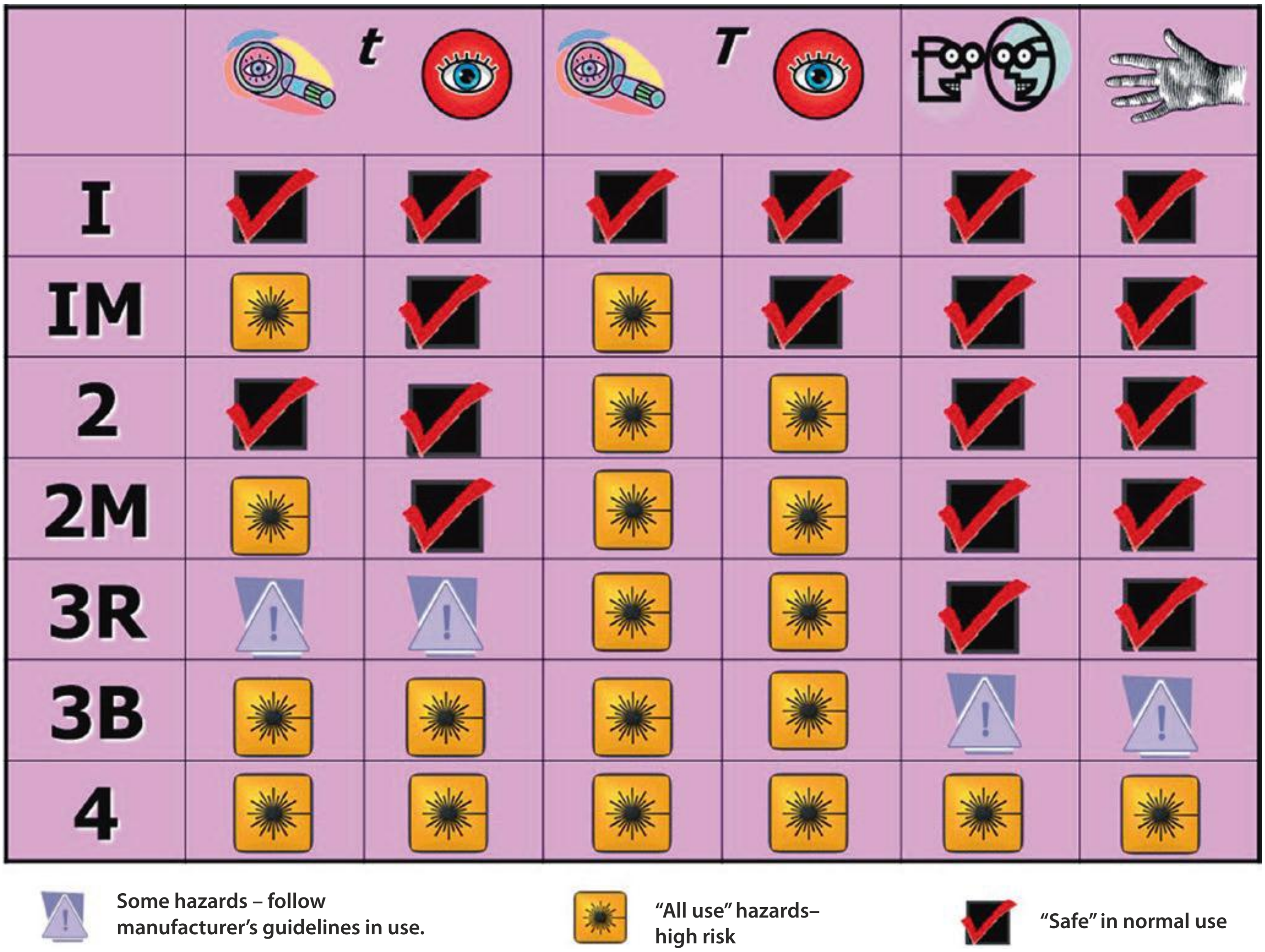
Incident laser wavelength	Pathological effect
315–400 nm (UV-A)	Photochemical cataract (clouding of the eye lens)
400–780 nm (visible)	Photochemical damage to the retina, retinal burn
780–1400 nm (near-IR)	Cataract, retinal burn
1.4–3.0 μm (mid-IR)	Aqueous flare (protein in the aqueous humor), cataract, corneal burn
3.0 μm–10.6 μm (far IR)	Corneal burn

Table 5.4 MPE values for unprotected eye exposure to laser wavelengths. Note: blink reflex applies only to visible wavelengths

		MPE level (W/cm^2)		
Laser type	**Wavelength (μm)**	**0.25 s**	**10 s**	**30,000 s**
KTP (CW)	0.532	16.7×10^{-6}		1.0×10^{-6}
HeNe (CW)	0.633	2.5×10^{-3}		17.6×10^{-6}
GaAs (CW)	0.810		1.9×10^{-3}	610.0×10^{-6}
Nd:YAG (FRP)	1.064		17.0×10^{-6}	2.3×10^{-6}
Er:YAG[a]	2.94		1.0×10^{-2}	1.0×10^{-2}
CO_2 (CW)	10.6		100.0×10^{-3}	100.0×10^{-3}

[a]Source ANZI Z 136.1. Schulmeister and Sliney [25]

Table 5.5 List of laser classes (IEC post-2002) with attendant risk that each may pose



«t» denotes instantaneous risk to both unprotected eyes when using magnification devices
«T» denotes longer exposure. Risks posed during reflection scenario and to unprotected skin are also represented

5. *Nontarget skin:* The potential for risk to the skin from laser photonic energy is considered low in terms of dental treatment. There may be specific scope of practice limits to a dentist delivering clinical (surgical) treatment beyond the vermillion border of the patient's lips. As such, the need for protective measures is not as high as would be applicable to facial cosmetic and dermatological laser procedures.

Notwithstanding, the varying absorption coefficients of pigmented and nonpigmented structures will predispose to varying depths of penetration, as shown in Fig. 5.2. The greater level of depth is seen with near-IR wavelengths and the additional phenomenon of high photon scatter at these wavelengths may compound the risk.

The most common transdermal exposure using lasers that may affect dentists may occur during sub-ablative photobiomodulation techniques as adjunct to TMJ and associated muscular dysfunction conditions. In view of the use of near-IR wavelengths as preferred in these treatments, some recommendations suggest relatively high fluences to allow the deep penetration of the energy into the TMJ area. Care should therefore be taken to ensure surface irradiance of the skin does not lead to structural damage and dosage modified to accommodate differing skin types, racial differences and those who may have drug-associated skin hypersensitivity.

6. *Inhalation and laser plume risks:* A by-product of the surgical ablation of the target oral tissue is the production of the «laser plume». This represents a significant hazard from breathing airborne contaminants produced during the vaporization of tissues. Studies of the production of both the chemical toxicity of photothermolysis products and the potential viability of infectious particulates (e.g., viral fragments) have shown cause for concern unless efficient aspiration, local exhaust ventilation, and operating staff facial protection measures are employed. Although many associated factors may provide some influence, the amount of plume produced and volume of

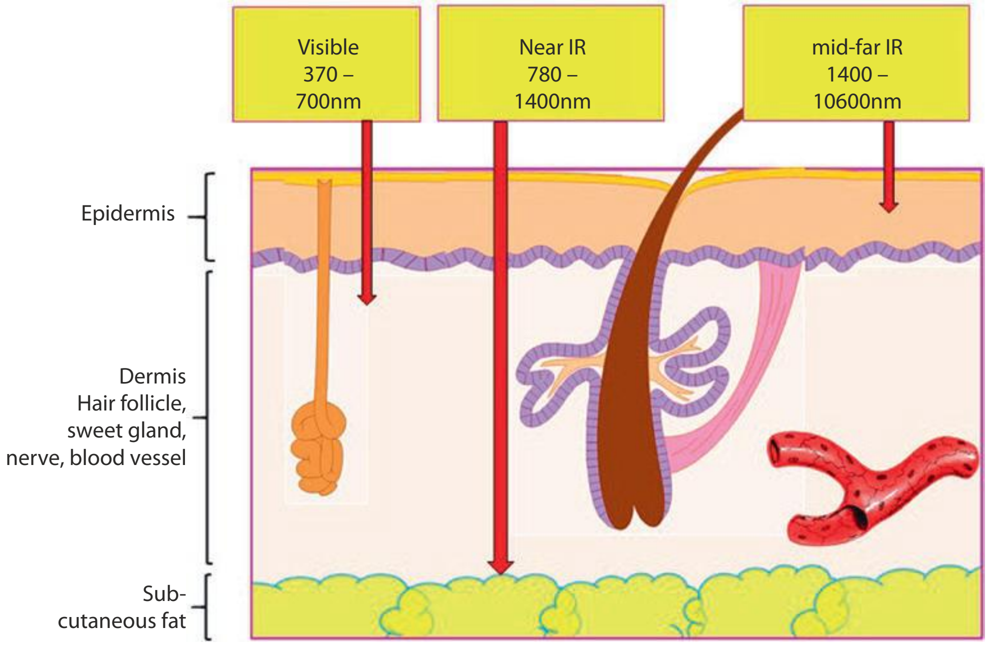


Fig. 5.2 Schematic showing superficial skin structure and penetration of laser photonic energy relative to wavelength

contaminants will be related to incident laser power, nature of target tissue, laser emission mode (CW, FRP), and coaxial supplies such as water and air spray [26–29].

Investigation into the components of the laser plume has shown a number of chemicals – water vapor, hydrocarbon gases and carbon monoxide and dioxide, together with metal fumes, particulate organic and inorganic matter, bacteria, and viral bodies [30–33]. The hazard presented by the laser plume may include eye irritation, nausea, and breathing difficulties, together with the possibility of transfer of infective bacteria and viruses [34, 35].

In dentistry, additional aspects of plume production and control may be seen in terms of the site of interaction and potential for airborne chemicals and bacteria [36], the use or otherwise of coaxial water spray [37] and the potential for using near-IR lasers that could be operated on the soft tissue within a film of water that acts as a shield [38]. In any event, to combat the risks associated with the laser plume, eye protection, specific fine-mesh face masks capable of filtering 0.1 micron particles should be worn and the spread of the plume minimized through the use of high-speed suction aspiration that is capable of closed-circuit filtration [39]. In addition, normal surgical protective clothing must also be employed.

Figure 5.3 provides a summary of the mechanisms associated with surgical ablation of the target tissue and variables that might influence the degree of laser–tissue interaction. The components of the plume produced will depend upon the type and constituent structure of the target tissue. Effects on the operator, support staff and patient will be minimized through adequate protective measures

(vii) *Other associated hazards:*

Service Hazards

Most laser systems involve high-potential, high-current electrical supplies. Early lasers used three-phase mains electrical supply, but this is no longer necessary for units used in dentistry. However, even with compact units, the risk from electrocution is significant and the most serious accidents reported with lasers have been due to electrocution [40]. Safe manufacturing practices offer adequate protection from these hazards, and insulation, shielding, grounding and housing of high-voltage electrical components provide adequate protection under most circumstances from electrical injury. No attempt should be made to access internal parts of the machine during use.

Installation of laser equipment should always be performed by qualified personnel and not by the dentist. The laser should be serviced regularly according to manufacturer's recommendations and only by qualified personnel.

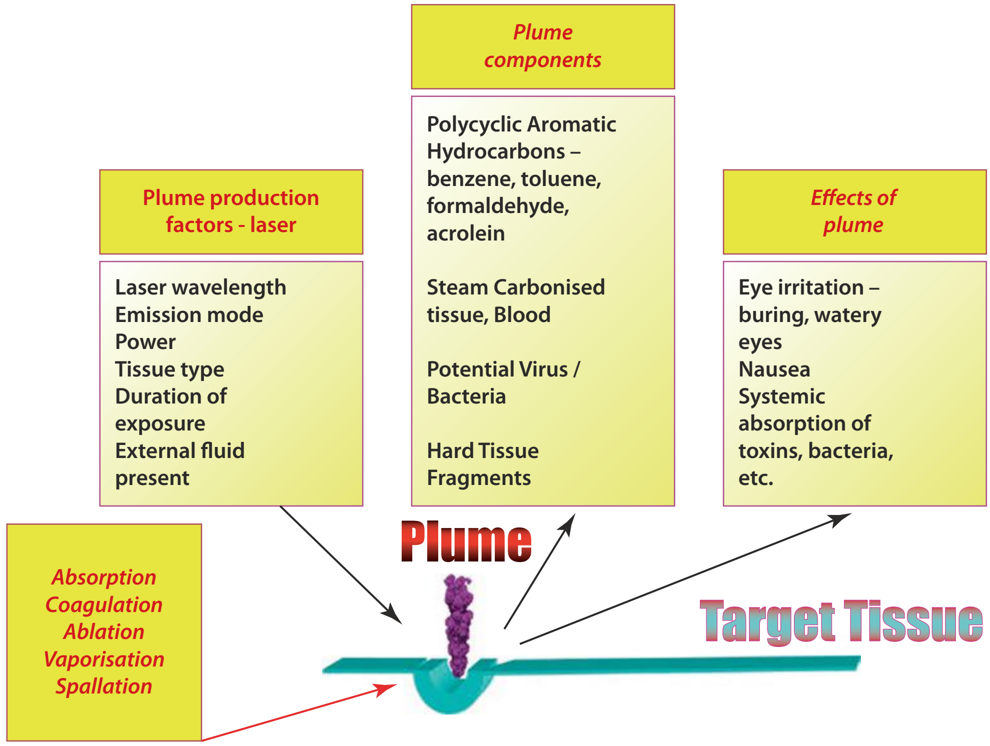
Many surgical lasers will have electrical, water, air and supply cabling, connectors and filters in close proximity. Coaxial air or water supply may be under pressure. The practitioner should inspect the supply lines and cables, clean and maintain the external portions of the laser and change necessary filters or other user serviceable items.

Mechanical Hazards

As referenced earlier, the construction and safe operating of all laser machines is governed by strict criteria [11, 41]. Engineering controls are normally designed and built into the laser equipment to provide safety. Modern laser machines employ multilevel safety features (fusible plugs, interlocks, pressure relief valves, warning lights, etc.) to inactivate the machine in the event of a component failure.

Mechanical hazards and safety mechanisms may be listed as follows [12]:

Fig. 5.3 Laser plume production, composition and effects



Laser Device Hardware

- Locked unit panels to prevent unauthorized access to internal machinery.
- Control panel to ensure correct emission parameters.
- Emission port shutters to prevent laser emission until the correct delivery system is attached.
- Covered foot switch, to prevent accidental operation.
- Remote interlocks to govern against accidental access to the operatory by unauthorized and nonprotected personnel.
- Casters, if present, must be lockable.

During Laser Use

- Key or password protection. When disabled (key or code removed), the laser cannot be operated.
- Laser software diagnostics and error messages.
- Display of parameters.
- Audible or visual signs of laser emission – recommended as an area control for Class IIIB laser operation. Such a warning system is mandatory for Class IV lasers.
- Specific standby and laser emission modes.
- Time-lapsed default to standby mode Class IV lasers requires a permanently attached beam stop or attenuator which can reduce the output emission to a level at or below the appropriate MPE level when the laser system is on «standby».
- Emergency «stop» button.

Additional hazards may exist, however, due to heavy articulated arm delivery systems or the risk of needlestick injury with fine quartz optic fiber cables.

Chemical and Fire Hazards

In the presence of flammable materials, lasers may pose significant hazards. The high temperatures that are possible in the use of Class IV and certain Class IIIB lasers can themselves either cause ignition of material and gases or promote flash-point ignition. Some of the common flammable materials found in the dental treatment areas are clothing, paper products, plastic, waxes and resins. Liquids used as adjuncts to restorative materials may include ethanol, acetone, methyl methacrylate, and other solvents.

Toxic fumes released as a result of combustion of flammable materials present an additional hazard. With regard to certain lasers, e.g., gas lasers, there are risks associated with possible leakage of active medium components [42, 43].

With general anesthetic or gaseous anesthetic-sustained conscious sedation techniques, significant risks exist relative to the sustainability of explosion or fire [44]. Any combustion requires an ignition source and a Class IV surgical laser is an example; the field temperature during soft tissue ablation may reach several 100°, and the build-up of debris on delivery tips may exceed that temperature to a point above the flash point of chemicals and equipment. Such high-temperature ignition may burn with a blue flame and this may be very difficult to spot under intense operating lights. Additionally, and more dangerously, the ignition may occur within the respiratory airway and be delivered deeper through forced inhalation.

With a laser as an ignition source, the presence of fuel sources (gauze, drapes, prep fluids, alcohol, and anesthetic gases) may be commonplace items within a dental operatory. Greater risk is further posed when an oxygen-enriched atmosphere (above 20%) is used in anesthetic and sedation techniques.

Rubber-based endotracheal tubes should be avoided to prevent the possibility of combustion of the material and subsequent airway burns, either through coatings of nonreflective, nonabsorbent material or cuffed tubes to prevent leakage of anesthetic gases. With gaseous conscious sedation procedures, such as the use of a nosepiece to deliver oxygen/nitrous oxide mixtures, it is recommended to use a closed-circuit delivery system and scavenging system. A summary of risk and hazards associated with laser use is provided in ◘ Table 5.6.

▪▪ Other Hazards: Sterilization

There exists a risk of damage posed by those personnel working in close proximity to the laser. Care should be shown to the possibility of contamination of all laser hardware and protective sleeves and screens used where possible, any components that may contact the surgical site subject to bagging and autoclaving or disposal in a safe container. Especially, care must be exercised in the manipulation of quartz optic fibers and details of safety measures should be entered in the local rules.

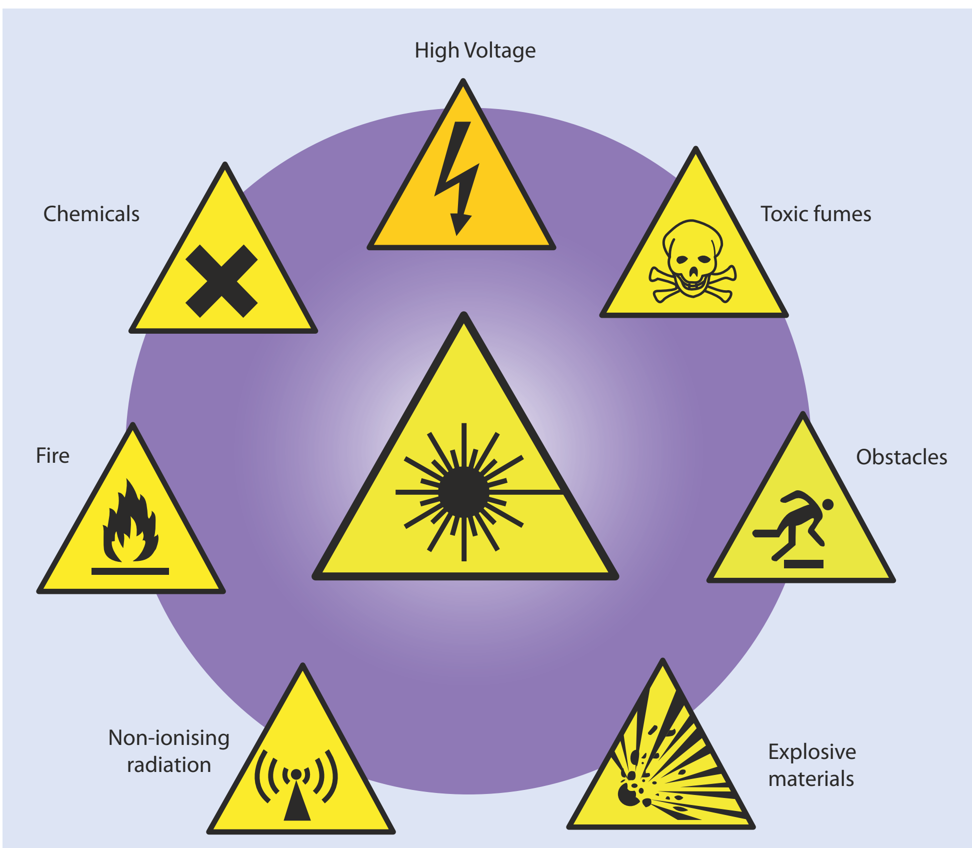
It is considered a «best practice» approach to utilize a tray system for instruments used during laser-assisted procedures and to rotate such through a «sterile» to «operation» to «unsterile» status before disposal or re-sterilization.

Staff should consider the wearing of disposable gowns during surgical procedures.

5.5 Laser Safety Within the Dental Operatory

By far the provision of primary dental healthcare occurs within privately run bespoke practices. These small-to-medium businesses are run as self-sufficient establishments, and it will be well known to those involved, the breadth of regulation and compliance that allows the provision of dentistry to be such an efficient and safe health profession available to the patient. Such efficiency mirrors those public healthcare establishments that are bigger clinics and hospitals. Within such a framework of efficiency and safety, a protocol is necessary to allow all laser instruments, from low-powered units up to those high-powered Class III and IV lasers, to be used with predictable regard for acknowledgement of risks, planning to anticipate and avoid such risk, and in a way that is readily applicable to all staff and patients who may be exposed to laser irradiation.

◘ Table 5.6 Areas of risk and hazards associated with laser use



For all operators using lasers within the delivery of dental care, the concept of this protocol may be seen within four areas:
- The physical dimensions of the care delivery area – the «controlled area» and «nominal ocular hazard zone». «Laser protection advisor» role
- The duties of the «laser safety officer» in determining and enforcing safety within the controlled area during delivery of dental care to patients
- Physical laser protection of the eyes and skin and general sterility within the controlled area
- Local rules, record-keeping and adverse reaction protocols

Controlled Area

The «controlled area» is any location or area where there are one or more lasers and where activity of personnel is subject to control and supervision. In many cases, such an area will be a dental operatory, with physical barriers – walls, doors and windows – by/through which any laser beam shall be attenuated. Control of such an area can be achieved through display of notices, remote interlocks, etc.

The controlled area must be indicated and marked by laser warning signs that specify the risk and conform to national regulations. Within the controlled area, all surfaces should be nonreflective and suitable measures should be employed to ensure that all laser supply cables and delivery systems (optic fibers) are protected from inadvertent damage. A secure designated place for the (applicable) laser operating key should be assigned together with a designated place for all laser accessories. A suitable fire extinguisher should be sited for easy access.

Those dental clinics that operate a multi-chair, open-plan environment would need to address the physical dimensions and administration of the controlled area in greater detail.

The defining goal is to provide an area for treatment of dimension beyond which laser irradiation falls below MPE value. This may be a primary laser beam or reflected, scattered, and diffuse photonic energy that may pose a danger to the unprotected eye.

Having regard to permissible MPE levels, the controlled area may be also referenced as the «nominal ocular hazard zone» (NOHZ). Calculation of the MPE has been discussed earlier and appropriate values for exposure of the unprotected eye at 0.25, 10 and 30 × 10 [3] seconds periods determined.

The NOHZ is a complex calculation that can be done by a medical physicist, but for practical purposes a concept of a controlled area should be applied, whereby a combination of the NOHD and physical barriers can minimize risk [45]. The following factors are required in NOHZ computations:
- Wavelength and maximum/minimum laser energy output
- Emission mode (CW and pulse repetition if applicable). Maximum exposure duration
- Beam diameter, beam optics, beam path and beam divergence
- Lens: focal length

Subject to federal or national regulations that may apply, dental practices offering Class III(B) and IV laser treatment must appoint a laser protection advisor (LPA) and/or a laser safety officer (LSO). The LPA is usually a medical physicist who will advise on the protective measures required, MPE and NOHZ calculations and additional measures to provide attenuation of lasers being used and generally provide assistance and advice regarding all laser, LED and intense pulsed light units within the practice of dentistry.

Laser Safety Officer

The LSO is appointed to ensure that all safety aspects of laser use are identified and enforced. Ideally, the LSO could be a suitably trained and qualified dental surgery assistant.

The LSO standing duties refer to the minimum level of responsibility:
1. Read the manufacturers' instructions concerning installation and use of the laser equipment and. confirm the class of the laser.
2. Be familiar with and oversee maintenance protocols for laser equipment.
3. Train other staff in the safe use of lasers.
4. Maintain an adverse effect reporting system.

LSO responsibilities during laser use include:
1. Define and oversee the controlled area specific to the laser being used and limit unauthorized access.
2. Post appropriate warning signs at all points of access to the controlled area.
3. Make sure that laser equipment is properly assembled for use, together with all disposables. Carry out or supervise a «test fire» of all laser equipment before the patient enters the controlled area.
4. Recommend appropriate personal protective equipment such as eyewear and protective clothing (suitable face masks, gowns, etc.).
5. Maintain a log of all laser procedures carried out, to include the patient details, the procedure performed and laser operating parameters employed.
6. Assume overall control for laser use and interrupt the procedure if any safety measure is infringed.

Laser Protection and Sterility

Earlier sections of this chapter have dealt with the beam hazards that exist to the unprotected biological tissue. Key measures to be adopted should include the following:
1. The test fire procedure is designed to allow all working components of the laser to be checked before attempting the clinical procedure on the patient. It is obligatory for the LSO or dentist to carry this out before admitting the patient to the operatory and all safety measures – warning

signs door/window protection and interlocks employed, to prevent unauthorized access as though a laser procedure was being performed. All personnel within the controlled area shall wear appropriate eye protection before the laser device is switched on. The laser delivery system is assembled and minimum operating parameters are chosen. The laser is directed away from the eyes and a suitable absorption medium should be used. The laser is fired within that medium so that the beam is attenuated.

Some authorities believe that this would be an ideal opportunity to establish the level (if any) of power loss through the laser delivery system. The use of an approved laser power meter allows the LSO to check the parameter display on the laser control panel and to check the value against the meter reading. Associated with this check is the opportunity with many laser units to use a calibration port on the laser as part of the set-up procedure.

For visible and near-infrared wavelengths, a suitable medium would be pigmented/dark articulating paper, and for longer mid- and far-infrared wavelengths (erbium family and carbon dioxide), the suitable medium should be water. See ◘ Fig. 5.4.

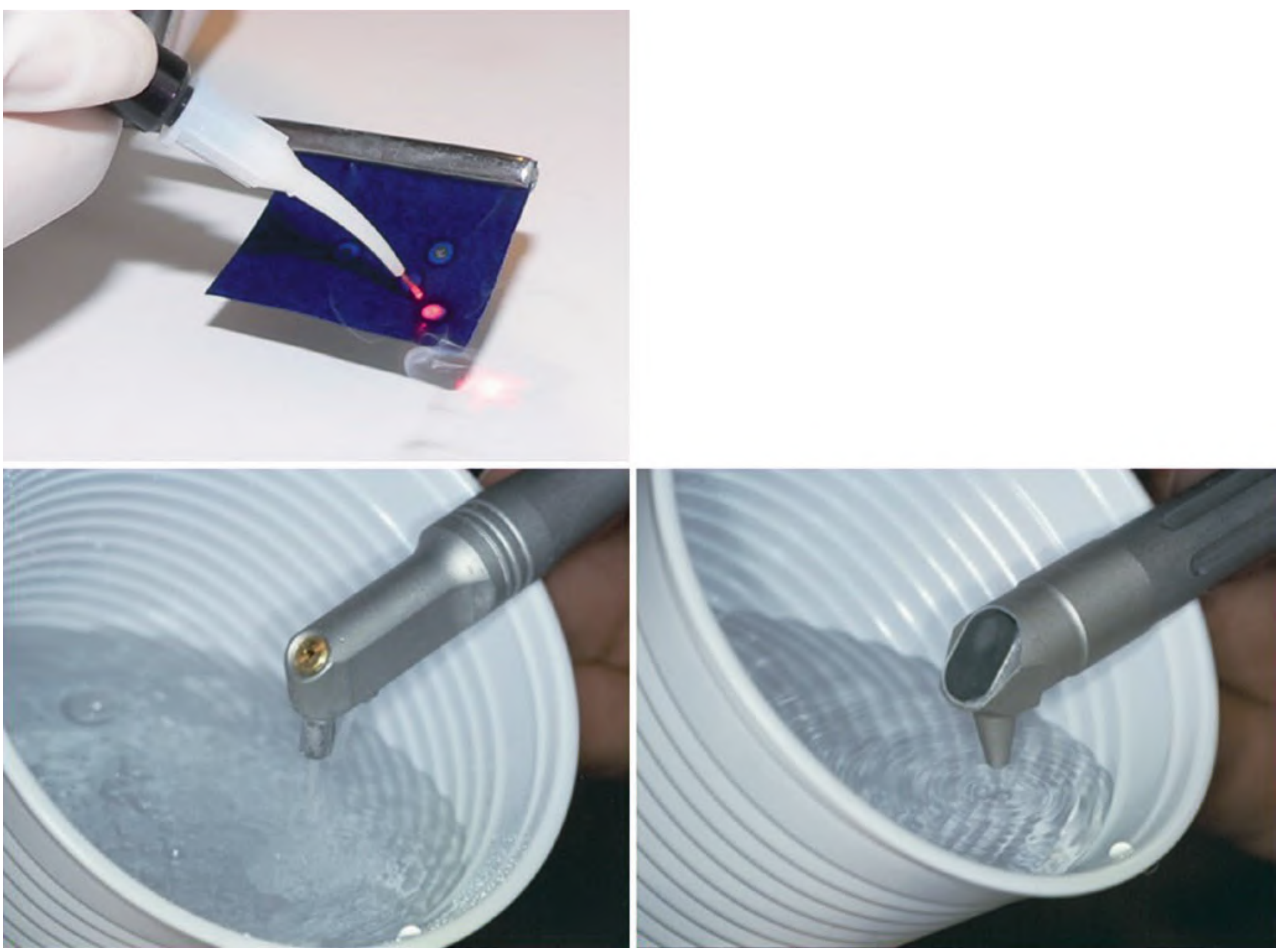
The objectives of the laser test fire are to check the following:

- Test operational ability of the machine.
- Test cleavability of fiber (where appropriate).
- Demonstrate patency of delivery mechanism.
- Demonstrate patency of aiming beam/coaxial air/water.

In this way, it can be satisfied that the laser is in operating mode for the chosen clinical procedure.

2. Skin protection may not be a prime risk factor for the dentist working within the oral cavity. For those ablative procedures within the vermilion border of the lips, care should be observed to avoid encroaching beyond the target tissue, especially with mid-, far-infrared, and shorter wavelengths operating at high power. Shielding of the skin can be employed, using damp gauze, to minimize the possibility of collateral damage.

◘ Figure 5.5 provides an example of laser handpiece selection (Lumenis Corp. Israel). Metal delivery conduits are potentially liable to overheating, and care should be taken when using



◘ **Fig. 5.4** Laser test fire. Using minimum laser operating parameters, the beam is directed into a suitable attenuation medium. Top center, for visible and NIR wavelengths pigmented articulating paper. Bottom left, water for (mid-IR) Erbium YAG; bottom right, water for CO_2 wavelengths

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■ **Fig. 5.5** Examples of dental laser handpieces. Center: this metal CO_2 delivery tip is liable to overheating, and care should be exercised to avoid contact with perioral skin tissue

these delivery mechanisms for intraoral soft tissue surgery and the metal conduit rests against the lips and perioral skin.

3. Eye protection for all persons within the controlled area is mandatory with all Class IV lasers and any other laser classes as advised by individual manufacturers and regulatory agencies. (See ■ Table 5.5.) Regulations that specify the nature and suitability of laser protective eyewear are contained in ANSI Z136.1 and IEC 60825 (EN 207/208) documentation.

Eye protection during laser use can be summarized as follows:

- A protocol as to use is mandatory, including «patient on first – off last» as a maxim to represent the safety of the patient as paramount. With the patient considered first, each member of the clinical team within the controlled area would be obliged to similarly wear eye protection.
- Glasses/goggles must cover the entire periorbital region, be free of any surface scratches or damage and be fitted with suitable side panels to prevent diffuse laser beam entry.
- Eyewear should be constructed of wavelength-specific material to attenuate the laser energy or to contain the energy within MPE values.
- Glasses or goggles should be marked with the wavelength for which protection is given, either as a specific wavelength value or range of wavelengths within which protection may be afforded by the chosen eyewear.
- The level of protection is specifically expressed in terms of optical density (OD). This quantitative measurement represents the ability of the eyewear lens material to reduce laser energy of a specific wavelength to a safe level below the MPE. The OD value is measured as a log10 scale of laser beam attenuation and should be «5.0» or above for adequate protection [46]. See ■ Fig. 5.6.

Worldwide, minimum information that must be present on protective eyewear (laser wavelength or a range of wavelengths that are covered by the material and OD value) may be further enhanced according to the nature of the eyewear, its specific intended use and other factors pertinent to

■ **Fig. 5.6** Examples of laser safety eyewear, with relevant optical density (OD) values applicable to specific wavelengths. OD scores of 5.0 and above are considered explicitly safe in protecting the wearer's eyes. This information may be found on the eyewear lens or on the sidebars national, regional or continental regulations. This additional information can be referenced against laser safety requirements (ANSI/IEC/EN) for individual laser clinicians, and laser protection advisors/laser safety officers may provide additional advice. Examples of supplemental eyewear data may include:

- «DIR» defines the emission mode of the laser for which the eyewear is intended. «D» signifies continuous-wave emission (CW), «I» pulsed mode and «R» Q-switched mode. The significance of this is further enhanced in respect of
- «DIN»: direct impact number – this is the ability of the eyewear material to attenuate direct laser beam energy within MPE limits. This ability may be applied to exposure to a train of 100 pulses when the emission mode is gated or free-running pulsed, or to withstand direct exposure to a continuous-wave emission for 10 s.
- «L6A»: a protective grade which defines a suitability for use of the protective eyewear within an intended clinical, industrial or research condition.
- «CE» logo: «Conformité Européenne» will indicate a licence approved for distribution and use within the countries of the European community.
- Manufacturer's identification mark

An increasing number of dental practitioners use loupes during clinical work, and such magnification may significantly increase the risk to the unprotected eye. For those procedures and laser classes of risk to the eye when using loupes (laser Classes IM, II, IIM, IIIR, IIIB and Class IV), the clinician must wear the appropriate protective insert or shield that is specific to the wavelength being used. See Fig. 5.7.

In the same manner and with the same breadth of laser classes, dental practitioners using an operating microscope to facilitate high-definition observation of laser surgery must fit the appropriate filters and maintain close eye contact with the oculars. The following is taken from a published paper (Saegusa et al. 2010) to investigate the effectiveness of wavelength-specific ocular filters with an operating microscope [47]:

> The aim of this study was to investigate the safety of laser use under the dental microscope. Nd:YAG, Er:YAG and diode lasers were used. The end of the tips was positioned at a distance of 5 cm from the objective lens of a dental microscope. Each eye protector was made into a flat disc, which was fixed on the lens of the microscope. The filters were placed in front of the objective lens or behind the eye lens. Transmitted energy through the microscope with or without the filters was measured. No transmitted laser energy was detected when using matched eye protectors. Mismatched eye protectors were not effective for shutting out laser energy, especially for Nd:YAG and diode lasers. None or very little laser energy was detected through the microscope even without any laser filter. Matched filters shut out all laser energy irrespective of their positions.

Fig. 5.7 Example of surgical loupes with wavelength-specific inserts, designed to fit on the inner aspect of the eyewear between the loupe lens and the operator's eye. Picture courtesy Dr. D. Coluzzi

The current trend in dental hard tissue surgical ablation has witnessed a growing development of ultrashort-pulsed irradiance of target tissue. The delivery of femto- and picosecond pulses of 0.4–3.0 µm range coherent EM waves takes us far away from conventional understanding of wavelength-targeted chromophore absorption in target tissue. Although average power delivery of laser photonic energy may be very low, such is the peak power achieved by individual photon bursts within 10^{-12} and possibly 10^{-15} s of fluence values and hence ablation capability is transformed. With such developments, laser–tissue interaction becomes evermore plasma mediated as opposed to photothermal in nature. Some investigation has shown that the modern laser eye protection seems to be robust except for the irradiance possible with ultrashort laser pulse exposure [48]. As always, it is incumbent upon the laser protection advisor and laser safety officer to ensure that protective eyewear is appropriate to the laser being used and the procedure being carried out.

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5.6 Training of Staff Using Lasers

As has been seen throughout this chapter, in accordance with all federal, national and local regulations that may pertain, the responsibility of the lead clinician shall be to ensure the protection of the patient and operatory personnel and prevent inadvertent exposure of others during laser emission. In some countries, this responsibility is part devolved through the senior personnel in charge of the dental clinic, as part of broader overreaching statute governing care standards in healthcare [49]. Despite the nature of assumed responsibility for patient safety, the day-to-day approach to its observance must be measurable in qualitative and quantitative terms. Through this approach, not only should a written protocol exist, but also staff performance within such protocol should continue to develop a «best practice» approach to laser safety with audit-driven refinement at regular intervals. The prime tenet of any structured laser safety program should be the protection of the patient from inadvertent harm during laser-mediated clinical dental care. It is vital that all staff involved in the patient's/client's treatment are aware of each other's role during treatment. Good communication between staff is essential.

Regulatory agencies recognize the essential nature of appropriate training in laser use, and there is an implied necessity that clinicians should receive training as part of their duty of care and dental licensing [50]. It would be incumbent upon the laser users to acquaint themselves with how their laser use is regulated in their country or region, and in many countries, laser manufacturers and suppliers have a legal duty to inform. The support of a laser safety advisor would overcome any doubts.

All healthcare establishments should have written local rules specific to each clinical application and for each laser, IPL (intense pulsed light) and LED device. All staff involved in the use of these devices should read the local rules and sign them to indicate that they have been understood. This should be undertaken before staff use the equipment.

The following summarizes a «best practice» approach to laser safety in dental practice:

- Appointment of a laser safety officer (LSO), suitably trained and aware of responsibilities. As referenced earlier, general responsibilities of the LSO shall include the reading and understanding of the laser operating manual, with specific regard to suitability as to use, operating settings by procedure, «set up» and «set down» procedures as applied to a specific laser and laser safety features.
- Above all, the class of laser being used must be established, together with the nature of visual operating enhancement (loupes/operating microscope) as they may impact upon the safe nonrisk (relative to MPE) levels and need for specific laser safety measures.
- The LSO (under direction of the LPA if required by national regulation) must define the nominal hazard (safe ocular) zone (NHZ). In practice, any operatory confined by (nontransparent, physically intact) walls and doors would satisfy this requirement, but any «open-plan» operatory should adopt a protocol, whereby adjacent areas are marked by signs to limit traffic and alert others to the need for caution.
- The LSO should ensure the laser is appropriate to the proposed clinical procedure and is properly maintained and assembled. Accessories (optical fibers, tips, connectors, etc.) must be suitable for both the make and model of device that they are to be used with. Only use the accessories in accordance with the manufacturer's instructions. Additionally, equipment error messages or fault should be recorded in the equipment fault log. The log should be regularly reviewed and appropriate action taken to inform the laser protection advisor or laser protection supervisor of all issues.
- Identify and eliminate all environmental risks. Apply laser warning signs, at the boundaries of the controlled area. Such laser warning signs must meet approved standards as applied through IEC/ANSI regulations and might include the laser wavelength being used, the need for eye protection as well as overriding precaution against unauthorized access. Arm all remote interlocks if applicable.
- Test fire the laser prior to admission of the patient within the controlled area. Following this, the laser is deactivated and the patient admitted.
- The surgeon/practitioner shall choose the laser operating parameters appropriate for the intended treatment, commensurate with a policy of minimal power values to achieve the desired clinical outcome. The LSO shall closely monitor and assess the procedure and advise or adjust those operating parameters.
- Commensurate with need defined by laser class, the patient and personnel within the controlled area (NHZ) shall wear appropriate eyewear. Adjunctive safety measures – suitable filtration masks, gloves and high-speed suction – shall be employed. Nontarget tissue shall be suitably protected (tissue retraction, use of nonreflective instruments, wet gauze).
- The LSO shall be authorized to abort the procedure in the event of detected risk. The prime responsibility shall be the safety of the patient.
- An adverse effect is defined as one that causes injury or death through direct use of the laser and will involve regulatory agency notification, according to national use. Additional effects reporting may require access to emergency clinical services in the event of eye or skin damage.
- Suitable sterilization control measures should be employed. Reasonable measures should be employed to minimize risk of cross infection, but minimally to include the use of protective barriers and chemical and autoclaving sterilization procedures.
- The standard of care dictates that any part of the dental laser that contacts the oral tissues and/or the bloodstream must either be heat sterilized or, if a single-use device, be properly disposed. Portions of the

laser that can contact the oral tissues must be disinfected with a suitable chemical agent.

- Optimally, instruments should be employed through a tray system. Most clinicians will be used to employing specific protocols to recognize «dirty», «clean» and «sterile» in relation to dental instrumentation. Steam autoclaves are mandatory as part of a recycling of adjunctive nonconsumable instruments, and most will use metal trays which can be used as part of the correct storage of sterile elements. Additional to some recommended sterilization protocols, «dishwasher» style disinfecting units may deliver pre-autoclave cycles capable of destroying prions and removing proteinaceous debris. It should be the responsibility of the lead clinician to avail of all supporting advice as would apply to which parts of the laser may be disposable and, if reusable, what cleansing, disinfecting and sterilization treatments are recommended and applicable.
- With those delivery systems that use quartz optic fibers, thorough cleaning before autoclaving and appropriate cleaving techniques should be employed to remove damaged or contaminated elements. The cleaved piece must be disposed into the «sharps» container and regard given to disposal of plastic delivery tips. Many fiber delivery units have optic cabling as part of the assembly, and the outer sheath will require regular checking to ensure sufficient quartz fiber is available to pass through the handpiece. This checking should be done prior to «bagging» (if applicable) and autoclaving of the delivery cable. Other laser units have fiber tip inserts which may be deemed as single use or reusable. In these cases, the manufacturers' recommendations must be followed to minimize the risk of cross-contamination between successive patient treatment sessions.
- Smoke plumes – minimizing harmful effects [9]. The LSO shall take precautionary action to reduce, if not remove, the plume. The amount of smoke plume and other deleterious matter generated varies with the procedure being undertaken, nature and type of target tissue, technique employed, duration of energy applied to tissue and laser emission mode used to vaporize the tissue. Staff involved in procedures resulting in smoke plumes should be educated on how they are produced and how to reduce or eliminate exposure.
- Training by suitably qualified in-house personnel or smoke evacuator manufacturers should be considered. The most effective way of protecting clinical personnel and patients from inhaling the constituents of the smoke plume is to use either a stand-alone smoke evacuator or an evacuation system that is incorporated into the laser system. All smoke evacuators should have a high-efficiency filter that collects all smoke generated during the procedure.
- Medical vacuum systems (operating theater wall suction systems) are not suitable for smoke plume removal. The accumulation of particles over time eventually decreases suction capability in theater evacuation systems. All evacuated airborne particles are deposited into a central vacuum system, which can become blocked, and bacteria can then multiply.
- All clinical staff within the controlled area and especially involved in the clinical procedure should wear well-fitting, high-filtration efficiency face masks (e.g., particulate respirators that filter particles of 0.1 μm in size) during all laser procedures. Standard surgical face masks are not sufficient to act as the primary method of particle filtration.
- Record the laser-assisted procedure in the patient's notes. It is advisable and may be mandatory to keep an additional log of laser use, to record each clinical procedure according to laser, wavelength, operating parameters and clinical outcome.

5.7 Local Rules

The following is taken from the 2015 publication «Lasers, intense light source systems and LEDs in medical, surgical, dental and aesthetic practices» in which the author acted as dental consultant to the United Kingdom Medicines and Healthcare products Regulatory Agency [51].

Local rules should be related to a risk assessment. They should contain the working practices, procedures and information required to address the hazards and risks identified in that assessment.

The local rules should be prominently displayed in the laser/IPL room or the theater office.

All authorized users, assisting staff or other individuals who work within the delivery of laser treatment should read the local rules, then sign the associated form to show that they have understood them and agree to follow them.

Example of local rules:

- **Local Rules for the Use of the "X" Laser in "X" Dental Practice/Dental Clinic Premises:**

  Dental Surgery: NAME, ADDRESS

- **Nature of hazards to persons**

The laser can injure the skin and eyes from both the direct and scattered beams. The aiming beam may also be hazardous. Safe use of the laser depends on people strictly following the rules:

- The operating beam(s) is (are): X laser type, at operating wavelength(s) of X nm. It (they) constitutes an appreciable hazard.
- The device(s) aiming beam is a low-powered diode laser and operates in the visible region of the EMS (X nm). It is designated as a Class I laser.

(Other wavelengths to be specified)

- **Laser device(s):**

1. Name of the laser
2. Any other Class IV laser (unspecified)

■ **Laser authorized users:**

1. Dr. NAME
2. Manufacturer's/ supplier's representative(s)

■ **Laser protection advisor:**

1. As appointed by regulatory authority

■ **Laser safety officer:**

1. NAME

■ **Personnel authorized to assist in the operation of the laser(s):**

1. NAME
2. Any other assistant, following training by laser protection supervisor(s)

Controlled Area Designation and Access

The room in which the laser is used is designated a «controlled area» and the laser should only be used in this area. Approved warning signs should be fitted to the door.

A notice should be fixed to the laser indicating that its use is subject to the local rules.

The controlled area is the dental surgery in which the laser(s) is (are) installed. The controlled area shall be that area as designated by the laser protection adviser, in accordance with the safe use of laser(s) and respective nominal ocular hazard distance(s). The controlled area shall be enforced only during such times as the laser is in clinical use. A sign shall be placed on the outside of the surgery door during the periods when the laser(s) is (are) in use.

Protective spectacles or goggles must be worn by the operator, assistant, patient, and visitors whose presence is required. Eyewear must be wavelength specific to attenuate emitted laser light of laser in use. The laser safety officer shall be responsible for ensuring that protective eyewear shall be worn prior to activation of the laser and during all emission periods.

Restriction of Use to Authorized Persons

The equipment should only be used by an authorized user. Responsibilities and duties of laser protection supervisors shall be to:

- Ensure that the local rules are followed
- Inform the laser protection adviser if they consider that the existing rules require amending
- Ensure that the register of authorized users is maintained and that the correct procedure for authorization has been undertaken
- Obtain written statements from each authorized user that they have read and understood the local rules and send copies of statements to the laser protection adviser
- Ensure that only authorized users operate the laser
- Inform the laser protection adviser as soon as possible in the event of an incident occurring
- Seek assistance from the laser protection adviser on the safety implication when a change in operating procedure is envisaged
- Decide, in consultation with the laser protection adviser, if another person is suitable to use the equipment. Their names can be added to the register, provided they have signed a statement that they have read and understood the local rules. A copy of the signed statement should be sent to the laser protection adviser

Operation of Equipment

1. The laser(s) may only be operated by an authorized user (see above).
2. Keys required to activate laser equipment may only be held by authorized user(s). Keys should be marked «LASER – for authorized use only» and should be stored in the safe.
3. The operating beam should never be activated unless accurately aimed at the operating site. Exception to this is during the «test fire» of the laser to be used, which shall be under the strict supervision of the laser safety officer and in accordance with safe practice regulations.
4. Neither the aiming nor operating beam(s) shall be directed towards the eyes of the operator, assistant(s), or patient.
5. When not in use for a treatment procedure, the laser shall be switched to «standby» mode.
6. When not in use for treatment, the laser shall be switched off, by use of the operating key or screen command.
7. The laser(s) shall not be used in the presence of anesthetic gases, or other explosive gases or liquids.
8. The operating beam shall not be directed towards amalgam restorations, since these are prone to vaporize, or other shiny surfaces, especially metal.
9. The operator/laser safety officer shall be responsible for ensuring that other individuals present at operation are sufficiently trained in laser safety and is responsible for the safety of any visitors within the controlled area.
10. When the laser is to be used, anyone who does not need to be present should leave the controlled area.
11. All operators must sign statements that they have read and understood the local rules. Assistants must sign statements that they have read and understood the local rules. These will be filed by the laser protection supervisor.

Accidents Involving the Eyes

Should a person's unprotected eyes be exposed to radiation from a laser beam, an arrangement exists between us (dental practice NAME) and the consultant ophthalmologist at NAME Hospital, who will carry out an examination within 24 h of the accident occurring.

Consultant: NAME.Tel: X.

Copy of report to be sent to: Dentist defense indemnifier/ manufacturer/H & S contact as regulated.

All accidents arising from inadvertent and nontarget laser radiation must be reported in the first instance to the laser protection advisor.

Record-Keeping

Full operating details are to be logged in the patient records. A separate book shall be kept, in which a record is made for the inspection of the registering authority. Details shall include the following:

1. The name of the operator
2. Date and nature of procedure carried out
3. Identification of patient
4. Statement of machine maintenance
5. Appropriate information from the manufacturer, enabling the registering authority laser protection advisor to be adequately informed in respect of his/her duties in advising the registering authority on the control of the laser hazards that may be potentially involved
6. The name and contact number of the appointed service agent

Maintenance of Laser(s)

The authorized user is responsible for ensuring that the manufacturers' recommended planned preventative maintenance schedule is followed and that records are kept of service attendance.

Date
Signed: ______________________ Dr. NAME Dentist

______________________ LPA as appointed

Review date + 2 years.

Conclusion

The development of laser photonic technology within primary healthcare has highlighted the absolute need for safety considerations. In general, a multitiered administrative structure has been developed and applied internationally, drawing upon various national regulations to form an overriding set of guidance and rules that may govern and enhance the safe use of lasers. Within this framework, it has been possible to explore where and to what extent the use of laser photonic energy can be safely employed by the dental clinician.

The various classes of lasers have been demonstrated and their impact on risk explored and demonstrated. Of prime consideration has been the risk to the unprotected eye and all environmental, operatory and personnel aspects of this important consideration, explored together with guidance on the use of correct protective eyewear for all personnel within a designated «at-risk» zone.

Secondary issues of nontarget protection, post-ablation laser plume management and the impact of lasers within general health and safety at work policy have been explained. Through the presentation of specimen local rules, guidance has been offered to support the adoption of appropriate and compliant measures that may be employed within the practice/office setting and for the use of all staff.

The prime concern is to safeguard the patient receiving laser dentistry procedures, and it is hoped that the foregoing chapter can provide both the background and applicable measures to implement the highest levels of safe practice when performing laser-assisted therapy.

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Laser-Assisted Diagnostics

Alex Mathews Muruppel

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Core Message

An objective and accurate diagnosis is an essential and key component in the formulation of safe, comprehensive management, and treatment of dental patients. The framework of such diagnosis should be based on clear criteria, applied with sound diagnostic methodologies which can assess, grade and detect the presenting symptoms of any individual case. Various diagnostic approaches therefore play an essential part in developing a provisional and final diagnosis, from which treatment modalities and strategy can then be planned and implemented.

The dental clinician plays a pivotal role in being a skilled examiner, a physician and a surgeon, all of which is dependent upon each patient's needs and desired treatment outcome. The oral cavity and its varied range of both hard and soft tissues coupled with the concomitant host of microbial flora are easily subject to pathology that may be a simple, single tissue disease or extending to anatomical and regional or may render multi-structural tissue change. Hence the role of an appropriate and accurate diagnosis cannot be understated.

Specifically, diagnostic techniques should ideally be simple, cost-effective, noninvasive, reproducible, measurable and most importantly should be in tandem with advancing scientific research and technology. The diagnostic technique should have application within hard tissue as well as soft tissue pathology and should ideally be available within a general dental practice setting.

Laser photonic energy has been shown to interact with oral tissues, and within a sub-ablative power envelope may provide measurable data to assist the clinician in distinguishing between healthy and diseased tissue and furthermore can quantify or assay the disease process, and can even provide for time-related monitoring of the potential disease progress.

This chapter sets out the underlying science of laser fluorescence and its integration and application within a hierarchy of diagnostic measures in the assessment of oral disease.

6.1 Introduction

Lasers when applied to the realm of diagnostic sciences signify minimally invasive techniques that provide unparalleled precision and accuracy. An illustration would be the case of optical biopsies that provide elaborate and miniscule details of tissue without actually having to physically injure the patient by having to take a sample to do so. The varied plethora of techniques available today is testament to the concerted and dedicated research work, in tandem with the growth of the field of lasers and their use in medicine and dentistry. These techniques could be applicable to soft tissue and hard tissue in various clinical scenarios and even branch out to the treatment of specific conditions as in the case of photodynamic therapy (PDT). However, some techniques continue to be expensive, and hence not all of the benefits of these methods have been universally available yet.

It is intriguing to note that though there is indeed a veritable list of laser-assisted techniques in diagnosis, the scientific basis of all these boils down to light-related phenomena like fluorescence, phosphorescence and spectroscopy. Such physical outcomes of incident irradiation of target material have been the subject of pioneering work by investigators such as George Gabriel Stokes [1] (1852) and Sir Chandrasekhara Venkata Raman [2, 3] (1930).

Stokes in his treatise, «On the Change of Refrangibility of Light» [1], reported the ability of mineral calcium difluoride, CaF_2 (fluorspar) and uranium glass to convert incident invisible (UV) light beyond the violet end of the visible spectrum into re-emitted blue light. He coined the word fluorescence (being light from fluorite) taking a leaf out of the term opalescence being derived from the color change of hydrated silica, SiO_2.

Similarly, Sir C.V. Raman's seminal work [2, 3] on the inelastic scattering of light led to the development of spectroscopic techniques which could detect vibrational and rotational changes caused in a molecule by photonic energy and therefore even lend a description to the molecular framework of a particular material.

Photochemical changes induced by lasers and the subsequent vibrational and radiational relaxation evoked in molecules would give distinctive information on their constitutional make up and led to the development of a myriad of diagnostic techniques [4]. The high-intensity energy of laser light allowed easy excitation of any molecule, and furthermore differentiation from spontaneous radiation induced by absorption of background low-intensity ordinary sources of light was simple and unambiguous. Thus the phenomenon of florescence and phosphorescence and spectroscopic techniques are the basis and foundational fundamental in these diagnostic methods. Hence to enrich our understanding of these methods, we would first dwell on the theoretical processes of these phenomena.

6.2 Basics of Fluorescence and Phosphorescence

All matter around us is in a state of vibration; such vibration is the resultant effect of electrons within constituent atoms in a molecule being in constant translational and rotational motion. M. Blank [5] writes that all organisms have an endogenous electromagnetic field (EEMF) albeit of very low intensity (below 1 Hz up to 1015 Hz). Cellular processes like enzymatic peroxidation, ATP production, the Krebs cycle, and natural luminophores in nucleic acids and proteins generate an electromagnetic field [6].

The energy levels that dictate such translational and rotational motion are «quantized» (M. Planck, N. Bohr) and are described according to discrete quantities of energy that the electron has according to the four quantum numbers that characterize the electron according to (1) the radius of distance from the atomic nucleus (principal quantum number); (2) orbital angular momentum of the electron as *s*, *p*, *d* or *f* (orbital quantum number); (3) direction of the electron cloud vector relative to an electric field (orientation quantum

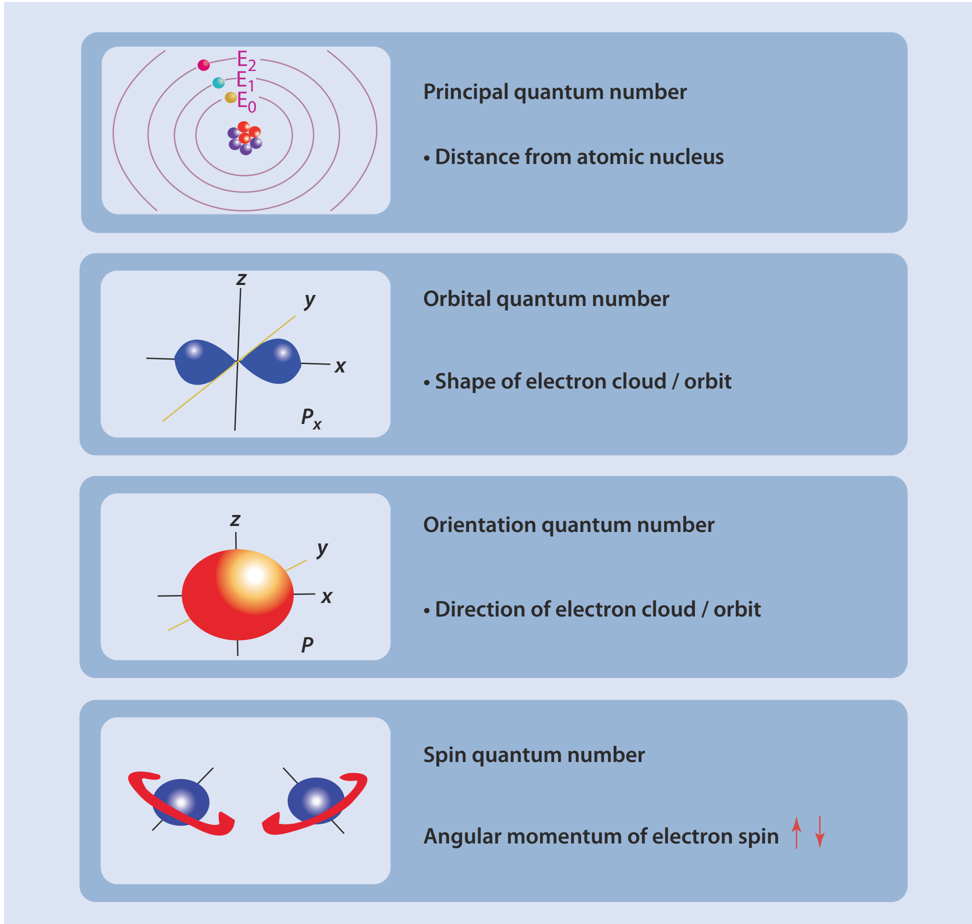


Fig. 6.1 Description of quantum numbers .Quantum numbers indicate the energy level of an individual electron in terms of both electrical and magnetic (spin and orientation) energy

number); and (4) electron spin or angular momentum (the electron has an intrinsic magnetic moment directed along its spin axis) (spin quantum number) (Fig. 6.1).

Note

Electrons normally are configured in atomic orbitals as pairs with opposite spins within the same orbital.

Such molecular vibration could be increased by excitation caused by absorbing a quantum of energy, E, corresponding to the vibration's frequency, ν, according to the relation, $E = h\nu$ (where h is Planck's constant) (Fig. 6.2).

The term «ground state» applies to the normal electronic state of an atom or molecule where the electron has stable and paired spins. However, it will still have a normal rotational and vibrational energy characteristic to the element or molecular bond.

The term «excited state» on the other hand refers to a higher energy level to which an electron has climbed subsequent to absorption of a quantum of energy. The «lifetime» of the excited state would vary according to the quantum of energy gained or mode of excitation. Eventually de-excitation can occur by radiating a quantum of energy (fluorescence or phosphorescence), by expending the gained quantum of energy as vibration and heat, internal conversion or intersystem crossing.

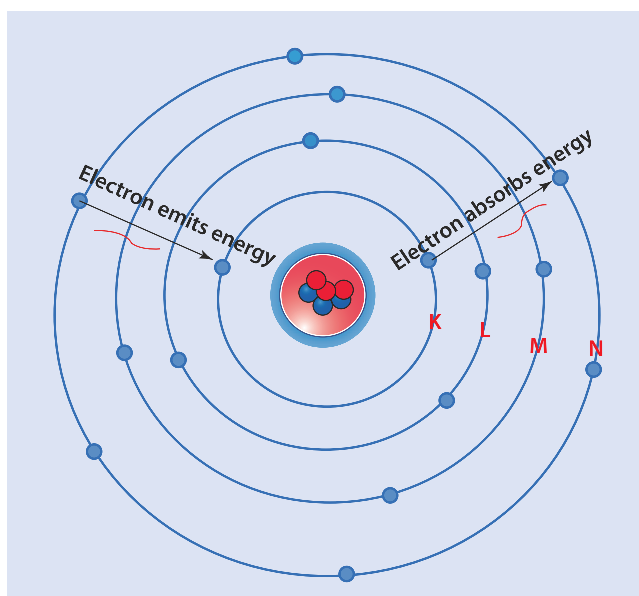


Fig. 6.2 Excitation and de-excitation of electrons – absorption occurs when an incident photon's energy couples with the electron in the ground state (nonexcited state) and goes to an excited state (higher energy level). Emission occurs when the electron «decays» from the excited state or sheds the energy it gained to return to the ground state

6.3 Light as an Oscillating Electric Field

Thus a quantum of energy, for example, from an incoming «green» photon (for illustration sake) could excite an electron of a target atom that is in a ground state if the frequency of the light wave equals the natural frequency of free vibrations of the atom. This excitation can lead to the electron absorbing the energy of the green photon, leaving its paired electron (having opposite spin) in the ground state, and forming an excited singlet state (Fig. 6.3).

Interaction strength between the incoming photon and the molecule depends on various factors such as the field dipole, induced dipole strength and the distance between them, and most importantly it is imperative that the frequency (ν) of oscillating field of the molecule must «match» the electronic oscillation frequency of the incoming photon [7, 8].

It is termed as a singlet state as even in the excited state the electron still has the paired and opposite spin to its counterpart electron which is in the ground state. Thereafter, the excited singlet electron loses some of its absorbed energy through vibrational relaxation which is dissipated as a small packet of heat called a «phonon». It now only has a lesser amount of energy left and hence emits a longer wavelength and yellow photon and returns to the ground state by internal conversion. Internal conversion is a term used to describe the transition of an excited singlet state electron back to its paired counterpart in the ground state dissipating some of the energy through vibration. The difference in energy levels between the absorbed (excitation) and emitted light, termed as Stokes shift, is due to the energy lost as vibrational relaxation in internal conversion. The phenomenon, in general, where there is the absorption of higher-energy (shorter wavelength) light and emission of lower-energy (longer wavelength) light is termed fluorescence. It is short-lived in the realm of 10^{-9}–10^{-7} s.

Another possibility is when absorption of high-energy photonic energy drives an electron to an excited state wherein it even changes its spin. It is now no longer paired with its counterpart in the ground state and undergoes what is termed as the «forbidden transition» to an excited triplet state. Now a relaxation to the ground state is very slow giving rise to a phenomenon called phosphorescence. The unpaired excited electron called a free radical is chemically highly reactive, and its pathway of relaxation to a ground state is called intersystem crossing. Phosphorescence and intersystem crossing occurs in the region of 10^{-3}–10^{2} s. It is longer-lived and more persistent than fluorescence [9].

Specific molecules in tissue can be easily excited by photonic energy of a particular wavelength. Such molecules or substances are termed as chromophores. Ronald. W. Waynant [10] defines a chromophore as «a substance or specific target tissue that serves as an attractant for a laser photon». A. Arnat and J. Rigau [11] terms chromophores as «molecules that transform their electronic energy levels after light absorption». Similarly, a molecule or chemical compound that can re-emit light upon light excitation could be called a fluorophore. Fluorophores could be constituted by aromatic groups, or plane or cyclic molecules, for example, conjugated dyes

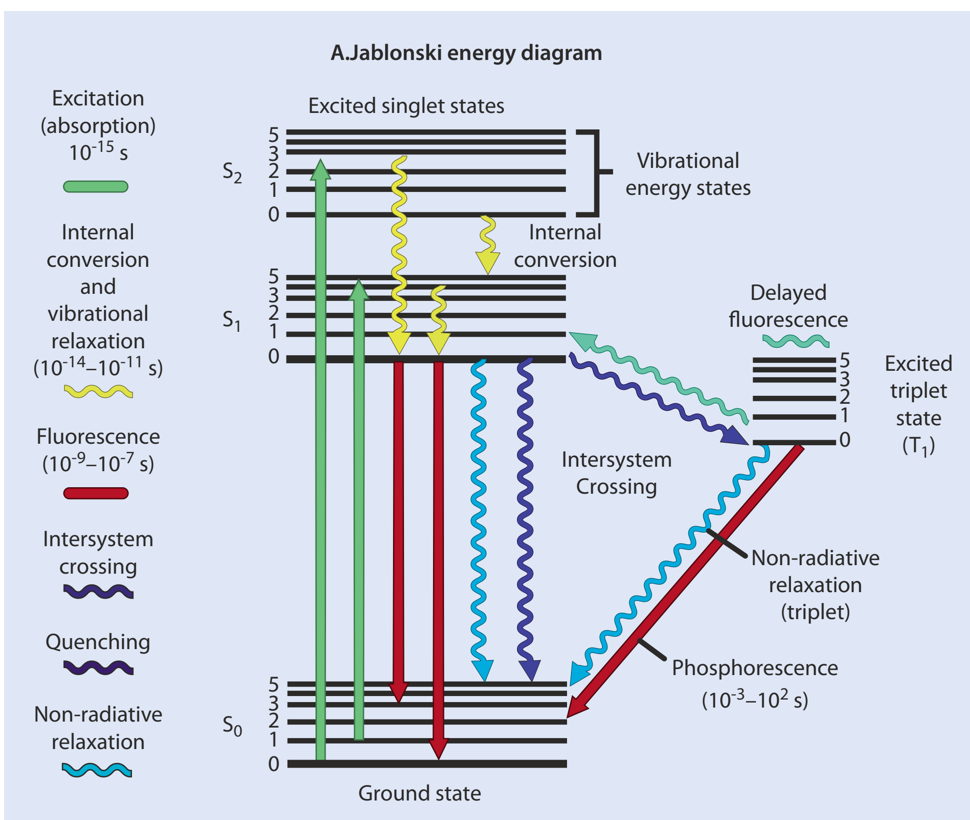


Fig. 6.3 Jablonski energy diagram – Excitation → S_0 + h ν_{ex} → S_2, De excitation → S_2 – S_0 non radiative relaxation – heat lost as vibartion giving rise to stokes shift + h v_{em} → Fluorescence + HEAT. Radiational relaxation of the electron occurs from an excited state (light is liberated) by fluorescence-radiative decay from an excited singlet state or by phosphorescence-radiative decay from an excited triplet state. Nonradiative relaxation occurs by internal conversion or intersystem crossing, but could also occur by intermolecular energy transfer as quenching when the energy is consumed (collisional or complex formation) or when a new excited species is created it is called photosensitization

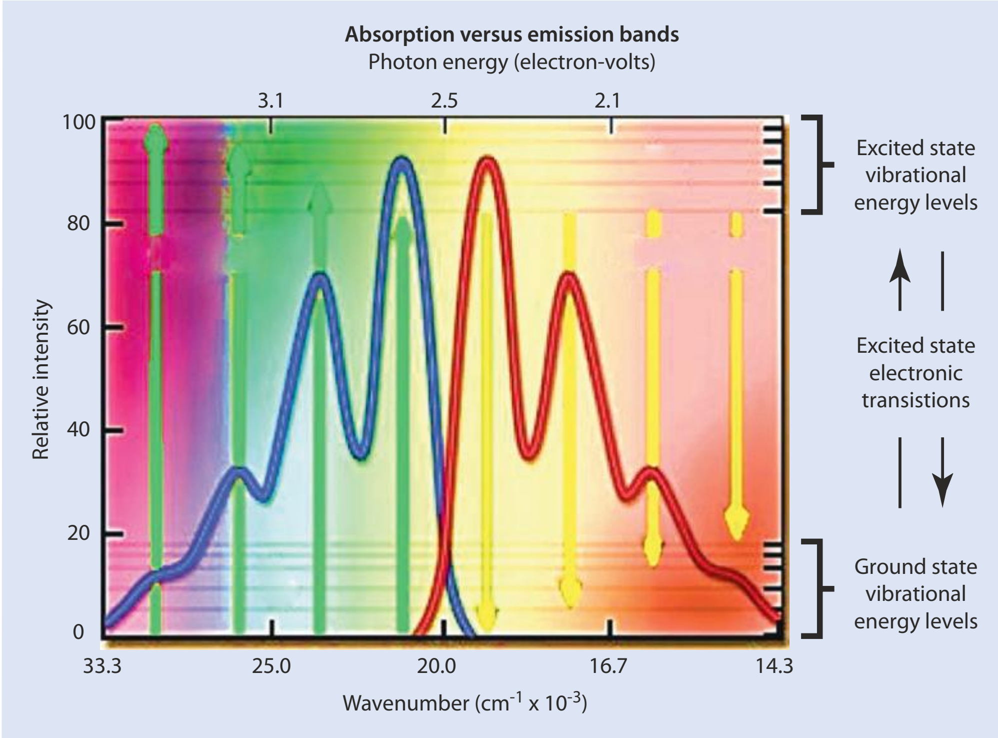


Fig. 6.4 Mirror image rule where though the spectrum changes according to the wavelength of the excitation light the absorption and emission spectrum is diametrically the same for the same fluorophore. Adaptation of this rule is useful in estimating the radiative lifetime, excitation levels and absorptive levels of any particular fluorophore in diagnostics

and fluorescent proteins. They can be excited by laser light of specific wavelength and can be used to stain target tissues and or cells in several diagnostic and therapeutic techniques.

Fluorescence and its excitation follow certain principles such as the mirror image rule which states that the emission spectrum is independent of the excitation wavelength as vibrational energy level spacing is similar for the ground state and excited state of the fluorophore and the fluorescence spectrum would strongly resemble the mirror image of the absorption spectrum for that fluorophore for any wavelength of excitation light. In other words the emission spectrum of a fluorophore would be the mirror image of its absorption spectrum. It has clinical significance in estimating the radiative lifetime of a photosensitizer dye (Fig. 6.4).

However, there are exceptions to this rule too. Resonance fluorescence (electron absorbs two photons instead of one) leads to the emission of a shorter wavelength of higher-energy light than what was absorbed. In terms of spectroscopic principles, such a decrease in wavelength of emitted light is called blue shift. Usually in fluorescence, there is an increase in the wavelength (lower energy) of the emitted light, virtually demonstrating a shift to the red end of the spectrum and is called a red shift. In practical terms a redshift would entail a lower frequency and lower photon energy, whereas a blue shift means a higher frequency and higher photon energy of the emitted light. In summation, redshift or blue shift describes the relative difference between the absorbed and emitted wavelengths (or frequency) of a fluorophore.

Michael Kasha's rule states that photon emission (from fluorescence or phosphorescence) would occur in appreciable yield only from the lowest excited state. Sergei I. Vavilov modified this dictum and stated that the quantum yield of luminescence is generally independent of the excitation wavelength. This has clinical significance in that the fluorescence yield is proportional to the fluorescence lifetime Φ = photons emitted/photon absorbed.

Understanding of these basic phenomena is important as they would serve as the basic mechanisms for the formation of excited singlet states such as singlet oxygen in photobiomodulation and even the formation of long-lived excited triplet states such as superoxide formation in photodynamic therapy (PDT) or photo-activated chemotherapy (PACT).

Biological tissues are composed of dipole structures like enzymes, ionic pumps, nuclear material and nucleotide molecules, polar molecules like water and bound electrons which can be stimulated chiefly by the electric field of light (as biologic tissues are not magnetic, they are not much affected by the magnetic field of light) [12, 13]. Tissues are composed of 70% or more of water which is highly polar and have energy carriers such as ATP and also macromolecules of proteins having transition metal complexes. The polar nature of water and dissolved tissue oxygen can make it highly reactive with fluorophores in the triplet state, leading to the formation of free radicals (singlet oxygen) that are toxic to cells. Fluorophores in the triplet state can also react directly with the above-mentioned biological molecules too through sequential decay and effect oxidation of cell structures [14]. Such a compound which is capable of causing light-induced reactions in other sensitive and receptive molecules is called a photosensitizer. A photosensitizer has also been termed as a «spectrally adapted chromophore» as it can be activated only by light of a specific wavelength [14].

Christopher S. Foote [15] (though first proposed by H. Kautsky in 1939) classified the subsequent chemical

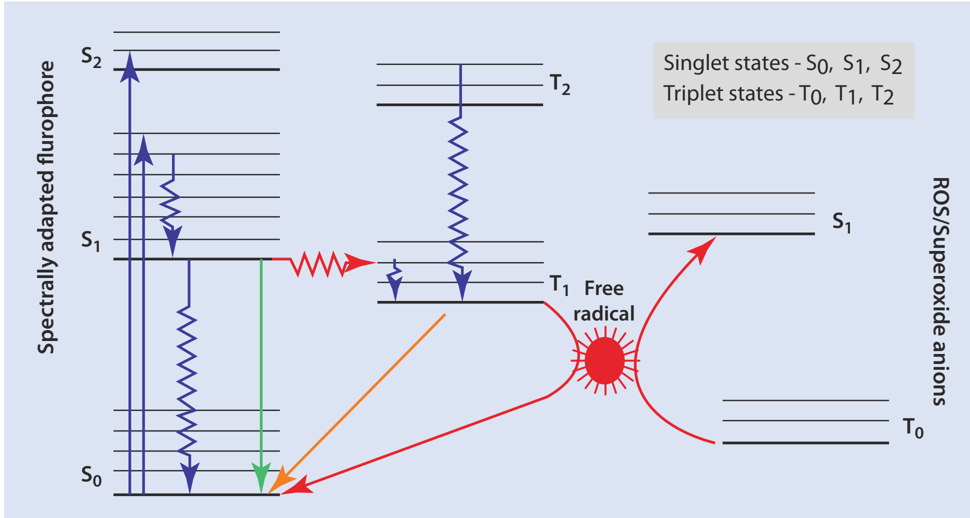


Fig. 6.5 Pathways of de-excitation of a photosensitizer through fluorescence (singlet) or phosphorescence (triplet) in photodynamic therapy (PDT). Excited singlet states or triplet states give rise to cytotoxic species which are used therapeutically against bacteria or even cancer cells

reactions that ensue after light activation of the photosensitizer as either type 1 or type 2. Typically, type 1 reactions involve a direct interaction of the photosensitizer and the surrounding molecule and the creation of a free radical. The commission of the photosensitizer into a long-lived triplet state (milliseconds to several seconds) allows it to then react with other biological molecules (other than oxygen) leading to the production of hydroxyl and superoxide anions. On the other hand, type 2 reaction entails transfer of energy from the photosensitizer to oxygen producing a singlet state of oxygen [14] (Fig. 6.5).

Singlet oxygen reacts readily with cellular constituents like amino acids in proteins such as tryptophan, tyrosine, histidine, cysteine and methionine and guanine bases of DNA and RNA, and also in unsaturated lipids, including cholesterol and unsaturated fatty acids [16, 17]. Such radiative singlet decay after activation of photosensitizer by light of a specific wavelength is by fluorescence (short-lived – nanoseconds). They can effect various changes in cells including photomodification of cell membranes, alteration of cell functions, cellular oxidation, and necrosis.

The application of these mechanisms is varied and explains photosensitization of cells in photodynamic therapy and the use of the same towards photosensitization of viruses in blood banks without damage to the blood cells or plasma, also photosensitization of plants and animals by photodynamic pesticides or by naturally occurring photosensitizers like hypericin [16, 17].

6.4 Fluorescence Microscopy

6.4.1 Soft Tissue Applications

Fluorescence microscopy has become ubiquitous and invaluable in almost every branch of medical and biologic sciences. Various techniques and a host of fluorescent proteins which serve as optical probes to investigate cellular processes noninvasively have been developed and lend further clarity to diagnostic processes. A fluorescence microscope utilizes emitted light from fluorescence and phosphorescence to develop the image; hence, it would have an excitation source, an optical element that is receptive to longer wavelength, i.e., fluorescent light, and filters which blocks out all other light including the exciting light and autofluorescence sources too.

There are a wide range of techniques used for assaying fluorescence such as fluorescence lifetime imaging microscopy (FLIM) which investigates the interactions between fluorescent proteins and cellular processes involved in its immediate proximate environ. Fluorescence resonance energy transfer (FRET) refers to the transfer of energy from the excited fluorophore to another molecule in the near proximity, and this leads to it emitting light of a longer wavelength. This allows resolution of a very high detail to the realm of molecules within cellular processes and their interactions thereof. Other techniques such as total internal reflection fluorescence (TIRF) (which allows imaging within hundreds of nanometres and selective imaging of molecules such as of a cell membrane) and stimulated emission depletion (STED) which gives a high degree of selectivity by allowing illumination and fluorescence of only a particular area and thereby providing precise resolution are also being researched [16, 17].

Fluorophores employed in these microscopic techniques can be endogenous or intrinsic fluorophores such as the amino acid tryptophan (which fluoresce in UV light) or nicotinamide adenine dinucleotide (NADH) which fluoresce in the blue region. They form the basis of autofluorescence techniques (Table 6.1). Synthetic organic fluorophores such as tissue dyes like rhodamine, Hoechst, 4-6-diamidino-2-phenylindole (DAPI) (UV and blue) or quantum dots form a second class, whereas fluorescent proteins capable of forming an intrinsic fluorophore by being genetically encoded like avGP from *Aequorea victoria* jellyfish (fluoresce in green light) or even a hybrid of a synthetic dye bound by a covalent bond to a genetically encoded protein forms a third class of fluorophores [17].

Table 6.1 Absorption and fluorescence maxima of endogenous fluorophores – corresponding spectral light to be used according to fluorophore in tissue

Chromophore	Solvent	Absorption (nm)	Fluorescence (nm)
Tryptophan	H_2O	220, 280, 288	320–350
Tyrosine	H_2O	220, 275	305
Collagen		300–340	420–460
Elastin		300–340	420–460
NADH	H_2O	260, 340	470
NADPH	H_2O	260, 340	470
Flavins	H_2O	260, 370, 450	530
Zn-coproporphyrin	DMSO	411, 539	580
Zn-protoporphyrin	DMSO	421, 548, 585	592
Uroporphyrin	DMSO	404, 501, 533, 568, 622	624
Coproporphyrin	DMSO	398, 497, 531, 565, 620	622
Protoporphyrin	DMSO	406, 505, 540, 575, 630	633
Chlorophyll a	Ether	425, 670	685
Chlorophyll b	Ether	455, 642	660

Reproduced from Koenig and Schneckenburger with permission [17]
Such fluorophores like NADH are the basis of autofluorescence diagnostic techniques
DMSO dimethyl sulfoxide

Fluorescent proteins can even be in a dormant stage and can then be «photoactivable», like PA-GFP, «photoconvertible» meaning changed from one band of fluorescence to another like Kaede (518–582) or «photoswitchable» like Dronpa by being able to be activated when illuminated at 488 nm or not [16].

Autofluorescence of endogenous fluorophores in tissues can be assayed by laser-induced autofluorescence and can have a range of diagnostic applications such as differentiation between types of tissues, detection of infections by microorganisms and metabolic states of tissues and even detection of metabolic defects. Mitochondrial intracellular oxidation rates and intracellular oxygen concentration were evaluated by B. Chance et al. [18] in 1962 in vivo (on rat brain and kidney) by studying NADH fluorescence at 460 nm (higher NADH concentrations as titered by its fluorescence, means reduced intracellular oxygen levels). This work is in fact a continuation of B. Chance's work with F. Jobsis [19] in 1959 on frog Sartorius muscle, demonstrating increased fluorescence at 443 nm of cytoplasmic and mitochondrial pyridine nucleotides on muscle contraction. A. Mayevsky [20] continued on the same line of work (1972 and 1988) by surface fluorometry-reflectometry using flexible optical fibers and a corrected fluorescent signal (at 450 nm) devoid of other background influences of tissue absorption or blood volume changes (which reflected light at 336 nm) in the puppy or adult dog brain in vivo and also on Mongolian gerbil [21]. They demonstrated the effects of ischemia, hypoxia, and anoxia with a correlated increase in fluorescence of NADH.

Autofluorescence when employed for differentiation of tissue could be effective for detection of tumors. W. Lohmann and E. Paul in 1988 [22] showed that melanomas could be detected in situ at 475 nm when excited at 365 nm. W. Lohmann (1990) [23, 24] used the same technique to describe and correlate the detection of cancer and also cellular dysplasia in vitro cryosections of the uterine cervix and in ex vivo sections of lung tumors as compared to fluorescence of normal tissue and found that the fluorescence in the areas around the tumor had markedly higher intensity. However autofluorescence of the skin becomes slightly more complicated as in addition to the established diagnostic autofluorescence of the reduced pyridine coenzymes NADH and NADPH; the presence of various other fluorophores (such as collagen, elastin, and keratin extracellularly in addition to tryptophan and hemoglobin found intracellularly) can confound the resultant spectrum. Furthermore in vivo redox states may make quantification of NADH more difficult. Non-melanoma skin cancers were detected in vivo by Hyejun Ra et al. [25] using a indomethacin-based fluorescent probe called fluorocoxib (developed by Mannet et al.) administered systemically on genetically engineered mouse with an accuracy of up to 88% for macroscopic tumors and up to 85% for microscopic tumors. In this study, fluorescence signals from 500 to 800 nm were monitored at 10 nm intervals after excitation from 503 to 555 nm.

Understanding the basis of autofluorescent detection of cancer and the biologic fundamentals is a foundational prerequisite before practical evaluations and clinical modalities are discussed. Much of our present perception of these processes can be attributed to the work of I. Pavlova [26] and her team (from 2003 through 2008). In her study in 2008, autofluorescence of 49 biopsies of normal, benign and neoplastic samples was captured by confocal microscopy, and the images proved that the autofluorescence patterns, from UV light (351 and 364 nm) and 488 nm Argon laser, depended not just on pathologic or normal nature, but also according to the site in the oral cavity. While UV light was intended for autofluorescence of NADH in the epithelium and collagen in the connective tissue, the 488 nm was directed at autofluorescence of flavin adenine dinucleotide (FAD) of the epithelium and the connective tissue. The study found that epithelium of the palate and gingiva were highly fluorescent as compared to the epithelium from the buccal mucosa, floor of the mouth and tongue. Notably, benign lesions of the epithelial mucosa had only weak fluorescence, whereas neoplastic versions had increased fluorescence to UV light as compared to normal samples. Intriguingly connective tissue of both benign and neoplastic samples (irrespective of anatomic site) had decreased fluorescence to both 488 nm and UV light [27, 29]. They surmised that this decreased fluorescence of the connective tissue in neoplastic samples is because of the loss of collagen cross-links due to inflammation, lymphocytic activity and matrix degrading proteases [28].

The epithelium of the normal palate and gingiva being highly fluorescent was attributed to the highly keratinized masticatory mucosa which limits the penetration and increases the scattering of light, thereby having only a NADPH contribution to fluorescence and not from collagen. In a neoplastic condition however the biochemical pathways of cell signaling between the epithelium and connective tissue is changed, this coupled with neoangiogenesis of the cancerous tissue, and loss of collagen in the connective tissue is thought to be the reason for the decreased fluorescence of neoplastic epithelial samples [29].

D. Roblyer et al. [30] confirmed the above-mentioned facts in their study designed on 56 patients and 11 volunteers through quantitative autofluorescence imaging using the multispectral digital microscope (MDM, a wide-field optical microscope, color CCD camera, variable range of 1–7 cm) at 365, 380, 405, and 450 nm. The focal region to be analyzed was selected by another practitioner who was blinded to the grouping of the samples, and thereafter diagnostic algorithms related to the red-to-green fluorescence intensity ratio, etc. were applied. The results showed that this diagnostic modality of quantitative autofluorescence could discriminate between neoplastic and non-neoplastic tissue with a sensitivity and specificity of 96%.

D. Shin et al. [31] in 2010 described the various diagnostic techniques in vogue today like ViziLite (Zila Pharmaceuticals, USA) which has chemiluminescent blue light source and can detect pathologic changes; however, studies are yet undecided about its accuracy.

The VELscope or Visually Enhanced Lesion Scope, (LED Dental, USA) invented by M. Suyama is a handheld device that is designed for the diagnosis of oral precancerous, cancerous or pathologic lesions using fluorescent light of 400–600 nm. It works on the notion that normal mucosa would appear green or pale green due to autofluorescence and a pathologic or neoplastic lesion would appear brownish to black. It is based on the concept of *visual* autofluorescence as opposed to the autofluorescence imaging techniques described earlier in this text. It can however aid a practitioner in identifying and delineating cancerous or precancerous lesions. However, it is quite subjective as it relies heavily on the judgment, training and experience of the practitioner; false positives with benign lesions may also occur as they may also have connective tissue changes leading to a change in autofluorescence of tissues. A range of studies have been designed to evaluate the efficacy of this device and the results have been ambiguous.

Lane et al. [32] were the first group to investigate the VELscope device in 2006 and reported a sensitivity of 98% and specificity of 100%. Subsequently Poh et al. [33] did their evaluations on 20 patients from whom they derived 122 oral mucosa biopsies and reported a sensitivity of 97% and specificity of 94%. Poh [34] designed a similar study a year later in 2007 with another team and published a report that out of a total of 60 patients who underwent surgery for oral cancer, 7 patients (25%) of the 22 control group patients experienced recurrence, while none of the 38 patients, where the surgeon was guided by the visual fluorescence (VELscope) to place a 10 mm margin of excision, experienced recurrence. However studies done by McNamara et al. [35] in 2012 on 42 patients do not concur with the previous studies and stated that visual examination was better than visual fluorescence by VELscope.

Cancer diagnosis through autofluorescence could also be based on the detection of porphyrin or its derivatives in neoplastic tissues. There are various porphyrin-related fluorophores in the tissue such as protoporphyrin IX (PP IX), coproporphyrin III (CP III), uroporphyrin Ill (UP III), and hematoporphyrin IX (HP IX). Strong red fluorescence of porphyrins when exposed to UV light was reported as early as 1924 by Policard in sarcomas of rats. This would later on develop into the foundational work of photodynamic therapy (PDT). It was not until 1942 when Auler and Banzer demonstrated hematoporphyrin in malignant cells and later in 1960 when F. N. Ghadially and W. J. P. Neish studied squamous cell carcinoma in rabbits that endogenous PP IX was established as the main fluorophore responsible for red autofluorescence [36].

Y. Yuanlong et al. (1987) [37] showed that squamous cell cancer tissues when exposed to 365 nm xenon ion pulsed laser showed fluorescence at 630 and 690 nm at 89% correlation with the traditional biopsy method. Koenig and Schneckenburger [38] continued these investigations using the 364 nm argon laser with a fiber-optic sensor and elicited autofluorescence at 673 nm in the skin and in subcutaneously transplanted solid Ehrlich carcinoma of mice at 638 and 680 nm and at 635 nm in patients with squamous cell carcinoma.

6.5 Optical Coherence Tomography

6.5.1 Optical Biopsy

Optical coherence tomography (OCT), a modality adapted from ophthalmology (Naohiro Tanno, David Huang 1991) is a noninvasive, live, imaging technique that provides three-dimensional high-resolution (10–15 μ) images to a depth of ~2 mm. Literally it allows the diagnosis of pathology in tissue by optical methods without actually physically harvesting it from a patient surgically [39]. It is based on the principle of backscattered light analyzed through low-coherence interferometry, which in simple terms means that the light scattering back off a surface is superimposed (as constructive interference and destructive interference) to develop useful diagnostic data. The backscattered (reflected) light from the substrate generates a low-coherence beam from differing depth levels (depending on tissue structures in the volume being imaged) to the interferometer (Fig. 6.6). The optical data from each single scan point is interpreted by the interferometer as an interference pattern and recorded as a depth profile (A-scan), whereas in a linear scan across the sample delivers cross-sectional (B-scan) data. The images can be based on spectral domain scans of a single focus or swept laser light sources where light of varying frequencies can be emitted sequentially.

The light is directed along two arms, a reference arm (mirror) and a sample/substrate arm using a handheld (X-Y) scanning device similar to an endoscopic probe (Fig. 6.7). The source of light typically is a near-infrared diode lasers operating in continuous wave or a short-pulsed femtosecond laser and is used in tandem with time domain or frequency domain interferometers (Fig. 6.8).

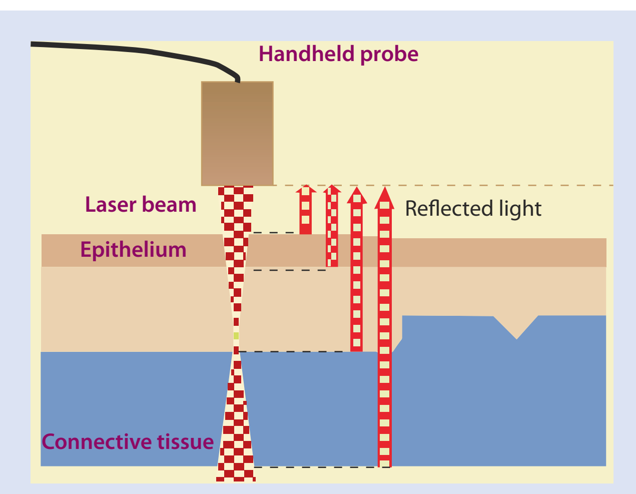


Fig. 6.6 Light from a laser source generates backscatter depending on tissue components at various depth levels. This is analyzed by a low-coherence interferometer that generates depth-wise information or a series of cross-sectional images according to tissue constituents that cause the backscatter at different levels

Normal and pathologic tissue can be visualized in three-dimensional images with differing contrast as the spatial differences in refractive index of different tissue constituents change with depth, and hence capturing this variation lends intricate detail and difference to images. Furthermore it allows qualitative morphological imaging of skin in vivo and can help in diagnosis of precancerous or cancerous lesions of the skin [40]. Optical biopsies from this modality has led to the diagnosis of neoplastic lesions of both non melanoma skin cancers (NMSC) like basal cell carcinoma and squamous cell carcinoma (Strasswimmer et al. 2004 [41], Olmedo JM et al. 2006, 2007 [42], Gambichler T. et al. 2007 [43], Mogensen M. et al. 2009 [44, 45],) and also melanomas (de Giorgi SM et al. 2005 [46], Gambichler T., 2007 [47]).

OCT has also been used in the diagnosis of mucosal lesions of the oral cavity. O. K. Adegun et al. (2012) [48] applied OCT for the diagnosis of epithelial dysplasia and compared B-scan images to histological sections. The relevance and significance of this study that they stated was that the choice of determining the anatomic site for obtaining the biopsy is subjective to the clinician and hence the diagnosis also would vary, on the other hand OCT provided for a noninvasive technique that could in the future direct the practitioner to select the appropriate site for taking the biopsy, only if necessary and if prompted by the OCT image. The results showed a poor correlation between OCT images and actual biopsies in the case of moderate and severe dysplasia. O. K Adegun et al. in the following year (2013) [49] had evaluated OCT in the diagnosis of vesiculobullous mucosal lesions compared to normal mucosa or fibroepithelial polyps using a modality called «scaled intensity drop», a two-dimensional imaging mode. The results showed that SID was indeed able to discriminate between fluid-filled and solid tissue with a sensitivity and specificity of 80%.

However other diagnostic modalities may also be used similarly to deliver an optical biopsy such as multi-photon excitation microscopy which is essentially a type of fluorescence microscopy which works on the principle that two-photon excitation can induce fluorescence emission at much longer wavelengths in fluorophores like NADPH which usually fluoresce to UV light. B.R. Masters et al. [50] reported the use of this technique with a 730 nm, 100 mW, Ti:Sapphire femtosecond laser at an average power of 10–15 mW with a galvanometer driven scanner. They concluded that they were able to obtain a sample to an image depth of 100 μ (UV light had penetration depths under 30μ only and also had cell viability issues) and that this technique could be applied to obtain deep sections for in vivo optical biopsies. Elastic scattering spectroscopy (ESS), Raman spectroscopy and laser-induced breakdown spectroscopy are other modalities for taking an optical biopsy.

6

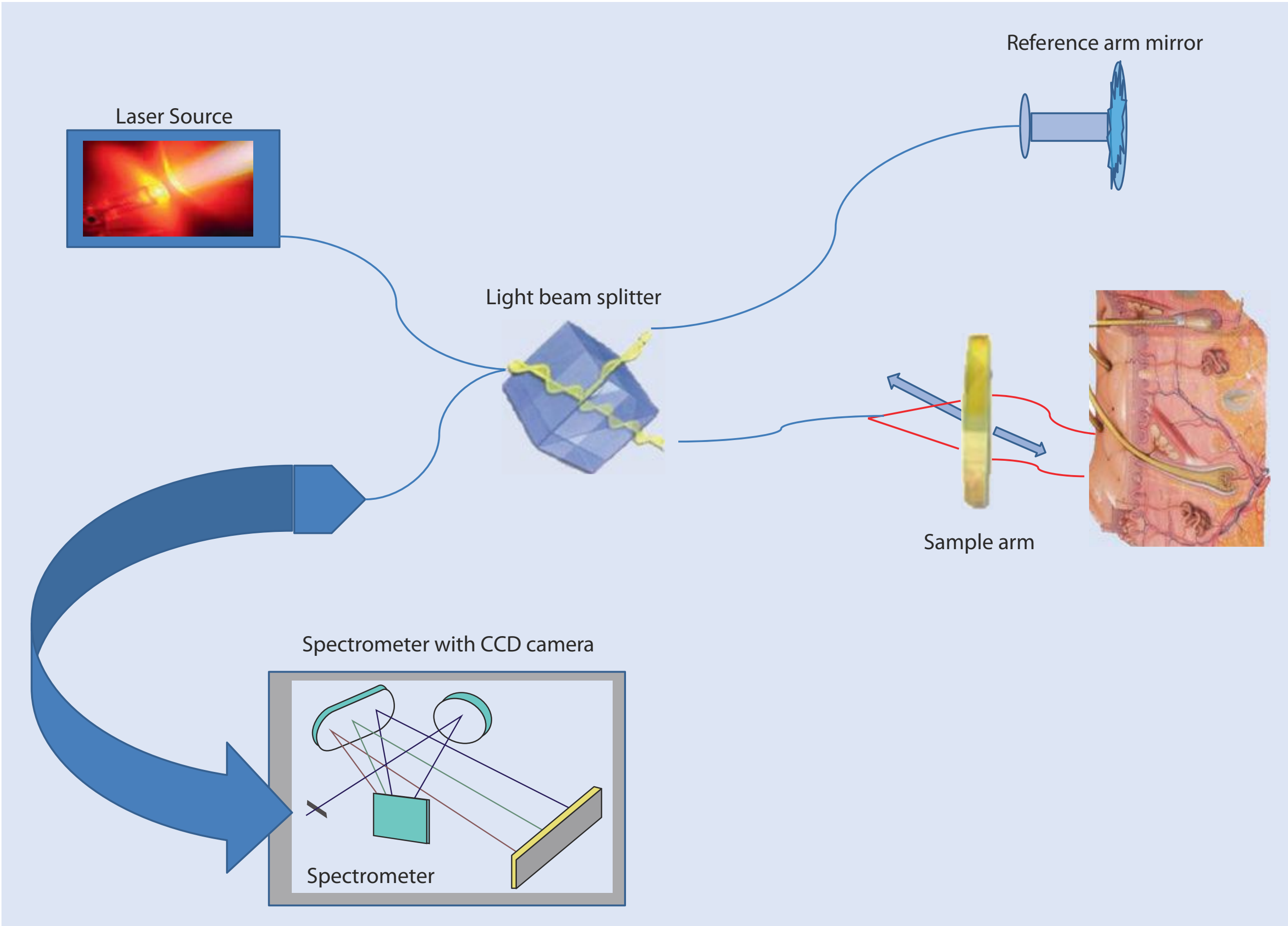
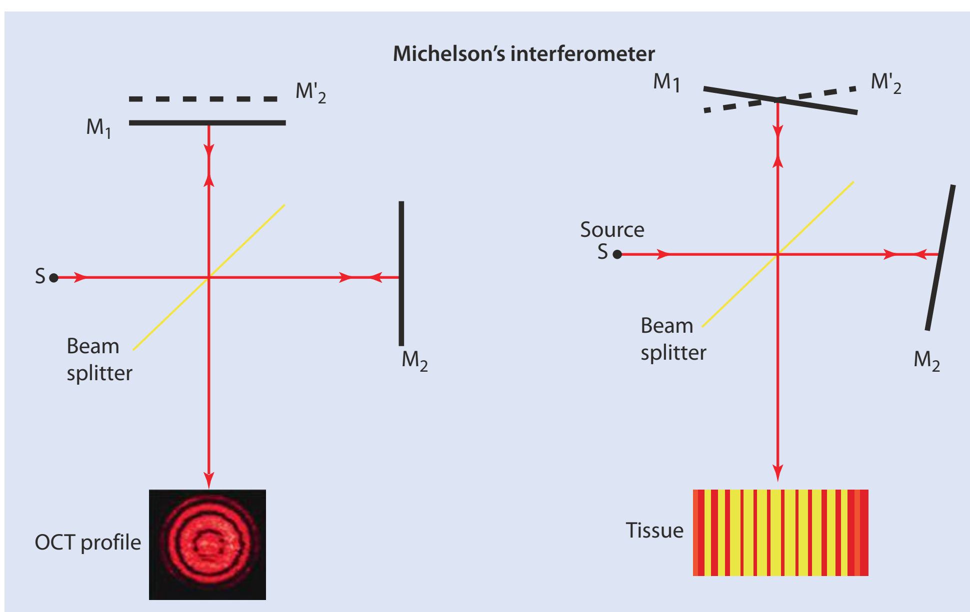


Fig. 6.7 The components of optical coherence tomography – which consists of a scanner probe, which has the laser light source, is directed along two arms by a beam splitter, one from the sample (recorded by CCD detectors or CMOS imaging) and second from a reference mirror. The light from both arms is recombined and the spectrum analyzed by computer. *CCD* charge-coupled device, *CMOS* complementary-symmetry metal oxide semiconductor

Fig. 6.8 Michelson's interferometer consists of a beam splitter that splits the light from the source into two arms; the reflected light from both arms (sample and reference mirror) is then recombined to produce the OCT image



6.6 Spectroscopic Techniques

Skoog D. A. and Holler J. [51] define spectroscopy as the study of the interaction between matter and electromagnetic radiation. A. M. Helmenstine [52] refines this definition further by stating that this analysis (of the interaction between matter and radiation) can be with *any* region of the electromagnetic spectrum. Therefore, the range of spectroscopy techniques available can be based on any particular wavelength region and also could be based on absorption of a wavelength region of the electromagnetic spectrum or by thermal emission caused by a particular wavelength.

While most spectroscopy techniques deal with electronic transitions of molecules and band spectra related to their respective absorption, atomic emission spectroscopy and atomic fluorescence spectroscopy catalogue the *emission* from an excited atom and hence in plain terms are able to give information regarding specific elements in a compound and their concentration. Atomic emission spectroscopy is able to characterize the particular wavelength (color) emitted from an excited atom and is based on the principle that the number of excited atoms is proportional to the emitted energy. The sample is thermally excited using a flame or plasma.

These techniques are founded on the observation of Josef Fraunhofer in 1817 that the spectrum of solar radiation had a continuous spectrum of numerous dark lines (he designated the dark lines with letters). Later, Gustav Kirchhoff in 1859 showed that the absorption of solar radiation by sodium atoms gave the D line at 589 nm.

Molecular absorption of UV/Vis light leads to a excitation that is depicted by an increase in vibrational energy, and the subsequent emitted wavelength could be measured as against the absorbed wavelength in techniques of absorption spectrometry such as atomic absorption spectroscopy (displays these as black lines on a white background). Laser-induced breakdown spectroscopy (LIBS) is a type of atomic emission spectroscopy where a highly energetic focused laser pulse is the excitation source which atomizes the substrate to form plasma. This plasma would have a characteristic atomic or molecular signature of the substrate.

Kumar et al. (2004) [53] had demonstrated the use of LIBS in vivo in canine hemangiomas and showed that calcium and potassium and copper and potassium levels were different in tumor cells compared to the normal cells.

R. Kanawade et al. (2015) [54] applied LIBS for the differentiation of tissues by analyzing their basic atomic composition as against the National Institute of Standards and Technology (NIST) [55] database using an excimer laser 193 nm, 28 ns pulses at 10 Hz, 0.6 × 0.4 mm spot size and energy/pulse 38 mJ on fat, muscle, nerve and skin tissue samples from pig source. They proved that emission intensity ratios of Na to C, K to Na, and O to C ratios could be used to differentiate between tissues and that this information could be used for future application in minimally invasive laser-guided surgeries

Photoluminescence spectroscopy specifically assays the fluorescent (fluorescent quantum yield) or phosphorescent (phosphorescent quantum yield) pathways of relaxation and dates back to the mid-1800s. The spectra depict the intensity of the emitted radiation as a function of either the excitation (excitation spectra) wavelength or the emission (emission spectra) wavelength. Excitation spectra show the emission at a given fixed wavelength while varying the excitation wavelength, whereas the emission spectra show the intensity of the emitted radiation when a fixed wavelength is used to excite the sample.

Spectroscopic measurements of scattered light are applied in the case of techniques such as Raman spectroscopy.

6.7 Inelastic Scattering of Light Versus Elastic (Rayleigh) Scattering

Elastic scattering suggests that the scattered light has the same energy as the incident light and the particle on which it was incident is much smaller than the wavelength of the light. This is based on Rayleigh's law which states that scattering is inversely proportional to the fourth power of wavelength, which means that the shorter the wavelength (violet, blue) the greater will be the scatter [14].

Conversely inelastic scattering would cause a change in the frequency and wavelength of the incident light in that there is a transfer of energy towards vibrational states of the molecule. This transfer of energy enables the molecule to reach higher (excited) «virtual» vibrational states, and as a result there would be an equal and proportional decrease in energy from the scattered light than its incident energy. This would increase the wavelength (redshift) of the scattered light, and the difference in energy would correspond to the difference between the vibrational states of the molecule. This is called Stokes shift.

However in such a situation when the incident photon was to hit a molecule which is already in its excited vibrational state, then the scattered photon would have more energy than the incident, and hence it would have a shorter wavelength (blue shift) thereafter. This is termed as anti-Stokes shift (◘ Figs. 6.9 and ◘ 6.10).

6.8 Raman Spectroscopy and Its Diagnostic Potential

6.8.1 Soft Tissue Applications

The use of Raman spectroscopy for quantitative identification of intra-oral bacterial species (*S. mutans*, *S. sanguinis*, and *S. gordonii*), such as that of biofilms in plaque, was suggested in the work of Q. Zhu, R. Quivey and A. J. Berger [56–58] (2003, 2004, 2007) where they used an 830 nm diode laser, with a low error rate (±0.07). This thread of work was continued in association with B. D. Beier and the same team in 2012 [59] which proved that Raman spectroscopy with confocal microscopy using an 830 nm diode laser yielded 93% of accuracy in classifying and validating the bacterial species (*S. sanguinis* and *S. mutans*) in a culture of different bacterial species (◘ Fig. 6.11).

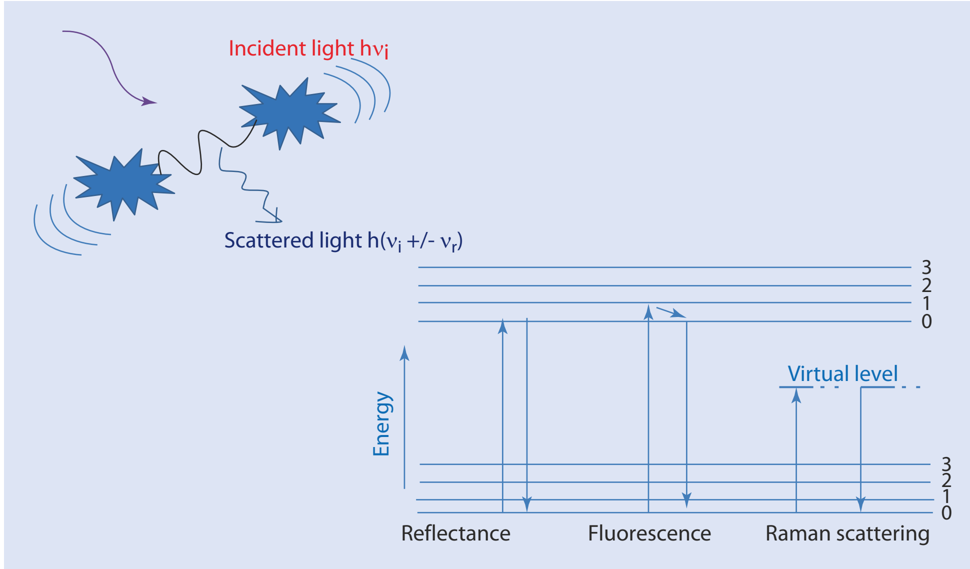


Fig. 6.9 Inelastic scattering of incident light (hνi) that induces the molecule to a higher «virtual» excited state with subsequent loss (or gain) of energy of scattered light (h$\nu_{R)}$. This loss (or gain) of energy of the scattered light can be detected by spectroscopic means

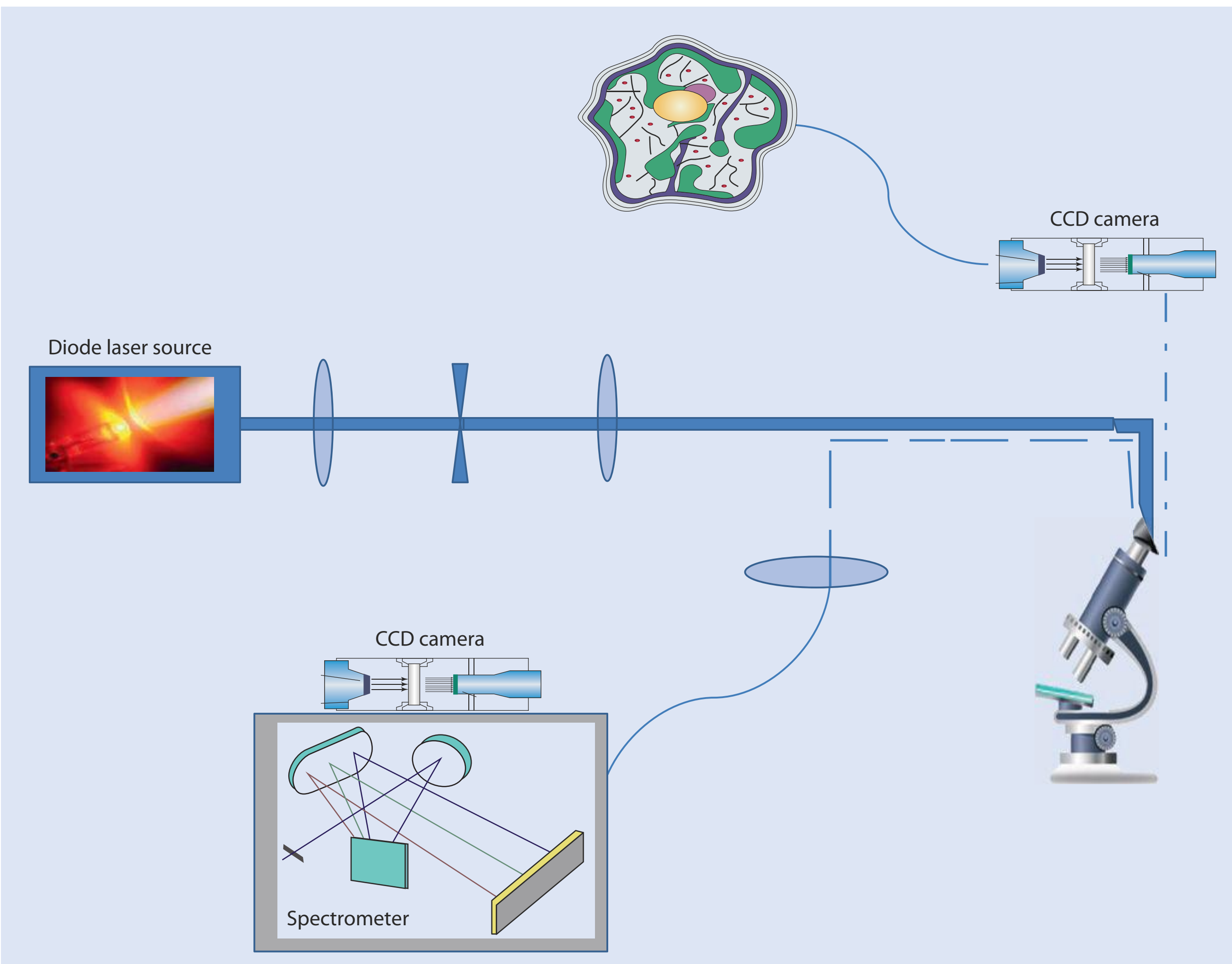


Fig. 6.10 The diagnostic setup for Raman spectrometry. The excitation source can be a diode laser, a fibre-optic sampling probe (which directs the laser light to the source and also channelizes the scattered light from the source to the spectrometer) and a spectrometer detector (Reproduced from Beier et al. [59], © 2012; licensee Springer)

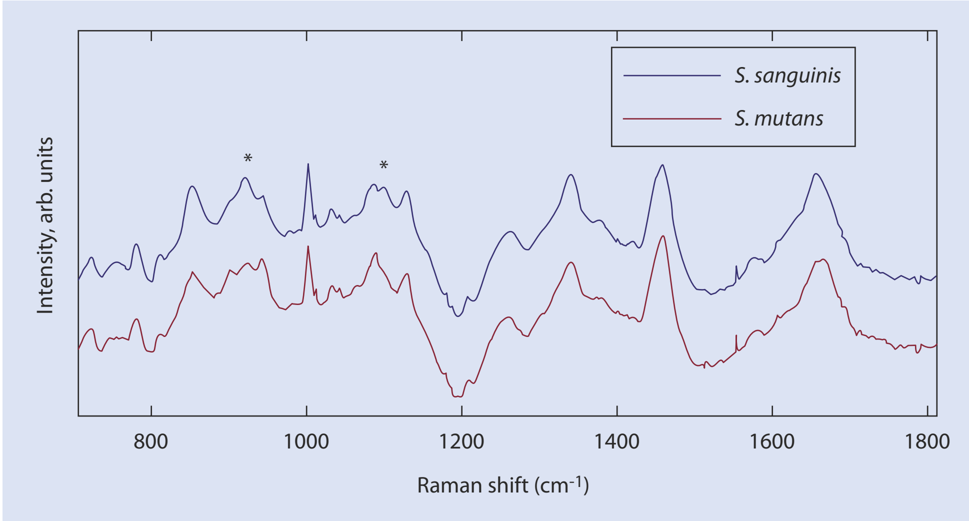


Fig. 6.11 Raman spectra of bacteria (Reproduced from Beier et al. [59] © 2012; licensee Springer)

K. Maquelin et al. in 2002 [60] first reported the use of confocal Raman microscopy for the identification of *Candida* species using 100–150 mW, 830 nm Ti:Sapphire laser with a high accuracy of 97–100%. They advised that this modality provided a viable and fast alternative to conventional techniques in identifying *Candida* infections particularly in hospital settings as it is possible with just 6 h of culturing as compared to the 24–48 h by conventional histopathological processes.

Confocal microscopy allows the laser beam to be focused to a very small spot size (~250 nm in diameter), then magnified by a microscope and projected onto a confocal spot of 100–150 μ diameter or into an optical fibre and then connected to a CCD camera for spectral data analysis. The objective here is that all other signals from other than the focal point are simply blocked out.

Such work gives the promise that Raman spectroscopy can be invaluable in the early identification of caries as well as susceptibility of the patient and designation of preventive measures. The inspiration for such work though dates back to the work of Puppels [61–63], Nelson [64], Sperry [64], Manoharan and Ghiamati [65–67] in the early 1900s who first used this technique for the identification of bacteria. The choice of bacteria used in these studies is indeed obvious as *S. mutans* is implicated as one of the primary causative organisms and *S. sanguinis* and *S. gordonii* are secondary causative agents in dental caries.

J. W. Chan et al. in 2006 [68] had used the same principle with over 98.3% accuracy in the identification of neoplastic cells and differentiation of live healthy hematopoietic cells and later with 97% accuracy using laser tweezers Raman spectroscopy (LTRS) with a 30 mW 633 nm He-Ne laser as an excitation source [69].

LTRS utilizes a single beam of infrared lasers to analyze a cell several microns away from any other substrate, virtually as an optical tweezer, thereby precluding any other background signals. This is based on the principle of «optical trapping or optical levitation» described by A. Ashkin and J M Dziedzic [70] (using a 120 mW argon laser) where viruses, bacteria or cells in gaseous or liquid media are virtually held at a focal point of the laser beam where the scattering and intensity of the laser radiation is at a balance. Pre-requisite to this process is that the biologic (or otherwise) particle being «trapped» should have a refractive index that is higher than the surrounding medium. «Optical trapping» works on the principle that a gradient force proportional to the intensity of the laser beam draws high refractive index particles towards the beam axis but repels low refractive index particles away from its axis. The laser bean could virtually suspend a particle as the radiational field counterbalances the gravitational forces on a particle. (Magneto optical trap, Dipole trap) [71]

Previously in 2004 J. W. Chan et al. [72] had demonstrated the successful use of confocal laser tweezers Raman spectroscopy in identification of single *bacillus* spores using a 50 mW argon laser. Later the same research team headed by J. W. Chan in 2008 [73] demonstrated the application of LTRS using 10 mW, 633 nm He-Ne laser (both as excitation and optical trapping) in differentiating between T and B cells of young leukemic patients with an accuracy of 95% in the case of normal cells and 90% in classifying cells according to their respective types. S. Huang et al. [74] employed a similar technique of microfluidic Raman tweezers using 785 nm diode laser source (this wavelength is preferred as there is very less water absorption at this range and hence damage to optically trapped cells is prevented) in quantifying the levels of pyridine-2,6-dicarboxylicacid (dipicolinic acid or DPA) chelate with calcium ion (Ca-DPA) in bacillus spores. Ca-DPA levels have been correlated with spore resistance and stability in a medium [75]. The study showed that identification of individual bacillus spores was possible without altering individual spores with a laser exposure time up to 20 s; beyond 20 s there was the release of DPA as all bands disappeared from the Raman spectrum [76].

The microfluidic technique is a flow cytometry like patented technique developed by the researchers themselves which comprised a square quartz capillary tube (50 μ by 50 μ; 5 cm long) with two connecting chambers, one with the spore sample and the other with water. A precise flow pump controlled the flow that would deliver individual spores to the focal point of the laser where optical trapping of the spore would give the Raman spectrum and then the flow was immediately turned off so that the spore is held for Raman acquisition. Once the Raman spectrum is obtained, the flow is turned on again, while the laser beam is blocked for a short time (~10 ms) and when it is turned back on the measured spore flows away from the trap towards the waste chamber. Now the system can receive the next spore in the flow. The above procedure is repeated until 200 individual spores are evaluated.

Nearly a decade back, Ellis and Goodacre (2006) [77] in a critical review of a diverse range of research work had discussed the possibility of using Raman spectroscopy and allied techniques like Fourier transform infrared spectroscopy in a range of applications such as in the diagnosis of cancer (prostrate and cervical), leukemia and arthritis and even in the identification of metabolic markers of diabetes and in reproductive biology. Mahadevan-Jansen A et al. (2014) [78] had discussed the capability and potential of Raman spectroscopy to detect biochemical changes in cancer cells such as the increase in nucleic acid content, glycogen and collagen.

J. Q. Nguyen et al. (2016) [79] successfully employed Raman spectroscopy in the in vivo verification of tissue margins between normal and neoplastic tissues in soft tissue sarcomas with a sensitivity of 89.5% and specificity of 96.4%. They used a portable Raman spectroscopy device with a handheld probe, 400 μ excitation fibre and seven 300 μ collection fibers excited at 785 nm, providing information to a depth of 700 μ. This technique, they reported, allows for more accurate appraisal of designing margins in surgical resection of tumors.

Raman spectroscopy when combined with intuitive computer-aided statistical analysis of the spectra by multivariate analyses (MVA) such as principal component analysis (PCA), hierarchical cluster analysis (HCA), discrimination function analysis (DFA) or geometric-based vertex component analysis (VCA) gives a clearer and composite picture leading to the interpretation, classification and diagnosis of the sample under study.

In related work by M. F. Escoriza et al. in 2000 [80], Raman spectroscopy was successfully employed to discriminate and differentiate between viable and nonviable cells of *Escherichia coli* and *Staphylococcus epidermidis*. The study demonstrated a sensitivity of Raman spectroscopy to differentiate viable and nonviable cells up to 86% and was able to discriminate between species with accuracy of 87%.

Raman spectroscopy provides a unique fingerprint that differentiates the biochemical molecular alterations between the samples. Most interestingly B. D. Beier et al. in 2012 [59] showed that this technique lends further depth to the diagnosis by giving actual information on the difference in spatial positioning of the different bacterial species in the three-dimensional network of the biofilm. Such essential constitutive differences can build up a three-dimensional mosaic of the complex microbial structure such as of a biofilm and could give unique information and inference regarding cariogenicity and its progression too.

Raman spectroscopy (which uses continuous wave lasers that rely on spontaneous emission) could be clarified into a much more amplified, efficient, coherent signal free of background fluorescence by coherent anti-Stokes Raman scattering (CARS) and stimulated Raman scattering (SRS) which uses two-pulsed laser sources to excite the sample (instead of a single CW source). One pulsed-laser source initiates the Raman scattering (pump) and Stokes shift, whereas the second source is specifically tuned to the frequency of a single peak on the spectrum bringing about a blue shifted signal that is exponentially stronger than the original Raman signal and can be used for specific imaging and isolation of known molecules.

CARS has been used for the specific and quantitative intracellular identification of lipid molecules in living cells. X. L. Nan et al. (2006) [81] have been able to correlate this to the tracking of hepatitis C virus whose pathogenicity is closely linked to its insidious ability to be concealed in triglyceride-rich lipoprotein particles. They used two-pulsed Ti:Sapphire lasers with a repetition rate of 80 MHz, 2 ps pulse width and pump wavelength at 711 nm and Raman resonance (Stokes shift) wavelength at 892 nm. CARS had been employed using fibre-optic delivery by H. P. Buschman et al. in 2000 [82] and thereafter by L. Mostaco-Guidolin et al. in 2010 [83] in animal studies of myocardial infarction prone, Watanabe heritable, hyperlipidemic rabbits for detection of atherosclerosis in ex vivo samples (dissected arteries) using Ti:Sapphire oscillator at 800 nm (for Raman resonance), 100 fs pulse duration, and a 532 nm 7.25 W green laser provided the pumping. They were able to establish a correlation between the severity of atherosclerosis and age of the animals. Significantly J. T. Motz et al. in 2006 [84] demonstrated (830 nm diode laser) in vivo usage of Raman spectroscopy on diagnosis of atherosclerosis in femoral bypass and breast lumpectomy surgeries. CARS has also been used for the identification and imaging of bacterial spores.

Another technique for amplification of the Raman signal (by 14 or 15 orders of magnitude) is surface-enhanced Raman scattering (SERS) spectroscopy. X. Zhang et al. in 2003 [85] used a 632 nm He-Ne laser to detect low concentration of dipicolinic acid (DPA) using this technique.

6.8.2 Choice of Wavelength in Raman Spectroscopy

These studies mentioned illustrate the range of differing excitation wavelengths used by the various research groups using differing techniques across the decades. However, the common feature is that the wavelength chosen for Raman spectroscopy is mostly in the red or near-infrared region. This is because shorter wavelength particularly below 600 nm will elicit considerable background autofluorescence from cells which can confound and confuse results and also because cells typically have chromophores (proteins, amino acids, nucleic acids, etc.) which will absorb shorter wavelengths and cause cellular alteration or even cell damage (opticution). A key feature of Raman spectroscopy is that it is noninvasive and gives real-time, vital information of living cells. Wavelengths between 600 and 900 nm have low water absorption and elicit more scattering. Blue or green wavelengths have also been used by some studies, but notably these are on fixed cells or ex vivo tissues and not in live homeostasis state of tissues.

6.9 Hard Tissue Applications

Dental caries is often overlooked or continues undetected owing to the insidious nature of the lesion. Radiographic detection often requires at least around 30% of demineralization to warrant detection and uses ionizing radiation [86]. Early detection of incipient caries (noncavitated – «white spot») avoids the use of invasive restorative modalities. Incipient caries has a sub-surface second layer which is very porous and can extend to a depth of 100–250 μ, whereas a cavitated lesion can extend up to 1.5 mm or deeper.

Fibre-optic transillumination (FOTI) and *digital imaging fibre-optic transillumination (DIFOTI)* are transillumination techniques. DIFOTI uses high-intensity light from a fibre-optic device source to illuminate a tooth, and the backscattered light is captured by a digital camera and analyzed by a computer. Carious enamel and dentin would scatter light more than sound tooth structure and appear darker (Fig. 6.12). This technique has the advantage that it precludes the use of ionizing X-radiation and also provides diagnosis in real time, and studies have shown that DIFOTI has a higher sensitivity than conventional radiography. The technique relies heavily on the judgment of the practitioner and suffers from a lot of variability. It does not describe the lesion depth or severity, and this has been reported in a study by Young and Featherstone (2005) [87].

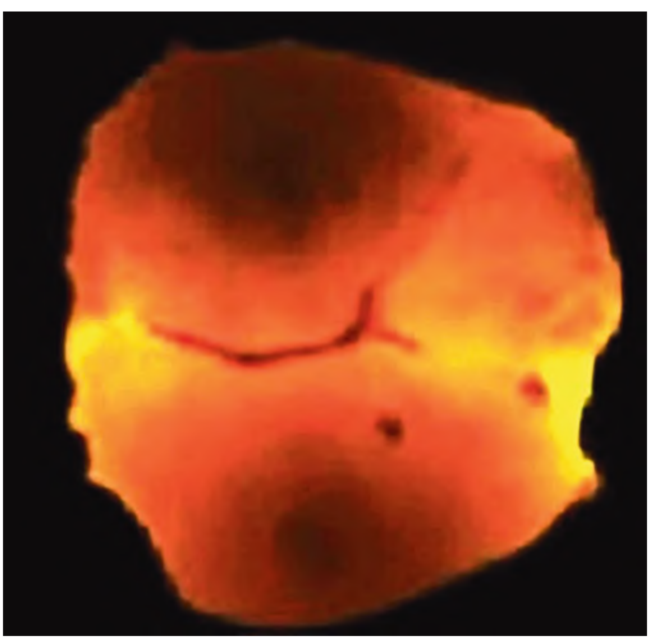


Fig. 6.12 FOTI image – Transillumination depicts the carious areas as darker areas contrasted against sound enamel (Reproduced from Gomez [90] under the terms of the Creative Commons Attribution License (▶ http://creativecommons.org/licenses/by/4.0), © 2015)

M. S. Bin-Shuwaish et al. (2008) [88] evaluated the accuracy of DIFOTI as against digital radiography using complementary metal oxide silicon (CMOS) sensor in 52 patients having class II carious lesions. They concluded that though DIFOTI does significantly detect the lesion depth, particularly smaller lesions, in comparison to radiographs, the technique was less accurate. They add that DIFOTI had a sensitivity and specificity lower than visual examination, however, they remarked that it can be a useful adjunct to radiographic diagnosis [89].

Electroconductivity measurement (ECM) is based on the principle that sound tooth surfaces will have little or no conductivity, whereas areas which have demineralization due to caries would have conductivity proportional to the extent of demineralization. It involves covering the tooth surface with a conducting medium and measuring conductivity using a probe. But this technique had a lot of false positives and lack of specificity. Reports from literature average its accuracy to around 80% [91]. The ECM could be used to predict the probability that a sealant or a sealant restoration would be required within 18–24 months after eruption [92].

A related technique is electrochemical impedance spectroscopy (EIS) which is based on the application of electric currents of differing frequencies to detect carious lesions. Dental hard tissues have their own characteristic electrical signature, and these reference values can be used to detect carious tooth structure as compared to normal enamel and dentin.

On the other hand, laser-assisted diagnostic techniques lend the advantage and accuracy of early detection by assessing biochemical and fluorescent changes in tooth structure. Following on the work of Bommer in 1927 using UV light to detect plaque on tooth, Benedict in 1928 and Hartles and Leaver in 1953, and later Armstrong in 1963, examined the fluorescence of healthy and carious dentin samples under UV light. However it was Alfano who reported the fluorescence of carious teeth at 550 nm on excitation at 488 nm. These foundational works led on to the development of newer and still emerging diagnostic techniques in hard tissues [17].

6.9.1 Quantitative Light Fluorescence and Laser Fluorescence (DIAGNOdent, KaVo)

Based on the technique developed by Bjelkhagen and Sundström (1981) [93] and later applied clinically in vivo in conjunction with Josselin de Jong (1995) [94], quantitative light-induced fluorescence (QLF) traditionally used argon laser light at 488 nm to induce fluorescence in a tooth. More recently, QLF devices use an arc lamp or xenon lamp that generates light at 370 nm light (290–488, violet-blue) that is then transmitted through optical fibre into a handpiece and captured using a charge-coupled device (CCD) camera [95]. The display of natural fluorescence of the tooth would contrast against dark areas of caries where the tooth's natural fluorescence is impeded. The fluorescence generated from the tooth by the exciting light would then be filtered by a high-pass filter which allows only wavelengths greater than 520 nm to be detected. L. Karlsson and S. Tranaeus stated that QLF can detect carious lesions on occlusal and smooth surfaces to a depth of 500μ [95].

QLF is based on the quantitative comparison between the fluorescence values obtained from normal tooth structure and the areas in the tooth which have been demineralised due to caries. The change in fluorescence ΔF (expressed in %), over an area A (in mm), is estimated based on the formula $\Delta Q = \Delta F/A$.

Saliva, plaque and hypoplastic areas would skew the results; nonetheless, an application of QLF that is not so widely researched is that it can detect red fluorescence from bacteria in plaque [95, 96]. But the technique was not able to specifically differentiate between caries, hypoplasia or similar conditions. Another serious limitation of this technique is that it is not able to differentiate or detect lesions extending into dentin [97].

6

An application based on the same concept of autofluorescence is Soprocare (Acteon, France) which uses light at 450 nm from three diode lasers in a clinical handpiece and elicits autofluorescence from the tooth to detect caries or even from plaque and can even detect gingival inflammation. P. Rechmann (2014) [98] et al. reported the use of this device recently. The device has a perio mode that detects plaque in an orange to red gradient and gingival inflammation in a magenta color and a caries mode that could detect carious areas as red fluorescent regions. In their study on 55 subjects and 638 teeth, they compared the Soprocare autofluorescence grading of plaque and gingival inflammation to conventional grading methods such as Loe and Silness index for gingival inflammation and a plaque index, which was a Turesky Modification of the Quigley Hein Plaque Index. They concluded that the autofluorescence method of Soprocare correlated well to the clinical evaluation methods for plaque and gingival inflammation (Fig. 6.13).

In the technique of laser fluorescence (DIAGNOdent, KaVo), longitudinal laser light at 655 nm is directed at the tooth substrate, and the reflected fluorescence from bacterially produced porphyrins is detected and measured (much like the detection of sarcomas described by P Policard as early as 1924). This technique was developed based on the work of Hibst R. and Gall R. The amount of fluorescence produced can be graded (0–99) and correlated to the extent of caries (5–25 enamel caries, dentin caries greater than 35). Dental plaque, stains, calculus and deposits could influence and interfere with the diagnostic results of this modality. Various studies have given different sets of validity and accuracy to the DIAGNOdent's assessment and specificity, but most of them are in vitro and cannot perhaps be directly extrapolated to clinical practice as such studies do not simulate clinical scenarios. In a clinical situation DIAGNOdent readings may be adversely affected by stains, calculus or even developmental or mineralization anomalies of teeth [99].

E. Barberia et al. (2008) [100] reported a specificity of 89% in a convenience sample of 320 molar teeth in children aged 6–14 years where the DIAGNOdent was able to successfully diagnose carious lesions with a high sensitivity of 0.89 in primary molars but only 0.40 in permanent molar teeth and a specificity of 0.87 overall. Lussi et al. (2001) [101] in a previous clinical study had showed that DIAGNOdent was not able to clearly differentiate between superficial and deep dentinal caries.

Differences between QLF and DIAGNOdent

QLF uses a much shorter wavelength at 488 nm and is designed to detect and receive 540 nm autofluorescent light from the enamel (it filters out the shorter wavelength scattered light suing a 520 nm filter)

The DIAGNOdent uses a longer wavelength 655 nm light and measures fluorescence intensity (uses a 680 nm filter).

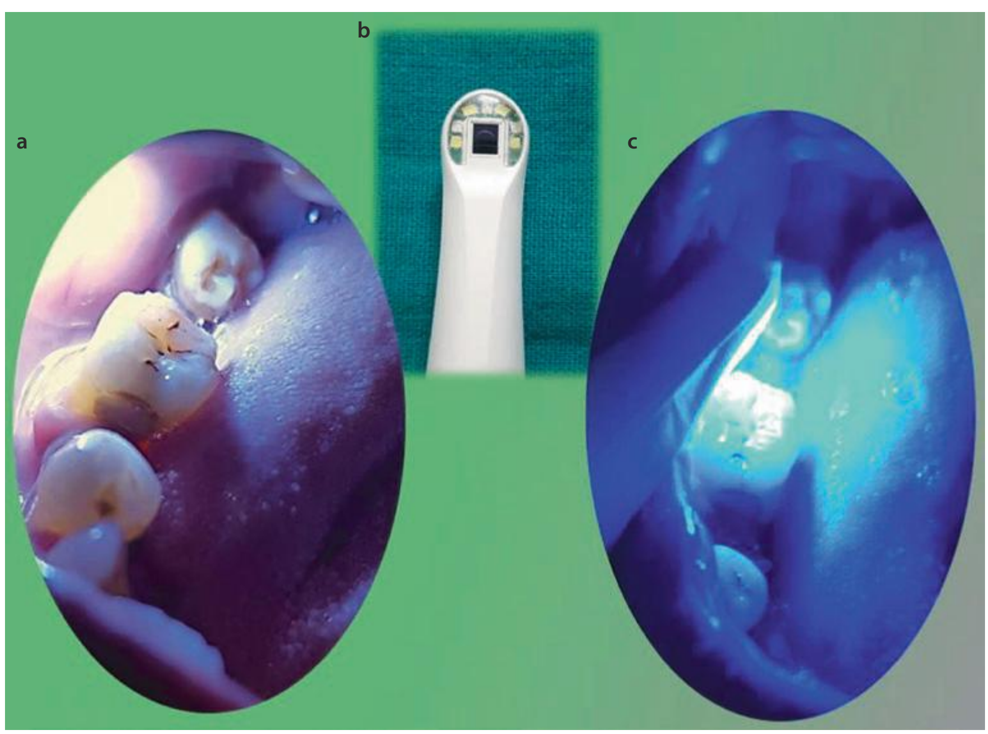


Fig. 6.13 Soprocare autofluorescence showing **a** carious tooth in daylight mode, **b** the Soprocare handpiece with three *blue* light-emitting diode lasers, and **c** carious tooth in *blue* light autofluorescence (Courtesy Dr. Niladri Maiti)

DIAGNOdent can be related to dentinal decay but QLF results cannot correlate with dentinal decay.

QLF measures the amount of induced natural (autofluorescence) fluorescence from the tooth structure, particularly enamel; hence it is better suited for detection of early lesions and more so on smooth surfaces rather than occlusal or in fissures [102]. This autofluorescence decreases according to the severity (demineralization) of the carious lesion.

DIAGNOdent detects and grades fluorescence released from metabolites and organic molecules such as protoporphyrin IX and coporphyrin IX released by bacteria which absorbs the red laser light (655 nm) of DIAGNOdent. It can hence even monitor the progression of the lesion [97, 101].

> American Association of Dental Consultants (AADC) position statement [103] on laser fluorescence in caries diagnosis based on the studies and clinical trials conducted states that, "laser fluorescence can be used as an adjunct to traditional caries detection methods and not used as a primary diagnostic tool."

6.9.2 Raman Spectroscopy in Hard Tissues

Raman spectroscopy has varied noninvasive diagnostic applications for oral hard tissues. The precision of such techniques makes it invaluable in the early diagnosis of carious lesions. Tactile, visual or radiographic detection perhaps is not until the carious lesion has considerably progressed with an accompanying quantum of mineral loss from the teeth whereas this diagnostic technique is even able to identify changes in crystallinity such as orientation and symmetry of crystals of the tooth structure.

Raman spectroscopy has also found useful indication in the detection of fluorosis and manifestations of developmental disorders such as amelogenesis imperfecta and characterization of the mineral phases in calculus. The fluorophores that could be detected by Raman spectroscopy are also produced by various groups of bacteria too; hence detection of plaque or incipient carious lesions is also possible.

Raman spectroscopy has been applied experimentally for the compositional assessment of bone by evaluating bone mineral characteristics and collagen. A. J. Makowski et al. in 2013 [104] used phase matching (for polarization control) with confocal Raman microscope at 785 nm on cadaveric specimens of femur bone of both genders in a diverse age group of 48–96. They found that phase matching (to quantify the phase and amplitude Raman peaks of bone) to reduce polarization bias could give specific diagnostic information related to peak rations of bone composition like mineral to collagen ratios; however, they added that optimizing polarization is necessary for specific discrimination between bone characteristics.

Raman spectroscopy is unique and unparalleled in caries detection as it allows for wide spatial resolution and thus early diagnosis of caries. A range of studies have been conducted in this area in the past decade comparing this technique to conventional methods and other spectroscopic methods and has lent a lot of clarity to this technique sensitive area of diagnosis. A.C. Ko et al. (2005) [105] discussed a technique combining the high resolution, (20μ) [106], morphological imaging of OCT with the biochemical and molecular specificity of Raman spectroscopy in the diagnosis of dental caries. The OCT images were acquired using a diode laser 850 nm and spot size 10–20 μ at 750 μW, and Raman spectroscopic data was acquired using an 830 nm diode laser at 24–52 mW from tooth samples extracted for orthodontics reasons (caries free and with incipient caries). While OCT images lend morphological depth as to the extent and spread of the carious lesion, Raman spectroscopy could diagnose even early and incipient caries through biochemical changes (Table 6.2).

F. B. De Carvalho et al. (2013) [107] compared Raman spectroscopic techniques to laser fluorescence (DIAGNOdent) measurements on teeth having smooth surface carious lesions and noncarious lesions. Raman spectra were obtained using a 785 nm, 500 mW diode laser with a 20 s exposure time. They concluded that the DIAGNOdent could not detect subtle changes in mineral content such as in an incipient carious lesion and had a lower sensitivity as compared to the specific detection of mineral changes by Raman spectroscopy. The DIAGNOdent was able to detect organic changes much more than inorganic changes, and this they felt corroborates the finding of earlier studies regarding the suitability of DIAGNOdent for initial detection of caries.

B. Coello et al. (2015) [108] proposed diagnostic quantitative mineralization indices of teeth through Raman spectroscopy with the objective of establishing a diagnostic scale with regard to demineralization. Raman spectra were obtained using an Nd.YAG laser at 1500 mW, from different zones of extracted teeth. They concluded that the ability of Raman spectroscopy to assess and differentiate the organic and inorganic areas of the tooth qualifies it to assess demineralization of the tooth. The MIb (mineralization index bending) and MIs (mineralization index stretching) indices, which they suggested, were able to diagnose even initial demineralization and demonstrated the value of Raman spectroscopy in this area. Thus Raman spectroscopy can be a convenient and effective modality in diagnosis and monitoring of diseases like fluorosis and amelogenesis imperfecta.

Similarly Raman spectroscopy was able to deepen our understanding of the chemical composition and make up of dentin, particularly in laying to rest the speculation about the composition and make up (organic and inorganic) of peritubular and intertubular dentin. C. Xu and Y. Wang (2012) [109] cleared the confusion regarding the collagenous or noncollagenous nature of the peritubular dentin and composition of the intertubular dentin using micro-Raman spectroscopy (μRs) with a He-Ne (632.8 nm) laser, 60 s, and atomic force microscopy (AFM). They proved that the peritubular dentin was hypermineralized with respect to the intertubular dentin with a mineral: matrix ratio three times

Table 6.2 Raman spectral bands and assignments

Spectral bands	Assignments	Author
431, 446 cm^{-1}	Phosphate PO_4^{-3} (symmetric bending ν_2)	Ko et al. [105] Coello [108]
579,590, 608, 614 cm^{-1}	Phosphate PO_4^{-3} (asymmetric bending ν_4)	Ko et al. [105]
~575 cm^{-1}	Fluoridated apatite	de Carvalho et al. [107]
~960 $cm^{-1}{}_4$	Symmetric stretching (ν_1) phosphate hydroxyapatite	Ko et al. [105] de Carvalho et al. [107]
1023, 1043, 1046 cm^{-1}, 1052, 1069 cm–1071 cm^{-1}	Asymmetric stretching vibration PO_4^{-3} (ν_3)	Ko et al. [105] Coello [108]
1069 cm^{-1}	Symmetric stretching mode of CO [3]-type B (ν_1)	A. Boskey et al. [110]
1104 cm^{-1}	Symmetric stretching mode of CO [3]-type A (ν_1)	A. Boskey et al. [110]
1200–1400 cm^{-1}	Amide III	Coello [108]
~1450 cm^{-1}	Organic matrix	de Carvalho et al. [107]
1670 cm^{-1}	Amide I	Xu and Wang [109]
2941 cm^{-1}	Lipids and proteins, (C-H and C-H_2 groups)	Coello et al. [108]
2874 cm^{-1}	Unsaturated bonds of lipids	Coello et al. [108]
2926 cm^{-1}	Saturated bonds of lipids	Coello et al. [108]

higher than the intertubular dentin. The study showed that the peritubular dentin had an inorganic content of 96% (organic content of 4%) as compared to the inorganic content of 88% (organic content of 12%) for intertubular dentin though the crystalline nature of the peritubular dentin was much similar to the intertubular dentin.

6.9.3 Optical Coherence Tomography in Hard Tissues

OCT or its newer adapted advanced versions provides for varied and versatile applications in hard tissues such as the detection of caries and even marginal gaps of restorations or cracks in teeth. Y. Shimada (2015, 2012) [111] illustrated this in his review article.

Polarization-sensitive OCT (PS-OCT), a functional OCT technique, with near-infrared excitation could give structural and positional information based on birefringence of the sample and polarization of backscattered light [112]. PS-OCT can detail dental carious lesions and give images which potentially can even monitor the progression of lesions over time [113].

X. J. Wang et al. (1999) [114] had shown that PS-OCT using 856 nm, 0.8 W diode laser, could be applied towards the investigations of enamel and dentin by analyzing their intrinsic birefringence. They were able to determine refractive index values of enamel and dentin, but though banded birefringence of enamel crystals was seen up to the enamel dentin junction, considerable scattering and anisotropy in dentin were observed with no birefringence and resolution of finer features [115]. Gossage KW et al. (2003) [116] had stated that this was due to speckle interference (in dentin structures such as collagen form birefringence) and that speckle noise prevents resolution of structures and gives only sub resolution features.

However, dentin of attrited teeth was investigated successfully by M. M. Mandurah et al. (2015) [117] using swept-source OCT in extracted teeth, where a 1310 nm laser (use of longer wavelength gives greater penetration and more resolution of the deeper layers) with higher-frequency scanning speeds of 20 kHz provides better axial (11 μ) and lateral resolution (17 μ). Y. Shimada et al. (2010) [118] had shown that this technique could deliver an imaging depth of up to 2–3 mm. The dentin showed different backscattering patterns between carious and sound dentin, and in attrited dentin there was a low attenuation coefficient because of the sclerosed dentinal tubules. P. Makishi et al. (2011) [119] and Bakhsh et al. (2011) [120] had used the same modality for evaluation of marginal adaptation of resin-based restorations in class I cavities. The authors report that gaps up to even a half micron could be detected by SS OCT

En face OCT, a time domain OCT technique, is a newer advancement that provides the ability to precisely localize lesions by giving transverse (cross sectional) images of layers at a specified even microscopic depth. C. Todea et al. (2010) [121] used en face OCT to evaluate and compare the quality of endodontic treatment between diode laser assisted (980 nm), Nd.YAG laser assisted (1064 nm) and conventional groups of extracted teeth. They found that though all the groups had obturation defects, the laser groups had significantly lesser defects compared to the conventional group and that en face OCT allowed a precise, noninvasive, diagnostic evaluation.

6.9.4 Laser-Induced Breakdown Spectroscopy in Hard Tissue and Soft Tissue

Laser-induced breakdown spectroscopy (LIBS) works on the principle that highly intense but very short laser pulses of ultraviolet (UV), visible or infrared range (IR) would ablate target tissue into an expanding plasma plume of electrons, ions and atoms. This luminous plasma plume would emit characteristic qualitative and quantitative structural and molecular information about the tissue being examined. The creation of such plasma and theoretical basis of its breakdown was first suggested by R. V. Ambartsumyan and N. G. Basov et al. [122] as early as 1965 (unpublished work by W. S. Boyle 1962); however, it was J. Maxwell who gave the first description of the equipment which used a Q-switched ruby laser at the Jarrell Ash laboratory. Later R. Rosan [123] presented the first spectra on biologic samples using this equipment at the First Annual Conference on Biologic Effects of Laser Radiation at Washington, USA, in 1964.

The phenomenon of plasma formation, «optical breakdown» through shock wave generation, cavitation and jet formation by the Nd.YLF laser (1053 nm) with 30 ps pulses, 30 μ spot size, and 1 mJ pulse energy was discussed in detail by M.H. Niemz in his textbook [14]. Further and sustained laser pulses can lead to a cascade of laser induced plasma. This was proven further in Niemz's work (1994) [124] on LIBS for diagnosis of caries. Ca and Na spectral lines were observed in healthy and carious teeth. The spectra from carious tooth mineral were «weaker» (in intensity and line width) than those from healthy tooth structure.

Samek et al. (2001) [125] used a Q-switched Nd.YAG laser, 1064 nm at 20 Hz, 4–8 ns pulses, with pulse energy 10–30 mJ on 159 carious and healthy extracted teeth and even in vivo on the molar tooth of a volunteer. They confirmed that LIBS along with pattern recognition algorithms like discriminant analysis is able to positively identify between carious and healthy tooth structure to a precision of 100–200 μ laterally and 10 μ in depth. They inferred that this is possible through analysis of the spectra of matrix elements such as Ca or P and non-matrix elements like Li, Sr, Ba, Na, Mg, Zn and C using pattern recognition algorithms. They stated that in carious tooth structure there would be a decrease in matrix elements and an increase in non-matrix elements.

LIBS has found varied applications [126] in the breakdown or (Fang et al. 2005) [127], qualitative and quantitative characterization of urinary and kidney stones (Singh VK et al. [128], Anzano et al. 2009 [129], Pathak et al. 2011 [130, 131]) or gall bladder stones and even the analysis of fluids (Wu et al. 2008 [132]) like those containing glucose or organic matter.

6.10 Photodynamic Diagnosis

Photodynamic therapy has manifold applications in dentistry, from invaluable and unparalleled use in implantology, periodontal disease, dental caries, endodontic infections, oral mucosal lesions, mucosal infections such as in candidiasis and also in diagnosis and treatment of oral neoplasias. Photodynamic therapy involves the administration of a photosensitizer (topically, intravenously or locally), which is a spectrally adapted chromophore (mostly organic dyes), which means it can be activated by a light of a particular wavelength(s) of the electromagnetically spectrum only. It accumulates by having a selective uptake at areas of diseased or pathologic tissues (areas of rapid cell turn over). It then undergoes certain molecular or chemical transformations on absorption of the light (of a particular wavelength) and is excited from the ground state to an excited triplet state. The triplet state can interact directly with biomolecules producing free radicals or with molecular oxygen producing reactive oxygen species like singlet oxygen, superoxide and hydroxyl radicals. These can prove to be cytotoxic by causing disruption of phospholipid molecules of cellular membranes and even DNA.

Migita M et al. (2010) [133] demonstrated the use of talaporfin sodium (mono-L-aspartyl chlorin e6/NPe6) in conjunction with a hyperspectral imaging system in detecting oral squamous cell carcinoma in 69 Sprague Dawley rats to which a carcinogen was administered. 5 mg/kg of talaporfin sodium was given intravenously in 0.1 ml saline and the subjects were kept in the dark. Talaporfin is expected to have selective uptake and accumulate at areas of the squamous cell carcinoma. After the animals were sacrificed and the absorbance of 664 nm light by talaporfin sodium in tissue was measured by hyperspectral imaging and compared to histological samples, the tissues were classified as normal or neoplastic. The study proved the efficiency of talaporfin sodium in photodynamic diagnosis in that it had higher absorbance signifying higher accumulation at areas of neoplastic tissue than normal tissue. The authors surmise that this is because there is a higher rate of intranuclear cell division in the areas of squamous cell carcinoma and this would engender higher uptake of the photosensitizer.

C. J. Chang et al. (2005) [134] evaluated the efficacy of Photofrin (Porfimer sodium) in photodynamic diagnosis in hamsters. Carcinoma was induced in cheek pouches and the photosensitizer was applied topically. They used xenon lamp (380–420 nm) for excitation of the photosensitizer after 3 h. The digital images were then analyzed using Photoshop 5.0 software under RGB gradient and grey scale modes. The biopsies from the cheek tissues were taken and studied histologically. They concluded that Photofrin indeed had clearly made identification of the neoplastic areas better with a high degree of sensitivity (93.27%) and specificity (97.17%). They believed that topical application was better than the intravenous administration of photosensitizers as there could be possibility of other areas being affected other than the tumor site. They stated that the fluorescence emitted from Photofrin is because of its interaction with endogenous protoporphyrin IX (PP IX) in the tumor areas.

6.10.1 Laser Doppler Flowmetry

Laser Doppler flowmetry (LDF), originally in development, termed as laser Doppler velocimetry, uses laser light (632, 780–820 nm) to measure pulpal blood flow and thus tooth vitality by measuring the backscatter (change in frequency or collimation) on the same principle of interferometry as used in OCT. Though the first reports of clinical use of this technique in ophthalmology came in the early 1970s (Riva C et al. 1972 [135]), the adaptation of this technique to dentistry was only in the late 1980s (Gazelius et al., 1986 [136], Olgart et al., 1988 [137]).

Laser Doppler flowmetry has since then found a range of applications in dentistry, though chiefly in endodontics and pediatric dentistry (in assessing the pulpal vitality of traumatized or avulsed teeth [138, 139] and age-related changes in pulp [140]) but also in other fields like in orthodontics (measuring pulpal blood flow during tooth movement and treatment such as rapid maxillary expansion [141, 142] (RME)), in maxillofacial surgery (to confirm the vitality of teeth after orthognathic surgery [143] and revascularization of reimplanted teeth [144, 145]) and even in implantology (as an aid in evaluating implant stability [146, 147]).

A range of review articles describe the reliability, role and value of this diagnostic measure [148]. Unlike other biomedical applications where LDF is limited or affected by artifacts produced by movement of the imaged structure (such as the heart), in dentistry the tooth, alveolar bone or periodontal structures are static, and the only movement is that of the red blood cells in the pulp and their mean velocity per second. Polat et al. 2005 [149] have shown that LDF could penetrate up to 6–13 mm (depending on the density) in teeth.

However, it does have limitations, LDF may not be very effective in teeth with restorations, the signal being affected by adjacent tissues like periodontal tissues and requiring isolation of the teeth being examined by a rubber dam or cotton rolls. Variations between the anatomy and position of the tooth in the arch, the laser wavelength, frequency of bandwidth and filter, probe design and fibre separation (250–500 μ) all can affect the reliability of LDF. But studies have attributed 80–90% accuracy for pulp vitality assessments (Wilder-Smith 1988 [150], Evans et al. 1999 [151], Roeykens et al. 1999 [152], Roebuck et al. 2000 [153]). It is definitely a noninvasive method, but incumbent costs and initial investment have yet to make it a ubiquitous diagnostic methodology [154].

Conclusion

Lasers have virtually ushered in a newer, accurate, and noninvasive era in diagnosis. Laser-assisted diagnostic techniques have indeed shed light on the intricacies of disease processes and lent better modalities to treat them. In developing a theory for the mechanism of homeopathy, Emilio del Giudice [155] suggests that the electromagnetic information of a substance can be transferred into the surrounding water molecules there by affecting the field produced by a large group of molecules). Light and its electromagnetic energy are similarly transferred to molecules such as fluorophores or photosensitizers.

William Ross Adey [156] further illustrates this idea by stating «Biological effects of oscillating environmental electric fields are related to the electric gradient which they introduce in the tissue. This will be determined by the degree of coupling between the field and the tissues». Such coupling of energy (or loss of energy) can be detected by spectroscopic processes to the extent that they elucidate molecular mechanisms of functioning in cells and their biochemical structure. These techniques do give us the early start over disease processes by diagnosis of incipient lesions or neoplasia, yet translating research into painless, nonintrusive treatment methodologies still remains a challenge and is at a pioneering stage

Laser-assisted diagnosis has indeed given us the winning edge over disease and infection, yet today's understanding is but at the verge and threshold of greater discoveries which need to be proofed by future research work.

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Suggested Further Reading

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PBM. Theoretical and Applied Concepts of Adjunctive Use of LLLT/PBM Within Clinical Dentistry

Ercole Romagnoli and Adriana Cafaro

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Core Message

Low-level laser therapy (LLLT), nowadays also known as photobiomodulation, consists of the therapeutic use of monochromatic coherent (laser) or noncoherent (LED) light sources.

Light can be considered a drug at all effects, having the advantage of few contraindications and of the lack of significant adverse or side effects and interactions, therefore being a perfect example of mini-invasive therapy.

Starting from the photo-physical phenomenon of the absorption of light by intracellular photo-acceptors, located in mitochondria, a chain of biochemical reaction is triggered, leading to the increase of the available energy under the form of ATP and to the downstream activation of pathways at cellular level that modulate the subsequent effects at tissue level.

The clinical effects of LLLT are anti-inflammatory, analgesic, biostimulating, and also bactericidal. As such, the derived clinical applications are those where these effects can be helpful in reducing pain, speeding up the inflammatory processes, and the healing of injured tissues. All branches of clinical dentistry can take advantage of LLLT. Even if there is no universal consensus about the managing parameters, some simple rules and precautions enable to perform treatments based on the best available evidence.

7.1 Introduction and Historical Background

Low-level laser therapy (LLLT) is a medical treatment that utilizes monochromatic light to interact with specific tissue chromophores in order to achieve positive effects in terms of analgesia, anti-inflammatory action, biostimulation, and bactericidal activity.

Further to these basic concepts, we can point out three different aspects:

- **Low Level**
  The energy parameters are set in a different way from those used in other applications, such as surgery.
- **Laser**
  A source of monochromatic coherent light is used; however, LEDs (noncoherent monochromatic light-emitting diode light sources) are included in a group of the available devices.
- **Therapy**
  The objective is the treatment of symptoms and clinical manifestations of pathologies and diseases.

The beneficial and therapeutic properties of light have been acknowledged since antiquity, and ancient peoples have identified the light and its power with deities, like Ra, the Egyptian god of sun.

It was known to the Egyptians, as well as to the Hindus and Arabs, the ability of light to interact with some vegetable substances to heal some skin diseases, like psoriasis and vitiligo, an archaic form of photodynamic therapy [1]. At the end of the nineteenth century, after some sporadic observations about the bactericidal properties of sunlight [2], Ryberg Finsen invented a device for the treatment of «lupus vulgaris» (a painful cutaneous tuberculous skin lesion), and in 1903 he was awarded a Nobel Prize [3, 4].

Heliotherapy (exposure to sunlight) in the pre-antibiotic era, was a widespread therapeutic option for tuberculosis, a disease very difficult to treat and with a high social impact [5].

It is interesting to note that even at that time it was observed that an overexposure to sunlight could lead to undesired effects: the origins of the «dose» concept.

In 1960 Theodore Maiman realized the first laser – a ruby laser (694 nm) – and the surgical possibilities of laser use were first investigated within the field of medicine.

In Hungary the physician Andrè Mester was studying the use of a ruby laser in oncology. He observed the regression of a skin melanoma after irradiation with a defective device, delivering insufficient energy for a surgical action. After he implanted cancer cells under the shaved skin of lab rats and irradiated the implantation area of some of them with a common ruby laser. Surprisingly the healing of the surgical incision and the hair regrowth were faster in the irradiated mice [6–8] .

Mester called this effect «biostimulation» and continued his studies in the following years, highlighting a relationship between dose and effect, verifying that an excess of energy leads to bioinhibition instead of biostimulation. Due to his research and to the discovery of the possibilities to modulate the effects of laser irradiation, Andrè Mester can be considered «the father of photobiomodulation,» a new concept that enables to elaborate a definition for laser therapy:

> *Laser therapy (application of photonic energy at specific wavelengths) works on the principle of inducing a biological response through energy transfer, in that the photonic energy delivered into the tissue by the laser MODULATES the biological processes within that tissue and within the biological system of which that tissue is a part. LLLT has no appreciable thermal effect in irradiated tissue. (Prof. Steven Parker, MSc in Laser Dentistry, University of Genoa, Italy)*

Now universally accepted, the term «photobiomodulation» being correlated to the mechanism underlying light therapy is replacing the different acronyms correlated to laser therapy, such as low-level laser therapy (LLLT), low-power laser therapy (LPLT), low-energy laser therapy (LELT), low-intensity laser therapy (LILT), high-intensity laser therapy (HILT), and so on.

In our dissertation, we'll use indifferently the acronyms low-level laser therapy (LLLT) or photobiomodulation (PBM).

In the years following Mester's discoveries, there has been an exponential increase in studies about the nonsurgical applications of laser photonic energy, as well as about the management of the energetic parameters in order to assess the potentials of this revolutionary therapeutic approach and to define accepted protocols.

On one hand this has led to a development of the possible applications; on the other hand, due to the high number of variables, there are still difficulties while obtaining the scientific evidence necessary to validate clinical evidence.

A review of published literature, using the keyword «LLLT» offers a wide range of scientific articles. PubMed www.ncbi.nlm.nih.7gov/pubmed) provides more than 3000 articles published in the last 10 years and about 700 specifically with the keywords «LLLT dentistry.» The reports are partially contradictory, and careful reading of the articles shows that in many cases negative results depend on mistakes in the management of the energetic parameters or in the irradiation technique [9–11].

The clinical evidence supports the fact that light can be considered a drug and, like a drug, can induce local and systemic effects. In 2013 Tiina Karu, expert and worldwide recognized researcher, underlined the importance of the developments in clinical applications in several fields of medicine that takes advantage from photobiomodulation [12]. Observed effects range from the neuroprotective action in Parkinson's disease to the treatment of myocardial infarction, from a protective action on the retina to nerve regeneration, from prevention and treatment of chemo- and radio-induced oral mucositis to the acceleration of wound healing, and so on. The prescription of a drug requires the knowledge of its active principle, pharmacokinetics, toxicity, side effects, interactions, dosage, duration of treatment, and modalities of administration.

The same applies for light, with the significant difference that undesirable side effects, toxicity, and interactions are virtually nil or comparable to a placebo, as results from the scientific literature are available [13–17].

One of the main goals of modern medicine is to reduce invasive aspects of therapeutic pathways, from diagnosis to surgery and to physical or pharmacological treatments. Endoscopy, medical imaging reducing the use or the dose of ionizing radiation, and new drugs with less side effects are examples of this tendency, where the central thread is the concept of health as stated by the World Health Organization (WHO) in 1946: «good health is a state of complete physical, social and mental well-being, and not merely the absence of disease or infirmity.»

It is worth pointing out that the invasiveness of a procedure depends not only on the procedure itself or on its secondary pharmacological treatment or its outcomes (pain, slow healing, functional impotence) but also on patient conditions, such as age, illness, disability, comorbidity, concomitant pharmacological treatments, or simply anxiety.

LLLT is perfectly included among the therapeutic tools available nowadays that can reduce the invasiveness of the clinical procedures, and this cannot be ignored from a deontological and ethical point of view [18].

7.2 Mechanism of LLLT

The principle of conservation of energy determines and rules the existence and development of life. Every form of energy can be converted to another form but never destroyed.

The first step in the interaction of light with living matter is photo-physical. The light of a given wavelength is absorbed by specific molecular chromophores that consequently become excited. If no absorption occurs, no photobiological and no phototherapeutic effects will be observed (first law of photobiology) [19]. The natural tendency to return to a more stable state (ground state) is satisfied through different possible pathways, non-radiative when the stored energy is released as heat (vibrational relaxation and internal conversion) or radiative (fluorescence). We may have a transition from the excited state (singlet) to a more stable and long-lived one (triplet state, with a change in the spin state, having unpaired electrons). The residual energy can be released through radiative processes (phosphorescence or delayed fluorescence) or used to trigger photochemical reactions, favored by the long life of the triplet state, transferring electrons to molecular targets [20, 21].

The sun is the primary and essential source of energy, and chlorophyll photosynthesis is an example of one of the interactions of light (in this case nonionizing radiation) with living organisms, interactions that are studied by the science of photobiology.

Chlorophyll photosynthesis is a photochemical process, whereby solar energy, absorbed by green plants, is converted into chemical energy, stored in the bonds of glucose and oxygen.

This is the starting point of the food chain and the human being, as a consumer, is at the top of this chain.

The foods introduced with the diet (organic matter) will undergo catabolic processes to be converted into energy used for anabolic processes and other cellular functions (biosynthesis, locomotion, or transportation of molecules across cell membranes): this is known as «cellular respiration» that requires oxygen (O_2) in order to create adenosine triphosphate (ATP).

ATP is the molecule used to store energy that can be released through its hydrolysis. Glycolysis, Krebs cycle, and overall oxidative phosphorylation are the principal mechanisms of production of ATP.

At cellular level, the combustible molecules like glucose (and also fat acids and amino acids) are transformed into acetyl CoA, a coenzyme. In cytoplasm the glycolysis degrades glucose to pyruvate that is transported inside the mitochondria where it is oxidized by a specific dehydrogenase to acetyl CoA (oxidative decarbonization)

Acetyl CoA is the substrate of citric acid cycle – also known as tricarboxylic acid cycle (TCA) or Krebs cycle, a series of chemical reactions involved in many biochemical pathways.

During the several steps of the cycle, the coenzymes nicotinamide adenine dinucleotide (NAD) and flavin adenine dinucleotide (FAD) are involved in redox reactions, act as electron carriers, accept electrons from other molecules, and are reduced to NADH and FADH2, electron donors and reducing agents.

NADH and FADH2 enter the oxidative phosphorylation (electron transport) pathway. Several redox reactions occur

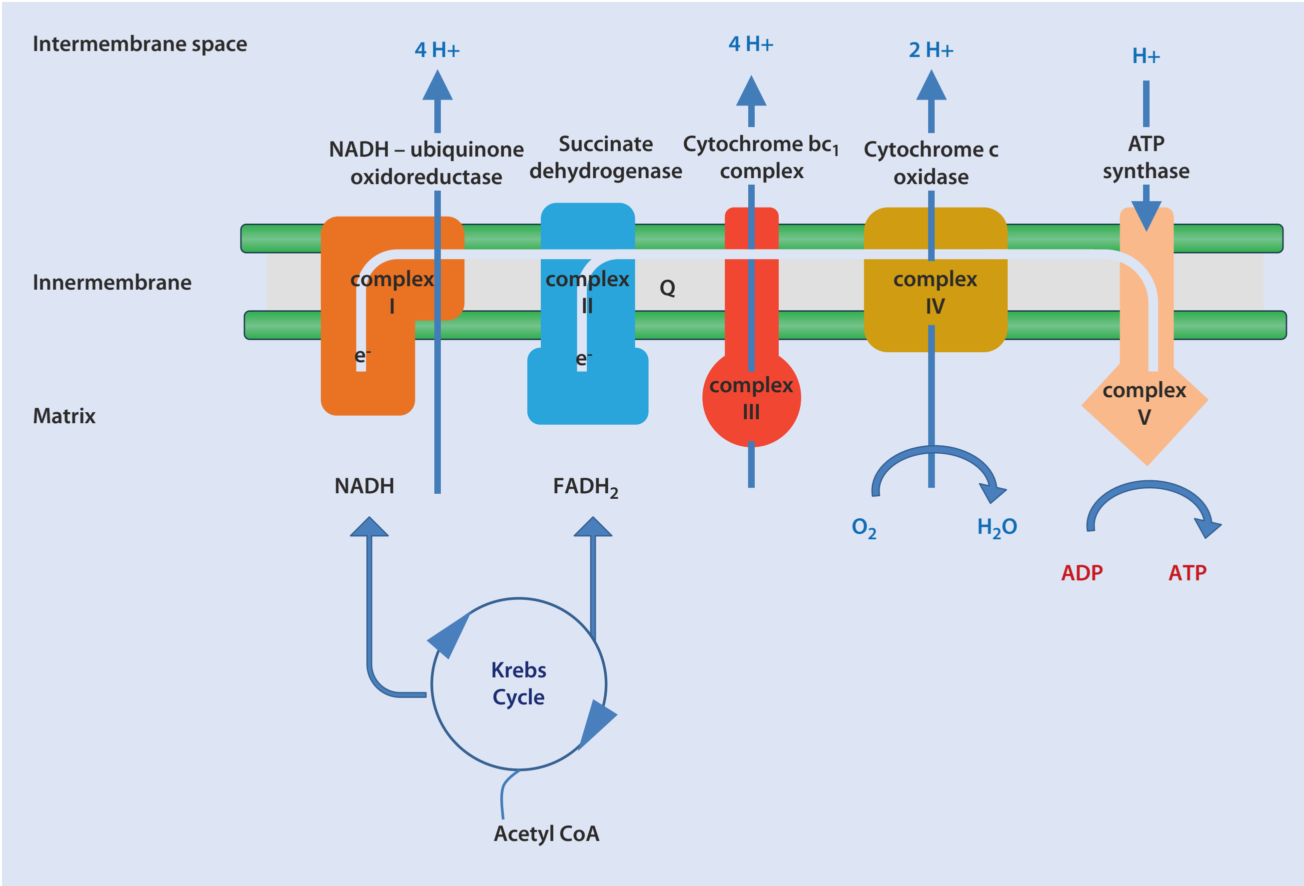


Fig. 7.1 Mitochondrial respiratory chain

carried out by a series of five protein complexes located in the inner membrane of mitochondria and linked each other to form the «electron transport chain» or «respiratory chain» where molecular oxygen is the final acceptor of electrons in aerobic respiration (Fig. 7.1).

Cytochrome c oxidase (CcOx) complex IV of the chain catalyzes the final step of electron transfer. It receives electrons from complex III (cytochrome c) and reduces oxygen to make H_2O.

The electron transport is coupled with the transfer of protons across the inner mitochondrial membrane, generating a proton gradient able to activate the ATP synthase enzyme. ATP synthase catalyzes the phosphorylation of ADT to ATP, using the electrochemical energy of the proton gradient.

The phosphorylation also produces free radicals, by-products like reactive oxygen species ((ROS) that include superoxide ion, hydrogen peroxide, and hydroxyl radical) and reactive nitrogen species ((RNS) such as nitric oxide).

These molecules play a significant role in cell signaling, regulating several functions like protein synthesis, nucleic acid synthesis, enzyme activation, and the progression of the cell cycle [22, 25].

The electron transfer reactions of the respiratory chain can be accelerated by the generation of electronically excited states induced by photon absorption [20, 22]. At cellular level this leads to an acceleration of the synthesis processes, like the production of ATP [23–25].

The ability of a chromophore to absorb light of different wavelengths can be plotted as an «absorption spectrum» that gives us the information about the probability that the energy of light of a given wavelength will be absorbed. Different wavelengths will be absorbed more or less by a specific chromophore, leading to different intensities of the biological process in which the chromophore is involved. It is possible to plot an «action spectrum» for every given biological effect that enables to choose the optimum wavelength and the optimum dose of radiation and to extrapolate, comparing absorption spectra and action spectra, which could be the ultimate target. For example, comparing the absorption spectrum of cytochrome c oxidase, its action spectrum, and the production of ATP, it's possible to support the hypothesis that cytochrome c oxidase is the primary photo-acceptor [26–28].

Nitric oxide (NO) is another important element that can be involved in the mechanisms underlying LLLT. It is produced by the enzyme NO synthase that degrades arginine to citrulline releasing a molecule of NO, a potent vasodilator. It acts as a second messenger, able to modulate the activity of enzymes like guanylyl cyclase that synthesizes cyclic guanosine monophosphate (cGMP) starting from guanosine-5′-triphosphate (GTP). cGMP relaxes smooth muscle of tissues and blood vessels, inducing vasodilation that leads to an increased blood flow.

NO can also act regulating the cell respiration, binding to cytochrome c oxidase and competing with oxygen, as an answer to environmental conditions that make necessary to divert oxygen to other sites. This creates a hypoxic situation, increasing the oxidative stress. This leads to the activation of transcription factors and a downstream production of pro-inflammatory and anti-inflammatory mediators. It is also supposed that NO might be involved in the production of ROS by mitochondria, ROS that, at low concentrations, have a role in the regulation of apoptosis and that can trigger the activation of key transcription factors like nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB), a protein complex that controls transcription of DNA, cytokine production, and cell survival [29–32].

PBM acts by dissociating NO from its binding sites to CcOx, leading to an increase in ATP production and to a reduction of the oxidative stress by balancing prooxidant and antioxidant mediators.

Another possible mechanism of LLLT could be the release of calcium ions Ca++, involved in several biochemical pathways like signal transduction, from the intracellular depots due to a small thermal increase, a nonspecific effect following the absorption of energy by specific photo-acceptors [33, 34].

Summarizing, even if all the mechanisms underlying the effects of LLLT have not been completely clarified, the evidence nowadays available shows that there is a chain of events that starts from a biophysical event (the absorption of the light by a intracellular chromophore) and continues with biochemical effects at cellular level and subsequent biological effects at tissue level, responsible for the clinical performances of LLLT: anti-inflammatory effects, analgesia, biostimulation, and also bactericidal effects.

7.3 Clinical Application Step by Step

A correct management of the energy delivered with LLLT involves several parameters and factors that stem from a proper planning of a diagnostic and therapeutic pathway. The flowchart can be synthesized as follows:

- **Diagnosis**
- **Protocol**
- **Safety**
- **Setting**
- **Treatment**
- **Follow-up**

7.3.1 Diagnosis

Diagnosis is the first step, common to every kind of therapy. Caution is even more necessary when it is considered the possibility that the treatment involves lesions that could be neoplastic or adjacent to neoplastic pathologies.

Photons of the light usually used in the LLLT (red, near infrared) have not enough energy to break the molecular chemical bonds of nucleic acids (DNA); therefore, they are not carcinogenic, but from a conceptual point of view, the biostimulation could speed up proliferative processes underway.

Under this point of view, the literature is contradictory. In 2013 Myakishev-Rempel et al. [35] in a study about the irradiation of UV skin tumors with red light induced in the rat found a transitory reduction of the neoplastic area compared to the control.

In 2013, Sperandio et al. [36] studying dysplastic and neoplastic cellular lines irradiated with 660 nm and 980 nm wavelengths found an increase of the expression of proteins correlating to the progression and invasiveness of tumors, underlying how these results could determine the need to evaluate the opportunity to treat, e.g., oral mucositis in patients affected by head and neck cancer.

In 2009 Frigo et al. [37] called to caution about the irradiation of melanomas with a red laser, but the parameters had values far away from those adopted in standard LLLT. Lower doses even if still high didn't cause any change in the behavior of cancer cells compared to the controls.

Also Dastanpour et al. [38] in 2015 found an increase in the proliferation of irradiated leukemic cells, suggesting caution.

Sonis et al. [39] in 2016 see things in the same light, suggesting an «investigational strategy» to ensure that the positive effect of the LLLT on the oral mucositis in head and neck cancer patients is independent from every effect on the speeding up of the neoplastic disease. The number of variables at stake is so high that a comparison among the articles is very difficult.

It is also possible to combine different strategies in the attempt to find the best therapeutic options. In 2015 Barasch et al. [40] in a study on leukemic cells found that a pre-irradiation with a red laser was able to render the cells more sensitive to a treatment with ionizing radiations.

In the absence of a universal consensus, caution is necessary, studying carefully the clinical history of the patients before the treatment and avoiding irradiation if there are doubts about the differential diagnosis.

7.3.2 Protocol

The therapy of every pathology is performed following guidelines or recommendations based on scientific evidence or on the most extended consensus. LLLT finds its indications in its minimal invasiveness compared to other therapies or in its support to other elective treatments.

If there are no indications provided by scientific associations or academies, the most recent and accredited scientific literature will help in defining an acceptable protocol.

To define a protocol [10, 41], it is necessary to evaluate and choose several parameters as follows:

Protocol Parameters
- Wavelength
- Dose (fluence – energy density)
- Power density – intensity
- Emission mode
- Irradiation technique
- Number and timetable of the sessions
- Duration of the therapeutic treatment

In detail:

Wavelength

7

LLLT is mostly performed with light whose wavelength is included in the «optical window,» ranging from about 600 nm (red) to about 1100 nm (near infrared) [42].

In this range the maximum effective penetration of light into the tissues is observed, with a peak around 800 nm, and some fundamental photo-acceptors show a high absorption (e.g., cytochrome c oxidase). Even if the distribution of the energy inside a tissue can be conditioned by its optical characteristics and by parameters like pulsing and power density, from a general point of view, the red light will be absorbed by the first layers of the tissue, being more suitable for the treatment of superficial lesions (like mucositis), while the near-infrared light penetrating deeper will be able to reach osteo-muscular-articular targets. The presence or the absence of chromophores (e.g., pigments like hemoglobin or melanin) that act as competitor will condition in a significant way the absorption and therefore the energy distribution volume and may require to modulate parameters like fluence, power density, and delivery time in order to administer the prescribed dose at the target or to avoid undesired heating.

Dose (Fluence - Energy density)

Fluence (energy density) is considered the basic parameter in LLLT, usually described as «dose,» and corresponds to the amount of energy (Joules) delivered to the unit of surface area (cm^2).

The debate about the optimal dose for every kind of pathology curable by LLLT is still open and is subject of several and increasing number of studies and researches, often with contradictory results [43].

Even if a consensus doesn't exist, all agree with the observation that there is a biphasic response to light irradiation [44]. Dosages lower than a given threshold are ineffective; dosages above a given threshold may have an inhibitory effect. This behavior can be illustrated by the so-called Arndt-Schultz law (Fig. 7.2) based on the concept of «hormesis,» historically referred to toxicology and chemical risks [45].

This aspect also helps to explain the concept of «photobiomodulation,» that is, the possibility to modulate the dose in order to obtain a positive effect, like biostimulation, or an inhibitory effect, e.g., like analgesia (stoppage of the neural transmission).

The doses reported in literature having a biostimulating effect range from few mJ/cm^2 to ten or more J/cm^2 [46–48]. It is necessary to distinguish between experimental studies and clinical trials. The former are usually made on cells, often on monolayers or on suspensions that can be considered optically homogeneous, thus offering the possibility to observe the relationship between dose and effect in a repeatable way. This condition is far different from the clinical ones, where the dishomogeneity and the anisotropy of the tissues strongly affect the effective distribution of the energy, in a poorly predictable way. Furthermore, there is the lack of biological response at tissue level. This is a really complicated topic, and there are algorithms that try to simulate the distribution of the energy inside a given tissue taking into account all the factors

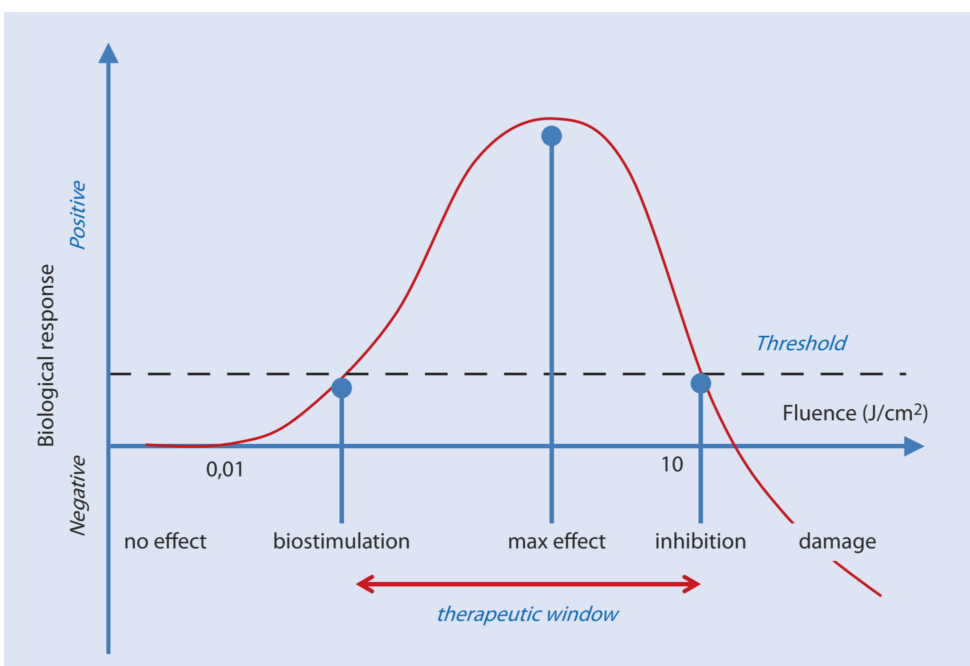


Fig. 7.2 Arndt-Schulz law diagram

involved (e.g., Monte Carlo simulation) [49]. Therefore, clinical trials are the best way to test the efficacy of a therapeutic protocol and to give indications about the optimal dose, even more if addressed to the highest level of evidence (e.g., double-blind randomized clinical trials). Due to the high number of variables and often to the limits established by the ethical committees, the number of these studies is still relatively small, even if with a diffuse clinical evidence [50].

Both lasers and LEDs emit monochromatic wavelength, even if the latter have a broader emission bandwidth. The main difference between LED and lasers is coherence. It is known that coherence refers to the light emitted by lasers that is in phase from a spatial and temporal point of view. There is a debate about the relevance of coherence to the effects of photobiomodulation, and it seems that this particular characteristic doesn't lead to a significant difference in the clinical outcomes, comparing laser and LED sources [51–53]. If this is true for thin layer of tissues, it seems that on bulk tissue coherent light (together with polarization) is able to create a speckle pattern of intensity, due to random positive interferences with an enhancement of the biological effects in the depth [54].

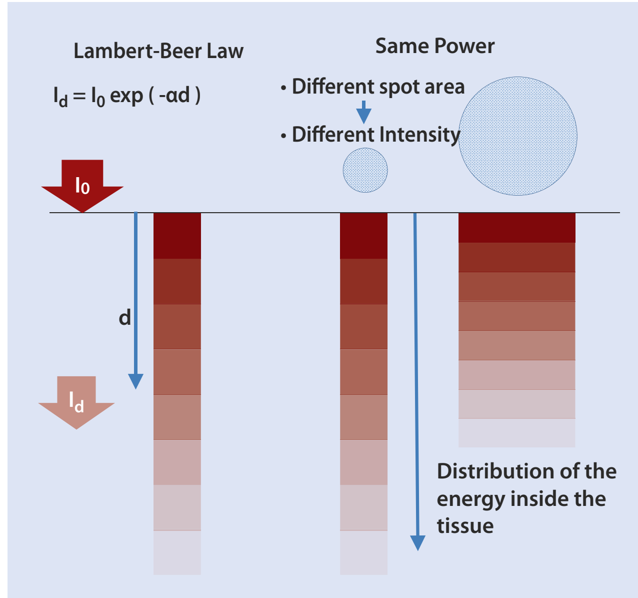
Power density (also usually known as intensity) is a fundamental parameter that correlates the energy with its delivery time and the irradiated area. Strictly speaking, intensity involves the concept of solid angle (power/solid angle) and refers to the rate of flow of radiant energy at the source (flux), while irradiance (power/surface) is the rate of flow of radiant energy striking a surface. However, for the purpose of this chapter, we'll use the terms intensity and power density, referring to irradiance. Being equal in all other conditions, it determines the depth of the distribution of the energy inside a given tissue. The Lambert-Beer law, an exponential function, states that the intensity at a given depth is equal to the intensity of the incident radiation corrected by factors like the distance and a coefficient that takes into account absorption, scattering, and anisotropy (◘ Fig. 7.3).

Generally, treatments with low-power densities and long delivery time are considered effective. However, there is a tendency to reduce the time, increasing the power density for practical and economic reasons. In any case the power density shouldn't exceed values leading to a thermal increase.

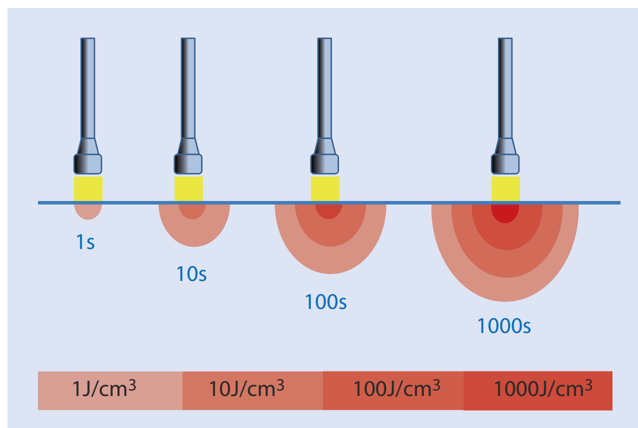
Even if in literature we can find different values of power density [46], the possibility that a thermal increase occurs depends on the absorption features of the tissue target.

If we consider melanin, that is, one of the main chromophores absorbing visible and near-infrared light, its percentage in the skin is about the double in black-skinned people compared to light-skinned people. This means that in light-skinned people, the energy delivered with relatively high-power density will penetrate deeper and won't be harmful from a thermal point of view; with dark and black-skinned people the high surface absorption restricts deeper penetration and increases the risk of thermal rise. Consequently, the parameter that allows us to modulate the energy in order to avoid a thermal increase and to reach a certain depth with a given amount of energy are power density and the delivery time.

In fact:



◘ **Fig. 7.3** Lambert-Beer law – power density distribution inside a tissue



◘ **Fig. 7.4** Distribution of energy per volume inside a tissue (fluence) over time

Fluence = energy/surface energy = fluence × surface
Energy = power × time
Fluence x surface = power × time
Fluence = power × time/surface as power/surface as power density
Fluence = power density × time

As fluence and power density are clinical and primary parameters, time becomes a derived operative parameter:
Time = fluence/power density

This means that we can obtain the same fluence decreasing the power density and increasing the delivery time and vice versa.

It is necessary to bear in mind that the laser beam hits a surface but spreads its energy into a volume. Due to absorption and scattering, the distribution of the energy in a given tissue will vary with time (◘ Fig. 7.4).

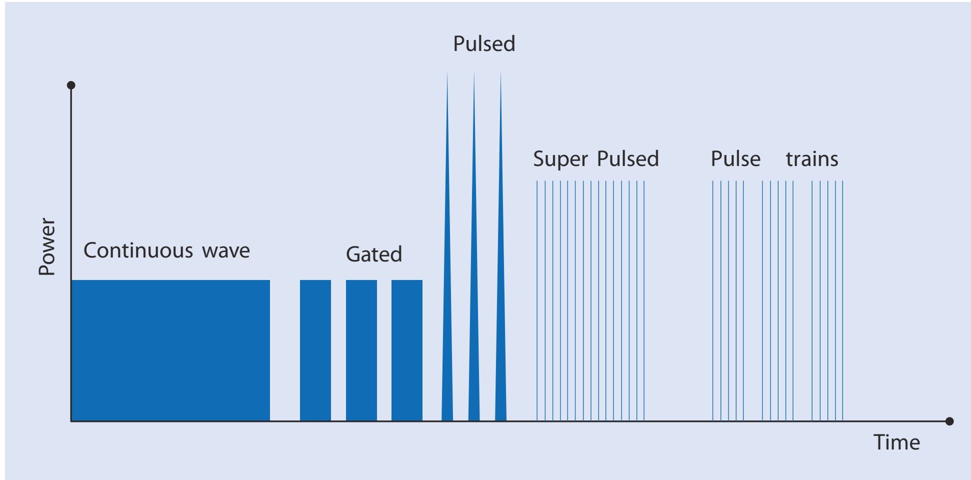


Fig. 7.5 Laser emission modes

Emission Modes

The laser beam can be emitted with different modes (Fig. 7.5) that are substantially «pulsed» (FRP lasers) and «gated» or «chopped,» a mechanical or electrical interruption of a continuous wave with a given frequency (e.g., diode lasers).

However, it is common to find that the term «pulse» is erroneously and indifferently ascribed to both the modes. The diode lasers used in dentistry cannot achieve high peak power when used in continuous-wave mode or gated mode, due to the intrinsic characteristics of the semiconductors (too much heat generation that would destroy the semiconductors).

Therefore, in some devices the electrical pumping system is modulated to produce very short T_{on} (micro- and nanoseconds), with a frequency up to several thousands of Hertz. In this way, even if the average power is relatively low, the peak power and the peak power density can reach high values.

The peak power density deriving from this kind of emission mode modulation leads to a deeper distribution of energy inside the tissue without appreciable thermal increase.

The lasers operating in such a way are called «superpulsed,» and some devices offer the possibility to deliver packages of «pulses» called «pulse trains.»

There is no consensus about the clinical relevance of pulsed or gated emission compared to continuous emission, and the data reported in literature are insufficient to determine accepted protocols. In 2010 Javad T. Hashmi et al. [55] published a meta-analysis of peer-reviewed literature about the effects of pulsing in LLLT and conclude that all being equal, pulsed light seems to be superior to CW light for wound healing, while CW light seems to be superior for nerve regeneration.

A possible explanation for the superiority of pulsed light could be the need of periods of rest, to contribute a further stimulation of the cells.

Irradiation Technique

Several lasers, suitable for the LLLT, are available on the market. From a general point of view, in dentistry the most diffused devices are polyvalent, being possible to use them for several applications like surgery, bleaching, LLLT, etc. Even the most economical and simple lasers have a probe for the dental bleaching, having a diameter at the end of few millimeters, and the emitted beam is often collimated by an internal lens system. More sophisticated devices have probes of different diameter and different manufacture, to cover in an easier way larger surfaces. It is useful, if not mandatory to check if the effective output power corresponds to the set power using a power meter, as losses due to several factors can reduce it [56].

Usually the beam maintains its original Gaussian profile, unless transformed by a lens system in a flat profile, where the energy is evenly distributed over the spot (Fig. 7.8).

Depending on the beam profile, some tricks are needed to make the protocol as much as possible repeatable and comparable, and the skill of therapist plays a crucial role, leading to different results in spite of the same applied parameters [57].

The probes, if not sterilizable, are protected with sleeves to avoid cross contamination and transparent to avoid light absorption or diffusion. It is better to work in contact mode and, as much as possible, perpendicular to the surface of the tissue target. Working with a certain degree of inclination or from a distance varies the parameters correlated to the surface, fluence, and power density, due to reflection or to beam divergence. While irradiating, if not in contact with the tissue, the probe must be held at the same distance and, if in contact, with the same pressure.

If the treatment is performed extra-orally, the skin of the patient has to be cleaned of makeup that could act as a screen, absorbing the laser light and possibly causing heating or reflecting.

The patient's reactions must be observed, to intercept unwanted thermal side effects.

There are two techniques that may be adopted to irradiate the tissue target:

1. *Spot technique*: the energy is delivered «point by point» until the entire surface to be irradiated is covered. If the laser beam is collimated, it is possible to work in noncontact; the beam diameter won't change with the distance, even if some reflection occurs. As previously said,

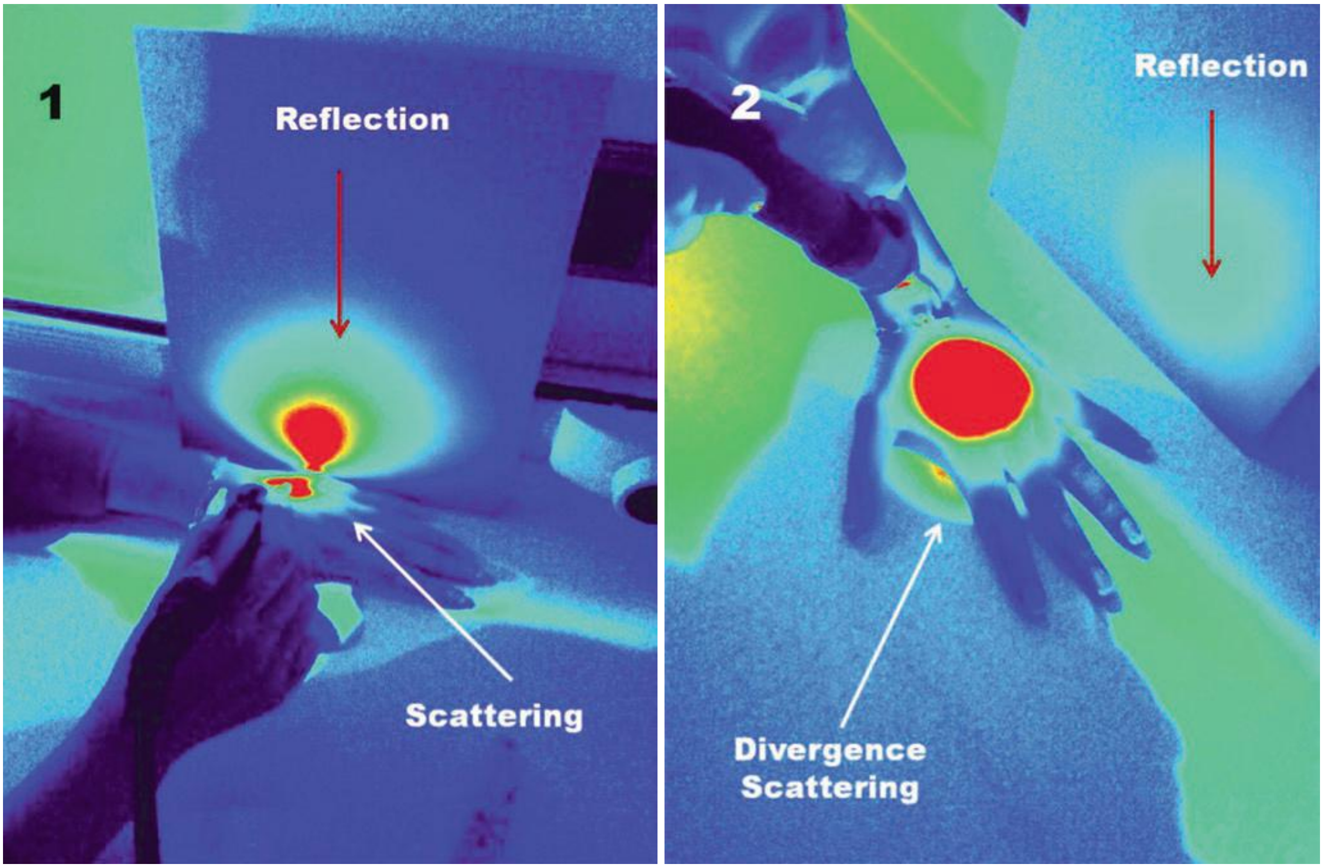


Fig. 7.6 Diode laser 904 nm. (*1*) Probe in contact, inclined to perpendicular. (*2*) Probe from a distance

the probe must be held perpendicular to the tissue to avoid at best any reflection of the laser light due to inclination. If the emitted beam is divergent, it will be better to work in contact, to avoid variations in fluence and power density due to the possible change in the distance (Fig. 7.6).

Working in contact, the applied pressure can influence the amount of energy that actually reaches the target if located inside the tissue, reducing the distance from it and causing a relative ischemia that brings away an absorbing chromophore (e.g., hemoglobin) (Fig. 7.7).

We also have to consider the spatial beam profile. If the laser beam has a Gaussian distribution of energy, the parameters correlated with the surface, fluence, and power density will decrease from the center to the periphery of the spot. The «spot size» (beam diameter) depends on the beam radius, that is, the distance from the beam axis where the intensity drops to $1/e^2$ (≈13.5%) of the value on the beam axis.

Roughly, from a clinical point of view, we can consider that the power density will double the average in the center and half at the periphery. In this case, it's more correct to speak of «spatial average power density» and «spatial average energy fluence» considering the distribution of the intensity and of the energy over the whole irradiated area.

To equate as much as possible power density and fluence, the spots could be overlapped. Overlapping leads to an increase of the average power density and average fluence that must be corrected by changing the value of the set power.

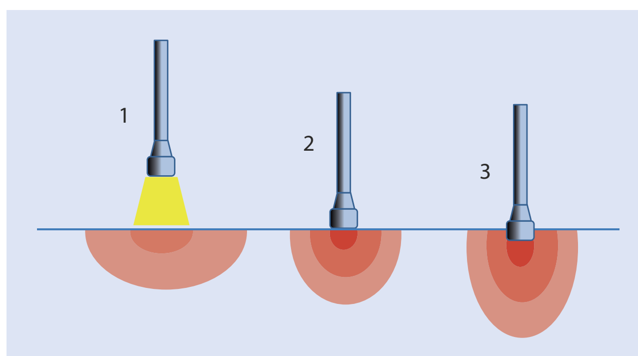


Fig. 7.7 (*1*) Probe not in contact, divergent beam. (*2*) Probe in contact. (*3*) Probe in contact, applied pressure

This kind of problem can be solved using a «flattop handpiece,» where energy is evenly distributed and the power density has the same value at every point of the beam, thus facilitating a uniform distribution of the light and the calculations (Fig. 7.8).

To set the equipment, the first step is the calculation of the spot area that we consider, for practical reasons, equal to the area of the probe terminal or to irradiated area if working from a distance:

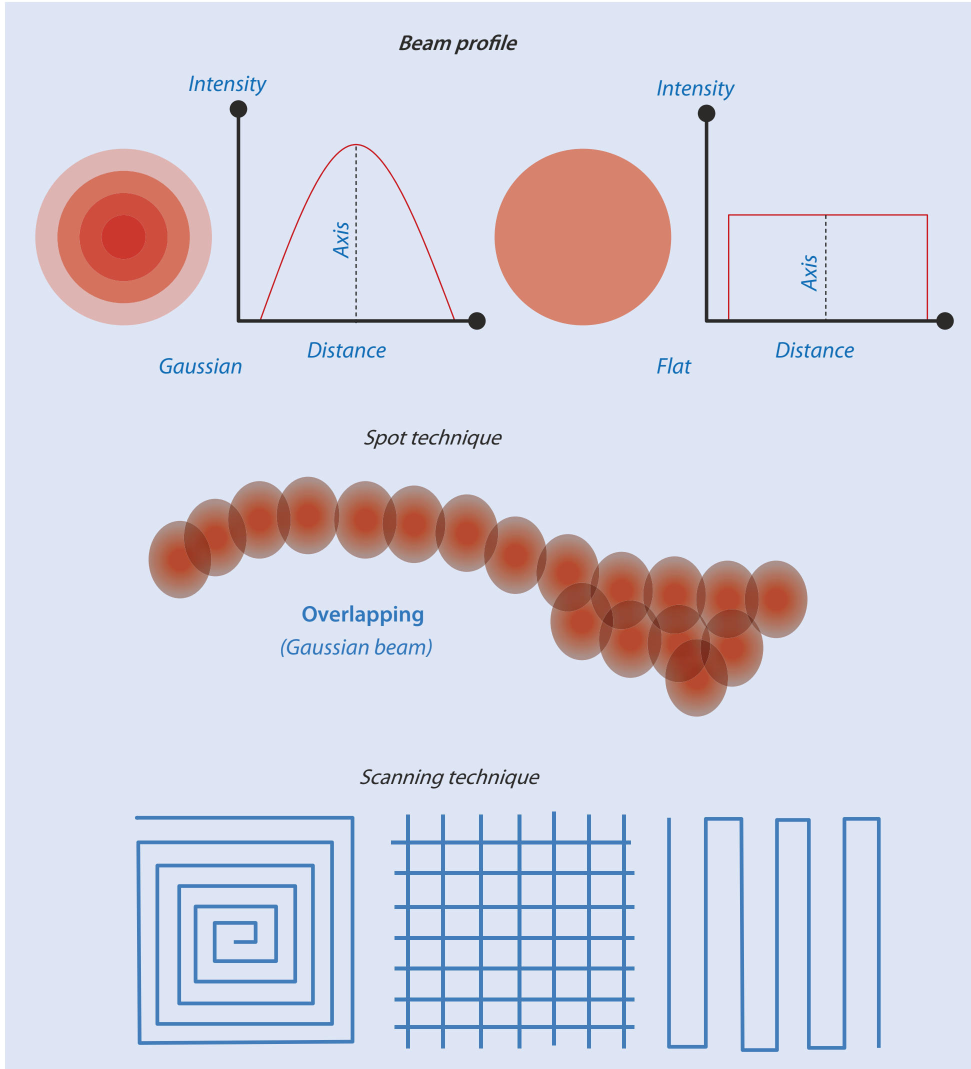


Fig. 7.8 Beam profiles and irradiation techniques

Spot area = (diameter/2)^2 × π

The second step is the calculation of the power that we need to set to obtain the required power density:
Power = power density × spot area

The third step is the calculation of the delivery time, depending on the required fluence:
Time = fluence/power density

(Due to scattering, the distribution of energy can undergo same variations, e.g., backscattering can contribute to increase the power density in the first layers of tissue.)

2. *Scanning technique*: the probe is slid over the surface to treat, using different figures (grid, spiral, lawn shaving) (Fig. 7.8). Whatever is the chosen figure, the surface to be treated must be irradiated in a uniform way.

In this case, once set the power with the same method used for the spot technique, we calculate the total dose of energy to be delivered, that is:

Total dose = fluence × target surface.

After, the delivery time is calculated dividing the total dose by the set average power.
Time = total dose/power

The scanning technique, if performed manually, is predictably less precise due to the fact that it is often impossible to stay in contact and contemporarily in movement (e.g., open wounds or ulcers), to stay perpendicular at the same distance, and to irradiate evenly.

The market provides some devices with a software that calculates automatically power and delivery time, once power density and fluence have been set.

Number and timetable of the sessions, duration of the therapeutic treatment

They depend on the protocol suitable for the disease or symptoms to be treated. Also from this point of view, the studies found in literature are unable to reach unequivocal conclusions. On average, 2/3 sessions a week are advisable, until healing has been obtained or until symptoms disappear.

7.3.3 Safety

We can distinguish between the safety issues connected to the use of a laser device (which requires the use of specific individual protection devices (IPD) and in respect of the procedures as detailed in ▶ Chap. 1.5) and the safety issues connected to the patient. Besides the checking of the systemic and local conditions (e.g., the skin color, the presence of pigmented areas, the presence of non-diagnosed lesions), there are some contraindications or precautions to be taken into account.

Most of the contraindications and precautions (listed below) arise from the possibility that the biostimulating and immunomodulating effects of LLLT could interfere with some physiological and pathological conditions or from the possibility of electromagnetic interferences with some obsolete implantable devices, such as pacemakers or implantable cardiac defibrillators (ICD) [59, 60]. However, there is no evidence of an effective risk for all the situations listed below:

- Direct irradiation of the eyes
- Neoplasms
- Thyroid, gonads
- Hemorrhage
- Pregnancy (abdomen)
- Immunosuppressant treatments
- Epilepsy
- Bone growth plates in children
- Neuropathies
- Hematological disorders

7.3.4 Setting

Before treating it's necessary to set the laser equipment according to clinical parameters and to irradiation technique, checking carefully that the setting matches the data calculated in advance.

7.3.5 Treatment and Follow-Up

When all the procedures relative to the choice of the protocol suitable for the diagnosed clinical condition (to laser setting; to safety) are concluded, the treatment can be performed. During and after the application, the patient reactions must be detected, and the outcomes must be evaluated in order to verify the efficacy of the treatment and to intercept possible, although rare, side or adverse effects.

7.4 General Effects of LLLT

7.4.1 Anti-inflammatory Effect

Inflammation is a defense mechanism, a protective answer to the action of damaging physical, chemical or biological events.

The final goal is to identify and remove the initial cause and the triggering of the reparative processes.

Besides the well-known local effects (rubor, tumor, calor, dolor, and functio laesa), we may have systemic effects of different extent, such as fever, asthenia, and anorexia.

Inflammation consists of a sequence of phenomena that begin with an intense vascular reaction; the plasmatic proteins are released in the interstitial fluid, and in the involved zone, there's an attraction of neutrophils, mast cells, basophils, and, in a later phase, macrophages.

These processes are regulated by the activation of inflammation mediators: vasoactive mediators (e.g., histamine, prostaglandins, and nitric oxide) that are responsible for vasodilation, vascular permeability, and the onset of edema. Chemotactic factors (e.g., chemokines and lipoxygenase products) are responsible for the recruitment and stimulation of the inflammatory cells (polymorphonuclear cells, platelets, and monocytes) that are activated in the initial acute phase, macrophages, lymphocytes, and plasma cells that are activated in the chronic late stage.

From a clinical point of view, it's impossible to split the inflammation from the subsequent tissue reparative stage (healing); both the mechanisms are closely related to each other, and this must be taken into account during the execution of the therapeutic strategies. In daily practice, the inflammatory process is managed through a systemic therapy with drugs called «ant-inflammatory drugs,» a misnomer because inflammation cannot be stopped, but only modulated.

The most used drugs are nonsteroidal anti-inflammatory drugs (NSAIDs) and steroids that act at different stages of the inflammatory chain. NSAIDs act on cyclooxygenase and prostaglandins, while steroids act on the conversion of membrane phospholipids into arachidonic acid. The pharmacological therapies, even if used following proper schemes and dosages, can cause adverse effects, even significant, and this is the reason why we are oriented toward treatments minimally invasive as much as possible.

LLLT, because of the absence of adverse effects, has been studied in depth with regard to its mechanism of inflammation modulation, evaluating the action of different wavelengths and different parameters on the damaged tissues. Laser light, in the range between 650 and 980 nm, works on the activation of cytokines [58], on the oxidative stress inducing a decrease in the level of ROS, and on the activation of macrophages, whose number is increased in the simulation models of inflammation [61].

There are several studies in vitro or on animal models, while few are studies performed on humans that show a speeding of the inflammatory process, with the activation of both pro-inflammatory and anti-inflammatory cytokines and mature collagen formation only 7 days after injury [62, 63].

It was also observed that the action of LLLT on inflammation is comparable to the action of dexamethasone [64].

The fluences that led to positive results, with an increase in the activation values of the phlogosis mediators, were in the range from 1 to 7.5 J/cm^2 [65], while higher fluences didn't obtain the same result [66].

Furthermore, it was observed on animal model and in vitro that heat with a temperature over the 45 °C threshold for protein denaturation can induce a condition of phototoxicity with erythema that leads to cellular apoptosis that can be found also for treatment durations lasting more than 30 s, regardless of the laser source and the fluences used [67]. It was proposed to treat 2–3 times a week.

7.4.2 Analgesic Effect

The official definition of pain has been proposed by the International Association for the Study of Pain (IASP) in 1979: «an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage.» This definition emphasizes the subjective nature of pain sensation that in addition to the somatic component is accompanied by an emotional charge that makes complex the assessment of the perceived pain level. Between a painful stimulation at the tissue and the subjective experience of pain, a series of complex chemical and electrical events that involve four distinct mechanisms is interposed:

Transduction

A mechanism by which a noxious factor triggers a chemical event that, at the level of the specific nerve endings or nociceptors, is transduced into electrical activity (A-delta fibers and c-fibers)

Transmission

Neurological mechanism through which the impulse from the periphery reaches the posterior horn of the spinal cord and from there, directly or through interneurons, reaches the brain via second-order neurons (spinal-thalamic tract) and then the cortical-thalamic pathways carry the stimulus to the cerebral cortex

Modulation

The painful signal can be modified (amplified or inhibited) at various levels of the algic circuit both before and after the projection of the stimulus to the specific cortical areas and can lead to a variety of possible answers. The modulation is activated by the painful input itself, by endogenous substances, by stress or emotional states, by cognitive processes, by some drugs, and by several analgesic techniques.

Perception

Still obscure mechanism by which the nociceptive event becomes a subjective phenomenon which leads to a considerable diversification of the response in the various subjects.

The pain is regulated at several levels: a first level is located in the gray matter of the dorsal horn of the spinal cord, where the inhibitory action on the afferents to the spinal-thalamic tract that is deputed to convey the stimulus to a higher level (Gate theory) is exerted; a second level consists in the pathways descending from the thalamus and that are activated by opioids (enkephalins, β-endorphin, dynorphin) [68].

A very important role in the modulation of pain is given by the ionic channels whose opening, following a nociceptive stimulus, causes an increase in the permeability of the axon membrane and its depolarization, generating action potentials that allow the transmission of the stimuli in the posterior horns of the spinal cord, leading to a decrease in the stimulation threshold. These channels (Na, K, Ca, etc.) are inhibited by opioid receptors activated by endogenous opioids (also produced by immune cells) and/or exogenous opioids and by substances produced in the damage site, such as anti-inflammatory mediators (chemokines, cytokines, catecholamines) [69, 70].

The pharmacological treatments used for the control of pain fall into two broad categories: NSAIDs (for mild/moderate acute and chronic pain caused by inflammation) and the centrally acting analgesics (opioids, for chronic pain of high degree).

LLLT has been studied with regard to the action on the painful stimulus even if the intrinsic mechanisms have not been fully elucidated. Bjordal [71], in a systematic literature review, identified several laboratory studies that have sought to identify the biological mechanisms underlying the control of pain, both acute and chronic. A decrease in the peripheral nerve conduction, an increased release of endogenous opioids, an increase in the microcirculation with formation of new vessels in the area of the damage, a decreased oxidative stress and edema, a local anti-inflammatory effect with production of biochemical markers, and a reduced cyclooxygenase-2 (COX 2) with short-term action on the acute inflammatory pain have been observed.

Other researchers have reported how the laser, especially in the range of red and near infrared, acts on the physiological mechanisms of pain modulation; it was observed that, at the level of the gray matter of the dorsal horn of the spinal cord, there was an inhibition of the rise of the stimulus to the following level by acting on the transmission of the fibers a-δ and C [72, 73] and an inhibition of 30% of the action potential in the first 10–20 min (rapid analgesia, so that a higher noxious factor is needed to obtain a painful response) and also the synaptic activity is inhibited at the level of the second-order neurons that lead information to the brain [74]. At axon level, there is a neural block probably due to the decrease of the membrane potential of mitochondria in the neurons of the dorsal root ganglia, with subsequent reduction of ATP production that could explain the stoppage of the neural transmission and the decrease of production of algic substances such as substance P [74]. A greater synthesis of endorphins and opioid receptors was noted, modulated both by endogenous opioids and by those produced by leukocytes [75, 76].

It is difficult to establish the «dose» effective for the analgesic effect; positive results were obtained with fluences ranging from 1 to 30 J/cm^2, with an average of three treatments a week [77]. Analgesic results even with higher doses, up to 138 J/cm^2, have been reported [78], while for the pain deriving from inflammation, the effective fluences are within 7.5 J/cm^2 [71].

7.4.3 Biostimulating Effects

The main goal of every medical treatment is the promotion and the maintenance of health. This concept is fully suitable to dentistry, where, besides the need to face the manifold pathologies that can affect the oral cavity, our therapies can, by themselves, be invasive and can induce discomfort. The treatment of oral lesions is of particular interest as their onset has often significant consequences on the quality of life, regarding mucous tissues, muscles, nerves, or hard tissues (bone and teeth).

Improving the quality of healing but also its speed definitely represents a way to reduce the invasiveness of a pathology or of our therapies.

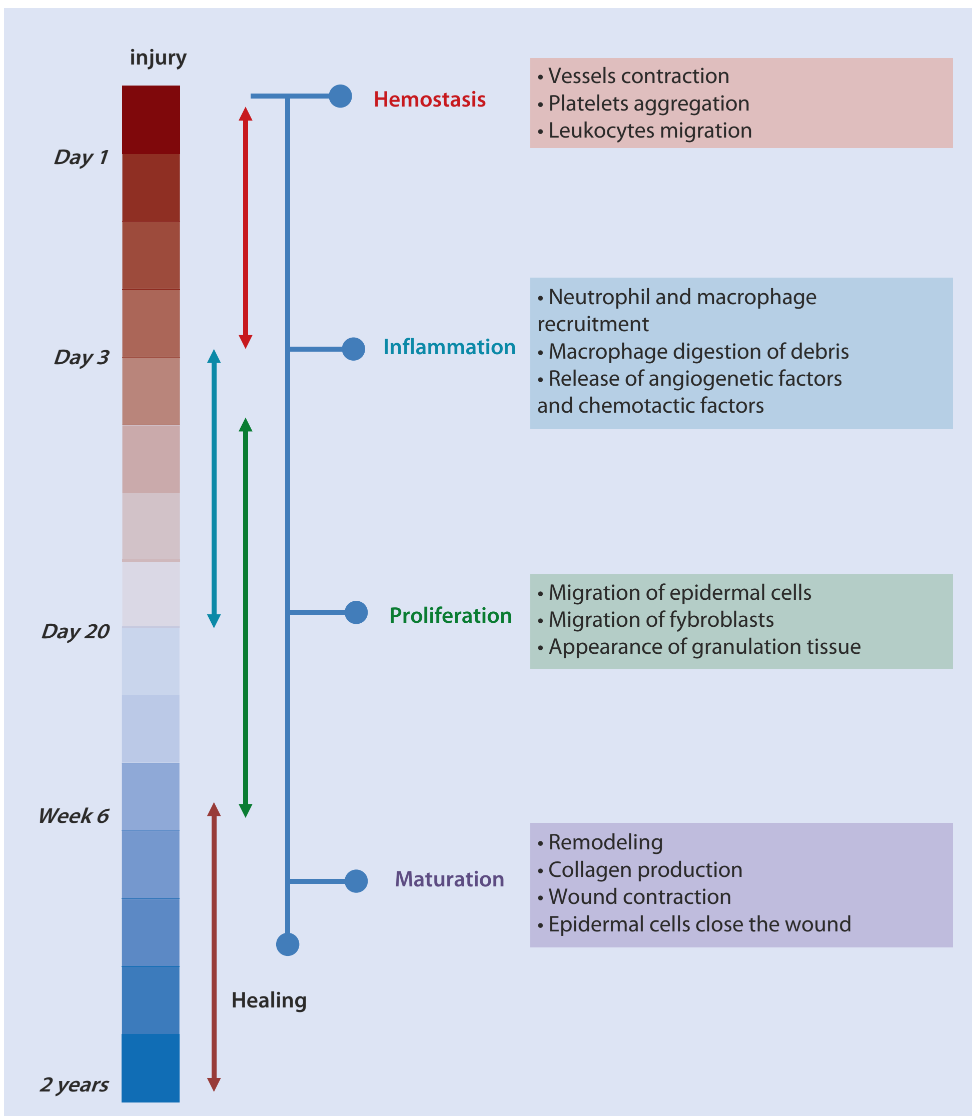
The LLLT plays a significant role from this point of view, with its anti-inflammatory and analgesic action, combined with biostimulation.

Wound healing is one of the most studied conditions that takes advantage from LLLT.

A wound consists in the lack of integrity of a tissue caused by a traumatic event that can be planned (such as a surgical intervention) or accident. Regardless of the kind of injured soft tissue, the healing process has the same evolutionary scheme: inflammation, cellular proliferation (granulation tissue, re-epithelialization), and maturation (contraction and remodeling of the newly formed tissue) [79].

It's difficult to anticipate the duration of the reparative process that begins within 24 h after the injury, while the scar (final result) can be considered solid after 15 days and completely remodeled in 6 months [80, 81] (◘ Fig. 7.9).

Several medical agents have been studied in order to improve and speed up the growth of new tissue and to counteract any negative factors, such as the possibility of bacterial infection. The therapeutic choice will be evaluated for every



◘ **Fig. 7.9** Phases of wound healing

single case and could include anti-inflammatory drugs, analgesic drugs, topical or systemic antibiotics, growth factors or herbal products (aloe, curcumin), and animal-derived products (honey) or based on hyaluronic acid.

LLLT, being able to control pain, to modulate the inflammation, and to speed up the growth of new tissue, is considered effective in promoting the wound healing. Within this area of application, many of the wavelengths included in the optical window have been studied, from red (635 nm) to near infrared (mostly 810 nm and 980 nm), used individually or in combination.

As said in the previous section, when light enters the tissue and is absorbed, biochemical processes are triggered that lead to the activation of the mitochondrial chain and then mainly to the increase in the production of ATP, NO, and small amount of ROS, resulting in an acceleration of the cell activities and on the onset of effects at tissue level. These effects consist of an activation and increase of the microcirculation on the wound site with a greater supply of oxygen and modulation of pro-inflammatory and anti-inflammatory cytokines, in a reduction of edema, in an increase of the synthesis of growth factors, determining an early synthesis of pre-collagen, fibroblasts, their maturation, and spatial organization [58, 62, 63]. There is also an activation of the sensory system with production of serotonin and endorphins and of the other mechanisms of pain control, besides the activation of the immune system with the recall of immune cells and increase of the macrophage activity [82].

There are several applications in dentistry – traumatic lesions, erosive lesions of the oral mucosa, all the surgical interventions (teeth extractions, implantology, periodontology, etc.) – that are performed daily or to all the situations where the healing supported by usual medical devices has a lower quality than expected.

In order to achieve the effects mediated by the LLLT, biochemical at first then at cellular and tissue level, it is very important to correctly choose the wavelength of the light emitted by the laser source; the power density and fluence only if in correct combination of these parameters, together with a correct clinical application, will the desired effect be obtained.

Inside the oral cavity, the lesions of the soft tissues, especially mucosa, have a shallow depth (few millimeters), while the lesions involving the skin or the muscles or bone can reach greater depths. A laser whose wavelength is at the limits of the optical window, such as red light (from about 635–700 nm), could be useful in the treatment of superficial lesions (traumas, mucosal erosions, or ulcers), while a laser whose wavelength is in the near-infrared spectrum (from about 700 to 1000 nm), with deeper penetration depth, could be used for skin lesions and osseous and muscular lesions [83–86].

Once the proper wavelength is chosen, it is necessary to decide the «dose» of energy to deliver to the tissue, i.e., the fluence. As reported in a previous section, according to the Arndt-Schulz law, several studies suggest as effective fluences within the value of 10 J/cm^2, with a positive biostimulating effect. If the expected result is not obtained, it could depend on an excessive dose or on a dose that is insufficient to trigger all the biochemical and cellular mechanisms.

The frequency of the treatment sessions must also be established. In literature there are suggestions for administrations performed either daily or every other day, using either single dose or fractionated dose [87–89]. This variability can be attributed to the fact that the experimental conditions of the studies are different and many are performed in vitro or on animal model.

Generally, it is suggested not to perform daily treatments, to avoid the possibility of a summative effect of the doses that could lead to an inhibition of the desired biological processes. Therefore, 2/3 sessions a week are considered preferable [88–90].

Of course, like every other pharmacological therapy, the treatment scheme must be adjusted depending on the pathology to be treated, on the characteristics of the patient, and on the outcomes detectable during the treatment (Fig. 7.10).

7.4.4 Bactericidal Activity

The World Health Organization (WHO) has launched a warning about the risk of bacterial resistance to the antibiotics known to date focusing on the indiscriminate and sometimes needless use of these drugs. As such, the search is on for new antibacterial treatments, and LLLT can be one of these.

Pharmacological therapies are not very effective on the oral biofilm and the poor diffusion of the drugs inside it, by virtue of the extracellular matrix rich in polysaccharides which act as a protective environment for the microorganisms that it holds [91]. As said in in the introduction, the antibacterial action of light has been recognized, and on the basis of this, some researchers have studied how this happens; it was seen that noncoherent blue light (400–500 nm) in association with peroxide is able to determine a damage to the bacterial cell membrane, following the formation of the OH^- radical which is a powerful oxidant [91, 92]. In the absence of chemical agents acting as photosensitizers (toluidine blue, methylene blue, indocyanine green), the light can act directly on pigmented bacteria. The wavelengths that have been studied are located in the blue band (400–500 nm), with different fluences depending on the bacterial species tested in vitro, 4.2 J/cm^2 for *Prevotella intermedia* and *Prevotella nigrescens* and 21 J/cm^2 for *Porphyromonas gingivalis* and *Prevotella melaninogenica* [93] and in the red and near-infrared bands (630–660–810–904 nm), obtaining a decrease in the colonies with values of fluence greater than 20 J/cm^2 [94]; no effect was obtained with lower values [95]. By virtue of the action that LLLT place on cell proliferation and on the facilitation of the chemotactic activity on phagocytosis by neutrophil and macrophages, the control of bacterial proliferation may also take place based on a mechanism of stimulation of the immune system [96].

Fig. 7.10 (*1*) Four-year-old patient, with a traumatic painful lesion: biting following local anesthesia. Treatment performed with diode laser 645 nm, fluence 4 J/cm^2, average power 5 mW, spot diameter 2 mm, power density 0.16 W/cm^2, CW, spot technique, 25 s per point, irradiations every other day. Immediate analgesic action, complete healing after five sessions. (*2*) Five-year-old patient, with a traumatic lesion with bone exposure (Following impact against the wooden edge of her bed). Treatment performed with diode laser 904 nm, fluence 4 J/cm^2, average power 0.28 W, spot diameter 5 mm, power density 1.4 W/cm^2, superpulsed, spot technique, 3 s per point, irradiations every other day. Immediate analgesic action, complete healing after eight sessions. (*3*) Fifty-year-old patient: delayed healing after implant positioning and GBR, with fixture exposure. Treatment performed with diode laser 810 nm, fluence 4 J/cm^2, average power 0.3 W, spot diameter 6 mm, power density 1.07 W/cm^2, CW, spot technique, 4 s per point, irradiations every other day, five sessions to trigger and to speed up the healing process. Complete healing after a month

7.5 Clinical Applications

7.5.1 LLLT in Oral Medicine

Oral medicine is concerned with the diagnosis and treatment of diseases affecting the maxillofacial region and especially the oral cavity; be they local expressions of systemic diseases or specific illnesses of the region, it is the link between dentistry and internal medicine. LLLT, by virtue of its analgesic, anti-inflammatory effect and its ability to promote the regeneration of tissues, is particularly useful in the treatment of many pathological conditions of the oral cavity, especially in erosive manifestations of the oral mucosa [97].

Recurrent Aphthous Stomatitis (RAS)

Aphthae are ulcerations that vary in size (from a few millimeters to over a centimeter), affecting the oral nonkeratinized mucosa; they are painful, have a rounded appearance gray/white in color, and have an erythematous rim. The etiology remains unknown; they affect the population with a variable incidence (5–60%) and tend to heal spontaneously in 10–15 days. They may be single or multiple, scattered in several areas; the pain can be intense enough to prevent feeding, speech, and oral hygiene.

There are many aids designed to reduce the symptoms and speed the healing of these injuries, painkillers, herbal or hyaluronic acid gels, topical corticosteroids, and oral vitamin B12.

In literature there are many studies that have investigated the efficacy of LLLT in the treatment of RAS, and they agree that with laser treatment a good pain control is achieved from the first application and a speeding up of healing compared to other therapies or placebo groups [98–100].

Diode lasers of various wavelengths (635–670, 810–904) with fluences of between 2 and 6 J/cm^2 with different treatment times according to the setting have been used.

Herpes Simplex

Herpetic lesions, caused by the HSV-1 virus, a primary form (especially common in children) and a secondary form are known. The primary form is the body's first contact with the virus, while the second form is an exacerbation of the virus that had remained silent in the trigeminal ganglia. After a first phase that can vary from several hours to a few days, the formation of small vesicles in clusters can be seen, often confluent with each other, full of liquid and virus. Highly contagious, when these vesicles break, they become deep erosions.

Until the formation of surface crusts, the area is painful; during this time, symptomatic, topical, or systemic antiviral drugs (for large lesions or immunosuppressed patients) may prove helpful. Additionally, emollient creams, anesthetic ointments, painkillers, and anti-inflammatory drugs can be used, according to the severity of the case.

LLLT has been used successfully in the treatment of herpetic lesions for pain control and for the speeding up of the healing process [101–103], reducing the number of relapses over time [101]; also when treatment is carried out in the prodromal phase, the results are immediate, and the formation of vesicles is not observed [97]. Diode lasers of different wavelengths (660–1100 nm) with fluences between 2 and 4 J/m^2 have been used (Fig. 7.11).

Mucosal Chronic Inflammatory and Autoimmune Diseases

The most well-known diseases included in this category are the vesiculobullous diseases and oral lichen planus.

Vesiculobullous Diseases (Pemphigus, Mucous Membrane Pemphigoid)

These diseases clinically appear with blisters that can affect the skin and mucous membranes. Intact blisters are rarely found; it is more common to see the result of their bursting: erosions or ulcers that can be extended to large areas can be very painful to the point of limiting the normal functions of the stomatognathic apparatus (hygiene, nutrition, speech).

The treatment of choice is based on topical and/or systemic corticosteroids and other immunosuppressive drugs depending on the severity of the disease expression, with all the adverse effects that these substances have. There are few studies that have evaluated the effects of LLLT on these pathologies, and in each case a small population was studied, both because these diseases are not frequent and because of the involvement of other districts in addition to the mouth and because LLLT was almost always used in addition to conventional therapy [104–106].

Laser diodes with a wavelength between the red (660 nm) and near infrared (810–980 nm) have been tested, and two studies also used CO_2 lasers in defocused mode, with different fluences (4–30, –60 J/cm^2). The results indicate a short- and long-term reduction in pain, faster healing of injuries, and a minor recurrence of the disease.

Oral Lichen Planus

The various forms of this disease fall into two broad categories, white and/or red lesions. While «white» lichen is asymptomatic, the «red» ones (the atrophic-erosive and bullous variants) are very painful and have significant functional limitations. Erosions can hit multiple locations simultaneously, the most affected are the buccal mucosa, tongue, gums, and more rarely the lips and the hard palate.

Therapy is based on topical and/or systemic corticosteroids depending on the clinical severity; a variable percentage of subjects are not responsive to this therapy, and therefore alternative treatments were considered and LLLT is one of them. The ability to modulate the inflammation, the analgesic effect, and the increase of the regenerative capacity of laser light are at the core of the excellent results obtained by the studies in literature [107–110]. Diode lasers (630 nm, 904 nm, 980 nm) were used, on average two treatments per week with fluence of 4 J/cm^2.

Bisphosphonate-Induced Osteonecrosis

Osteonecrosis of the jaw is an adverse effect following the use of drugs used for various metabolic and oncological diseases concerning the skeletal system (bone metastases, malignant hypercalcemia, Paget's disease, osteogenesis imperfecta, osteoporosis). This category includes bisphosphonates and antiangiogenic drugs. Bisphosphonates are drugs that have the ability to modulate bone turnover and reduce the process of resorption; they tend to be deposited in the tissue where they have a time-cumulative effect which seems to be at the basis of the adverse events.

The pathogenesis of osteonecrosis to date is not yet fully established. Among the most reliable theories are the inhibition of osteoclast activity, anti-angiogenic action, and the negative effect on circulating endothelial cells. Clinically, surgical therapy and tissue trauma are considered prime predisposing factors in the development of osteonecrosis; additional negative prognostic factors such as periodontal disease and poor oral health may predispose to the development of this condition [111].

Osteonecrosis treatment options are aimed both to the treatment of overt injury and especially to the prevention of them [112, 113], even if there are not yet any specific guidelines based on scientific evidence. LLLT in recent years has been particularly studied for control of the osteo-mucous lesions as in addition to conventional surgical therapy or laser surgery (pain-relieving action, mucosal healing, support after resective surgery), but also to improve the healing of tissues in patients that underwent oral surgery to prevent exposure of necrotic bone and especially to induce formation of healthy bone [114, 115].

The action of LLLT on bone, studied both in vitro and in vivo, is performed through the proliferation and differentiation of osteoblasts with increased calcium salt deposit which accelerate calcification, through the activation of MCM genes (mini-chromosome maintenance proteins) regulated by DNA replication and through type I collagen formation [115]. The most commonly used wavelengths are in the range between 650 and 1064 nm, power density between 5 and 150 mW/cm^2, 30–60 s per point, and fluence between 0.3 and 9 J/cm^2 [115]. For 1064 nm wavelength, the parameters used are power 1.25 W, frequency 15 Hz, fiber 320 μ, PD 1562.5 W/cm^2, and fluence 7 J/cm^2 **(116)**. On average, laser sessions are 2/3 times per week. (Fig. 7.12).

Burning Mouth Syndrome (BMS)

Burning mouth syndrome (BMS) has been classified as a distinct disease in 2004 by the International Headache Society, which defined the primary form as «a feeling of intraoral burning sensation for which no medical or dental cause can be found» [116]. The diagnosis is mainly by exclusion; it is a chronic clinical entity characterized by burning or itching that affects the oral mucosa and perioral regions with a generally bilateral and symmetric distribution. Symptoms such

Fig. 7.11 (*1*) Fifteen-year-old patient, with a painful major aphthae. Treatment performed with diode laser 904 nm, fluence 4 J/cm^2, average power 0.28 W, spot diameter 5 mm, power density 1.4 W/cm^2, superpulsed, spot technique, 3 s per point, irradiations every other day, immediate analgesic action, and complete healing after four sessions. (*2*) Seventeen-year-old patient, with a painful major aphthae. Treatment performed with diode laser 904 nm, fluence 4 J/cm^2, average power 0.28 W, spot diameter 5 mm, power density 1.4 W/cm^2, superpulsed, spot technique, 3 s per point, irradiations every other day, immediate analgesic action, and complete healing after four sessions. (*3*) Twenty-six-year-old patient, with herpes simplex labialis. Treatment performed with diode laser 810 nm, fluence 4 J/cm^2, average power 0.3 W, spot diameter 6 mm, power density 1.07 W/cm^2, CW, spot technique, 4 s per point, irradiations every other day. Complete healing after five sessions

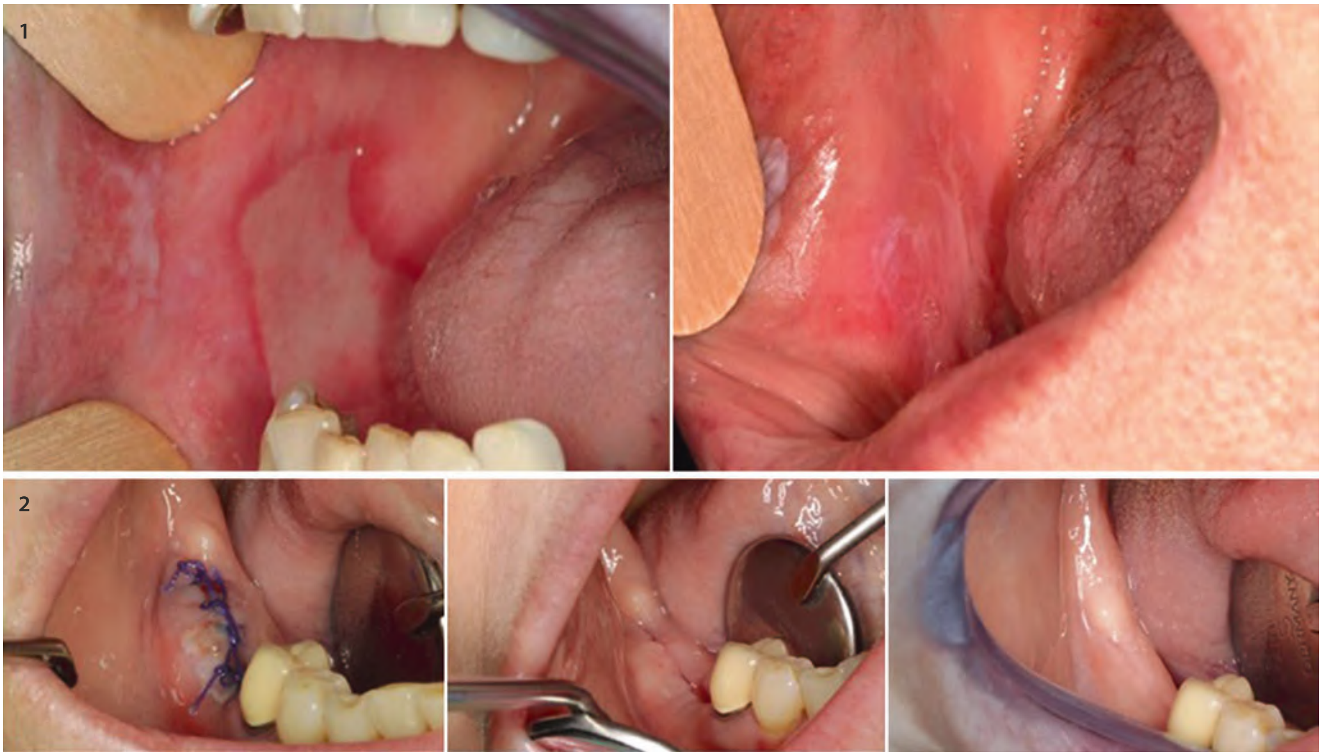


Fig. 7.12 (*1*) Fifty-eight-year-old patient with oral lichen planus (erosive form, unresponsive to topical steroids). Treatment performed with diode laser 980 nm, fluence 4 J/cm^2, average power 0.3 W, spot diameter 6 mm, power density 1.07 W/cm^2, CW, spot technique, 4 s per point, irradiations every other day, appreciable remission after 16 sessions. (*2*) Sixty-year-old patient, assuming high doses of steroids and immunosuppressive drugs for a severe form of autoimmune hepatitis, with consequent osteoporosis and spontaneous bone fractures. The patient is undergoing a therapy with bisphosphonates by injection, with a high risk of ONJ. Preventive treatment, following dental extractions, performed with diode laser 904 nm, fluence 4 J/cm^2, average power 0.28 W, spot diameter 5 mm, power density 1.4 W/cm^2, superpulsed, spot technique, 3 s per point, irradiations every other day, six sessions. Complete healing after a month.

as dysgeusia and xerostomia may accompany the burning sensation, but without clinical and laboratory data that may suggest the combination of an organic disease.

The physiopathology of BMS is not entirely clear; it is believed that dysfunctions in the central nervous system, such as different processing by the brain of nociceptive and thermal stimuli [117] and dysregulation of the dopaminergic nigrostriatal system, may represent plausible causes of oral burning. There is growing evidence in the most recent scientific literature that links the BMS to a peripheral neuropathic mechanism. Histopathological studies show a lower density of epithelial and sub-papillary nerve fibers with axonal degeneration and an increase in the level of receptor mediators in charge of the processing of nociceptive response in patients with BMS compared to a control population [118, 119]. The tongue is the most frequently affected site.

There is no effective treatment plan; patients get some benefit by the use of anxiolytic drugs, anticonvulsants, herbal remedies, acupuncture, and psycho-behavioral techniques. In recent years, LLLT has also been used [120–122]. The positive results in the treatment of BMS reported after laser treatments are due to the action that laser radiation has on pain control, through the release of endorphins, as well as preventing the arrival of ascending nociceptive stimulus to the higher cortical centers, a reduction of TNα and of IL-6 levels in saliva of patients after LLLT has also been reported. The lasers used have a wavelength between 660 and 980 nm, power set from 40 to 300 mW, and fluences from 0.4 to 176 J/cm^2. The sessions are performed one or two times a week for up to ten total treatments.

The wide diversity of the parameters used suggests that the positive outcome of the treatment is attributable to a placebo effect and not to the actual action of the laser [123], certainly in the lengthy treatments of diseases with a high psychological involvement can create empathy with the therapist, but the stability of the results over time and the effective reduction of inflammation mediators also suggest that there is a real photobiomodulating action.

Chemo- and Radio-Induced Mucositis

Oral mucositis is one of the cytotoxic effects of anticancer therapies; the incidence is variable (30–100%) in relation to drugs and/or treatments used. Clinically it presents various aspects ranging from moderate redness of the mucosa and mild symptoms, to serious cases with extensive ulcerations that cause functional limitations. The most severe manifestations cause the inability to perform vital functions such as feeding.

Several scales for assessing the gravity of the clinical pictures have been used; the most commonly used are the WHO scale which provides four degrees corresponding to clinical conditions of increasing severity and National Cancer Institute Common Toxicity Criteria (NCI-CTC) which provide, in addition to the four WHO scale degrees, grade 5, which corresponds to death of the patient due to massive cytotoxicity [124]. The development of mucositis is predictable; after 3–4 days from the drug infusion or radiation treatment, the first lesions appear. They reach the maximum severity in 7–14 days and may regress spontaneously after completion of therapy.

Symptoms related to the clinical picture are described as burning (when there is only erythema), but as the integrity of the mucous membrane is lost and ulcers form, the pain becomes more intense, and high doses of painkillers are required, up to the necessity of the suspension of antineoplastic treatment with all related risks. Microscopically the evolution of the disease occurs in five stages: in the initial stage, direct DNA damage by ROS formation is observed and destruction of basal epithelial cells and activation of the immune system; in the second and third phases, gene transcription factors are activated, of which the NF-kB is the most studied, which determine the amplification of the process by means of the hyper expression of factors and pre-inflammatory cytokines. In the fourth stage, the integrity of the mucosa is lost; there is the formation of ulcers with bacterial superinfection that leads to further deterioration of the situation due to direct activation of macrophages and release of additional pro-inflammatory factors; in the fifth stage, spontaneous healing of injuries with full recovery of the mucosa is observed [125, 126].

Many therapies are used for the treatment of oral mucositis, cryotherapy, topical applications of palliative agents (honey [127], *Solanum nigrum* [128], vitamin E, and others), but above all drug therapies (palifermin, benzydamine, glutamine) [129] to promote healing of the mucous membranes or drugs to control pain [130].

The use of LLLT in both the treatment and the prevention of oral mucositis is well documented in scientific literature; Multinational Association of Supportive Care in Cancer (MASCC) guidelines recommend laser therapy in the prevention of oral mucositis in patients receiving pre-transplant conditioning; suggested parameters are 660 nm wavelength, 40 mW power, and fluence 2 J/cm^2 (level II evidence), while guidelines cannot be drawn up for other populations and other wavelengths because of insufficient scientific evidence [131, 132]. Caution is required in the treatment of mucositis when it is due to the treatment of head and neck cancers, as the mechanism of action of LLLT on tissue differentiation/proliferation and on cancer cells is not yet clear, and thus, the possibility of local invasion or metastasis or the possibility of having effects at a distance must be kept in mind [39]. While the in vitro results show an increase in the proliferation of cancer cells, in vivo this has not been observed, maybe because of the in vivo potential anticancer immunological reactivity.

The most authoritative researchers have joined in a task force just to try to draw up protocols to test the efficacy and safety of LLLT in the management of complications of anticancer therapy [133, 134]. Wavelengths of between 633 and 685 nm and between 780 and 830 nm are indicated as effective, with output from 10 to 150 mW, fluence from 2 to 6 J/cm^2 (2 J/cm^2 for prevention, 4 J/cm^2 for the treatment), 2–3 applications per week. If mucositis is severe, applications are recommended daily until symptoms subside, if pulsed, output frequency < 100 Hz, intra- and extra-oral applications [134]. It is recommended to start treatment before mucositis onset, to intercept with laser therapy the various stages of the disease, and to continue until the end of the cycles of chemotherapy and radiotherapy; all the oral mucosa has to undergo photobiomodulation, extending when possible until the beginning of the pharynx.

Peripheral Neurological Lesions (Paresthesia, Anesthesia, Hyperesthesia)

Injuries of the inferior alveolar nerve, its branches, and the lingual nerve are the major peripheral neurological lesions of oral interest. It is rare in everyday clinical practice to come across lesions to other nerve branches; they are mainly due to maxillofacial surgery.

The causes of injury of the IAN and the lingual nerve are third molar surgery, implantology, endodontics, orthodontic surgery, and regional anesthesia (dental causes), but also operations for the removal of benign or malignant growths or operations concerning the salivary glands. The resulting symptomatology is variable; complete absence of sensitivity (anesthesia) of the innervation district can be observed or a decrease in sensitivity (hypoesthesia), sometimes accompanied by disabling pain (hyperesthesia) with a significant decrease in quality of life. Some lesions tend to resolve spontaneously in 2–3 months, especially if the cause is compressive and the cause (e.g., pressure on the mandibular canal or edema) is removed; if the damage is partial in an estimated 6–8 months' time, a partial recovery of the nerve due to spontaneous nerve regeneration from the proximal to the distal stump can be expected. In the case of complete rescission, a reconstructive microsurgical intervention can be attempted.

Drug therapy (high-dose corticosteroids with gastric coverage and neuroprotective drugs) should be started as early as possible to get a quick resolution of edema and allow recovery of cell function; if there is algic therapy, potent analgesics (clonazepam, gabapentin, carbamazepine) [135, 136] can be used.

In literature, there are studies showing that the use of LLLT can be helpful in the management of peripheral nerve injury both in speeding up the regeneration of the nerve fiber and in control of pain. The clinical bases of these effects are due to the ability of laser light to promote quicker resolution of inflammation and edema that follow the damage, short- and long-term pain-relieving effect, and regenerative cell capacity. In vitro studies and then animal model studies have shown an increase in the number of axons, Schwann cells, and myelins and in the groups subjected to LLLT compared to control groups. An increase in metabolism in neurons was also observed, with increased production of basic fibroblast growth factor (bFGF) and neuronal growth factor (NGF) eGAP-43 (protein associated with peripheral axonal regeneration) [137].

The laser used are included in the range between 660 and 980 nm, the choice of the most suitable wavelength depends on the depth of penetration in relation to the anatomic site where the damage occurred [138]. Fluences that have given the best results are between 0.2 and 6 J/cm^2, treatment with repeatable cycles (ten sessions), irradiating the area affected by the nerve injury, after mapping, both intraorally and extra-orally [139–141].

Temporomandibular Joint Disorders

Temporomandibular disorders are a group of musculoskeletal disorders that fall within high prevalence facial pains in both sexes. Symptoms are variable, pain, functional limitation, clicking or popping and crackling, up to articular disk displacement without reduction, or dislocation. There are many causes – parafunctions, joint overload caused by impaired occlusion, stress, musculoskeletal diseases, trauma, acute and chronic inflammatory joint diseases [142].

The treatment of these disorders is multidisciplinary and is aimed at the control of pain symptoms through drug therapy, at treating the functional limitation through physiotherapy treatment of the masticatory muscles, stress control, using cognitive behavioral therapy, massage and relaxation techniques, occlusal plaques up to complex surgical and prosthetic rehabilitation [143].

LLLT has been used to relieve pain for temporomandibular disorders, alone or in combination with conventional therapies such as physiotherapy exercises and occlusal plaques. Pre-auricular, intra-auricular, and intraoral maxillary points in the rear maxillary area are stimulated; also muscles affected by the symptoms are treated (trigger point). Diode lasers with a wavelength of between 650 and 1000 nm, with fluences of between 1.5 and 35 J/cm^2 are used. Treatments are usually 2/3 times a week until the symptoms have disappeared [144].

Typical and Atypical Facial Pains

Facial pain is a real challenge for the clinician, both in terms of diagnosis and treatment. Pains secondary to specific causes such as inflammation, infection, trauma, cancer, neurological degenerative lesions, or abnormal contact of nerve and vascular structures (trigeminal neuralgia), whose treatment, besides symptomatic treatment, is aimed at removing the cause that has determined the symptom, are different from atypical or idiopathic facial pain, whose classification is not possible in any of the known pathologies (diagnosis by exclusion) and for which treatment is only symptomatic and psychological support.

Referred pain is excruciating with secondary symptoms such as paresthesia, paroxysmal response to minimal stimuli (allodynia), and depressive syndromes [145]. These conditions have a high social cost both for the number of working days lost and for the cost of drugs and imaging techniques needed to arrive to a diagnosis; for this reason, the search for effective treatments and with few adverse effects is important. LLLT's analgesic effect has been well studied and can be applied to various forms of facial pain in association or not with drug and/or conventional instrumental therapies.

Experimental studies on animals have investigated different fluences, and it has been noted that low fluences (e.g., 4.5 J/cm^2) are active on inflammatory mediators that can be found in chronic pain by lowering their levels (compared to the control group), making them effective in the treatment of acute stages of pain, while high fluences (e.g., 27 J/cm^2) cause the increase in β-endorphin, making them more suitable for the treatment of chronic and strong pain [146].

Clinical studies have reported that LLLT in the treatment of chronic facial pain is more or at least as effective as standard therapies [140, 147, 148]; in the latter case the result is still important since, despite having the same result, it is possible to choose a less invasive therapy that is also without adverse effects (Fig. 7.13).

Adverse Effects of Drug Therapy on the Oral Mucosa

Pharmacological treatments can cause side effects even when used according to correct therapeutic schemes and dosages, and oral mucosa is one of the most affected places. Excluding systemic allergic reactions or effects caused by anticancer or antiangiogenic drugs, in the oral cavity it is possible to observe erosions/ulcerations, gingival hyperplasia, lichenoid reactions, salivation disorders, candidiasis, burning and redness, angioedema, and multiform erythema, up to Stevens-Johnson syndrome. Many drugs can cause effects on the oral mucosa; there are about 500 molecules capable of causing hyposalivation (anxiolytics, antidepressants, bronchodilators, anti-migraine drugs, etc.); antihypertensives, anticonvulsants, and contraceptive drugs can determine gingival hyperplasia, but also substances more commonly used as mouthwashes [149, 150].

The treatment of these occurrences requires first of all, when this is possible, the replacement of the «offending» drug and at the same time the establishment of a new therapy to promote healing of the tissues and counter the associated symptoms, with the possibility of experiencing new effects adverse. LLLT has been used successfully in the treatment of many drug-induced events, such as gingival hyperplasia [151], or to promote faster healing of wounds from the most diverse origins [82, 152] with no contraindications or side effects (Fig. 7.14).

7.5.2 LLLT and Bone

The bone tissue is a dynamic and plastic biological tissue characterized by considerable hardness and strength. It modulates its structure as a result of organic and mechanical stimuli, has the function of support and protection for the body and the internal organs, is a mineral salt reserve (calcium,

Fig. 7.13 (*1*) Application points for muscular trigger points (sternocleidomastoid, temporal) and TMJ arthropathy. (*2*) Skin cleaning before irradiation for sinusitis (frontal and maxillary sinuses)

Fig. 7.14 (*1*) Seventy-year-old cardiopathic patient with a drug-induced hyperplasia and gingival painful inflammation (antihypertensive drug, non-replaceable). The patient was unable to wear the removable prosthesis. Treatment performed with diode laser 810 nm, fluence 4 J/cm^2, average power 0.3 W, spot diameter 6 mm, power density 1.07 W/cm^2, CW, spot technique, 4 s per point, irradiations every other day, appreciable improvement after six sessions. (*2*) Seventy-six-year-old patient, with Sjogren syndrome, assuming systemic steroids. Allergic reaction to chlorhexidine. Treatment performed with diode laser 980 nm, fluence 4 J/cm^2, average power 0.3 W, spot diameter 6 mm, power density 1.07 W/cm^2, CW, spot technique, 4 s per point, irradiations every other day. Almost complete healing after 2 weeks (six sessions).

95%), contains the bone marrow, and serves as insertion for the muscles. It is composed of an organic component rich in cells (osteoprogenitor cells, osteoblasts, osteocytes, osteoclasts), of the extra cellular matrix rich in amorphous substance and collagen type I, which gives strength and elasticity and of a part rich in minerals, inorganic salts (calcium phosphate and magnesium, sodium nitrate, potassium and manganese) which determines the hardness. The bone tissue is subject to a number of structural and functional changes due to age, nutrition, and subjective conditions such as drug therapies [153].

Bone is a tissue with a high regenerative potential: healing of fractures is a clear example of this characteristic. The physiological mechanism of regeneration occurs through sequences activated by molecular and cellular factors and is similar to the healing of other types of tissue: there is an initial inflammatory phase, followed by reparative phase and the remodeling phase.

In the bone wound, a hematoma is formed that favors the supply of inflammatory cells (macrophages, monocytes, lymphocytes, and nucleated polymorphic) that induce the production of bone morphogenetic proteins (BMPs) and growth factors. These in turn infiltrate the surrounding bone resulting in the formation of granulation tissue rich in newly formed vessels in which mesenchymal progenitor cells are recalled. During the reparative phase, the derived mesenchymal cells (monocytes and fibroblasts) begin to differentiate into bone cells, osteoblasts, which secrete the collagen matrix rich in fiber that creates a bridge between the various edges of the wound and leads to the formation of osteoid tissue, on which the mineral component is deposited. In the phase of tissue remodeling, the newly formed bone assumes the characteristics of the native bone in terms of shape, structure, and mechanical strength; this process occurs in 3–6 months [154].

It has been observed that the use of anti-inflammatory drugs in the first phase can alter bone healing, as well as the use of tobacco can inhibit the formation of the supporting stroma of newly formed vessels.

The effect of LLLT on bone tissue has been studied both in vitro and in vivo demonstrating an increase in the synthesis of osteoblasts, modulation of inflammation, production of TGF-β which includes the BMP, one of the important factors that regulate the proliferation and differentiation of new bone. A decrease osteoclast activity [155–158] has also been noted.

To validate the effectiveness of LLLT on osteoblasts, the activity of mitochondria was measured, after biostimulation with an 830 nm laser and fluence of 3 J/cm^2, and an increase of cell proliferation by 30–50% was observed [159].

The wavelengths commonly used are in the range of near infrared (deep penetration) with fluences between 2 and 5 J/cm^2.

The possibility to obtain a faster bone healing offers advantages in the treatment of surgical wounds in which the bone tissue is involved, after dental extractions, after oral surgery in general, for the osseointegration of implants and in intrabony defects subjected to periodontal surgery.

LLLT and Implantology

The success of implant therapy is the result of many factors and depends both on the health of the soft tissue and the connective/implants interface; LLLT has been studied for the effects on fibroblasts and on bone cells. It was seen that biostimulating the implant site a greater number of cells adherent to the implant surface [160] is obtained, as well as a greater osseointegration. Most of the studies available in the literature were performed on animal models [161, 162]. The wavelengths

used vary in the range of red and near infrared with fluences ranging from 2 to 92 J/cm^2, mainly with values between 3 and 8 J/cm^2 with daily applications daily or every 48 h during first weeks after implant placement. Despite the knowledge of the benefits of LLLT on inflammation, pain control, and regeneration of soft tissue and bone, the lack of randomized double-blind clinical trials precludes a repeatable protocol. However, the possibility to speed up the early phases of osseointegration could be relevant for immediate loading of implants or for implants with a poor initial stability [163].

LLLT in Intrabony Defects

The alveolar intrabony defects responsible for a decreased tooth stability are part of a framework of severe periodontal disease. The gold standard treatment is represented by resective/regenerative surgery with the aim of correcting the anatomy of the sites and to promote bone regeneration. In addition to conventional treatments, laser applications result in already accepted effects on inflammation, pain, and wound healing, as well as in an increased bone regeneration with improved clinical periodontal indices, more stable over the long term [164, 165].

LLLT can be used after nonsurgical periodontal therapy with reduction of the probing depth in the short term, while in the long-term results are comparable to scaling and root planning (SRP) [166].

7.6 LLLT in Orthodontics

Nowadays there is a high request for aesthetic interventions that also have led to an increase in dental treatments aimed at improving the alignment and occlusion as well as at to cure dysfunctional conditions. Orthodontics deals with the diagnosis, treatment, and prevention of malocclusion not only in children but also in adults.

During life, the teeth are subjected to forces that determine displacement both as a physiological adaptation and as a compensatory adaptation following the early loss of the dental elements, according to a «pressure-tension mechanism.» When a force is applied to the tooth surface, a biological response in the surrounding tissues is triggered, with remodeling of the periodontal ligament and alveolar bone through a reorganization, both cellular and of the extracellular matrix together with the micro-local circulation [167]. During a first inflammatory phase, there is a release of cytokines, chemokines, growth factors that activate osteoclasts at

Fig. 7.15 Laser application in orthodontics (fixed appliance and removable aligner). Treatments performed with diode laser 904 nm, fluence 5.6 J/cm^2, average power 0.28 W, spot diameter 5 mm, power density 1.4 W/cm^2, superpulsed, spot technique, 4 s per point. Six points per tooth (mesial, distal, apical, vestibular side, and lingual or palatal side). Irradiations every 15 days

pressure sites (bone resorption), and osteoblasts in tense sites (neo-bone formation).

The research is aimed at developing therapeutic modalities able to modulate this phase to obtain a speeding up of the orthodontic movement, and the laser treatment is one of these [168].

Numerous studies have investigated the action of LLLT on orthodontic movement, thanks to its biostimulating and analgesic action. It was observed that a single application immediately after the mounting of the brackets is able to control the pain generated by the insertion of the first arch wire [169] and the insertion of the separators used to create space to insert the bands [170]. Results have indicated an acceleration of orthodontic movement of 20–40% displacement [171, 172].

For these applications diode lasers are used, with a wavelength between 635 and 1064 nm, fluences ranging from 0.7 to 25 J/cm^2. The irradiation is performed on the vestibular side, both palatal/lingual of the involved teeth, with variable repetition rate, from a monthly application to a weekly application, depending on the movement required. For the retraction of the canine after extraction of the first premolar, it is considered very effective to perform applications with low fluences (2/cm^2) approximately every 10 days [173]. The laser applications can be used also in case of removable appliances such as orthodontic aligners (Fig. 7.15).

7.7 LLLT and Dentin Hypersensitivity

One of the most common requests for dental examination concerns increased tooth sensitivity, mainly perceived as painful sensation due to thermal, tactile, osmotic, or chemical stimuli. Excluding the most typical disease of the teeth (caries and its complications), dental hypersensitivity is established over time for dentine exposure due to factors such as gingival retraction or enamel erosion. The treatment of this condition involves the removal of the predisposing factors (incongruous brushing, saliva hyperacidity, eating disorders, hyposialia, parafunctions – teeth grinding and clenching, diseases of dental hard tissue, gastroesophageal reflux disease, etc.).

Several agents are used with the purpose of sealing the dentinal tubules inside of which there are the small nerve endings responsible for the painful sensations, administered as home therapy or in the office. The patient should be properly instructed on proper oral hygiene techniques, on the limitation of acidic foods and drinks, and on the use of toothpastes and mouthwashes containing fluorine or specific for dentin sensitivity. In-office professional therapies involve the use of fluoride varnishes, pastes containing oxalates, remineralizing agent (calcium phosphate + casein) fillings with composite resins, or glass ionomer cements and laser applications [174–176].

The action of LLLT on dentin hypersensitivity acts mainly on the control of the associated pain modifying the transmission of the nociceptive stimulus to the pulp and by stimulating the normal cellular functions, the laser would promote the production of sclerotic dentin, obliterating the dentinal tubules from the inside [177]. In literature there are articles that compare the laser treatment with applications of fluoride gel, and gel containing potassium and LLLT was found to be more effective [178].

Commonly, diode lasers are used with a wavelength of between 650 and 870 nm, with fluences between 1.8 and 4 J/cm^2 [179]. After cleansing the area to be treated, the irradiation is performed perpendicular to the sensitive area, in three points (mesial, distal, central), repeating the sessions every 48–72 h until symptoms disappear [180].

7.8 Laser Acupuncture

Acupuncture is a therapeutic technique whose aim is to promote patent's well-being by regulating the body's «vital» energy flow (Qi) using needles. Energy flows in 12 canals, known as meridians, (6 Yin and 6 Yang), each one related to an internal organ, in continuous communication with the outside. Acupuncture does not use meridians as such, but the single points that make them up and that project outside the energy that comes from inside the body. The needles used to stimulate the points behave as dipoles and can modify the magnetic field of the body, subtracting or yielding electrons to the protoplasmic matrix, causing the release of neurotransmitters or neuromodulators [195], thus reinforcing the immune system, increasing circulation, and promoting a sedative action of the CNS [186].

The first reports concerning the use of lasers on acupuncture points date back to the beginning of the 1970s in Russia [181–183], in these studies «cold» lasers were used, with low powers, applying without full knowledge of the scientific bases of LLLT.

The prompt to find alternative stimulation methods other than needles derived from the need to offer a noninvasive, painless treatment method without adverse effects (contamination and stimulation of wrong vital points) [184], suitable for phobic or special need patients.

Various studies in scientific literature have compared the effectiveness of the two methods and the result was that, apart from a few critical issues like light reflection on the skin that can reduce the overall absorption, or other variables like skin color that lead to parameter adjustment [185, 188, 189], or light diffusion within tissues that influences reaching the point to be stimulated [190], no other difference has been recorded [191–194].

In dentistry acupuncture and laser acupuncture are used in the following conditions:

Pain Control

Points ST6 ST7 L14 are considered general stimulation points for facial pain relief [187, 188] and for the induction of analgesia during small oral surgery procedures, for temporomandibular joint disorders [196] or for myo-fascial pain [197].

Gag Reflex

Points PC6 (the one mostly used) and CV24 individually or in combination. This method is widely used in all those conditions where an excessive oral stimulation induces an abnormal gag reflex (e.g., during the taking of casts or to perform intraoral radiographs) [198, 199] or for vomiting induced by anticancer drugs [200] or in the vomiting after surgery [201], without any adverse effect compared with antiemetic drugs.

Hyposalivation

A reduction in saliva flow determined by pathological conditions of the salivary glands, or as a side effect of radio- and chemotherapy, or by physiological glandular involution generates a progressive deterioration of oral health. In scientific literature, there are studies that have used the stimulation of acupuncture points to increase the salivary flow obtaining persistent good results [201–204]. In addition to points located on the face (ST6 ST7 ST5 SI19), points are used in other parts of the body (limbs and trunk) in relation to the energy imbalance of the subjects enrolled in the various studies.

Anxiety Control

Many patients live with extreme anxiety dental sessions; the stimulation of acupuncture points on the ear allows greater control of the levels of anxiety and stress.

The wavelengths used in laser acupuncture are 400 nm (blue), 635 nm (red) which is the most common, 700–1000 nm (infrared) which has a greater depth of penetration, and 532 nm (green) mainly used for the auriculotherapy, but few studies can be found in literature [205–208].

Regarding the dose to be administered as well as the repetition of treatments, there are no guidelines, a dose range, in accordance with Litscher G. and Opitz G. [209] between 0.001 and 10 J/cm^2, and therapy sessions every other day for diseases in acute stage and once a week for chronic conditions are generally considered correct (Fig. 7.16).

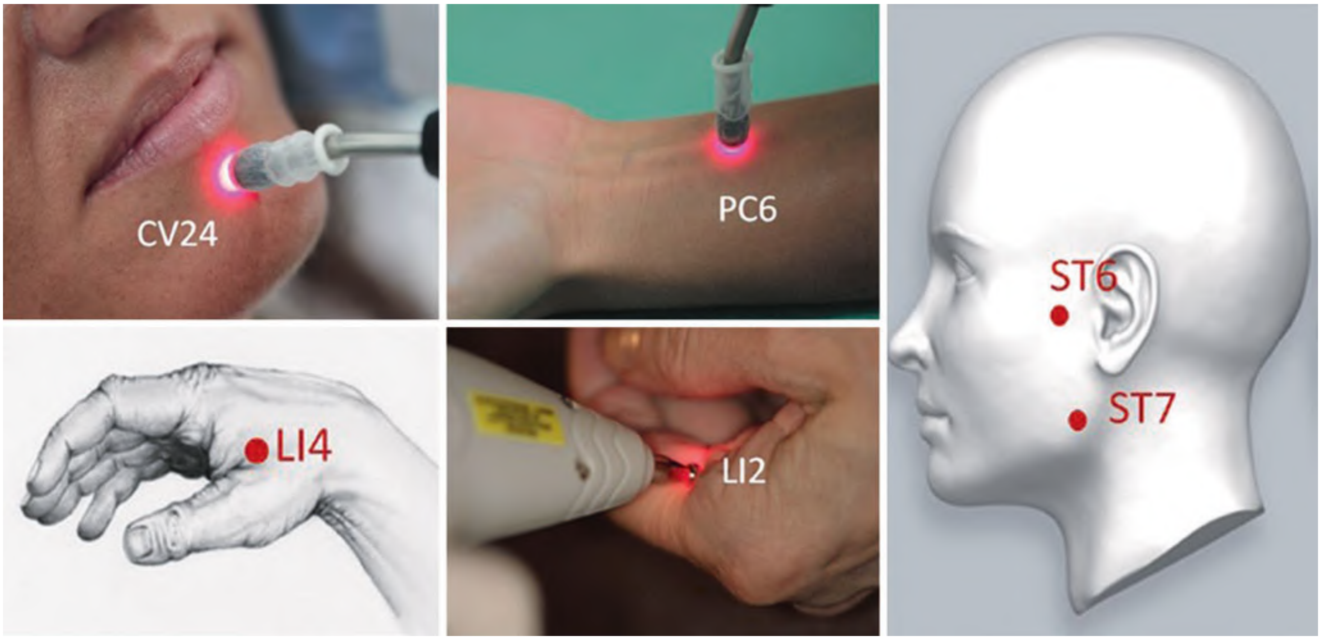


Fig. 7.16 Laser acupuncture application points. CV24 and PC6, specific points for nausea control; LI 4, LI2, ST6, and ST7, specific points for pain control

Conclusions

The use of light as a therapeutic agent has received general acceptance worldwide, both through research and consolidated clinical evidence. In achieving this acknowledgment, phototherapy has been shown to provide efficacy, lack of invasiveness, and absence of significant or negative side effects.

The route is not still complete, and further steps are necessary to build further strong scientific evidence, introducing low-level laser therapy (LLLT) in daily clinical practice, following the available protocols and contributing to its full inclusion among the therapeutic weapons.

Far from being magic or alternative medicine, the LLLT offers to the practitioners in every field of medicine and in every branch of dentistry the opportunity to interact with patients, with the maximum respect of their physical and psychological integrity, perfectly adhering to the new concept of health.

Due to its anti-inflammatory, analgesic, biostimulating, and bactericidal activity, LLLT has a broad spectrum of action, competing with drug therapy normally used or integrating with their effects. Dentistry is mainly a surgical branch, involving hard and soft tissues; therefore, inflammation, pain, and infections are common, together with the wish to obtain uneventful and rapid healing; LLLT contributes to treat these aspects, speeding up the healing processes, as well as in oral medicine. In the treatment of osteo-arthro-muscular problems, in orthodontics, in the treatment of dentin hypersensitivity, in the recovery of nervous lesions, and in many other pathological conditions, LLLT brings an added dimension to the approach to treatment.

The future prospects are exciting, and it's easy to predict more surprising developments surrounding the controlled use of this natural and essential form of electromagnetic energy.

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7

Laser-Assisted Oral Hard Tissue Management

Contents

Laser-Assisted Restorative Dentistry (Hard Tissue: Carious Lesion Removal and Tooth Preparation)

Riccardo Poli

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Core Message

This chapter explores the range of benefits that relate to laser-assisted oral hard tissue management and details aspects of each wavelength in delivering adjunctive therapy. Of the currently available wavelengths of dental lasers, only three can be used for hard tissue.

- Erbium lasers available on the market can have two different wavelengths: 2940 nm (Er:YAG) and 2780 nm (Er,Cr:YSGG), and their use is gradually increasing in dental practices as an alternative or as a complementary tool versus traditional dental treatments.
- During the last 10 years, researchers have developed a CO_2 laser, traditionally used for soft tissue surgery, into a powerful hard tissue laser. The emission wavelength is 9300 nm, and the performance within clinical use in restorative dentistry is very promising.

Table 8.1 shows Erbium laser advantages. These innovative properties can be easily perceived by comparing the use of these wavelengths and traditional techniques, envisaging the use of a high-speed handpiece and of a diamond bur, or alternative ones, for example, techniques such as air abrasion or the use of decayed material dissolving gels.

Thanks to its clear advantages, in restorative dentistry, every dentist can easily exploit the important characteristics that are revolutionizing dentistry.

This type of laser perfectly fits the minimally invasive dentistry philosophy. The experience reported by the patient during its use for cavity preparation is completely different from the one when dental drill is used to prepare a decay lesion (Figs. 8.1, 8.2, and 8.3).

In most cases, local anesthesia through injection is not required, because erbium triggers an analgesic effect in just a few seconds. This laser allows pain-free ablation of hard tissues. Furthermore, no vibration is felt as the bur does not work in contact with the surface, and thus, the patient does not hear the traditional noise of the dental drill.

However, the operator has to go through a learning curve because the use of these wavelengths is neither intuitive nor immediate. A certain period of time is required to learn which is the optimal distance of the handpiece vis-à-vis the dental surface to be treated. By working contactless, it is indispensable to place the laser tip at about 1 mm in order to maximize ablation. Furthermore, the operator must have an in-depth knowledge on how to set and modify the various parameters (among which energy output, frequency of pulses, and the air/water ratio for cooling irrigation) [1].

However, high- or low-speed burs used with the dental drill are still more efficient and fast in removing dental tissues. Preparing a cavity by dental drill is much quicker.

Burs ensure optimal control, and their use is more intuitive as all dentists have been using them for ages and because

Table 8.1 Table of hard tissue laser advantages

To be used on the hard tissues of the tooth, on the bone, and on soft tissues
Possibility to cut soft tissues at the same time during cavity preparation (i.e., gingivoplasty or pulp exposure treatment during conservative therapy)
Minimally invasive
Reduced or no need for local anesthesia
Suitable for preparation of very small cavities
Precision and accuracy in ablation on hard tissues
Limited risk of iatrogenic damages
Noiseless ablation compared to dental drill, no vibration, no contact
Ablation/excision selectivity of decayed hard tissues
Increased useful surface for bonding (micro-retentive surface)
Tissue decontamination
Biostimulation effect
No tissue/pulp heating
No hard tissue cracking
Limited coagulation effect on soft tissues
Working area on soft tissues stays clean
No smear layer in hard tissues

Fig. 8.1 Small cavity preparation on tooth #2 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Enamel settings: MGGG6 sapphire tip diameter 600 μm, length 9 mm, 3 W, 15 Hz, 200 mJ E per pulse, peak power 3333 W, average power density 492 W/cm^2, peak power density 546.710 W/cm^2, total energy 90 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (18 ml/min), 80% air. Dentin and smear layer settings: MGGG6 sapphire tip diameter 600 μm, length 9 mm, 2 W, 15 Hz, 133 mJ E per pulse, peak power 2222 W, average power density 328 W/cm^2, peak power density 364.473 W/cm^2, total energy 20 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (20 ml/min), 80% air. Parameters calculation made according to Prof. W. Selting indications

Fig. 8.2 Detail of completed preparation of tooth #2

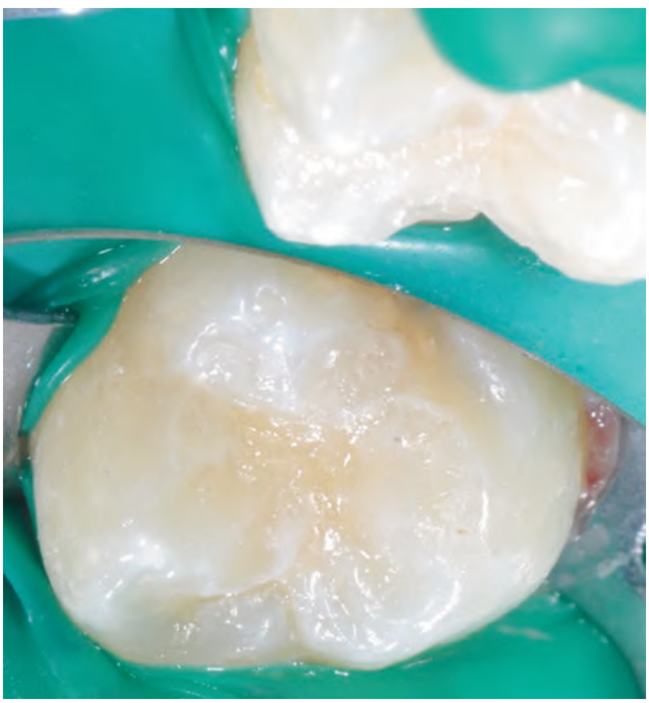

Fig. 8.3 Completed composite restoration in tooth #2 (acid etching with orthophosphoric acid 37%, OptiBond FL total-etch adhesive system (Kerr, Orange, CA, USA), composite material Herculite XRV Unidose (Kerr, Orange, CA, USA))

they received thorough training on their use. At the same time, however, burs are more aggressive and nonselective; they generate intense vibration which may be harmful to the tooth structure, and they may cause cracking and pulp heat damage.

Furthermore, during their use, a large amount of smear layer is produced requiring acid etching for its removal before the application of the chosen adhesive system.

Table 8.2 Comparison bur vs erbium laser

Restorative procedure	Handpiece and bur	Laser
Cutting enamel/dentin	Yes	Yes
Selective removal of caries	No	Yes
Precision	Precise >1–2 mm	Precise <300 µm
Smear layer	Smear layer produced	No smear layer
Thermal rise	Thermal rise >15 °C	Thermal rise <5 °C
Risk of iatrogenic damage	Greater	Less
Noise/vibration	120 dB/vibration	< 120 dB/no vibration
Bactericidal action	No	Surface decontamination
Speed of cutting enamel	Fast	<30% bur speed
Speed of cutting dentine	Fast	Comparable
Pain response	High	Less pain/no pain

Very frequently it is necessary to use local anesthesia by injection in order to avoid pain to the patients. The traditional technique is at the basis of the intense fear and phobia that patients feel when they have to undergo conservative therapy.

Table 8.2 shows a comparison among the characteristics resulting from the use of the traditional high-speed handpiece with diamond bur vis-à-vis the use of the erbium laser [2].

An alternative more delicate method, and less aggressive too, is represented by air abrasion, exploiting aluminum oxide particles (Al_2O_3) to remove carious tissues.

With this method, the risk of cracking is lower than with the one using the diamond bur, and no smear layer is produced. Adhesion of composite seems increased thanks to the created micro-irregularities and, as a consequence, we will have less microleakage.

The main disadvantage is represented by the particle layer that is deposited on the entire working area, which must be accurately removed before starting any adhesive technique.

Decay chemical and mechanical removal systems envisage the use of sodium hypochlorite type of chemical substances (usually in the form of gel) or of enzymatic type. These substances can selectively dissolve decayed tissues, which are then removed through excavating tools.

Fig. 8.4 Fracture of tooth #13 crown

Fig. 8.5 Gingivectomy and crown lengthening of tooth #13 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Gingivectomy settings: MT4 sapphire tip diameter 400 µm, length 6 mm, 2.5 W, 25 Hz, 100 mJ E per pulse, peak power 1667 W, average power density 1989 W/cm^2, peak power density 1.326.292 W/cm^2, total energy 300 J, pulse width 60 µs, in contact, 40% water (16 ml/min), 20% air. Crown lengthening settings: MZ6 quartz tip diameter 600 µm, length 9 mm, 4 W, 25 Hz, 160 mJ E per pulse, peak power 2667 W, average power density 656 W/cm^2, peak power density 437.368 W/cm^2, total energy 480 J, pulse width 60 µs, tip-to-tissue distance 1 mm, 60% water (20 ml/min), 80% air

8.1 Effect on Hard and Soft Tissues

An additional advantage resulting from the use of the erbium laser compared to other methods is represented by the intraoperative possibility of performing ablation/excision of hard tissues and at the same time of treating surrounding soft tissues by gingivoplasty, a more extensive gingivectomy, or also the clinical crown lengthening which simultaneously modifies gum levels and possibly the bone margin by restoring the lost biological width (Figs. 8.4 and 8.5).

In fact, if during decay preparation it is required to expose the healthy edge of the cavity, temporarily covered by the gum, it is very easy to perform a light gingivoplasty in order to remove the superfluous keratinized tissue.

Should it be required to remove the excessive gum margin due to the size of the decayed cavity, it is possible to perform such procedure during the same conservative therapy session by simultaneously removing decayed and soft tissues.

If the correct biological width is lost, performing the lengthening of the clinical crown with regard to soft tissues is very quick and possibly also including the underlying bone tissue.

The entire procedure can be completed in a single session by considerably reducing operative times.

Erbium lasers have moderate control over bleeding when used at low energy values, high frequency (30–40 Hz), with a high pulse width (i.e., 700 µs/pulse), without water, and little cooling air to facilitate thermal interaction with tissues.

This is a characteristic that can be used in conservative dentistry, as well as in oral surgery and dental prosthetics to facilitate hemostasis.

If necessary, should the pulp be exposed following a trauma or penetrating decay, it can be decontaminated and coagulated before performing pulp capping or selective pulpotomy.

8.2 Affinity with Water

Both erbium laser wavelengths (2780 and 2940 nm) have high affinity with water [3, 4]. In fact, they are both almost fully absorbed by this molecule (the second one even to a greater extent so).

The highest the content of water in the tissue, the greater the absorption will be.

Considering that the laser beam penetration is inversely proportional to absorption, impulses do not spread much in depth; thus, the beam can penetrate dental tissues by only a few microns (for the wavelength of 2940 nm, it is 7 µm into the enamel and 5 µm into the dentin, while for the wavelength of 2780 nm, it is 21 µm into the enamel and 15 µm into the dentin) [5–9].

If the tissue has high water content (i.e., soft tissues vs hard tissues, dentin vs enamel, deciduous dentin vs permanent one, decayed dentin vs healthy dentin), the energy of erbium lasers could more easily cause explosive ablation at lower energy levels. The average threshold level at which ablation of hard tissues occurs is about 8–11 J/cm^2 for the Er:YAG laser and about 10–14 J/cm^2 for the Er,Cr:YSGG laser [8].

This phenomenon is at the basis of selective ablation. Erbium more easily removes the most hydrated tissue vis-à-vis the one with the lowest water content; thus, it is more effective on decayed dentin, and it saves the healthy tissue surrounding it.

This is the reason why laser parameters will have to be adjusted according to water content, for example, by reducing the beam energy used for a deciduous tooth vs what one would do to perform the ablation of a permanent tooth.

If the level of energy is sufficient to remove the carious tissue, but not the healthy one, it is perfectly useless, and actually it is rather harmful, to increase it, as one would risk to excise part of the healthy tooth.

The energy threshold value that can allow a clinically efficient ablation of hard dental tissues is:

About 125 mJ (100–150 mJ) for primary dentin and decayed tissues
About 150 mJ (100–200 mJ) for permanent dentin and primary enamel
About 225 mJ (200–250 mJ) for permanent enamel

With regard to posterior teeth, or if tissues are highly calcified and with less water content, it could be necessary to further increase energy parameters (up to about 350 mJ for healthy enamel).

8.3 The Level of Laser Energy

Erbium lasers are equipped with external integrated irrigation systems through an air/water spray. This allows to cool off targeted tissues, to keep the working area clean as it is key to prevent damages and thermal alterations on the cavity surface and on the tooth pulp.

The operator should be able to accurately choose laser parameters in order to efficiently perform the ablation without damaging the surrounding healthy tissues.

The first decisive factor is represented by the level of laser energy. It is always good practice to use minimum efficient value to obtain adequate excision. Excessive energy may damage the dental surface by altering, for example, the possibility of performing a good adhesive technique of composites [10].

The chosen energy level can also be addressed toward a smaller or bigger surface. If the chosen level of energy is spread on a small surface, it will be easier to obtain the ablation effect vis-à-vis when the energy is spread on a bigger surface [11].

In fact, if the same amount of energy is spread on a bigger surface, the amount of energy per surface unit will be smaller.

Its density (energy density or fluence) could be unsuitable to achieve the threshold level capable of interacting with a tissue by inducing its excision.

By placing the tip in contact with the tissue, fluence will be maximum, while by increasing the distance, we reduce it by about 70% at 0.5 mm, by 52% at 1 mm, by 32% at 2 mm, by 22% at 3 mm, and so forth. Obviously, the greater the energy density, the greater the interaction between laser and target tissue.

Furthermore, this parameter can change, for example, by using a fiber or a tip with a different diameter. If the tip diameter is bigger, the energy is released and spread over a larger target surface compared to a tip with a smaller diameter.

Thus, the subsequent effect will be smaller. The removal of a tissue occurs with a specific level of energy starting from the «threshold» value. Below it, no excision will occur, but there could be important structural or microstructural modifications [12–15].

On the other hand, above the threshold of 150–200 mJ, there would be a proportional increase of the excision, but also an increase in the risk of structural thermal alterations, especially if the air/water spray cooling is insufficient [16–18].

In such event, these alterations concern a depth of a few tenths of microns.

The used energy is measured in joule (J) and its density in J/cm^2.

8.4 Pulses and Frequency

Erbium lasers operate by free-running pulse (FRP), i.e., by releasing energy pulses alternated by moments in which the energy is not released, and they are repeated several times every second.

The number of pulses released every second is called frequency (or pulse frequency). This value is expressed in hertz (Hz or p.p.s., i.e., pulses per second).

The larger the number of pulses in the time unit, the larger and quicker the interaction with the target tissue will be, because a larger amount of energy is transferred to it.

The amount of energy that is released in the time unit identifies the power, i.e., the energy of each pulse times the number of pulses per second. It is measured in watt (W).

Thus, power depends on the ratio between energy and the number of pulses per second ($W = J \times Hz$).

When energy is provided through a short pulse (a pulse duration of about 50–150 μs), you get a high amount of energy which interacts with the tissue in a fraction of a second, and this means achieving huge power value.

Each pulse can, however, achieve a maximum power (peak power) which has a major impact on the tissue. Interaction with a target is greater if the peak power is high. The shorter the pulse duration, the lower the energy converted into heat will be. As a consequence, thermal interaction and the damages to the teeth tissues following temperature increase will be reduced.

The irradiated enamel and dentin surfaces after interaction with the laser present valleys and peaks, deeper ones when the applied energy is higher.

The appearance is very similar to that of etched tooth tissues: without smear layer, clean, wavy, micro-rough, and irregular.

Fig. 8.6 Preparation of a class I cavity in tooth #14 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Enamel settings: MZ6 quartz tip diameter 600 μm, length 9 mm, 3 W, 15 Hz, 200 mJ E per pulse, peak power 3333 W, average power density 492 W/cm^2, peak power density 546.710 W/cm^2, total energy 90 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (18 ml/min), 80% air. Dentin and smear layer settings: MZ6 quartz tip with diameter of 600 μ, length 9 mm, 2 W, 15 Hz, 133 mJ E per pulse, peak power 2222 W, average power density 328 W/cm^2, peak power density 364.473 W/cm^2, total energy 20 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (20 ml/min), 80% air

Dentin, in particular, has open tubules, and it is subjected to a major excision in the intertubular area as it is very hydrated, while peritubular areas are more elevated and protruded.

8.5 Distance to the Target

It is key that the operator works by holding the laser handpiece at the correct distance from the target in order to optimize excision and treatment duration. Since the laser is contactless, excessive distance prevents the efficient interaction with tissues.

Furthermore, the hand holding the handpiece must move slowly to allow the laser energy to interact with the tissue. The speed of the movement must be slower than the speed normally used with the dental drill.

During a cavity preparation work (Figs. 8.6 and 8.7), the tip is gradually inclined on one side to obtain widening [19].

Fig. 8.7 Inclination of the tip toward the walls of the cavity during carious tissues ablation in tooth #14

As preparation proceeds, the tip must be positioned deeper to maintain the ideal distance vis-à-vis the target and thus obtain a high and continuous energy density.

8.6 The Problem of Laser Etching

The use of energy values below the ablation threshold (sub-ablative) allowing a microstructural modification in dentin and enamel creates a very similar surface to that obtained with orthophosphoric acid. Improperly, this effect has been long defined «laser etching» in literature [20–27].

The differences between acid etching and surface etching by erbium laser are numerous. More precisely, it would be appropriate to use the term «laser conditioning» [28, 29].

Acid etching is a process that has been used for decades to facilitate composite adhesion. Even though there are some issues associated with it (excessive decalcification with alteration of the enamel-dentin ideal architecture for adhesion, higher susceptibility to secondary decay, tooth sensitivity, excessive demineralization compared to the penetration ability of adhesive system monomers), the results obtainable through orthophosphoric acid are widely predictable [30–32].

With regard to the use of orthophosphoric acid at 34–38%, erbium lasers generate a more irregular surface; the greater the energy and the lesser the frequency, we, respectively, get deeper and more far-apart craters.

Even if the final surface is very similar to the etched one, composite adhesion process to irradiated tooth hard tissues is a controversial phenomenon, and its outcome should be further investigated as many authors deemed it of lower quality.

In literature, data are quite contrasting, and, often times, adhesion values came out much lower than those obtainable with the acid [25, 26, 33–37].

8.7 Microleakage

Difficulties encountered by operators during the bonding procedure between the composite and hard tooth tissues often translate into microleakages or the complete detachment of the reconstruction from its seat [38].

Microleakages can be defined as a loss of marginal seal between the restorative material used for tooth filling and the tooth cavity wall with the subsequent infiltration of bacteria, fluids, molecules, or ions [39–42].

Among the causes of microleakage, we can mainly keep the following elements into account:

1. Incomplete penetration of the bonding resin in the area that was decalcified by the etching acid or following the erbium laser effect. This gives rise to the formation of a weaker bonding area, which will be more sensitive to hydrolysis and infiltration.
2. Stress generated at tooth/reconstruction interface level following polymerization shrinkage, or due to oral environment temperature fluctuations [43], or due to cyclical phenomena of mechanical fatigue that are repeated during the masticatory load.

Infiltration of bacteria or of fluids along the interface can cause hydrolytic collapse, both of the adhesive resin and of the collagen present in the hybrid layer, jeopardizing bond stability between the resin and the dentin surface.

Microleakage is the main factor of secondary decay and of reconstruction failure [44–46], and it is at the basis of dentin hypersensitivity, discoloration, and pulp damages.

An additional cause of detachment between composite and tooth wall is related to the shape of the prepared cavity. The greater the number of walls (i.e., box-shaped cavities typical of class I of Black's classification), the greater the relationship between bonded surfaces and nonbonded ones. This principle is defined as C-factor [47, 48].

If the entire composite simultaneously adheres to the walls, as it happens in the occlusal cavities of molars, there will be many more cases of shrinkage-related stress because the composite adhering to many walls at the same time, by contacting, generates even greater stresses.

On the other hand, if cavity tooth walls are just a few (i.e., interproximal preparations of class II premolars and molars), we would assist to reduced stress since the part of nonadhering materials can compensate for polymerization shrinkage, releasing the effects toward the part free from constraints, and thus, there will be lesser risk of reconstruction detachment.

Insufficient compensation of stresses resulting from polymerization shrinkage reduces the efficiency of the seal due to the reduced initial strength of the composite-cervical dentin bond.

The larger marginal gap is usually located on class V gingival side and on the external edge of the class II gingival margin (V-shaped gap). This is due to a lesser capacity of the dentin sublayer and of cement at the tooth neck to favor strong bonding with the resin by means of an adhesive system [33, 49, 50].

Width gap below about 1 μ does not allow bacteria infiltration, but it may allow the spreading of toxins and of other tooth potentially dangerous bacteria-related substances (nanoleakage).

When the cervical margin is located on the limit line between root dentin and cement, the leakage problem becomes more relevant because adhesive systems become less efficient at the level of these substrates vis-à-vis when they are used on the enamel. The bonding process to dentin is much more technique-sensitive and substrate-sensitive.

The ability of adhesive systems to bind to hybridized cementum must be discussed. «Cervical margin leakage can be correlated to the absence of dentin tubules in 100 μ within the cervical border itself, to the relatively reduced number of tubules in the first 200–300 μ of the gingival floor in the cavity, and to the mainly organic nature of the gingival substrate» [51].

When present in the cervical margin, enamel is usually thin, aprismatic, and less receptive to bonding.

When polymerized, composite resin shrinks toward the upper adhesion site of the occlusal cavity margin, while it gets far apart from the weakest adhesion placed at the gingival margin level.

8.8 How to Increase Adhesion

In order to obtain better bonding conditions and facilitate monomers' spreading within the demineralized intertubular dentin, which was altered by laser irradiation, different post-irradiation dentin pretreatments have been suggested for adhesion procedure.

Among them, we point out the use of:

- Sodium hypochlorite at a concentration ranging between 5% and 10%
- Orthophosphoric acid at 33–38% with an extended etching time [52]
- Polyacrylic acid (for glass ionomer material)
- Chlorhexidine gluconate
- Propolis
- Hydrogen Peroxide
- Ozone gas

Sodium hypochlorite can be used to remove collagen fiber frustules and dentin fragments modified by laser interaction. In such a way, following its use, we obtain a clean surface, free from the alterations produced during laser use (even if, thanks to the erbium laser, as we have already flagged out, there is no smear layer).

The extension of the etching time by orthophosphoric acid apparently does not promote better adhesion, but, on the contrary, it can generate an excessively etched tooth surface. It is appropriate to consider that the irradiated tooth surface does not have smear layer, because the erbium laser does not produce it, unlike what happens when using the high-speed handpiece and the diamond bur. For this reason, by performing the etching on hard tooth tissues, we obtain an immediate contact between acid and intra- and peritubular dentin. An excessive contact between acid and tubules could, on the contrary of what we would desire, completely destroy the dentin architecture favorable adhesion.

Most recent clinical recommendations advise enamel etching not exceeding 30 s and a very limited acid treatment on dentin.

There is no certain clinical proof that the different pretreatments listed here could improve the action of adhesive systems for composites.

According to Arslan S. et al. [53], «No adverse effect of different cavity disinfectants on microleakage were found when etch-and-rinse adhesive system was used.»

8.9 Why Adhesion Can Be Impaired

There are different possible explanations on why the composite adhesion strength to the irradiated dentin could be lower than the one achieved through phosphoric acid.

Different researchers believe that the main mechanism causing insufficient bonding between irradiated dentin and composite is the collapse and/or melting of collagen fiber network during laser excision [54].

In fact, the considerable increase of temperature following irradiation causing the instantaneous vaporization of the water component of the mineralized tooth matrix and of collagen fibers, initially spread and supported in this framework, tends to collapse because they are no longer supported by the crystalline structure. The consequence will be a reduction of bonding spreading within the network because the interfibrillar structure is reduced. Thus, the hybrid layer will not be of optimal quality for adhesive procedures [54].

Ablation of dentin melts collagen fibrils together, resulting in a lack of interfibrillar space that restricts resin diffusion into the subsurface of intertubular dentin, causing a lack of penetration of the resin and even a possible peeling off of the resin layer from the ablated dentin surface [55–58].

Erbium lasers used with excessive parameters can furthermore have a harmful effect on hard tissues. Too high laser energy values can cause cracking in tooth dental tissues, surface melting, surface scaling and flacking, marked loss of intertubular dentin, and collagen melting [54, 55].

It has also been thought that pulses could generate intense elastic waves inside tooth hard tissues during excision as a result of the interaction with the laser beam and due to alternate thermal expansion and shrinkage.

By occurring inside a hard and stiff tissue, stress waves could cause micro-cracking and fractures in the dentin thickness and at the dentin/composite interface level, negatively affecting adhesion strength [1, 58, 59].

An additional explanation of the weaker bond between composite and dentin is represented by the deep craters that are created when laser energy is high: these valleys/hollows can prevent the optimal adaptation of the reconstruction material to the cavity walls since the resin would not be able to fill deeper concavities [60].

Furthermore, there could be an uneven distribution of the masticatory stress at adhesive-dentin interface [54, 61, 62].

Dunn et al. [34] as well underlined that «Laser irradiation of enamel surfaces produced surface fissures and a union or blending of a distinctive etch pattern normally seen in acid-etched enamel. This blending effect likely prevented the penetration of resin into enamel, resulting in lower enamel bond strength values.

It is very important that at the end of cavity preparation, unsupported enamel margins are removed, and margins are smoothed. This operation can be done at low-power and high-speed Er:YAG or Er,Cr:YSGG laser, or with hand tools (enamel cutter, excavators) or low- or high-speed tools with diamond or lamellar burs, or rubber tips [63] (Figs. 8.8, 8.9, 8.10, 8.11, and 8.12).

Fig. 8.8 The crowns of these anterior teeth are severely abraded

Fig. 8.9 The margins of abraded crowns are rounded thanks to laser irradiation (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Enamel settings: MZ5 quartz tip diameter 550 µm, length 9 mm, 2.5 W, 30 Hz, 83 mJ E per pulse, peak power 1389 W, average power density 461 W/cm², peak power density 256.030 W/cm², total energy 75 J, pulse width 60 µs, 1 mm tip-to-tissue distance, 50% water (20 ml/min), 80% air

Fig. 8.10 Isolation with dam

Fig. 8.11 Acid etching with orthophosphoric acid 37%

Fig. 8.12 Finished restoration of anterior teeth (adhesive system OptiBond FL total-etch adhesive system (Kerr, Orange, CA, USA), composite material Herculite XRV Unidose (Kerr, Orange CA, USA))

Forgetting this step may result in a diminished wall strength; it may cause incomplete adaptation of the composite to the preparation margin and a subsequent chipping of the reconstruction margin and/or the enamel subjected to the masticatory load with subsequent microleakage.

Recent researches took into account the possibility that during irradiation by erbium laser, calcium phosphate insoluble molecules could be formed, which would prevent optimal composite adhesion [54].

On the other hand, authors believe that collagen denaturation during ablation causes an acid-resistant surface containing charred granular structures or structures covered with melted dentin particles. This denaturation could jeopardize infiltration of the adhesive system into the dentin structure, and it could prevent the creation of the hybrid layer [58, 64].

Such phenomenon could concern cement during classes II and V cavity preparation, because «When cement is reached by erbium irradiation, it is altered and a thin layer (5.7 μm) is formed. This can hamper hybridization because it becomes less affected by acid etching» [65].

If the resin cannot efficiently infiltrate into intra- and peritubular dentin, we could only obtain shorter resin tags, without funnel-shaped morphology and lateral resin projections, and this would entail a damage to the resulting adhesion [57, 66, 67].

When using this type of laser, the absence of the smear layer, which is instead inevitably created during cavity preparation with burs, allows the immediate exposure of dentinal tubules and accentuates their permeability to dentin adhesives. Furthermore, the absence of smear plugs allows the passage of intratubular fluids to and from the pulp [68].

«Loss of smear layer due to laser irradiation exposes the dentinal tubules and enhances the permeability of dentin adhesives. Intrinsic dentin wetness, as affected by pulpal pressure, could also affect the hydration state of dentin and the bond strength to dentin adhesives. Laser affects fluid perfusion of dentin more than bur.»

It is important to keep into account the fact that greater perfusion could make dentin more moist, and for that reason, it may interfere with some adhesive systems, especially water-based ones which could end up being more diluted.

The best way to avoid or minimize the impact of these surface alterations which may cause difficulties to achieve optimal bonding is to reduce the laser energy for ablation to the lowest efficient level, compatibly with the time required to completely remove the decay.

Many authors [69] agree on the fact that after irradiation, it is however preferable to perform enamel acid etching by orthophosphoric acid in order to obtain an even microrough surface. Enamel laser conditioning, on the other hand, would not be useful.

The use of an acid on the dentin could be positive as it would allow the removal of the top layer altered by the erbium laser and exposes the network of collagen fibers which make up the ideal matrix required to create the hybrid layer for the bonding process. However, researchers' opinions are quite contrasting.

Thus, although different acid application times are suggested, it would be appropriate not to exceed 30 s of contact time on the enamel and 15 s on irradiated dentin.

It is advisable to remember that since the smear layer is absent, phosphoric acid acts more rapidly on the mineralized crystalline structure of hard tooth tissues, in particular on peritubular and intertubular dentin, and on collagen fibers.

Other authors [70] advise to etch irradiated enamel for max 15 s and to avoid acid treatment on dentin at all.

8.10 Adhesive Systems for Irradiated Hard Tissues

An extensive discussion has been going on for quite some time on the opportunity of completely eliminating the smear layer (etch-and-rinse technique, Total Etch) or to modify it through suitable self-etch adhesive systems which would only remove one part of it and then maintain and exploit the remaining part of it to create suitable substrate for bonding [59, 71–83].

With regard to adhesion between composite materials and irradiated dentin, researches are still debating if it would be possible to obtain optimal bonding through an etch-and-rinse or through self-etch adhesive systems. Results described in the most recent literature are extremely contrasting and contradictory. For the time being, the most advised therapeutic attitude with regard to the adhesive system is to adopt the same procedures that are normally used for tooth tissues treated by diamond burs. The combination between orthophosphoric acid and fourth-generation adhesive with two steps (three-step etch-and-rinse) still provides a very good bond between composite and tooth, also in case of erbium laser treatment. However, the enamel must be treated with acid etching for 15–30 s. At dentinal level, the result seems even better thanks to the sixth-generation self-etch adhesive (two-step self-etch adhesive). This system can also be used on irradiated enamel, however, after acid etching.

Irradiated dentin, but yet directly etched with acid, can be laser conditioned, provided that low energy values and low power are used (40–50 mJ), for a short period of time and with a considerable amount of water for cooling [84].

8.11 Decontamination Effect

One big advantage in laser dentistry is represented by the decontamination effect of tissues. Also during a restorative treatment, the operator performs dentin disinfection by vaporizing water of bacteria (bactericidal action), thus decontaminating the cavity [85–88].

Bacteria below surface are killed during laser cavity preparation to a depth of 300–400 μ. [89]. This means that the hard tissues treated with this wavelength have an important microorganism count reduction in the irradiated layers.

8.12 Effect on Tissue Temperature

The energy generated by the erbium laser can be so powerful to break down the crystalline structure of hard tissues of the human body; however, if the used energy levels do not excessively exceed excision threshold limits, they can be much less aggressive than the diamond bur used on a high-speed drill.

In fact, the vibration and pressure exercised by using a traditional technique can very easily create microfractures that branch out on the prepared decayed cavity walls. These will later on give rise to sensitivity, pain to heat/cold stimulation, risk of pulp infiltration damages, and secondary decay, till causing reconstruction failure.

If the erbium laser is used with the adequate selected parameters (i.e., low energy and frequency), sufficient enough to obtain decay ablation without creating any trauma inside the tissues, cracking will not occur.

The very high water absorption coefficient for the two erbium laser wavelengths allows to limit the penetration of the beam by just a few microns (7 μ in the enamel and 5 μ in the dentin for Er:YAG 2940 nm, 21 μ in the enamel and 15 μ in the dentin for the Er,Cr:YSGG 2780 nm) [5–9].

This limited penetration, especially if combined to a very short pulse width, allows a very limited transfer of heat into tissues. With optimal cooling made by an integrated air/water spray, temperature increase at pulp level will be below 5 °C [90–93].

On average, in fact, there is a temperature increase by 1–2 °C in the pulp chamber, while the use of a high-speed bur entails a more frequent potential heat damage, especially in cavities where the floor is in close proximity with a pulp horn.

It is obviously indispensable to use energy levels compatible with efficient excision and without being excessively traumatic or harmful for the tooth architecture.

8.13 The Cooling

It is also equally important to use a cooling spray with a water amount and an air volume sufficient to remove the fragments created during irradiation and cool the treated surface quickly.

The minimum amount of water which should be used is of at least 8 ml/min, but it would be better if it could be doubled. Not all erbium lasers available on the market accurately show on the display the amount of used water. Oftentimes, the display only shows a percentage vis-à-vis the 100% capability that can be held in the handpiece. However, the maximum value depends on the pressure present in the local aqueduct water network or in the building where the dental practice is, depending on manufacturer's settings and also depending on the setting of the individual laser entered by the installer. In order not to run the risk of using an insufficient amount, it is advisable that the operator personally measures how much water per minute is delivered by the handpiece in percentages of 10, 20, 50, and 100. In this way, we can be aware of how much water is used, and thus, we can be sure of not overheating tissues and avoid thermal damages which could cause tooth pulp necrosis, a phenomenon of dental hypersensitivity, or alter the tooth surface with subsequent worsening of composite adhesion.

8.14 The Welding Effect

It is also possible to select a cooling spray containing a reduced amount of water when more thermal interaction is required. This type of use, which can modify the tooth surface, is called «welding,» and it may allow to reduce dentinal sensitivity and can transform the outer tooth wall, especially at tooth neck level or in case of preparation of a fixed prosthetic, in order to be more resistant to acids produced by decay-inducing bacteria and less permeable. The microstructural effect, in fact, is represented by the obliteration of dentinal tubules by the melting of the dentin outer layer and coagulation of collagen fibers.

This procedure must be performed with low energy levels and for very short treatment periods, otherwise it is possible to cause severe pulp damage due to temperature increase.

8.15 Laser Analgesia

Use at low energy level and power allows to achieve one of the most important advantages that can be obtained through this laser in conservative dentistry: laser analgesia. In fact, erbium wavelengths allow cavity preparation also in deep dentin, without the need to perform local anesthesia by injection and without causing pain to the patient.

This is possible in a wide variety of cases [94], and it is also very useful in pediatric dentistry, for phobic patients, for all those patients who do not like injections, and for those who are allergic to local anesthetics.

Any dentist knows that the fear for needles discourages many patients to go see a dentist [95].

Vibrations, pain, and noise perceived when using the bur or the drill contribute to worsening the fear which is very frequently associated to dental care. In fact, all of this may trigger anxiety before dental treatments. Besides fear, the patient can report correlated psychosomatic symptoms (dyspnea, tachycardia, sense of suffocation or light head, etc.) which may involve the possibility of not treating the patient or cause real discomfort and emergencies on the patient chair.

Furthermore, anxious patients counteract the treatment by refusing it or by not collaborating.

The clinical situation and the symptomatology get further complicated if the subject is «dental phobic,» as extreme anxiety toward dental cares will grow exponentially.

It is believed that dental phobia affects 4–16% of adults and 6.7–20% of children [96, 97]. Its incidence tends to lower with age, but it may persist among the elderly.

Thus, anxious patients are treated with extreme difficulty.

The absence of rotating instruments, with discomfort due to vibrations and noises, and of local anesthesia can facilitate the interaction between patient and dentist. In this way, in fact, two important factors setting off anxiety are removed. Dentists must be able to identify and treat afraid patients in order to lower their anxiety level [98, 99].

8.16 Alternatives to Local Anesthesia for Cavity Preparation

Which are the possible alternatives available for a clinician to avoid the use of the two therapeutic options so much opposed by patients?

The methods that can somehow substitute local anesthesia for pain control during dental care include techniques with different degrees of probability of success and different abilities of anxiety and pain attenuation or suppression.

Possible therapeutic alternatives designed to minimize fear and anxiety toward traditional dental treatments include hypnosis, conscious sedation with a mixture of nitrous oxide and oxygen, electronic anesthesia or electrostimulation, high absorption coefficient topical anesthesia, general anesthesia, conscious sedation with oral drugs or by intravenous injection, and by using the erbium laser.

Each one of the above listed techniques has pros and cons. None of them has a 100% success rate to eliminate anxiety and to facilitate patient compliance. Unfortunately, none of them allows to perform a painless treatment, free from discomfort for all patients; furthermore, some of them could have side effects and/or potential risks.

It has been known for decades (or better, for hundreds of years) that achieving hypnosis status may allow to perform medical therapies, even very invasive ones (delivery, endoscopy, surgery) without any pain. In dentistry, for example, it is possible to perform wisdom teeth extraction without any pain whatsoever.

Not every patient, however, reaches a sufficiently deep level of trance able to obtain the hypnotic analgesia. Hypnosis, then, can be considered more helpful for its calming potential and to improve patient compliance.

Conscious sedation with nitrous oxide and oxygen is based on the inhalation of a mixture of nitrous oxide and oxygen gases in variable proportions using a nose mask. This mix reduces anxiety, it has a euphoric effect, it is lightly analgesic and reduces tissue sensitivity, and it gives a mild retroactive amnesia and a feeling of well-being and reduces the perception of time. With a customizable proportion of the two gases (on average, 20–50% of nitrous oxide and 80–50% of oxygen), after 3–5 min, it is possible to obtain the desired effect and maintain it for all the time needed.

Discontinuation of the mixture administration and the delivery of 100% oxygen allows the disappearance of the previous symptoms within few tens of seconds. This system, however, cannot allow to obtain a true and complete analgesia. It can be used as an aid to traditional local anesthesia or for laser analgesia support [100–103].

Some other therapeutic options are not completely proven or verified (e.g., different brands of electrostimulation or electronic anesthesia) or have unpleasant side effects like some topical anesthetics with very high absorption coefficient, i.e., EMLA 5%, cream containing prilocaine and lidocaine (which however give a feeling of numbness, need 15 min of waiting time before they take effect, and are quite distasteful), or potentially harmful (general anesthesia, conscious sedation with drugs, and/or intravenous injection) [104].

Dental lasers are not completely able to replace traditional bur, and it is not always possible to avoid injected anesthesia, but this technology is particularly useful in pediatric dentistry (above all for primary dentition), for phobic patients, and for those who do not like traditional anesthesia due to the feeling of numbness it causes or because they are intolerant to it.

This can explain why the use of this «no shot» modality can be highly appreciated by patients, especially by the youngest.

8.17 How Laser Analgesia Works

The mechanism by which the laser analgesia can take place is not completely known [84, 98, 105–113].

Laser pulses may hamper the possibility for neurotransmission to reach the central nervous system, since the former lasts only microseconds, while it needs milliseconds to be modulated by the brain (gate theory). This overloading of the peripheral and of the central nervous systems can be due to a physiological saturation caused by the laser beam.

It has been assumed also that laser irradiation on pulp C fibers may cause a reduction of the Na-K pump action. Temporary nervous transmission suppression could occur.

Actually, the opinion of researchers converges on the role played by *low-level laser therapy* (LLLT) in preconditioning tissues, and this is likely to be responsible for the onset of the analgesic effect. It is highly plausible that the laser phototherapy action on pain is a combination of several factors [114].

To obtain successful analgesia, it is necessary to apply low-level energy (and power) or, more precisely, it is indispensable low energy density and low power density.

Furthermore, initially it is useful to use low levels of air and water spray which can induce dental sensitivity due to the cooling effect of air and/or water (◘ Fig. 8.13).

◘ **Fig. 8.13** Laser analgesia of tooth #2 keeping the tip at 10 mm from the tooth neck surface with the aid of a spacer (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Analgesia settings: MGGG6 sapphire tip diameter 600 µm, length 9 mm, 0.1 and then 0.2 W (energy per pulse of 10 and 20 mJ), 10 Hz, 30 s each (without air/water cooling spray), tip-to-tissue distance 10 mm. Subsequently, the power was increased to 0.5 and then to 1 W (energy per pulse of 33 and 67 mJ), 60 s each, 15 Hz, water 15% (10 ml/min), air 20%, same distance from the tooth neck. Preconditioning of hard tissue before ablation: 2 W, 30 s, 15 Hz, water 50% (20 ml/min) and 80% air, tip-to-tissue distance 1 mm)

8.18 Techniques for Laser Analgesia on Teeth

Two different techniques have been proposed in order to obtain the laser analgesia:

- Rabbit technique (also called *hare technique*): the laser is immediately set on high power levels, able to perform hard tissue ablation, and this is maintained during the whole treatment. At the beginning, however, the beam is kept defocused at 6–10 mm from the tooth. So, the energy density is low, and it takes advantage of the low-level laser therapy. The tip is moved all around the tooth, at its neck level. Then, the tip is gradually brought closer up to 1 mm from the dental surface, and so the ablation effect can start. At this point, if the patient feels some discomfort, it is possible to move aside the tip again. As soon as the beam gets through the enamel and reaches the dentin, the tip is again placed farther away, the laser irradiation becomes defocused (thus reducing the energy density), and cavity preparation is complete.
- Turtle technique (also called *tortoise T.*): the tip is immediately placed at 1 mm from the tooth and kept at this distance for the preparation procedure. Low power is then set in order to obtain pulp analgesia and have a lower risk of discomfort for the patient. Then, the energy is gradually increased up to a sufficient level able to obtain tissue ablation, and this is carried on till enamel ablation is completed. When the dentin is reached, the power is lowered and cavity preparation is completed. This last technique is considered the most reliable to avoid patient's dental sensitivity during the restorative treatment. It is regarded as the most satisfactory, delicate, and effective to obtain dental analgesia [19].

It has been scientifically demonstrated that permanent teeth are more sensitive to pain than deciduous ones and that laser analgesia is easier for the latter [109].

According to Moritz A. (2006) [88], the laser analgesic effect on the tooth should last approximately 15 min, and after its disappearance, no histological alteration of the pulp occurs.

On the contrary, according to *Whitters CJ* et al. [115], the pain threshold after laser analgesia obtained by the means of a Nd:YAG laser returned to baseline approximately after 60 min.

8.19 Protocol for Tooth Analgesia with the Erbium Laser

In order to study erbium laser analgesia, we recently [94] studied a protocol in order to propose a systematic painless restorative treatment of the teeth. We used the Er,Cr:YSGG (2780 nm) laser applying a combination between *rabbit* and modified *turtle technique*.

Before starting cavity preparation, a laser-induced analgesia phase was always performed by initially using very low levels of energy, and then by gradually increasing them, without using any air/water cooling spray.

In this way, the dental pulp had the possibility to adapt to laser irradiation without triggering a mechanism of annoying sensitivity, but gradually performing analgesia. Then, it was possible to obtain a gradual painless ablation of tooth hard tissues.

The analgesia phase was therefore started with power values of 0.1 watt (consequently, the energy had values of only 10 mJ) at a pulse repetition rate of 10 Hz, and afterward these levels were gradually increased to 0.2 watt, then to 0.5 watt with a repetition rate of 15 Hz, and then, finally to 1 watt and to 2 watts with the same pulse repetition rate.

Overall, this stage always lasted 3′30″ (210 s).

The study of laser-induced dental analgesia with regard to cavity preparation was performed by adopting the following sequence:

A. Preliminary pulp test using the electric pulp tester to evaluate dental vitality and to establish the baseline threshold of dental sensitivity.
B. Beginning of the dental analgesia induction phase by using power settings of 0.1 and then 0.2 W (energy per pulse of 10 and 20 mJ) at a pulse repetition rate of 10 Hz, for 30 s each (without using any air/water cooling spray), keeping the tip at 10 mm from the tooth using a spacer. Subsequently, the power was increased to 0.5 and then to 1 W (energy per pulse of 33 and 67 mJ) for 60 s each, with a spray composed by 15% of water (for our laser this means approximately 10 ml/min) and 20% of air, at a pulse repetition rate of 15 Hz, keeping the tip at the same distance from the tooth neck.
C. Preconditioning of hard tissues with 2 W of power for 30 s with a cooling spray of 50% water (approximately 20 ml/min) and 80% air, at 15 Hz of pulse repetition rate, with the tip at approximately 1 mm from the tooth. The laser beam was kept in focus or, if the patient felt discomfort, it was defocused according to sensitivity.
D. Electric pulp test (EPT) performed again to evaluate the presence of analgesia and establish how the threshold value of dental sensitivity had changed.
E. Preconditioning and beginning of enamel ablation with a 3 W power for 30 s (same previous settings as for pulse repetition rate, distance, and cooling spray).
F. Enamel ablation with 4 W of power (same previous settings).
G. Possible enamel ablation with 5–6 W of power (same previous settings).
H. Possible dentin ablation with 3–3.5 W of power (same previous settings).
I. Preparation completion and smear layer removal with a power of 2 watts (same previous settings).
J. Pulp test at the end of the preparation. To assess if the threshold value of dental sensitivity had further changed after the ablative laser irradiation.
K. Pulp test after 15′–20′ from the end of cavity preparation to assess if analgesia was over.

The entire period of laser analgesia induction had an overall duration of 3′30″ (210 s), and it was performed on all patients.

At the end, as specified, cavity preparation started.

To correctly perform laser-induced analgesia in our protocol, we suggest to maintain the tip at a distance of 10 mm from the tooth from the start.

In this way it is possible to obtain a very low energy density from the initial stage (only 6 J/cm^2 with movement) and average power density (1 W/cm^2), thus allowing the pulp to progressively adapt to laser irradiation and achieve analgesia without risking painful or annoying sensations.

With regard to discomfort felt by patients, the factors that seem to have a higher tendency to promote the shift to greater discomfort categories are posterior teeth compared to a superficial one, the time needed for ablation of hard tissues, and the use of laser at high power levels.

One of the most important factors that influenced pain perception was age.

In this study, all patients that felt greater discomfort or pain were in age brackets 20–29, 30–39, and 40–49.

So we think that younger patients could obtain analgesia more easily and quickly as their dental hard tissues are more rich in water and they have wider dentinal tubules. This could facilitate ablation and progression of laser beam effect on pulp nerves.

With regard to older patients, they could be less sensitive to irradiation for the opposite reasons: their dental tissues are more sclerotic and calcified; they have narrow dentinal tubules; and even if they are more difficult to ablate, they protect the pulp more; and they are less influenced by stimuli.

When a restorative treatment with erbium laser is planned, without resorting to any local injected anesthesia, it should be considered that cuspids and incisors may be more sensitive, especially if decays are deep.

For these teeth, the energy can rapidly affect nerve fibers of the pulp because of the limited thickness and cause pain.

Actually, in our research we saw that the opposite was true: premolars and molars were more sensitive than front teeth.

By using our protocol, initially applying very low energy levels and gradual irradiation, we obtained a better and quicker laser analgesia for anterior teeth.

The possible explanation of this is connected to the greater thickness of hard tissues for posterior teeth compared to incisors and cuspids.

It is also our opinion that the depth of the decay is important sensitivity wise, but the time of preparation is more relevant in affecting it.

This is due to the effect of erbium on the dentin. This kind of laser, combined with water, opens the dentinal tubules. The more the laser is used, the more the tubules will be opened, and the higher patient's sensitivity will be.

Besides, if dental hard tissues are not easily laser ablated (e.g., if they include a lower water percentage) and if, for this reason, it is necessary to extend its use for a longer period of time or to increase the energy levels in order to facilitate ablation, then the risk of pain further raises.

One additional element to consider is the fact that laser analgesia could be not completely effective to also achieve periodontal tissues analgesia.

During this research, even if the tooth was completely insensitive to carious hard tissue ablation, we have quite frequently noticed that the patient could feel the discomfort provoked by the positioning of the dental dam clamp, the matrix, or the wedge.

Thanks to the proposed protocol, it was possible to perform a restorative treatment by using the Er,Cr:YSGG (2780 nm) in 24 patients out of 30 (80% of the sample) without resorting to any kind of local anesthesia and without the traditional handpiece and bur.

These patients did not feel any pain (in 57% of cases), or they felt only a very light sensitivity (in 23% of patients). The equipment we used was very likely to produce laser-induced analgesia, which allowed us to remove all the carious tissues and to complete the composite reconstruction without any pain for the patient.

In relevant literature, the comparison between traditional handpiece with bur and erbium laser showed that with the former, the dentist can obtain painless treatment in only 20–50% of patients [116].

The use of Er,Cr:YSGG laser allows to avoid the administration of local anesthesia by injection and to avoid the use of the traditional handpiece and bur. Thus, we can obtain reduced anxiety in patients, something that is frequently associated to dental therapies.

Following these considerations, is it possible to draw some firm conclusions on the strong correlation between anxiety and discomfort?

We believe it is possible to affirm that groups of patients reporting higher levels of anxiety before attending a dental session are the same who felt greater discomfort during therapy. So, it is likely that the anxiety factor contributes to generate a higher subjective evaluation of discomfort.

In adult patients we noticed that the level of anxiety felt during a dental session had more influence on the possibility to obtain complete leaser analgesia; this is probably due to the patient's individual difficulties related to dental care past experiences.

On the other hand, with regard to pediatric patients, if they never had dental experiences in the past, if they were not very anxious by nature, but rather calm and happy, and if they did not have a negative influence from parents and/or relatives, they may be more incline to accept the dental treatment. This will mostly and more easily occur if the dentist will adopt a psychological, positive, delicate, and serene approach.

All of this will be for sure facilitated by adopting the erbium laser if neither needles nor local anesthetics will be used, especially if the operator will avoid noises and vibrations which are typical of the traditional handpiece combined with the bur.

This approach will reinforce and maintain the patient trust toward the dentist.

8.20 The Laser Handpiece and Tips

Most modern erbium lasers are provided with two types of handpiece.

One uses interchangeable tips of various lengths, diameter, and materials.

On the market, there are tips with lengths ranging between 3 and 28 mm. With the shorter tips, it is possible to access small areas within the teeth arch or in difficult spots (i.e., the upper second and third molars, vestibular areas of posterior teeth) or perform treatments when the patient has limited mouth opening (i.e., pedodontic patients). With longer tips and with a small diameter of 200–300 μ, it is possible to perform endodontic and periodontal laser-assisted treatments.

They are made out of quartz or sapphire. Oftentimes, it is possible to differentiate them from one another because of their color, yellowish for the first one and whitish for the second one.

Usually, the most used tips in restorative dentistry are the ones measuring 4–10 mm (Figs. 8.14, 8.15, and 8.16).

Fig. 8.14 Minimal carious cavity and decalcification in buccal face of tooth #10

Fig. 8.15 Cavity preparation on tooth #10 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Enamel settings: MGGG6 sapphire tip diameter 600 μm, length 9 mm, 3 W, 15 Hz, 200 mJ E per pulse, peak power 3333 W, average power density 492 W/cm^2, peak power density 546.710 W/cm^2, total energy 90 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (18 ml/min), 80% air. Dentin and smear layer settings: MGGG6 sapphire tip diameter 600 μm, length 9 mm,2 W, 15 Hz, 133 mJ E per pulse, peak power 2222 W, average power density 328 W/cm^2, peak power density 364.473 W/cm^2, total energy 20 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (20 ml/min), 80% air

Fig. 8.16 End of composite reconstruction of tooth #10 (adhesive system OptiBond FL total-etch adhesive system (Kerr, Orange, CA, USA), composite material Enamel Plus HFO by Micerium, Avegno, Genova, Italy)

The tip-to-tissue working distance should constantly be kept at 0.5–1 mm in order to obtain optimal energy density. In some scientific articles, this operational modality is wrongly defined «in contact» since the operator is working at close proximity with the tooth. Nevertheless, there should never be contact, and the tooth surface should never be touched in order to avoid the creation of enamel-dentinal microfractures and to avoid damages to the delicate laser tips.

This working modality is also called «focused,» even if in reality the laser beam is not convergent, i.e., it is not focused on the target. The laser energy delivered by the tip is in fact immediately diverging with approximately an 8° divergence angle per side.

The reason to keep the tip at 0.5–1 mm is due to the fact that at that distance, energy density (fluence) is optimal, and it is the one that allows a more efficient ablation.

By increasing the distance, fluence will drop dramatically, preventing adequate excisional interaction with tissues.

On the other hand, if the working distance is below 0.5 mm, the operator may run the risk of causing dental damage following contact, and tip deterioration after accidental crash against the cavity surface, with reduced effectiveness of the air/water spray to cool and eliminate residues and a very limited visibility on the working area.

The diameter of tips used for hard tissue ablation usually ranges between 400 and 1000 μ. The smaller the diameter, the smaller the cavity the operator can prepare and save healthy tissues. Tips with larger diameter produce a spot size which will inevitably create a bigger size cavity; thus, it is not possible to do small or very conservative preparations. For minimally invasive dentistry, for example, for a minimal cavity including only occlusal grooves, it is preferable to use a tip with the smallest diameter as possible. By doing so, preparation will be quicker because there will be more energy density since all of the energy will be focused on a smaller surface.

Usually, tips used for this type of therapies are cylindrical with a circular section. However, on the market, there are truncated-cone-shaped tips, with rectangular section, chisel-shaped. Each one of them creates a different beam emission which, in its turn, provides an ablation print producing a different cavity shape.

The second type of handpiece is also called *tipless* because it does not have the previously described tips, but a lens which can also be interchangeable, and it focuses the beam at a distance of about 5–10 mm from the surface. Operators work at a greater distance compared to the previous handpiece. At times in the scientific literature, this type of use is defined as «defocused,» but this is not the correct term. In reality, the beam is focused at a few millimeters (usually 5–7 mm) away from the surface of the handpiece from which the beam is delivered. Such use is defined as «contactless.» This greater distance from the target improves visibility, but it provides a less favorable and uncomfortable perspective in poorly accessible areas such as the upper molars. The reason is that it is more difficult to position at that distance and keep accuracy at 5–10 mm from target. Furthermore, it is very difficult to accurately irradiate a small target since the beam is wider. The target area (spot size) covered by the beam tends to be larger than when the operator works almost in contact; thus, it is very difficult to prepare very small cavities, and, if the hand piece is not kept steady on the ablation target zone, the effect is often dispersed on a wider area, resulting in an unintended widening of the cavity and elimination of healthy tissue. This handpiece, however, is more efficient since it allows the removal of a larger amount of decayed tissue in less time.

8.21 The "Erbium Noise"

All types of handpiece produce a similar and characteristic noise. It is often defined as a «popcorn» type of noise, as it reminds corn popping in the pan. It is completely different from the noise produced by a traditional turbine and by the bur; thus, patients tend not to associate it to the fear for the dentist.

Noise intensity is directly proportional to the employed energy, which creates micro-explosions in the water present in tissues and in the one used for cooling. Also, irradiation frequency impacts noise. The higher the number of pulses, the lower the number of «explosions» heard as they will «merge» with one another and they will sound like one noise. At about 30–40 Hz, the noise is continuous, without interruptions between pops.

8.22 Approach According to Cavity Classification

Depending on the place where the decay lesion is, the removal approach will be different.

8.23 Class I

Occlusal decay on posterior teeth (class I) is obviously easier to treat, but the enamel is quite thick. Thus, it may be necessary, additional time to fully remove this type of lesions, especially in the case when they extend under the occlusal plane and when the decay opening is limited with a lot of healthy tissue covering the entire lesion. In order to avoid extended laser ablation, and to reduce operating times, the operator can also open the decayed enamel grooves by using a small diamond bur and only use laser irradiation later on.

Small-sized cavities are more difficult to treat because they are less accessible. The combination of small high-speed diamond bur and lasers with minimum diameter tips is certainly advantageous.

Usually, ablation starts by placing the tip perpendicular to the tooth surface, by making small, very slow continuous movements and by keeping that position from the beginning of the creation of a small cavity. Later on, the beam should be gradually oriented toward the cavity walls outwardly (up to a maximum of 45° per side) to complete preparation [19].

For larger cavities inside the dentin and with large geometries, it is very difficult to reach each side of the walls. In this case, it could be necessary to eliminate much healthy tissue in order to be able to complete the full decay removal. The use of low-speed burs and manual excavators may allow to remove the residual decayed tissue and avoid the elimination of healthy tissue.

8.24 Class II

Cavities concerning premolar and moral interproximal areas (Black's class II), when they need preparation from the occlusal surface, they normally require more execution time by using the laser rather than the bur because the volume of tissue to be removed is considerable and the enamel wall can be large.

Visibility is often reduced, as well as accessibility. To be able to reach any area concerned with the carious lesion, it is key that the tip is placed inside the cavity that is being created, in order to keep the correct tip-to-distance constant. The most difficult aspect is represented by the difficulty of sufficiently inclining the tip toward the walls to be prepared. It should be reminded, in fact, that the angle formed by the tip vis-à-vis the decayed cavity wall should not exceed 45° otherwise ablation becomes ineffective.

8.25 Classes III and IV

In the case of class III and class IV cavities, accessibility is, on the other hand, much higher; thus no major difficulties are noted. Enamel thickness is limited, and, thus, preparations normally require short times and reduced laser energy, compared to those to be used for posterior teeth.

Laser preparations can also be more conservative than the ones obtained with traditional techniques.

In order to protect nearby teeth and avoid damages to their surfaces, it is advisable to place a cellulose strip interproximally to prevent the laser beam to affect the healthy walls of nearby teeth. It would be better instead not to use metal matrixes for the same purpose as they could reflect the laser beam and thus become a source of potential risk for operator's eye safety.

8.26 Class V

Decayed cavities referred to the cervical area (Black's class V) can be prepared easily and in short times, thanks to the limited thickness of the enamel and to the presence of root cement nearby.

For front teeth, it is also possible to use a straight handpiece instead of the angled one (when the erbium laser manufacturer provides it) to facilitate access to tooth neck decay. With regard to the cervical area of posterior teeth, it is usually easier to use an angled handpiece and 3–4 mm length tips which facilitate access to vestibular or lingual areas, despite the interference of cheeks and/or the tongue (Figs. 8.17, 8.18, 8.19, 8.20, 8.21, and 8.22).

Fig. 8.17 Detail of class V carious lesions of teeth #27–28

Fig. 8.18 Ablation of enamel and dentin in tooth #27 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Enamel settings: MGGG6 sapphire tip diameter 600 µm, length 9 mm, 3 W, 15 Hz, 200 mJ E per pulse, peak power 3333 W, average power density 492 W/cm^2, peak power density 546.710 W/cm^2, total energy 90 J, pulse width 60 µs, 1 mm tip-to-tissue distance, 50% water (18 ml/min), 80% air. Dentin and smear layer settings: MGGG6 sapphire tip diameter 600 µm, length 9 mm,2 W, 15 Hz, 133 mJ E per pulse, peak power 2222 W, average power density 328 W/cm^2, peak power density 364.473 W/cm^2, total energy 20 J, pulse width 60 µs, 1 mm tip-to-tissue distance, 50% water (20 ml/min), 80% air

Fig. 8.19 Widening of preparation in tooth #27

Fig. 8.20 Gingivectomy performed to uncover the healthy margin of the preparation in tooth #27 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Gingivectomy settings: MGGG6 sapphire tip diameter 600 µm, length 9 mm, 2.5 W, 25 Hz, 100 mJ E per pulse, peak power 1667 W, average power density 410 W/cm^2, peak power density 273.355 W/cm^2, total energy 150 J, pulse width 60 µs, in contact, 40% water (16 ml/min), 20% air)

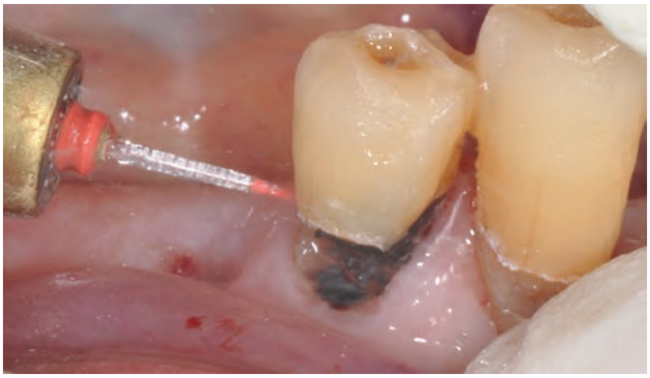

Fig. 8.21 Preparation of cavity in tooth #28 (Er,Cr:YSGG Waterlase iPlus laser with wavelength of 2780 nm by Biolase Technology, Irvine, CA, USA). Enamel settings: MGGG6 sapphire tip diameter 600 μm, length 9 mm, 3 W, 15 Hz, 200 mJ E per pulse, peak power 3333 W, average power density 492 W/cm^2, peak power density 546.710 W/cm^2, total energy 90 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (18 ml/min), 80% air. Dentin and smear layer settings: MGGG6 sapphire tip diameter 600 μm, length 9 mm,2 W, 15 Hz, 133 mJ E per pulse, peak power 2222 W, average power density 328 W/cm^2, peak power density 364.473 W/cm^2, total energy 20 J, pulse width 60 μs, 1 mm tip-to-tissue distance, 50% water (20 ml/min), 80% air

Fig. 8.22 End of class V composite reconstructions of teeth #27–28 (adhesive system OptiBond FL total-etch adhesive system (Kerr, Orange, CA, USA), composite material Herculite XRV Unidose (Kerr, Orange, CA, USA))

8.27 Interaction with Dental Materials

It is always important to pay attention to dental materials present on nearby teeth.

The erbium laser beam can very easily interact with the amalgam, composites, and dental metal alloys.

Irradiated silver-based amalgam can rapidly absorb energy, increase temperature, and create thermal problems to pulp and periodontium. Should the temperature further increase, amalgam melting may occur with subsequent damages to reconstruction and release of mercury vapor. In case of secondary decays or reoccurring decays under the amalgam filling, it is always necessary to remove the metal reconstruction through traditional methods (by high-speed bur), and only after this operation, carious tissues can be removed by laser.

Interaction with composites occurs very easily when they are irradiated. Their ablation is very easy thanks to the water content. However, the composite is exploded as a result of the interaction with the laser energy; it resolidifies and quickly aggregates around the tip and jeopardizes the integrity of the laser fiber.

Tips altered by resin fragments must be cleaned and polished rapidly to avoid this risk. Tip inspection can be done by wearing amplifying glasses or by using a jeweler's lens with 30 magnifications. Polishing can be done by using rotating disks to polish composites mounted on a low-speed handpiece. It is then possible to gradually move on to rougher disks to the smoother one, and this allows to remove residues, burn marks, correct possible nicks, and polish tips. Such procedure is much easier for quartz tips than for sapphire tips, because the latter are harder. However, polishing may be more complex when there are composite fragments attached to the tip end. These materials, in fact, are difficult to be removed when melted by laser energy, and then they resolidify on it; thus, it is absolutely advisable to avoid resin-based materials ablation during conservative therapy.

In case composite reconstructions need to be redone, it is preferable to remove the old material by diamond bur, and only later on should the laser beam be used to ablate decayed tissues and to extend enamel preparation laterally, to complete dentin excision and condition the final surface before adhesive techniques are performed.

If the tooth near the decayed element has a metal alloy crown, irradiation of the latter can involve thermal interaction quickly leading to temperature increase with potential risks of trauma to the tooth pulp and to the periodontium.

Ceramic crowns, as well as temporary resin crowns, are instead damaged by erbium laser energy. The first type of crowns can be fractured following quick thermal expansion.

If interaction is limited, they undergo scratches or nicks.

The second type of crowns, as one can easily imagine, erodes rapidly as it happens with composite fillings.

Non-precious metal alloys used for removable prosthesis are easily interested by temperature increase, while pink resins and artificial teeth can be damaged.

For all of these reasons, it is advisable to pay special attention to all surrounding dental materials during the entire conservative therapy.

8.28 Clinical Considerations

Clinical considerations for laser-assisted conservative dentistry are as follows:

- At the end of carious cavity preparation, eliminate unsupported enamel prisms by using manual instruments (enamel cutters, excavators) and/or high- or low-speed handpiece fitted with diamond fine burs or rubber tips to bevel cavity margins. Alternative to this process, it is possible to use the erbium laser to bevel cavity margins. It is advisable to set limited energy values (40–80 mJ) and frequency of about 25–50 Hz.

- Perform acid etching by using orthophosphoric acid at 34–38% to optimize and make the treated surface uniform to regularize the areas affected by the erbium laser beam.
- Use an adequate adhesive system that takes patient's characteristics into account, such as age, teeth conditions (deciduous or permanent), and decay depth, if the tooth has been subjected or not to the endodontic therapy. For superficial cavities, permanent teeth, and teeth treated with root canal therapy, it is advisable to use the *etch-and-rinse* adhesive system. In the other cases, it would be preferable to use a *self-etch* system, in particular if the cavity is deep and if the patient is very young (the same applies to permanent teeth).
- For deep cavities, it may be advisable to use glass ionomer cement or a flowable composite as liner on the cavity floor, in close proximity of the pulp, in order to obtain good protection of the pulp and of deep dentin, and to position in such area a low-elasticity material and limited polymerization shrinkage; these characteristics facilitate optimal reconstruction adaptation to the cavity internal surface.
- Use a photopolymerization lamp with controlled light irradiation (i.e., soft start or pulse delay technique) such to limit polymerization shrinkage of composites and evenly reach all stratified areas.
- Always use an incremental technique to stratify the composite, in order to have max 1–2 mm layers of material and compensate for and minimize its polymerization shrinkage.
- Use low polymerization shrinkage composite resins for reconstruction (i.e., silane-based composites, even if their clinical use should still be further studied and validated).

8.29 Erbium Laser in Reconstruction with Post in Endodontically Treated Teeth

Teeth subjected to endodontic treatments can benefit from the erbium laser use during composite reconstruction performed in combination with a post.

Thanks to irradiation, both canal walls following endodontic treatment and the post can be optimized for the adhesive process.

Most modern posts are made up of carbon, quartz, silica, or glass fibers, embedded in an epoxy matrix or in a methacrylic resin. They have an elasticity module similar to that of dentin, so that under mastication, the material behaves similarly to tooth tissues and forces are discharged in an equivalent way. By combining this property to the possibility of obtaining an adhesive bond among the various materials (root and crown dentin, adhesive system, fiber post, and core material in composite for cementing and reconstruction), it is possible to reduce the risk of fracture [117, 118].

These posts have high biocompatibility, they are easy to use, they have high mechanical resistance and good corrosion resistance, they are easy to be removed, and they have a very high appearance value (for quartz and glass posts).

Post retention by the root depends on the chemical interaction and micro-mechanical strength among post-, dentin-, and resin-based cement. Should there be insufficient bonds between resin and dentin or at interface level between composite and post, restorative rehabilitation will fail, in association with the partial or total detachment of the reconstruction and of the post embedded in it.

The bond strength is influenced by the degree of hydration/dehydration of the inter-canal dentin wall. If the inside of the canal is too dehydrated, hydrophile monomers of the adhesive system will not be able to penetrate dentinal tubules resulting in a lack of hybrid layer. On the contrary, if the water content is excessive, monomers will be excessively diluted, and they will not play their action.

Other factors that contribute to determine a higher or lower retention strength between post and root are represented by physical property of the composite cement, unfavorable canal configuration (accentuated curvature, root with very thin walls not allowing a wider preparation) or due to insufficient canal length which does not allow the positioning of a sufficiently long retaining post, from adverse effects of canal-sealing cements which, by containing eugenol, they combat resin polymerization used for cementing, and due to anatomic or histological characteristics of dental tissues (i.e., number of tubules at the different levels inside the canal) [119].

The post fiber polymeric matrix is highly cross-linked; thus, bonding phenomena with composite monomers do not easily occur. The bond between the reconstruction composite and the post occurs only partially, and the resin acts as a bond with glass or quartz fibers.

To improve the odds of obtaining such link, different types of post and canal wall pretreatments have been proposed. For example, several authors frequently proposed the roughening of post surfaces in view of increasing retention. However, this exposes glass or quartz fibers, and it may give rise to their weakening.

Sand blasting with A_2O_3 powders in 50 μ particles or the use of hydrofluoric acid must be performed with extreme attention to avoid a too aggressive alteration of fibers. For quartz posts, it has been underlined [120, 121] that it would be useful to use the HF acid at a concentration below 9%. In such a way, higher tensile strength is obtained. However, the same treatment can be risky for glass fiber posts because it would induce corrosion.

Some solvents could increase the adhesion strength between quartz or glass fiber posts and the resin core material. In particular, they have been tested with hydrogen peroxide (H_2O_2) at 24% for 1 min [122, 123] and dichloromethane (CH_2Cl_2) for 1 min [124].

Both solutions showed promising results but they should still be tested on larger samples.

Erbium laser, besides its decontaminating effect, allows to obtain a smear layer-free surface and a micro-rough texture which can facilitate retention. Following post space preparation, canal wall cleaning is a critical procedure, however indispensable, because there is a lot of smear layer inside the canal, as well as gutta-percha residues and endodontic cement on dentinal walls. All of this represents a contamination that may negatively affect adhesive procedures.

Intratubular moisture and residues of irrigation liquids inside the tubules can furthermore complicate or impair adhesion process steps.

The erbium laser used to provide thorough cleaning and decontamination of the endodontic space allows an extremely accurate cleaning of the dentinal surface and the elimination of the smear layer, but, on the other hand, it is advisable to avoid its excessive use since it may induce dentin dehydration.

It is very important to use limited energy values (from 100 to 125 mJ) and frequency of 10–20 Hz in order not to negatively impact the dental surface and not to create microstructural damages to the dentin and to its hybrid layer [123].

The main difficulty in obtaining efficient laser conditioning on canal walls is represented by the fact that the tips inside the canal irradiate toward the apex with a divergence of 8° per side; thus, the beam reaches dentinal walls with a very marked inclination and that, thus, does not interact much with the surface. For this reason, it is advisable to avoid excessive irradiation and excessively high parameters, since they could damage hard dentinal tissues and their organic portion.

The same parameters mentioned above can be used on the post surface in order to facilitate the formation of microroughness which may have a retention effect on the resin core material and increase post resistance and reconstruction.

8.30 The Use of the Dental Rubber Dam

Just like for all conservative dental procedures, laser-assisted procedures as well must be done with dental dam in place, in order to avoid contamination in the operating area. However, its positioning can also be done right before the preparation of decayed cavities, but after the step in which actual laser analgesia is attempted. The absence of the dental dam allows better irradiation in the tooth cervical area at the level of the dental neck and of the gum surrounding the tooth. Only after formal analgesia, it will be possible to place the dam in place and proceed with cavity preparation by removing carious tissues. In this way, mild analgesia will be achieved in soft periodontal tissues as well, allowing the positioning of the hook, the matrix, and the wedge, that will be perceived by the patient with less or no discomfort at all.

8.31 The Use of the CO_2 Laser with Hard Dental Tissues

The carbon dioxide laser (CO_2 10.6 μm) has been extensively used in the last 40 years for oral surgery.

Its continuous wave (CW) and complimentary gated mode allow an efficient and quick vaporization and ablation of soft tissues, also obtaining a very good hemostasis.

Early studies using a CW 10.600 nm CO_2 reported extensive cracking and charring of enamel, dentin, and bone [125, 126].

During the last 10 years, researchers have modified the native 10.6 μm CO_2 laser transforming it into a pulsed laser.

Now this laser has been changed thanks to the replacement of the normal $^{12}C^{16}O_2$ with an isotopic $^{12}C^{18}O_2$ and emits at 9.3–9.6 μm wavelength which is the peak of absorption for the molecule of phosphate in hydroxyapatite [127]. The absorption is also high in water and proteins (collagen).

This is particularly important because in this case enamel absorption is 5–6 times higher at 9.3–9.6 μm than at the more commonly used 10.6 μm wavelength and it allows more efficient heating and ablation of dental hard tissue [128].

Transverse excited atmospheric pressure (TEA) and radio frequency excited (RF) 3D computer-controlled programmable scanning systems are now on the market available from several manufacturers and seem even more versatile and efficient when compared to erbium family lasers [125, 126].

In fact, with them, it is possible to perform a wide range of procedures. Today, it is also feasible to modify the pulse duration of new carbon dioxide lasers in order to obtain an efficient removal of dental hard tissues (carious lesion ablation, caries prevention, removal of composite reconstructions) and bone, without losing the surgical effect on soft tissues [129] (Fig. 8.1).

The most important feature regarding modern carbon dioxide devices is that they can be operated at high pulse repetition rates in the order of KHz, and this allows a very practical removal rate of hard tissues and an incomparable ability of gum and mucosa cutting [128].

The erbium lasers presently used for hard tissue ablation operate most efficiently at very low repetition rates (10–25 Hz). Therefore, in order to achieve higher cutting rate, erbium lasers must deliver a larger amount of energy per pulse, in the range of 100–500 mJ.

CO_2 lasers can be operated with very low single-pulse energies (in the order of μJ up to mJ) and fluence, while frequency can be increased for higher cutting rates [130].

The laser beam can also be scanned to minimize heat accumulation in one area [125].

The wavelength of 9300–9600 nm is coincident with the strongest absorption of dental hard tissues due to phosphate ions in hydroxyapatite. Therefore, the energy necessary for ablation of tooth hard tissues is lower at these wavelengths versus others, and this allows a reduced accumulation of heat in the tooth. Moreover, due to this very high absorption, the penetration is limited to under 1–2 μm.

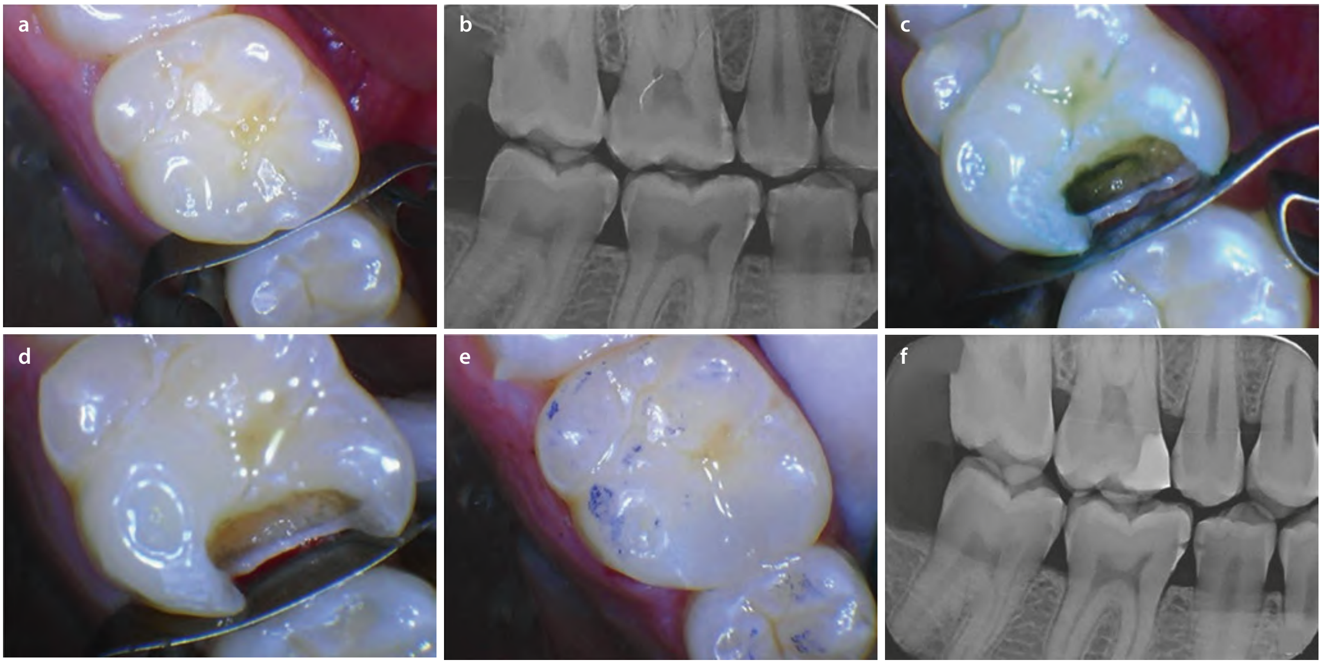

Fig. 8.23 Carious tissue removal in tooth #3 MO using Solea CO_2 9.3 µm laser (Convergent Dental, Natick, MA, USA). Image key: **a** preoperative occlusal view of the upper right molar with a carious lesion on the mesial surface. **b** Preoperative radiograph. **c** A photo of the partially completed carious lesion excavation. The 9300 nm laser with a 1.25 mm spot size was used with a cutting speed between 20% and 60%. Caries indicating solution was used to verify the progress of the preparation. Subsequently the laser was used with a 1.0 mm spot size at 20–40% cutting speed. **d** Photo of the completed preparation. **e** Immediate postoperative view of the restoration in place. **f** Post-operative radiograph showing the competed restoration. The entire procedure was performed without injected anesthesia using the «hard and soft tissue» setting and 100% mist. Caries indicator was used once more before restoring the tooth. The total laser time was 12 min (Procedure by Dr. Josh Weintraub)

With erbium lasers, the shortest pulse width is 50–60 µs, while the CO_2 allows to efficiently ablate enamel and dentin with laser pulses of 10–15 µs [127, 129], so it is possible to obtain high peak power values with lower energy levels, and this can be less aggressive and has a lower possibility to damage the dental structure [128, 131].

According to Staninec M. et al. [125], the thermal relaxation time of the energy deposited in enamel at these wavelengths is on the order of 1–2 µs for enamel and 5.5 µs for dentin [130], so the use of a laser with pulses of 10–20 µs width reduces the threshold for plasma shielding in the plume of ablated material, which would shield the surface and reduce the efficiency of irradiation, allowing the ablation of enamel and dentin at rates of 10–20 µm per pulse and 20–40 µm per pulse, respectively [125, 127].

The use of longer CO_2 laser pulses has the advantage of raising the plasma-shielding threshold allowing higher ablation rates per pulse; however, the longer pulses are more likely to produce a larger zone of peripheral thermal damage. The practitioner should remember that, although ablation rates are higher for longer pulses, the peripheral thermal damage caused by these longer pulses may be too extensive for practical use. Such thermal damage may result in thermal stress cracking, accumulation of non-apatitic calcium phosphate (CaP) phases on the surface, and excessive damage to the collagen matrix [125, 132], so it is advisable to limit the length of laser pulses (Figs. 8.23 and 8.24).

8.32 Resistance to Acid

Another important advantage of CO_2 use is the chemical and structural modification of enamel surface obtainable during irradiation [128].

This laser irradiation vaporizes water and protein and changes the chemical composition of the remaining mineral content of enamel and dentin, thus decreasing the solubility to acids with an enhanced resistance to secondary caries [126].

This allows to increase the acid resistance and consequently to reduce the incidence of carious lesions [133–136].

The occlusal pits and fissures are the areas of the tooth in which dental caries are more frequent. The thermal modifications of these surfaces due to CO_2 laser are desirable to transform them and obtain a greater resistance to acid dissolution.

One possible therapeutical approach is to irradiate the grooves of occlusal surfaces with this laser prior to placing sealants to further enhance the resistance to decay.

Should the practitioner need to remove a sealant due to its failure, the same laser can be used for this purpose [137].

It is also important to underline that irradiation with this wavelength reduces the sensibility of dental tissues to acid etching.

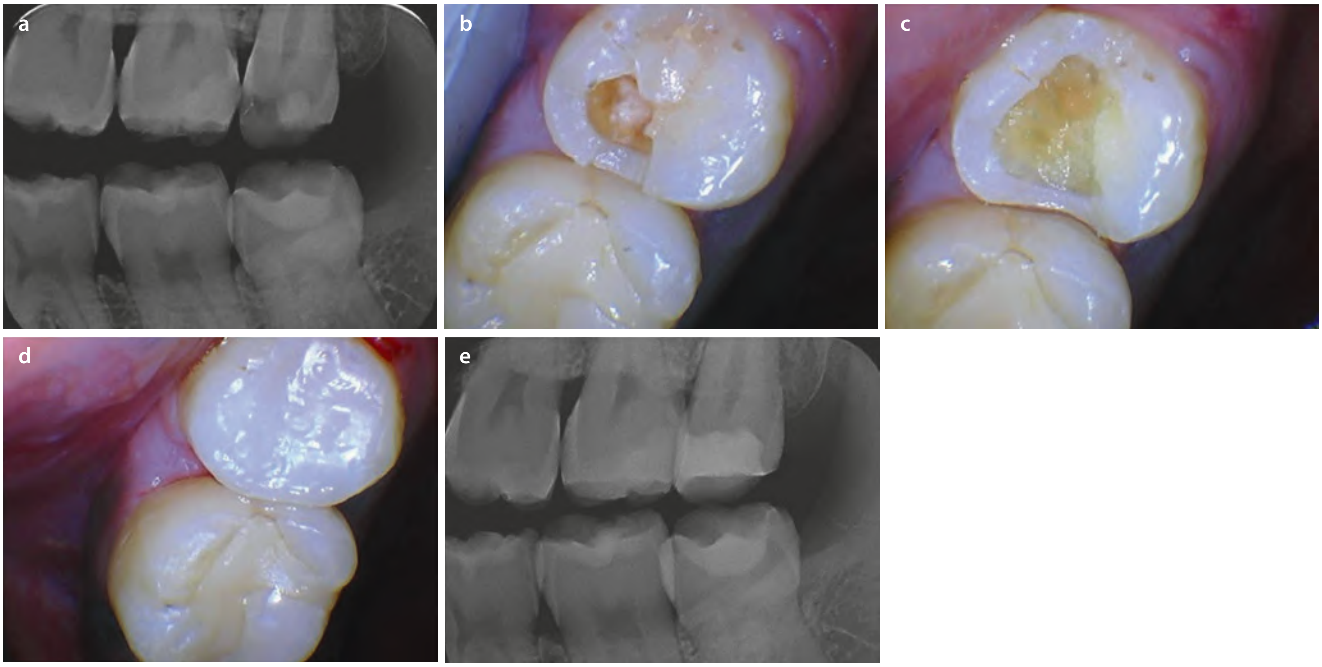

Fig. 8.24 Deep cavity preparation removal in tooth #16 MOB using Solea CO_2 9.3 µm laser (Convergent Dental, Natick, MA, USA). Image key: **a** preoperative bitewing radiograph tooth #16 (UL8). **b** Preoperative view of carious lesion. **c** Completed cavity preparation. The 9300 nm laser with a 1.25 mm spot size was used with a cutting speed between 40% and 60%. Then, for decay removal in dentin, the 1.00 mm spot size was used with cutting speed between 30 and 40%. Finally, the 1.00 and 0.25 mm spot sizes were used with 50% mist. **d** Photo of the completed preparation. **e** Postoperative radiograph showing the competed restoration. The entire procedure was performed without local anesthesia using the «hard and soft tissue» setting and 100% mist. The total laser time was 12 min (Procedure by Dr. Josh Weintraub)

8.33 Pulpal Temperature Considerations

Enamel, dentin, and bone can be rapidly removed thanks to CO_2 laser without peripheral thermal damage by mechanically scanning the laser beam and also with the aid of cooling water spray [128].

If compared to a high-speed traditional handpiece, this laser allows to avoid excessive peripheral, thermal, or mechanical damage [131], provided the use of enough water cooling is guaranteed, otherwise some desiccation of tissues might occur.

Thermocouple measurements showed an increase in temperature of 3.3°± 1.4 °C without water cooling versus 1.7°± 1.6 °C with water cooling [125, 127].

Even though the tooth temperature rise was less than 5 °C without water cooling during an irradiation at 50 Hz, it is still necessary to use a water spray to produce the desired effect. This is advisable for the possible formation of non-apatitic calcium phosphate phases that are produced without a proper cooling due to excessive overheating of the mineral phase [125].

One disadvantage related to the use of this powerful laser is the formation of highly conical and deep ablation craters created when the irradiation is performed in the same spot by repeated laser pulses. This is also at the base of stalling phenomenon (cessation of ablation after penetration of 2–3 mm) and of excessive heat accumulation.

To avoid it and obtain a more efficient ablation, it is necessary to use small spot sizes (< 0.3 mm), and the laser should be scanned in two dimensions to expose a new area for each pulse [125, 131].

Scanning and positioning of the beam is now feasible due to recent advances in compact high-speed scanning technology such as the miniature galvanometer «galvo»-based scanners [131, 138].

8.34 Composite Removal

Lasers can also be used for selective ablation of composite when replacing failed restorations or removing residual composite after debonding of orthodontic brackets [137].

The composite material can be easily and quickly removed without damage of dental surface, without any charring and limiting the removal of sound enamel (Fig. 8.2). It can be effortlessly obtained at a reduced fluence, cleaning the operative area with water spray, so to avoid discoloration and thermal damage [137].

For this purpose, the pulse duration should be comprised between 10 and 20 µs, and the pulse repetition rate should be 200 Hz.

The area of localized damage to enamel can reach a depth of less than 10 µm with a fluence of 3.2 J/cm² [136] or below 20 µm with a fluence in the range 5–10 J/cm² [137]. If the energy density exceeds the value of 4–5 J/cm^2, there will be a greater removal of enamel, but this is considered unacceptable on buccal tooth surface [136].

This very limited amount of healthy enamel loss, due to the high degree of selectivity and minimal deposition of heat in the tooth, appears to be less than what it is obtainable with the conventional means of removal using dental low-speed and/or high-speed handpiece.

Moreover, measurements of the enamel loss during a routine brush and prophylaxis reported average values ranging from 6 to 17 μm, depending on the material employed.

On the contrary, the Er:YAG and Er,Cr:YSGG lasers, which are usually employed for this purpose, adopt higher single-pulse energy levels (100–500 mJ per pulse) and greater energy densities (20–100 J/cm^2) to remove hard tissues, orthodontic cements, and resin materials.

These pulses can remove up to 50 μm of enamel and up to 200 μm of dentin each, possibly causing a severe damage to the underlying tooth structure.

The temperature rise at the pulp level during composite ablation has an average maximum value of 1.9°± 1.5 °C [136], below the critical limit of 5.5 °C [137] that is considered dangerous for tooth vitality according to Zach and Cohen [139].

In conclusion, dental hard tissues can be rapidly ablated with a mechanically scanned computer-guided CO_2 laser at high pulse repetition rates without excessive heat accumulation in the tooth or peripheral thermal damage that produce no significant reduction in the tissue's mechanical strength or a major reduction of adhesive strength to restorative material [127, 130].

Conclusion

For as long as laser photonic technology has been available within dentistry, there has been demand for laser-assisted hard dental and osseous tissue management. Notwithstanding the early adoption of the CO_2 soft tissue laser to offer bone ablation, much of the progress in developing clinically appropriate therapy occurred only with the development of the mid-infrared wavelengths, commonly and collectively termed the «erbium family.» Latterly, the emergence of a suitably tailored emission of 9300 nm CO_2 laser has broadened the options available to the restorative dentist and oral surgeon.

Through this chapter, the multiple variants in energy manipulation necessary to provide sufficient power to ablate target hard oral tissue have been explored, and their underlying association with the need to cause as little collateral damage to adjacent nontarget tissue, especially the vital pulp, is determined. Associated concepts of pain management through laser use have been evaluated together with appropriate techniques to allow the novice clinician to adopt these valuable added benefits.

With a thorough understanding of the concepts of laser-tissue interaction, the biophysics involved, and appreciation of the laser instruments available, the restorative clinician may easily and predictably incorporate laser photonic technology as a prime treatment adjunctive in the delivery of dental care.

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Laser-Assisted Endodontics

Roy George and Laurence J. Walsh

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Core Message

Conventional endodontic treatment relies on mechanically preparing the root canal space with either hand or rotary instrument prior to disinfecting a three dimensionally complex anatomical root space with irrigants and medicament. This painstakingly slow treatment process is further complicated by the inability to assess the quality of disinfection achieved in the root space. The use of lasers can assist in providing enhanced detection of bacteria and microbial biofilms in the root canal, to guide debridement approaches and help define endpoints for instrumentation. Fluorescence feedback can indicate where microbial deposits remain and where further treatment is needed. Further, there are a range of ways that lasers can enhance biomechanical preparation of the root canal system, particularly through fluid agitation and inducing cavitation in water-based fluids, to remove debris and smear layers. Such actions can be optimized using modified laser fibers tips to deliver the laser energy in various side-firing patterns. Lasers can achieve disinfection of the root canal through both photothermal and photodynamic processes, reaching areas that are difficult to access using conventional instrumentation and irrigating techniques. Additional applications of lasers in endodontics include the assessment of pulp vitality through laser Doppler flowmetry, photothermal and photodynamic bleaching of discolored sclerosed vital or stained nonvital teeth, pulp capping and pulpotomy, photobiomodulation and laser-induced analgesia, and endodontic surgical applications including periapical surgery and treatment of invasive cervical resorption. In each of these areas, the use of lasers can simplify treatment protocols and optimize clinical outcomes.

9.1 Introduction

The primary goal of root canal treatment is to eliminate microorganisms from the root canal system and radicular dentin. Laser technology can assist in the diagnosis of microbial deposits to guide biomechanical treatments and can help to inactive organisms through a range of thermal, photodynamic, and photomechanical processes. Unlike mechanical instrumentation such as hand or rotary endodontic files, laser effects reach across the entire root canal system and penetrate to some extent into dentin tubules. It is well known that with conventional instrumentation, large parts of the root canal system are untouched. The use of lasers, in many cases combined with appropriate fluids, can assist in achieving the goals of three-dimensional cleaning and profound disinfection of the canal.

Supporting these primary goals of endodontics are other laser applications in the diagnostic and therapeutic categories, as shown in ◘ Table 9.1. The uses of various lasers used in endodontics and some of their more popular applications are listed in ◘ Table 9.2.

◘ **Table 9.1** Classification of uses of lasers in endodontics

Primary application	Examples
Diagnosis	Detection of pulp vitality Doppler flowmetry Low-level laser therapy (LLLT) Laser fluorescence Detection of bacteria
Pulp therapy	Pulp capping Pulpotomy
Canal preparation	Biomechanical preparation Removal of smear layer Sterilization of the root canal High-level lasers – photothermal disinfection Low-level lasers –photodynamic disinfection
Periapical surgery	Ablation of granulation tissue Bone cutting and root resection
Laser photobiomodulation	Laser-induced analgesia Accelerated healing after pulpotomy or periapical surgery
Other	Removal of root canal filling materials and fractured instrument Softening gutta-percha Removal of moisture/drying of canal

9.2 Diagnostic Laser Applications

9.2.1 Laser Doppler Flowmetry

During dental pulp sensibility testing, a pain response elicited to a hot or cold stimulus or to an electric pulp tester provides information about the dental pulpal sensory supply, but not about its blood supply. Although the sensitivity of these commonly used tests is high, false results can lead to unnecessary endodontic treatment. This is a particular problem when teeth have experienced dental trauma or are undergoing orthodontic tooth movement [1].

In laser Doppler flowmetry (LDF), laser light is transmitted through tooth structure to the dental pulp by means of a fiber optic probe held in a reproducible position on the tooth surface. If the pulp is vital, there will be blood flow within the tissue. With movement of erythrocytes, the scattered light is frequency-shifted, whilst light reflected from static tissue is un-shifted. The reflected light is analyzed for its frequency shift to give a noninvasive, objective, painless, semi-quantitative assessment of pulpal blood flow. LDF has been used to estimating pulpal vitality in both adults and children, particularly in teeth which have been affected by dental trauma, excessive occlusal forces or orthodontic movement.

Table 9.2 Selected applications of lasers

Laser	Wavelength	Reported uses in endodontics
Short wavelength	Argon 488–514.5 nm	Endodontic disinfection
	KTP 532 nm	Soft tissue surgery in endodontics, endodontic disinfection
	He-Ne 633 nm Diode 635 nm	Doppler flowmetry, photoactivated disinfection of root canals
	Diode 810–980 nm	Soft tissue surgery in endodontics, endodontic disinfection, laser-induced analgesia, laser photobiomodulation
	Nd:YAG 1064 nm	Soft tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
Long wavelength	Ho:YAG 2100 nm	Tooth preparation, soft and hard tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
	Er,Cr:YSGG 2780 nm	Tooth preparation, soft and hard tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
	Er:YAG 2940 nm	Tooth preparation, soft and hard tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
	Carbon dioxide 10,600 nm	Pulp capping; soft tissue surgery in endodontics

LDF can also assist in the recognition of nonvital teeth. For this application, LDF has been found to be particularly valuable for assessing the blood flow in luxated teeth, as the pattern of results over time can guide decisions around "at-risk" teeth so that loss of vitality can be recognized and can then trigger endodontic intervention [2, 3].

While LDF is regarded as a highly accurate method for diagnosing the state of pulpal health and indeed comes closest to serving as a "gold standard," it must be recognized that LDF readings are prone to interferences from environmental and technique-related factors, including superimposed signals arising from blood flow in the periodontal tissues rather than in the pulp, the posture of the patient and their heart rate. If the laser light reaches the periodontium, then the reflected signal will not be entirely of pulpal origin [4–7]. One technique to overcome this is to place the probe on dentin in the floor of a cavity in the tooth, rather than on the enamel surface, since this is closer to the dental pulp and improves the signal-to-noise ratio [8].

There has also been work to explore the applications of transmitted laser light, rather than reflected laser light as in LDF. It has been suggested that transmitted light would be useful for the assessment of tooth pulp vitality both because the blood flow signals do not include flow of nonpulpal (e.g. periodontal) origin and because the response to blood flow changes are more obvious [9].

With both LDF and the transmitted light approach, it must be borne in mind that transmission of laser light may be influenced to some extend by tooth shade as well as by the presence of dental caries and restorations. Light can however be conducted within irregular secondary dentin, so the presence of carious lesions or tooth colored restorations in molar teeth does not always prevent laser light reaching the pulp space. Light will not, however, pass through amalgam restorations or gold crowns [10, 11].

Key Points for Laser Doppler Flowmetry

- Laser wavelengths must penetrate normal tooth structure.
- Visible red and near-infrared wavelengths are the most suitable.
- Finding a reproducible position for the tip is important of repeated measurements will be made.
- LDF cannot be used when the tooth is covered with an opaque full coverage restoration.

9.2.2 Fluorescence Diagnosis of the Root Canal System

Traditional culture-based techniques for assessing the presence of microorganisms in planktonic form or in biofilms in root canal system are difficult to use and prone to error. Real-time assessment of the microbial status of the root canal system using laser fluorescence has been developed to overcome these limitations and provide information that can guide clinical decisions around treatment endpoints [12].

The proof-of-concept for this application used an existing laser fluorescence device, the DIAGNOdent (KaVo, Biberach, Germany), which utilizes visible red laser light (wavelength 655 nm) to elicit fluorescence emissions in the near-infrared range. Initially this was used with a rigid sapphire tip to analyze the pulp chamber and coronal third of the root canal system in extracted teeth with infected and uninfected root canals. The fluorescence properties of bacterial cultures, mono-species biofilms in root canals, pulpal soft tissues, and sound dentin were also evaluated, together with extracted teeth with known endodontic pathology. The baseline for sound dentin and healthy pulpal soft tissue was established as an average fluorescence reading of 5 (on a scale of 100), whereas biofilms of *Enterococcus faecalis* and *Streptococcus mutans* established in root canals showed a progressive increase in fluorescence over time [13]. Fluorescence readings reduced to the "healthy" threshold reading of 5 when root canals were endodontically treated and the experimentally created bacterial biofilms were removed completely. High fluorescence readings were recorded in the root canals and pulp chambers of extracted teeth with radiographic evidence of periapical pathology and scanning electron microscopy evidence of bacterial infection. This confirmed that a laser fluorescence diagnostic approach could be useful for assessing the status of the pulp chamber and root canal system [13].

Development of thin flexible fiber tips to gain greater penetration into middle and apical thirds of the root canal was necessary to evaluate the performance of optical fibers (Fig. 9.1a, b). Fibers with either plain or conically modified

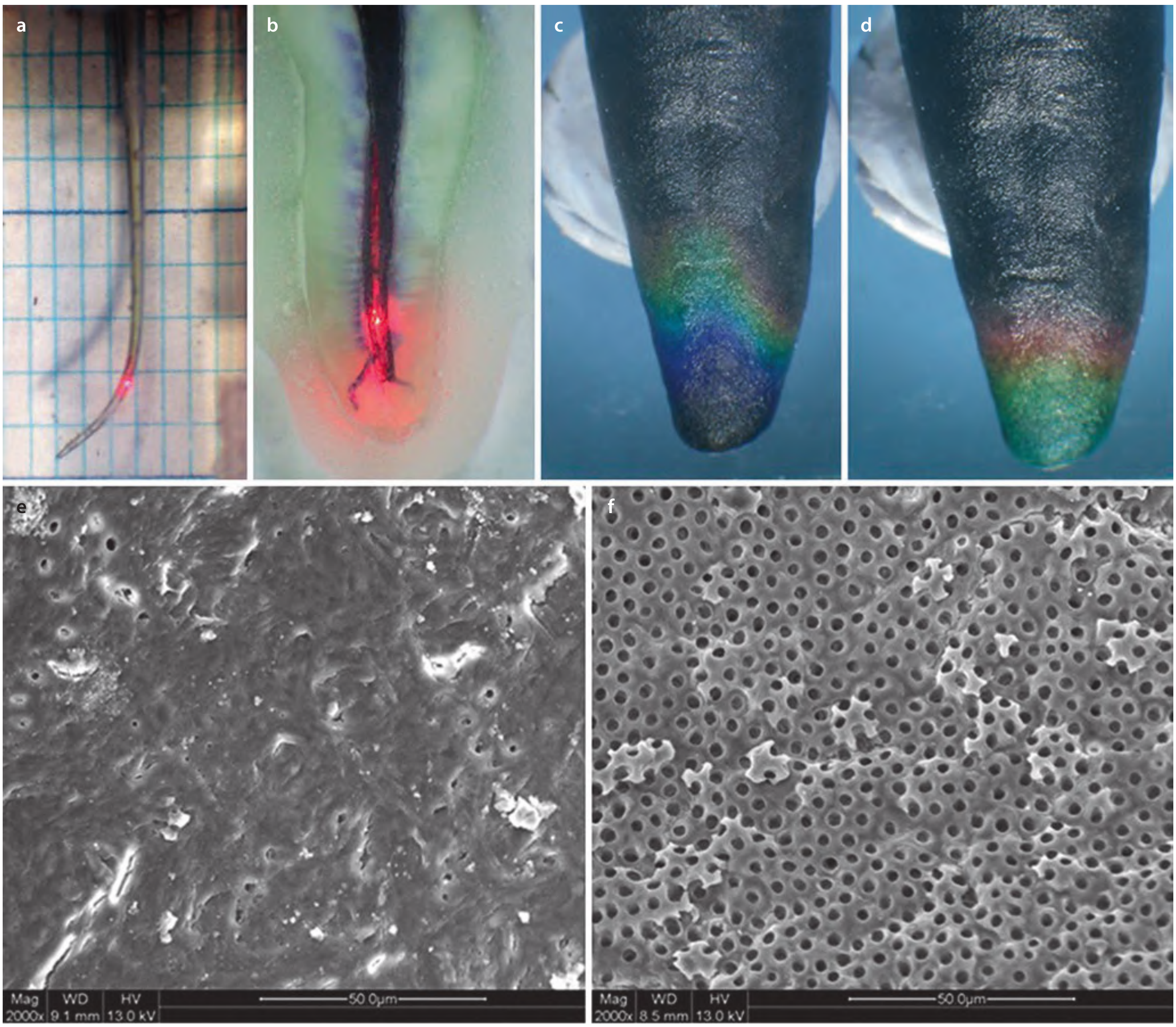


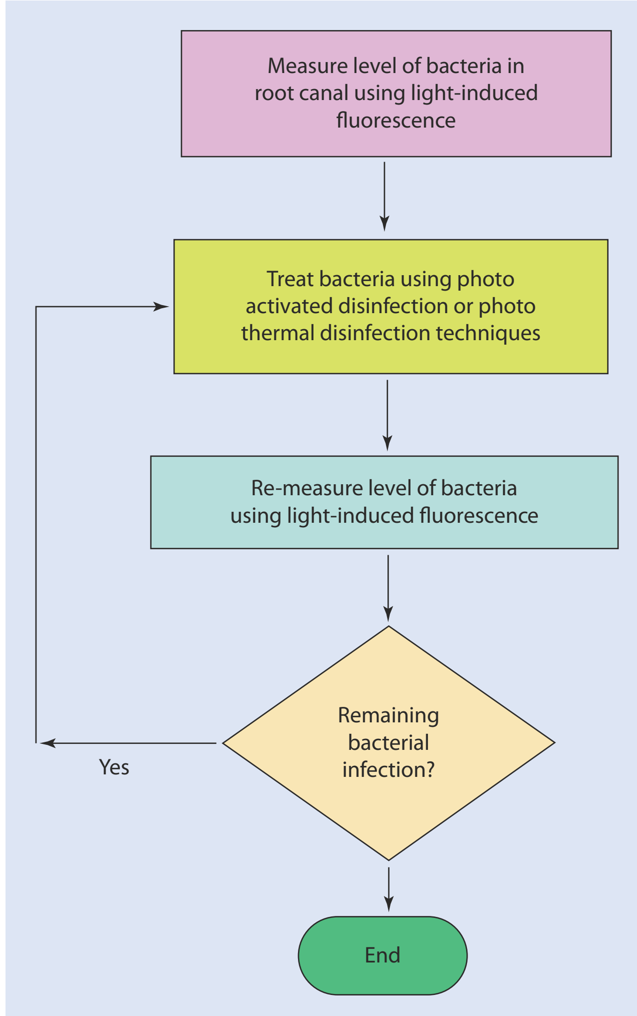
Fig. 9.1 Optical fibers and their applications in laser endodontics. **a** Conventional plain-ended fiber placed into an epoxy resin replica of the root canal showing forward emission of visible red laser energy. Using plain-ended tips requires the fiber to be moved to achieve irradiation of the canal walls. **b** Honeycomb fiber placed into the root canal showing lateral emission of visible red laser energy. To enhance visibility, the canal was filled with ink prior to inserting the fiber. **c** Thermochromic (heat sensitive) dye applied to the root surface showing subtle thermal changes during lasing of less than half a degree Celsius when the honeycomb tip is used to activate water-based fluid (500 mJ/pulse at 4 Hz). The point of greatest thermal change is the *blue color* change, followed by *green*, followed by *red*. **d** The same tooth 5 s after lasing has stopped, showing dissipation of thermal changes at the root surface. For details, see Ref. [14]. **e** Smear later present on the root canal walls when rotary instruments are used with water as the lubricant fluid. SEM magnification 2000×. **f** The same location after using a conical tip fiber to deliver 940 nm diode laser energy to activate EDTA irrigant. The laser was applied for 10 cycles of 10 s duration using 80 mJ/pulse at 50 Hz. For details, see Lagemann et al. [15]

ends, connected to a fluorescence diagnostic system, were also used to assess canals of extracted teeth with known periapical pathology. Diameter of fibers and their penetration into root canals with different curvatures were also tested. It was found that the fibers could reach the apical third of the root canal, unless the canals had distal curvatures greater than 15°. Penetration was greater for fiber optics with a conical/radial end design than for fibers with a plain/bare end design. The self-guiding action of the conical tip prevented frictional binding onto the canal walls and hence allowed for greater penetration. Fluorescence readings were significantly higher in infected canals (range, 19–99) than in noninfected canals and sound radicular dentin (range, 2–8) [16].

To further enhance the ability to take fluorescence fiber optic readings from the walls of the root canals, a cone-shaped tip with optimal properties for the lateral emission and collection of light was developed [17–19]. Commercial optical fibers were altered by tube etching with hydrofluoric acid, modified tube etching (after removing the protective polyimide coating), alumina abrasive particle beams, and etching and particle beams used in combination. Laser emissions both forward and laterally were measured and visibly traced using He-Ne lasers (632.8 nm) or InGaAsP diode lasers (635 and 670 nm). It was found that a particular etching/abrasion/etching combination gave a unique honeycomb surface configuration with grating-like properties. This had unique micro-patterns which were not seen on fibers which had been either etched or abraded. The honeycomb tips showed ideal radial emission and collection of light for fluorescence assessment of the root canal. This tip design was then used on fibers made of various materials and of different sizes [17–19].

The possibility now exists to combine fluorescence diagnostics with an endodontic treatment system (◘ Fig. 9.2). This has already been done for the removal of infected carious dentin and subgingival deposits of plaque, based on the fluorescence properties of the porphyrin compounds (contained in bacteria) [20–25]. For example, using the DIAGNOdent system, 655 nm visible red laser light elicits porphyrin fluorescence emissions over 780 nm in wavelength, which can readily be measured to give a quantitative relative fluorescence score ranging from 0 to 100. Healthy circumpulpal dentin, the walls of a healthy uninfected root canal and healthy dental pulp tissue all give fluorescence readings in the order of the 5–6 range using this method [13, 16] (◘ Fig. 9.3). There is also the possibility of using long wavelength ultraviolet light (380–400 nm) or violet light (405 nm) to elicit fluorescence emissions from bacterial deposits. In this instance, the emissions are in the visible red region [26–28].

For the successful use of fluorescence to guide laser-based treatment methods, it is important to recognize factors which could impair the fluorescence process, for example, by quenching fluorescence emissions (such as hydrogen peroxide or ozone). After such treatments, fluorescence scores are suppressed and take up to 24 h to recover fully in the absence of exogenous antioxidants, meaning that there is a false negative (suggesting bacteria are absent when in fact they are still present). Use of suitable scavengers such as sodium ascorbate in solution can obviate such problems. It is also important to recognize situations, which give rise to false-positive signals (i.e. when bacteria are not present), such as when tetracyclines are used in medicament pastes, and rapidly become incorporated into the dentin of the root canal walls. The use of oxidant fluids (such as hydrogen peroxide or ozonated water) can quench fluorescence signals, unlike other fluids such as ethylene diamine tetraacetic acid (EDTA).



◘ **Fig. 9.2** Algorithm for using fluorescence to control laser-based debridement and disinfection (Adapted from Ref. [17] and US patent 8,977,085)

Key Points for Laser Fluorescence Assessment

- False-positive fluorescence can occur with certain endodontic medicaments (e.g. tetracyclines).
- Oxidants can quench fluorescence signals.
- Fiber optics with lateral light collection properties are required.
- Low laser powers are used so there are no deleterious thermal effects.
- Suitable wavelengths include ultraviolet, visible and near-infrared laser light.

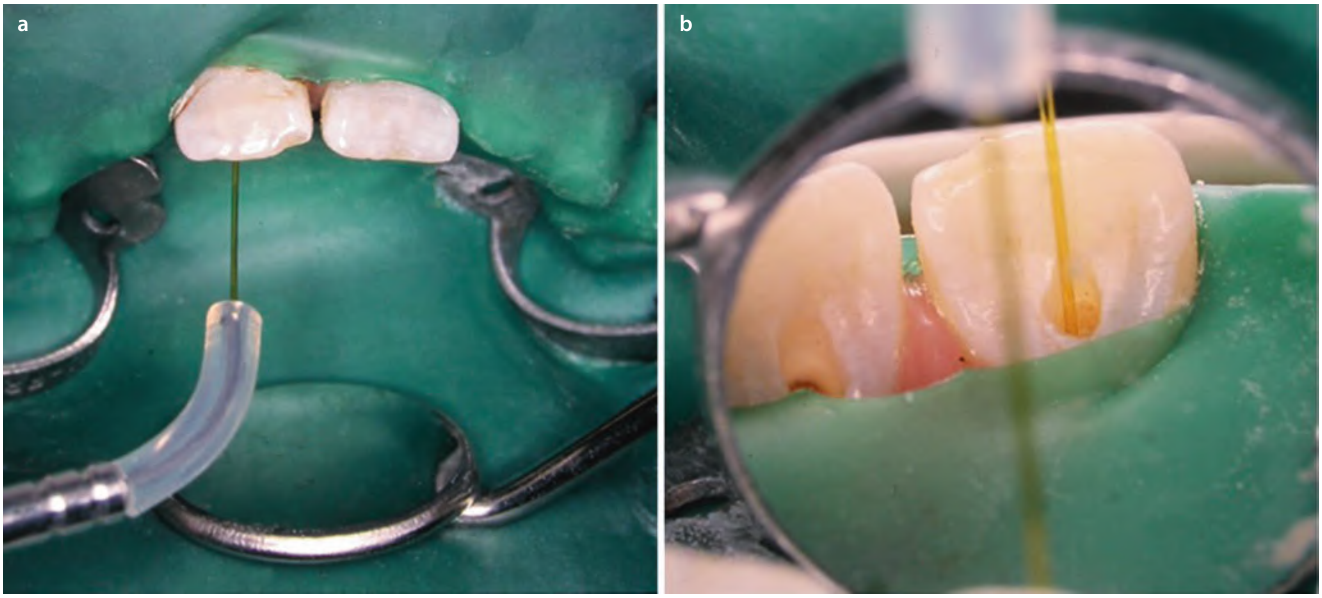


Fig. 9.3 Use of real-time fiber optic detection of bacteria. A flexible fiber with a specially treated surface is inserted into the canal. The typical fiber diameter is 150–200 microns. The fiber is then linked to a fluorescence diagnostic system

9.2.3 Laser-Assisted Widening of the Root Canal

One of the earliest explorations of the possible use of lasers to enlarge the root canal was the study of Levy [29], in which an Nd:YAG laser with water spray was used to widen root canals in the apical zone from ISO #20 to ISO #35, based on the fit of K files. The technique employed was a painting and sweeping action circumferentially, with lateral pressure on the canal walls during withdrawal of the fiber. The procedure took 60 s, using of 300 mJ and 1 Hz. Consistent with this, Matsuoka et al. [30] required approximately 2 min to enlarge root canals from 0.285 to 0.470 mm. Both Ali et al. [31] and Jahan et al. [32] took only 60 s of lasing time to prepare the root canal using a crown-down technique. This excludes the time required to change fiber optic tips. It would be predicted that canals with larger tapers would be easier to prepare than those with narrower tapers.

With regard to the Ho:YAG laser, Cohen et al. [33] used a 245 μm diameter optical fiber to enlarge canals. The fiber was inserted to the apex, energized and then withdrawn slowly at 4 mm/s. Using this technique, canals with internal dimensions of ISO #25 were widened to an apical size of ISO #40. Using the same laser, Cohen et al. [34] employed a step back technique with four different optical fiber tips (with diameters of 140, 245, 355 and 410 μm) to enlarge canals progressively, whilst Deutsch et al. [35] used six different-sized optical fiber tips for enlarging the root canal with the Ho:YAG laser.

With regard to the Er,Cr:YSGG laser, Ali et al. [31] reported the use of fibers of various diameters to prepare root canals using a crown down technique. While noting that this laser wavelength was useful for removal of smear layer and debris, the risk of ledging, zipping, perforation or over-instrumentation of canals was noted. Matsuoka et al. [36] reported that the Er,Cr:YSGG laser could be used successfully to prepare root canals with curvatures up to 10 °, using a step back technique, with an average energy of 2 watts, a pulse rate of 20 Hz and air and water spray. In contrast, Jahan et al. [32] reported that preparation of canals with a curvature above 5° could lead to zipping, ledge formation or perforations. There is more limited information regarding use of the Er:YAG laser for enlarging the canal. Matsuoka et al. [30] reported using the Er:YAG lasers to enlarge the root canal using three different size conventional optical fiber tips used sequentially, in line with the step back approach.

Although several studies have shown the potential for lasers to widen the root canal, it is difficult to attain all of the mechanical objectives of root canal preparation when laser energy is delivered with conventional optical fibers. This relates to their inability to deliver laser energy directly onto the walls of the root canal, as well as the operator challenge of maintaining a constant withdrawal rate. In 2006, Altundasar et al. [37] showed that delivery of laser energy onto the walls of the root canal using a conventional (plain) optical fiber to remove smear layer gives inconsistent ablation. From the standpoint of optics, a beam delivered from a plain fiber (and thus largely parallel to the walls of the root canal surface to be ablated) has low efficiency, and this has been demonstrated in the laboratory setting, by comparing the effects of parallel and perpendicular beams directed onto root canal dentin slices.

In an attempt to overcome some of these problems, fiber tips with sculpted polished ends and greater lateral emissions have been developed [35, 38–42]. Shoji et al. [38] employed a cone-shaped irradiation tip which could disperse laser energy in an annular pattern. This aluminum reinforced silicate tip was used to deliver Er:YAG laser energy, to enlarge root canals. This tip design produced maximal enlargement when the laser was used at 30 mJ and 10 Hz.

Key Points for Laser-Assisted Widening of the Root Canal

- Laser wavelengths should ablate hard tissue for maximum effectiveness.
- Thermal side effects need to be controlled.
- Special tip designs improve safety and effectiveness.
- Suitable wavelengths are in the middle infrared.
- Laser energy must be pulsed to ensure thermal stresses are reduced.
- Concurrent irrigation assists cooling.

9.2.4 Removal of Smear Layer from Root Canal Walls

Many laser types have been reported to be useful in the removal of smear layer from root canal walls, including the argon fluoride (ArF) and other excimer lasers [43], argon ion lasers [44], KTP laser (532 nm) [45], diode lasers, Nd:YAG lasers [46, 47], HoYAG lasers [48], Er:YAG lasers [49, 50], Er,Cr:YSGG lasers [32, 51], and CO_2 lasers [52].

Diode lasers are cost-effective, compact and portable devices. The near-infrared laser emissions from these devices (810–980 nm) have penetrating disinfecting actions, which is an additional advantage to being able to remove smear layer. Wang [53] used a 980 nm wavelength diode laser at 5 W for 7 s to remove smear layer; however, concerns remain in terms of generation and conduction of heat to the supporting apparatus if high irradiances are used [54].

Nd:YAG lasers are more effective for disinfecting the root canal, and relatively less effective for removing smear layer, compared to the erbium lasers [55]. Goya [56], who investigated the effect of the Nd:YAG laser on smear layer, found that black ink increases the removal of smear layer by enhancing absorption of laser energy. However, Wilder-Smith et al. [57] identified that thermal damage was a concern when using the Nd:YAG laser to remove smear layer.

The water-absorbing properties of the Er:YAG and Er,Cr:YSGG lasers make these useful both for disinfection of the root canal and removal of smear layer [47, 51, 58]. Takeda et al. [47] undertook a comparative study of the argon ion laser (1 W, 50 mJ, 5 Hz), Nd:YAG laser (2 W, 200 mJ, 20 Hz.) and Er:YAG laser (1 W, 100 mJ, 10 Hz) in terms of removal of smear layer from prepared root canal walls, compared to EDTA. All lasers achieved better smear layer removal than EDTA, and the Er:YAG laser was the most effective of the three lasers used. In a later study, Takeda et al. [52] reported that Er:YAG lasers were better than CO_2 lasers and three different acids in removal of smear layer. Ali et al. [31] reported less smear layer or debris when using an Er,Cr:YSGG laser, compared to the conventional root canal techniques; however, the mechanical quality of the canal preparation (smoothness, taper, etc.) was worse with the laser method. Biedma [59] also reported similar results of that of Ali et al. [31], but using the Er:YAG laser.

As already noted, several studies have reported inconsistent or inefficient removal of smear layer when using erbium lasers delivered using conventional optical fibers. Altundasar et al. [60] reported inconsistent smear layer removal of the walls of the root canal when the Er,Cr:YSGG laser (operated at 3 W and 20 Hz) was delivered using a conventional tip, whilst Anic et al. [37] reported greater efficiency of a perpendicular beam for ablation when compared to a parallel beam. Kimura et al. [61] stated that it was difficult to evenly irradiate root canal walls using a conventional fiber tip and advocated an improvement in the fiber tip design or method of irradiation to avoid obtaining an uneven surface.

To overcome such problems, several authors have employed sculptured fiber tips that have greater lateral delivery of laser energy [38–40]. Alves et al. [41] used the Er:YAG with forward-emitting sapphire tips and hollow fibers and compared these to modified tips which gave lateral emissions. Shoji et al. [38] used an Er:YAG laser delivered into a cone-shaped tip to enlarge artificial root canals in a block of bovine dentin using Er:YAG laser energy. The cone-shaped tip was faster for cavity preparation and smear layer removal, compared with conventional instruments. Likewise, Takeda et al. [52] used a conical tip with the CO_2 to remove smear layer from the root canal.

Stabholz et al. [14] designed an endodontic side-firing spiral tip (RCLase; Lumenis, Opus Dent, Israel) (Fig. 9.3), which comprised a hollow waveguide with spiral slits along the length of the tube. The end of the tip was sealed to prevent the forward transmission of laser energy. The Er:YAG laser was used at 500 mJ and 12 Hz through this tip to remove smear layer successfully. However, such tips are too large and rigid to be used in narrow, curved root canals. Moreover, if the tip were to bend, more energy would be emitted across those slits that are in a straight line with the beam.

Key Points for Removal of Smear Layer

- Laser wavelengths should absorb strongly in water to generate cavitation.
- Use of pulsed modes is essential.
- Laser [pulse energy must be limited to prevent fluid extrusion from the apex and excessive projection of fluid from the root canal system.
- Most suitable laser wavelengths are in the middle infrared.
- Water-based irrigant fluids should be used; the procedure should never be done dry.
- Laser activation enhances the action of EDTA in smear layer removal.

- Lasers can enhance the actions of other water-based fluids such as sodium hypochlorite through agitation and warming of the fluid.
- Thermal side effects need to be controlled.
- Special tip designs improve safety and effectiveness.
- Tips degrade readily during use and this alters their emission characteristics.
- Laser energy must be pulsed to ensure thermal stresses are reduced.
- Concurrent irrigation assists cooling.

9.3 Disinfection

9.3.1 Photothermal Disinfection

Laser light can penetrate areas of canals where irrigating and disinfecting solutions cannot reach, such as fins, deltas, and lateral canals [62]. Selective photothermolysis occurs when laser energy is applied into the root canal system. For water-absorbing laser wavelengths, rapid expansion of water contained within microorganisms leads to their rupture, while for the visible and near-infrared wavelengths, primary absorption of laser energy into porphyrins, melanin, and other pigments occurs. The increase in temperature then denatures proteins and this renders the organisms unviable [63–65].

When such methods are used, it is important to employ pulsed modes and rest periods to allow for cooling of the root structure so that there is no collateral injury to the periodontal ligament from thermal stress. Assessments of safety undertaken in laboratory conditions are based on threshold values around 5.5–7 °Celsius as the limit of acceptable temperature increases on the root surface [66, 67].

Directing laser energy onto the walls of the root canal is essential for effective disinfection. To maximize this effect, different fiber modifications have been developed to increase lateral emission of laser energy, including designs with safe tips to reduce irradiation directed toward the root apex. Examples include conical tips, side-firing honeycomb tips, and honeycomb tips with silver-coated ends (safe ended fibers) [68].

Photothermal laser disinfection is a useful supplement to existing protocols for canal disinfection as the properties of laser light may allow a bactericidal effect beyond 1 mm of dentin. It must be remembered that endodontic pathogens can be present not only in the canal but extending into the dentin tubules for several hundred microns. This emphasizes the value of actions such as laser fluid agitation to enhance the efficacy of current irrigating protocols, which can increase the distance of the laser effect [69].

At the present time, the lasers used most commonly for photothermal disinfection are the Nd:YAG, KTP and near-infrared diode lasers. All of these have been shown to have excellent antibacterial efficacy, with greater penetration of the disinfecting action than middle-infrared wavelengths [70].

Key Points for Photothermal Disinfection

- Laser energy must absorb into major chromophores (water, porphyrins, melanin and other pigments) for bacterial inactivation to occur.
- Can be done with almost any laser system, but preferred lasers are Nd:YAG, KTP, and near-infrared diode lasers. Middle-infrared lasers will show the lowest penetration (~0.5 mm).
- Lateral-emitting/side-firing tips are preferred to ensure even irradiation is achieved.
- Disinfection can be achieved for microbial deposits deep within dentin which would not be reached by most medicaments placed into the canal.
- Penetration depths vary according to the laser wavelength used. Maximum penetration occurs with near-infrared laser energy.
- Pulsed modes must be used to lower thermal stress to the root and periodontium.
- Total dosimetry must be monitored so that the irradiation remains within safe limits.
- Movement of the fiber enhances coverage of the walls of the root canal.
- The fiber is moved from the apex in a coronal direction, tilting and rotating the fiber to help gain better exposure of the canal walls.
- The fiber must be kept in constant motion.
- Several passes one after the other are required to ensure that all parts of the root canal receive sufficient laser energy to inactivate microorganisms.

9.3.2 Photodynamic Disinfection

Photoactivated disinfection (PAD), also known as photoactivated chemotherapy (PACT), is based on the interaction of laser light with photosensitizers. These may be endogenous (such as porphyrins found in Gram-negative bacteria) or exogenous, in the form of dyes such as tolonium chloride or methylene blue applied into the root canal, which then bind to microbial outer membranes (Fig. 9.4). When the photosensitizer is exposed to laser light of the appropriate wavelength, reactive oxygen species are generated, which then damage the microbial cell membrane, leading to leakage of contents through it and denaturation of microbial proteins and DNA [65, 71].

Since LLP relies on the chromophore becoming electronically activated, it is essential to match the laser wavelength used with the chromophore, in exactly the same manner as is done for laser photodynamic therapy of oral lesions, where the laser energy activates otherwise nontoxic dyes producing reactive oxygen species that cause injury and death of tumour cells [72, 73].

PAD is a specific interaction, in that treatment with the laser alone (i.e. in the absence of the enhancing dye), or with the dye alone, produces much less microbial killing than the

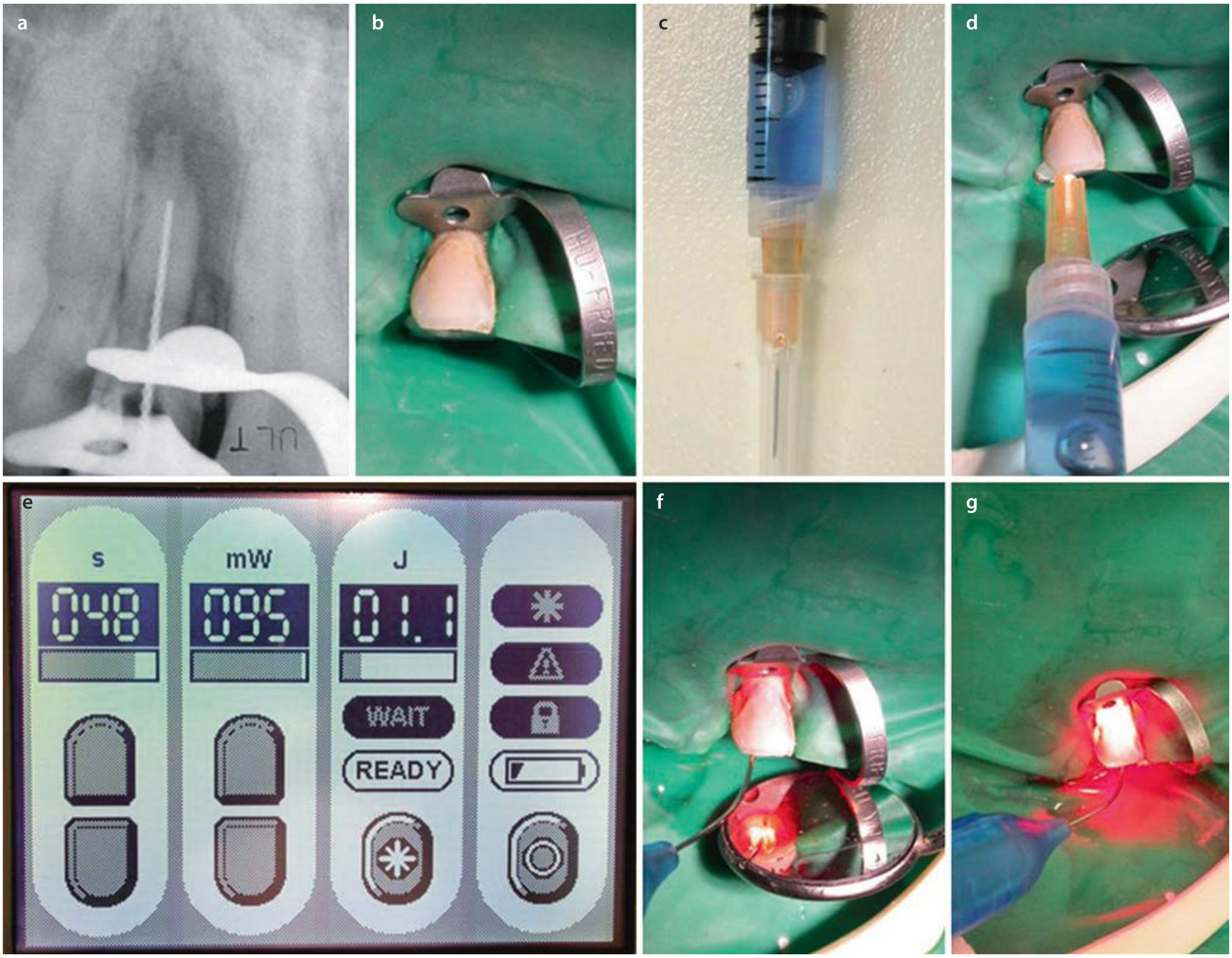


Fig. 9.4 Root canal photodynamic disinfection. This case presented with a large periapical lesion on the lateral incisor and apical root resorption. **a** Diagnostic file. **b** Isolated tooth. **c** Tolonium chloride dye solution. **d** Injection of dye solution into the root canal system. **e** Laser control panel for 635 nm diode laser midway during treatment showing delivered power 95 mW continuous wave mode. Typical irradiation is 60–90 s. **f**, **g** Transmission of visible red laser light through the coronal and radicular tooth structure. This activates the dye and provides biostimulation effects

combination of dye with laser. For example, using visible red laser light, bactericidal effects can be achieved using a range of blue, purple, and green dyes within the phenylmethane family, all of which are strong absorbers of red light [74, 75]. Other photosensitizers of interest include indocyanine green (ICG) and curcumin, which are activated at 808 and 470 nm, respectively [76, 77]. PAD can be undertaken with LEDs as well as with lasers, since either will activate the photosensitizers [78].

Both in vitro and clinical studies of PAD have demonstrated its ability to kill photosensitised oral bacteria (such as *Enterococcus faecalis*). To date, 12 studies have reported PAD as being effective in eliminating *Enterococcus faecalis* from infected root canals [79].

While PAD can be undertaken as part of the routine disinfection of the root canal system, it also has potential use for eradicating persistent endodontic infections for which conventional methods have been unsuccessful [80–82]. It does not cause significant thermal stress to the roots of teeth or the adjacent periodontal tissues [83].

There are many possible dyes which could be used for PAD. In its simplest form, the dye should undergo photodynamic activation and produce reactive oxygen species (ROS), which are the means by which microorganisms are inactivated. Dyes such as tolonium chloride and methylene blue are excellent producers of ROS in that regard. Using colored dyes which are activated by shorter wavelengths of light enhances effectiveness, since shorter wavelength light has a higher photon energy than longer wavelength light (such as in the near-infrared region of the spectrum).

There has been some confusion as to the mechanisms involved when green dyes such as indocyanine green (ICG) are exposed to near-infrared laser energy around 800–830 nm, which absorbs strongly in this material. The effect of the laser energy being absorbed is to heat the dye and therefore indirectly heat what the dye has become attached to. This is a type of photothermal disinfection process and is not a photodynamic process since the action is mediated through heat rather than through the generation of ROS. This underpins the applications of ICG dye in laser-based tumour therapies. ICG dye can absorb between 600 nm in the visible red region and all the way through to 900 nm, and it can emit fluorescence between 750 and 950 nm. ICG when exposed to 810 nm laser light will fluoresce, which is a major way ICG is used in medical diagnostics. Nevertheless, it is a simple fluorescence dye and is not a photosensitizer.

There has also been a level of confusion used in the terminology surrounding photodynamic disinfection, with terms such as photoactivated chemotherapy (PACT), photodisinfection and lethal laser photosensitization (LLP), all having been used to describe the effect with blue dyes; however, some studies using ICG also use these terms, which is incorrect.

Key Points for Photoactivated Disinfection

- Laser energy must absorb into the photosensitizer for bacterial inactivation to occur.
- Can be done with almost any visible or near-infrared laser system, as long as the laser wavelength matches the absorption of the dye.
- Preferred lasers are visible red (633, 635, 660, 670 nm) when blue dyes are used (tolonium chloride and methylene blue).
- Dyes used in photoactivated disinfection can also be activated using either lasers or LEDs.
- The liquid must be placed before laser activation to ensure adequate penetration into tubules and binding to bacteria.
- Effective dye solutions will contain low levels of surfactants to enhance penetration and reduce the formation of vapor locks.
- The dye used should not permanently stain teeth.
- Some dyes will effectively kill bacteria in the dark before being activated with laser light.
- Thermal effects caused by photoactivated disinfection are minimal.
- There are no adverse chemical effects on normal human cells.
- Lateral-emitting/side-firing tips are preferred to ensure even irradiation is achieved.
- Disinfection can be achieved for microbial deposits very deep within dentin which would not be reached by most medicaments placed into the canal.
- Penetration depths vary according to the dyes and laser wavelengths used.
- Longer irradiation times or multiple passes help ensure that all parts of the root canal receive sufficient laser energy to activate the dye to kill microorganisms.

9.4 Debridement of the Root Canal System

The use of lasers for debridement of the root canal systems offers several important advantages. Conventional instrumentation only touches some of the walls of the canal, since few canals are not perfectly round. Laser energy and laser-activated fluids, in contrast, can reach all the walls of the canal. In addition, use of files results in both widening and alterations in canal curvature. This problem of transportation does not occur when lasers are employed since energy can be delivered into the root canal without significant ablation of the walls of the root canal [84].

Finally, conventional instruments produce a smear layer, which then requires additional work to remove, such as alternating rinses with sodium hypochlorite and then extended periods of flushing with ethylene diamine tetraacetic acid (EDTA). Lasers can remove smear layer created by rotary or hand files and do not generate a smear layer when they are used to cut into root dentin.

9.4.1 Fluid Agitation

Sodium hypochlorite is the main irrigating solution used in endodontics to dissolve organic matter and kill microbes effectively. High concentration sodium hypochlorite (4%) has a better effect than 1 and 2% solutions. EDTA is needed as a final rinse to remove the smear layer [85]. Fluid agitation can enhance the action of irrigants such as sodium hypochlorite and EDTA. This agitation can be done using sonic activation or ultrasonic instruments. Greater cleanliness is achieved when endodontic irrigants are activated during the final irrigation regimen [86].

Because of their strong water absorption, Er:YAG and Er,Cr:YSGG lasers are ideally suited for activating fluids, both through warming them to enhance their chemical actions, and physically agitating them through cavitation actions (◘ Fig. 9.5). When using such lasers with water-based fluids in the canal, useful improvements can be gained in the removal of debris and smear layer (◘ Fig. 9.1f).

Using conical tips created using a tube-etching process, both Er:YAG and Er,Cr:YSGG lasers have been shown to be able to remove extraordinarily thick smear layers that had been created intentionally to provide a challenge to the laser system. When the extent of smear layer was assessed from scanning electron microscopy images with an objective digital method, it was found that lasing improved the action of EDTA in removing smear layer. Conical fibers performed better than plain fibers [68, 87].

Since the description of laser fluid activation in 2008, studies have documented the benefits of laser fluid agitation (also known as laser-activated irrigation, LAI) for enhancing cleaning of the root canal system, using EDTA, peroxide and sodium hypochlorite as the irrigant solutions. These show enhanced antibacterial actions for sodium hypochlorite and improved biofilm removal.

One of the variants of this is known as photon-induced photoacoustic streaming (PIPS), which is typically used with

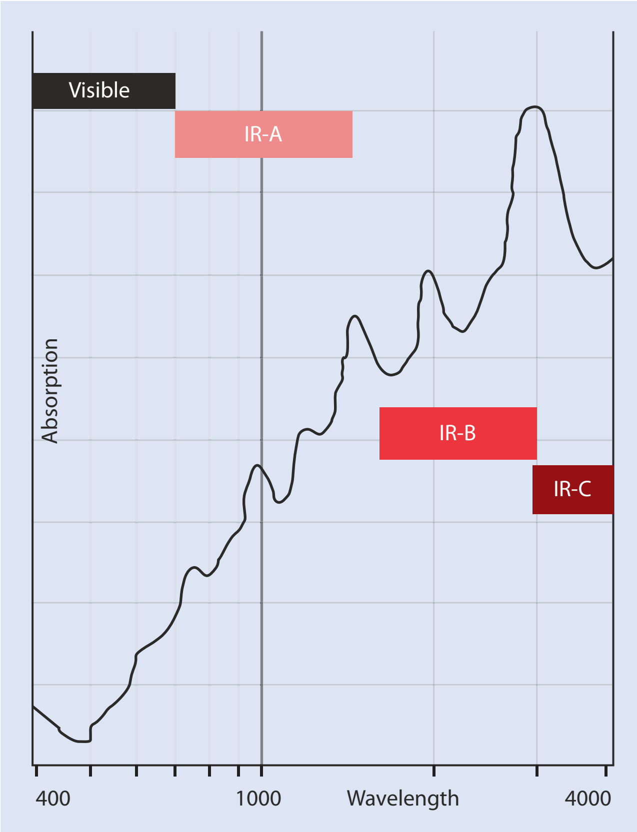


Fig. 9.5 Absorption of pure water in the visible region (400–700 nm) and adjacent infrared regions. The horizontal axis is wavelength in nanometers and the vertical axis is absorption. IR-A = 700–1400 nm; IR-B = 1400–3000 nm; IR-C = 3000 nm–1 mm

sodium hypochlorite. Laser-activated irrigation utilizing PIPS can enhance the disinfection of the root canal system [88–92].

Laser protocols which employ Er:YAG or Er,Cr:YSGG lasers with water-based fluids have been shown to cause minimal thermal stress to the root structure. Both plain and laterally emitting conical or honeycomb fiber tips can be used safely for intracanal irradiation without harmful thermal effects on the periodontium. When the irrigant fluid is refreshed between cycles of laser exposure, there is a strong beneficial effect on temperature, which attenuates completely the thermal effects of individual lasing cycles [93].

Key Points for Laser-Activation of Fluids

- Water-based fluids such as EDTA are preferred.
- Optimal lasers are the middle-infrared lasers which have strong water absorption.
- Absorption leads to cavitation and thus to agitation, fluid movement and shockwaves.
- Fluid can be ejected from the root canal, and the canal must then be topped up with kore fluid.
- Irrigation between lasing cycles reduces thermal stress.
- Excessively high pulse energies can cause fluid extrusion through the apical foramen.

9.4.2 Cavitation

With conventional irrigant solutions, fluid motion is limited to the relatively passive flow of fluid into and outside the root canal system. The root canal has confined geometry, which through surface tension effects makes the dispersion of irrigant more difficult because of the absence of turbulence over much of the canal volume [94]. Finally, in roots canals, the problems of bubble entrapment/vapor lock occur when using conventional irrigation approaches [95].

When lasers generate cavitation, the turbulence created agitates the fluids within the root canal. This can be done with the laser fiber stationary or being gently withdrawn. The laser tip does not have to be placed into the apical third of the root canal, while with conventional irrigation, it is important to place the tip of the irrigation needle to within 1 mm of the working length to ensure adequate fluid exchange [95, 96]. The laser-generated agitation causes fluid motion, which overcomes the bubble entrapment effect. Fluid streaming which is caused by the collapse of the laser-induced bubbles is a major aspect of how laser-activated fluids clean the walls of the root canal [97, 98].

Cavitation and agitation generated by lasers in fluid-filled root canals create fluid movement and shear stresses along the root canals walls, enhancing removal of the smear layer and biofilm. Rapid fluid motion is caused by expansion and subsequent implosion of laser-induced bubbles [99, 100].

When used with sodium hypochlorite and EDTA, laser activation of aqueous fluids can increase the efficiency of debridement and disinfection of root canals [101–103]. Moreover, there is now direct evidence that the pressure changes and shockwaves which accompany cavitation may enhance the susceptibility of bacteria in biofilms to antimicrobial agents. The problem of biofilms in root canals has direct parallels to the tubing of medical catheters, where such shock wave approaches are now attracting interest [104, 105].

An obvious problem which arises is whether fluid movement in the root canal leads to greater extrusion of fluids beyond the root apex. Conventional needles used for irrigation create apical pressure and extrude some fluid [106]. Studies of fluid extrusion beyond the apical constriction using Er:YAG and Er,Cr:YSGG lasers with bare or conical fiber tips positioned at distances of 5 or 10 mm from the apex have shown that the extent of microdroplets of fluid displaced past the apex was no greater than that seen when conventional 25-gauge non-side-venting irrigation needles were used [107].

When fibers with laterally emitting honeycomb patterns are used, these generate agitation with fluid movement directed onto the walls of the canal, while both the conventional plain fibers and tips with conical ends generate fluid movement largely in a forward direction. Having the laser energy directed laterally lowers the risk of fluid extrusion beyond the apex [103, 108].

Diode lasers in the 940–980 nm wavelength range can be used to generate cavitation, relying on their water absorption. Such lasers are used in pulsed modes, both to optimize the cavitation dynamics and to reduce collateral thermal effects on the roots (Fig. 9.1c, d). Such lasers can then be used with water-based fluids to remove debris and smear layers from the walls of the root canal. For diode lasers, the cavitation effects can be enhanced by supplementing the water with hydrogen peroxide to a final concentration of 3%. Any thermal stresses at the cementum are reduced when irrigation fluids are replaced, which enhances cooling of the root structure [109, 110].

In a recent study which evaluated the efficiency of EDTAC activation for smear layer removal using a 940 nm diode laser operated in pulsed mode and delivered by plain fiber tips into 15% EDTAC or 3% hydrogen peroxide, lasing EDTAC was found to considerably improve smear layer removal to a greater extent than lasing into peroxide. Of interest, the diode laser protocol for smear layer removal was more effective than the clinical "gold standard" protocol using EDTAC with sodium hypochlorite (NaOCl). In addition, when using diode lasers, there are additional benefits gained through photothermal disinfection and biostimulation [15].

When using a diode laser versus an erbium laser, it must be remembered that the fluid agitation effects are less for a diode laser than for an erbium laser; however, both are a great improvement on irrigants which are simply held static in the root canal [111].

Key Points for Laser-Induced Cavitation

- Laser energy must absorb into water for cavitation to occur in a water-based fluid.
- A small volume of water will show greater cavitation than a large volume for the same laser pulse energy; this has relevance to the effects seen in small versus large diameter canals.
- Middle-infrared lasers (Er:YAG and Er,Cr:YSGG) will show the fastest cavitation (microseconds) versus 940–980 nm diode lasers (seconds) and will cause the fastest fluid motion in the canal.
- Lateral-emitting/side-firing tips are preferred as this changes the direction of cavitation bubble formation and collapse.
- Pulsed modes must be used; shorter pulse durations will cause greater cavitation to occur for the same pulse energy, but will increase the risk of fluid extrusion through the apex.
- More fluid extrusion occurs when the apical foramen is larger.

9.5 Laser-Enhanced Bleaching

Sclerosis following dental trauma and the severe forms of intrinsic staining due to loss of vitality or endodontic treatment are challenging to manage. Some of these conditions are resistant to conventional bleaching treatments based on carbamide or hydrogen peroxide. Common factors in intrinsic staining include demeclocycline-containing tetracycline medicaments and bismuth oxide, an agent used to achieve radiopacity in some epoxy resin sealers and in mineral trioxide aggregate (MTA) [112–115].

The underlying chemistry which explains the patterns of discoloration with these different types of materials is quite complex. In the case of MTA, it is the formation of bismuth sulphide, which is black in color and therefore causes the tooth to appear grey. Iron released from hemoglobin following trauma can also form iron sulphide. Such sulphide compounds are very stable and not readily oxidized [116].

Removal of tetracycline medicaments from the root canal does not prevent later discoloration. In fact, studies have shown that current irrigation methods using plain needles, open-ended notched irrigation needles or side-vented needles do not completely remove all traces of such medicaments [117]. Laser-activated irrigation is however significantly more effective for removing endodontic medicaments than any protocols based on needle irrigation [118].

Tetracyclines bind readily to tooth structure and then form a red-purple degradation tetracycline product (4 alpha, 12 alpha-anhydro-4-oxo-4-dedimethylaminotetracycline, known as AODTC) when moisture is present. AODTC is resistant to oxidation, but can undergo photolysis when exposed to visible green light (530–535 nm), opening up possibilities for laser therapy using a KTP laser (Fig. 9.6) [119–121].

There are numerous ways that lasers can be used to enhance bleaching. These include photothermal effects (warming the gel to make hydrogen peroxide more active chemically), photochemical actions (such as the Fenton reaction), photocatalytic actions, and photodynamic actions, where the laser energy activates a suitable photosensitizer. There is also photo-oxidation, an effect which is essential for breaking up tetracyclines and AODTC [122].

Sclerosed discolored traumatized teeth, which have remained vital, can be treated using the KTP laser with photodynamic bleaching, employing rhodamine as the photosensitizer. The same technique can also be used successfully to treat using external bleaching applied in the office setting nonvital teeth with stains from endodontic treatment and teeth with tetracycline staining [123].

We undertook a clinical study of photodynamic bleaching for treating confirmed cases of tetracycline discoloration as a single-appointment procedure used the KTP (frequency doubled Nd:YAG) laser (wavelength 532 nm) combined with a rhodamine-B photosensitizer gel (Smartbleach) applied to the teeth and activated for 30 sec. Each tooth underwent four cycles of 30 s of laser exposure. Digital image analysis was undertaken in a blinded manner, and this showed a significant lightening effect was achieved in 78% of the teeth treated. An in-office KTP laser photodynamic bleaching treatment provides a useful option for improving tooth shade in teeth with tetracycline discoloration [124].

In later work, we showed that KTP laser photodynamic bleaching for tetracycline staining was more effective than using arrays of LEDs in the visible green range (535 nm) with the same photosensitizer or photo-Fenton bleaching using LED arrays in the visible blue (460 nm) [125, 126].

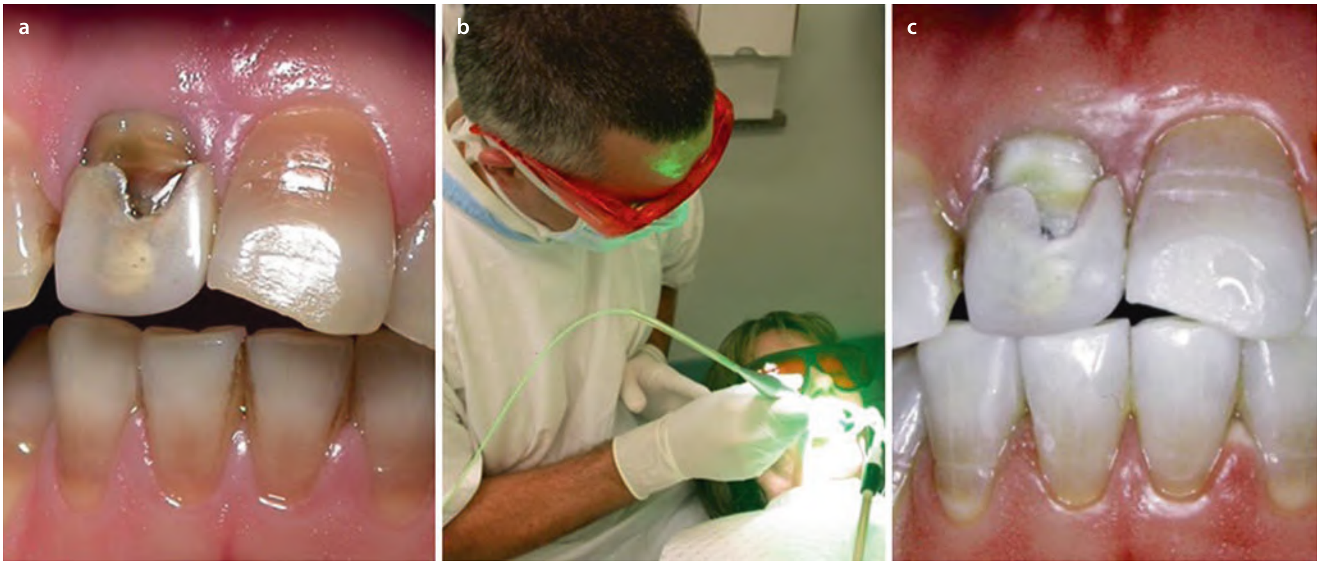


Fig. 9.6 KTP laser photodynamic bleaching of a discolored non-vital maxillary central incisor tooth (11) from an external approach. **a** Preoperative view of the discolored tooth. All the teeth have tetracycline staining of developmental origin. Tooth 11 has undergone endodontic treatment. **b** Application of KTP laser onto a rhodamine photosensitizer in repeated cycles, to treat all the anterior teeth. **c** Postoperative view at the end of the same appointment. There has been a useful improvement in the shade of the root-filled 11 tooth as well as the adjacent teeth from the laser treatment. A tooth colored restoration was subsequently placed 2 weeks later to restore the 11 tooth

Key Points for Laser-Assisted Bleaching

- Photo-thermal laser bleaching requires careful control of the irradiation protocol to limit heat stress to the dental pulp.
- Photodynamic laser bleaching is effective for more challenging intrinsic stains including tetracyclines deposited during tooth formation and sclerosed vital teeth.
- External bleaching approaches overcome problems of invasive cervical resorption associated with internal bleaching (walking bleach) methods where peroxides can come into contact with periodontal tissues.

9.6 Laser-Induced Analgesia and Photobiomodulation

Studies of restorative dentistry using free-running pulsed Nd:YAG lasers conducted in the early 1990s showed that pulsed laser radiation which could penetrate dentin was responsible for a component of the desensitizing effect of this laser on sensitive cervical dentin. Later studies of laser-induced analgesia with the free-running pulsed Nd:YAG and Er:YAG lasers by Orchardson and Zeredo, respectively, using rodents showed conclusively that there was a dramatic blockage of neuronal activity and a corresponding increase in the pain threshold of teeth after laser irradiation. The effect had a clear dose response for its onset, declined after 15–20 min, and was also associated with blockade of late-phase neurogenic inflammation (which is driven by the effects of neuropeptides). These effects were identical to those noted in clinical practice when preparing cavities with erbium lasers (Er:YAG and Er,Cr:YSGG). The animal studies however removed all possibility of placebo effects and psychogenic influences and demonstrated that there was a fundamental reversible alteration occurring in the nociceptive response caused by the laser treatment, which suppressed nerve firing for a given level of stimulus [127–131].

These effects can be used therapeutically for analgesia associated with restorative dentistry, oral surgery (including bone ablation procedures) and for endodontic procedures, including pulp capping and extirpation. Clinically, the blockade with shorter exposures is more selective for depolarization of A delta fibers (rapid, sharp, well-localized pain) than for C fibers, which explains why some patients experience vibrational sensations but not discomfort [132].

Analgesic effects can be induced by diode lasers operated in pulsed or continuous wave mode, as well as by pulsed Nd:YAG and middle-infrared erbium lasers. With the former, the wavelength and irradiance are key variables in determining the potency of the effect, while with the latter, the pulse energy and pulse frequency are critical variables [71, 133–136].

Low-level laser therapy (LLLT), also known as soft laser, biostimulation or photobiomodulation, is another laser effect of interest in endodontics. This photochemical effect arises from the action of visible red (633–635 nm) or near-infrared (810–1100 nm) light on the enzymes of the electron transport chain in mitochondria, resulting in a broad activation of normal cellular functions. LLLT effects underpin the beneficial effects of lasers when used for pulp capping and pulpotomy, where there is direct exposure of pulpal soft tissues. This explains why there is accelerated healing, nerve sprouting and dentinogenesis after pulpotomy [137].

Bystander LLLT effects occur in the periodontal ligament and periapical bone when lasers are used for intracanal procedures such as disinfection and promote the resolution of inflammation and healing responses after infection [65, 138].

Key Points for Laser-Induced Analgesia

- Analgesic effects can be induced with near- or middle-infrared lasers.
- Irradiation parameters for analgesia with diode lasers are higher than those for enhancement of wound healing and other photobiomodulation treatments with the same lasers.
- Laser-induced analgesia effects occur when lasers are used to treat hypersensitive cervical dentin and contribute to the overall clinical effects seen.

9.7 Pulp Therapy and Pulpotomy

Pulpotomy techniques for primary teeth traditionally have used formocresol, but this is becoming less widely used because of its toxic effects on living tissues and mutagenic potential. Alternatives such as MTA are expensive, and this has led to interest in using lasers for pulpotomy procedures. The lasers used have included Nd:YAG, Er:YAG, carbon dioxide and 632 or 980 nm diode lasers.

Several clinical studies support the use of lasers for pulpotomy. The reported advantages include better clinical as well as radiographic outcomes than ferric sulphate, MTA or electrosurgery, as well as a shorter operating time, simpler procedure and less postoperative pain. Effective photothermal disinfection combined with low-level laser effects likely accounts for the favorable outcomes seen clinically with laser pulpotomy [139–142]. Similarly, there is clinical trial data to support the effectiveness of direct pulp capping using lasers with carbon dioxide, 808 nm diode, Er:YAG and Er,Cr:YSGG lasers (◘ Fig. 9.7) [143–147].

Key Points for Laser Pulpotomy

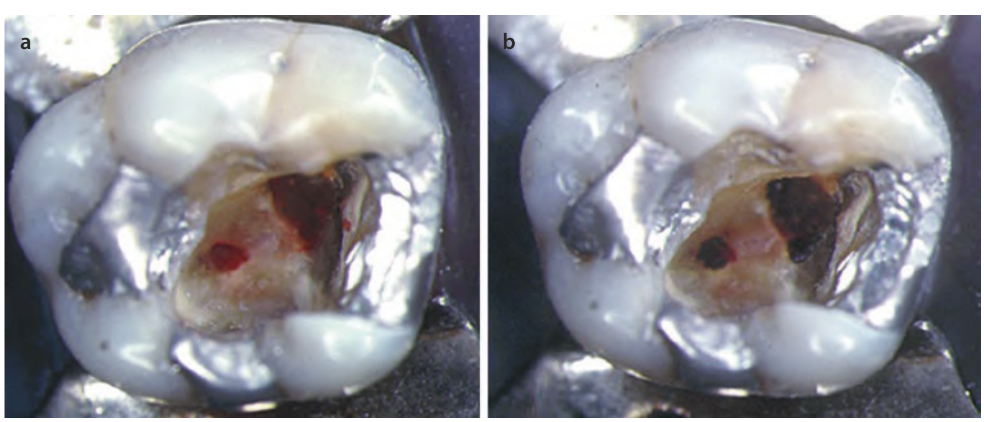
- Laser energy must absorb into major chromophores (water, porphyrins, melanin and other pigments) for coagulation and bacterial inactivation to occur
- Can be done with almost any laser system, but preferred lasers are Nd:YAG, KTP and near-infrared diode lasers.
- If middle-infrared lasers are used, long pulse durations are needed to maximize coagulation
- Typically employs very short exposure times
- The techniques to treat the exposed pulp stumps are the same as for direct pulp capping

9.8 Endodontic Surgery and Treatment of Resorption Lesions

Lesions of invasive cervical resorption can be treated by laser ablation, as an alternative to the traditional approach using trichloracetic acid. The advantages of using lasers for this application include greater precision and less collateral injury to the tissues (◘ Fig. 9.8) [148].

For periapical surgery, lasers can be used to ablate granulation tissue and to sterilize the root apex, as well as for gaining access to the lesion by removing overlying bone. Bone is ablated readily by Er:YAG and Er,Cr:YSGG laser radiation, and in clinical practice, this is typically undertaken using an accompanying water mist spray. Appropriate flow of water spray prevents desiccation of bone, ensures cooling of the site to maintain bone viability, and irrigates the site to remove debris. These middle-infrared lasers give deep cuts with sharp edges which are free of charring. Similar benefits are found when these lasers are used for root resection procedures [149, 150].

Lasers have been used successfully for root-end resection and root-end cavity preparation during apical surgery [151]. Use of an Er:YAG or Er,Cr:YSGG laser with an operating microscope for periapical surgery has been shown to give significantly better results in terms of postoperative healing, in comparison with using conventional surgical approaches



◘ **Fig. 9.7** Vital pulp capping. **a** Bleeding pulp at the base of the cavity preparation following an iatrogenic exposure of vital pulp tissue. **b** immediately after firing several pulses of carbon dioxide laser radiation to seal the area and control bleeding. The cavity was then lined with glass ionomer cement and the tooth restored with amalgam. There was no loss of vitality over time

Fig. 9.8 Laser treatment of invasive cervical resorption. Tooth 21 (left maxillary central incisor) distal developed invasive resorption after internal "walking" bleaching with hydrogen peroxide. The bleaching occurred prior to PFM crowns being placed on both maxillary central incisor teeth. **a** Preoperative view. **b** With a flap raised the granulation tissue filling the resorption defects on the root surface can be seen. **c** Pulses from a carbon dioxide laser were used to ablate the resorbing granulation tissue. After this the root surface was conditioned and a glass ionomer cement restoration placed. **d** 12 month follow-up showing a stable situation

for apicoectomy. Such lasers can be used safely for root resections provided short pulse duration is used and the water spray flow rate is sufficient [152, 153].

Key Points for Laser Endodontic Surgery

- Laser energy must absorb into major chromophores (water, porphyrins, melanin and other pigments) for soft tissue ablation to occur
- Can be done with almost any laser system, but preferred lasers are Nd:YAG, KTP and near-infrared diode lasers. With the carbon dioxide laser, extreme care is needed to avoid deleterious thermal changes to tooth structure and the dental pulp.
- Hard tissue ablation (bone cutting, root-end resection) requires a middle-infrared laser for high cutting efficiency.

9.9 Safety Issues Related to the Use of Lasers in Endodontics

Lasers can be used in conjunction with conventional endodontic equipment such as operating microscopes provided the appropriate considerations are made for eye safety, such as filters fitted to the objective of the microscope to match the laser wavelengths in use. With wavelengths longer than 2000 nm, this is not needed as the glass elements in the microscope provide sufficient attenuation.

9.9.1 Prevention of Transmission of Infection Through Contact

Laser endodontic fibers tips used within the root canal would be expected in many cases to encounter blood or other fluids which could be a source of patient-to-patient transmission of infection, if the fibers are not appropriately disinfected. Disposable tips have become available for some laser systems; however, many fiber optic systems are used where the fibers are cleaved after each use [154]. Appropriate disinfection and sterilization must be carried out for laser accessories and components that come into direct contact with oral soft and hard tissues. Other relevant recommendations include:

1. Fluid fed through a sleeve around the laser to cool it during surgery must be sterile.
2. Deposits of carbonized tissue residue can reduce the quantity and quality of the light emission. Therefore, it is necessary to wipe the tip after use. It may be necessary to calibrate the tip during the procedure.
3. Sapphire tips that come into contact with sterile tissue must be sterile and need to be cleaned and then sterilized after each use.

Piccione [155] further recommended that all controls of the laser should be disinfected or covered with a barrier, in a manner similar to other dental equipment, while smaller laser accessories such as handpiece should be steam sterilized.

9.9.2 Temperature Effects of Lasers on the Dental Pulp

In all endodontic applications using higher powered lasers, care is needed to address thermal changes in the root structure, to preserve tissue vitality. Andersen [156] has demonstrated that in the human dental pulp, both cold and heat evoked a decrease in pulpal blood flow, when measured using a Doppler flowmetry. There is, therefore, a low potential of pulpal blood flow for cooling. The absorption coefficient and the reflectivity of the laser wavelength used are important in determining the pulpal reaction. Nyborg and Brannstrom [157] determined that a temperature of 150 °C on the enamel surface for 30 s could cause necrosis of the dental pulp. According to Zach and Cohen [66], an intra-pulpal temperature increase of approximately 5.5 °C can promote necrosis of the dental pulp in 15% of cases, while temperature increases of 11 and 17 °C will cause necrosis in 60 and 100% of cases [66, 158].

Pulpal damage can be avoided or minimized by a suitable choice of laser parameters and by appropriate use of irrigation or an air/water spray. Armengo [159] studied the effect of water spray on the temperature rise when using an Er:YAG or Nd:YAP laser. Water spray reduced the temperature rise associated with laser treatment and also helped to clear the ablation site of debris and keep it moist. The importance of air/water spray is exemplified in the study of Glockner et al. [160], which demonstrated that during coronal cavity preparation with the Er:YAG laser, a temperature reduction occur after a few seconds from 37 to 25 °C, because of the cooling effect of the air/water spray.

9.9.3 Temperature Effect of Lasers on Periodontal Tissues

Maintaining the health of the periodontal apparatus is critical for the success or failure of endodontic treatment undertaken with lasers. Modern endodontic rotary instruments produce little or no increase in peri-radicular root surface temperature [161]. In contrast, several studies have shown that certain canal preparation techniques [162, 163] and obturation techniques [164–167] can transfer heat to the periodontal tissues. Er:YAG lasers cause evaporation and expansion of water within the crystals of hard tissue, and this evaporation can have a cooling action.

Several authors have studied the thermal effect of lasers on the periodontal ligament and surrounding bone [33, 34, 168, 169]. The supporting periodontal apparatus is known to be sensitive to temperatures of 47 °C, while temperatures of 60 °C and above will permanently stop blood flow and cause bone necrosis [170]. On the other hand, periodontal tissues are not damaged if the temperature increase is kept below 5° Celsius [171]. A threshold temperature increase of 7 °C is commonly considered as the highest thermal change which is biologically acceptable to avoid periodontal damage [67, 172–174].

Kimura et al. [175] using the Er:YAG laser noted that the root surface temperature increase was less than 6 °C at the apical third and 3 °C at the middle third. Similarly, Theodoro et al. [176] using the same laser reported temperature increases below 7 °C, while in the study of Machida et al. [172] where water spray was used, the temperature increase at the apex was less than 2 °C. Thus, the use of air or water coolants in combination with lasers will help prevent adverse thermal effects on the periodontal ligament and surrounding bone [159, 160].

A further consideration is that of the thermal relaxation time (T_R), which is the amount of time required for heat to flow into adjacent regions or otherwise be dissipated [177]. The use of pulsed lasers with short pulse durations will minimize the zone of thermal damage, by producing a thermal event that is shorter than the T_R of the tissue [178].

In case of root canal ablation, the conduction of heat from dentin to periodontal ligament and bone can be reduced by using a continuous stream of water during ablation. On the other hand, a dry root canal is devoid of fluid and will conduct energy similar to a solid body, which is uniformly in all directions. However, canals that are irrigated with fluids will benefit from transfer of heat into that fluid.

9.10 Future Aspects

The use of lasers in endodontics has entered a new phase with research over the past decade indicating that laser-based methods can provide not only equivalent but now superior results in terms of effective debridement of the root canal when compared to hand or powered conventional endodontic instruments. The potential in the future is to link systems for debridement and disinfection to approaches which also give accompanying analgesic effects and biostimulation, so that several therapeutic benefits are gained at the same time from a single laser irradiation protocol. There is considerable potential to incorporate feedback systems into endodontic laser systems so that fibers used within the root canal space for treatment can also support detection and diagnosis applications. This will enhance clinical efficiency and reduce the complexity of equipment which clinicians use. Further development of techniques for laser-induced analgesia will promote the development of endodontic and restorative treatments of teeth.

Conclusion

There are now several areas in endodontics where the use of laser technology offers superior outcomes for patients and simplification of techniques for the clinician. Pulsed near- or middle-infrared lasers combined with irrigants provide several advantages in terms of effective canal debridement as well as accompanying disinfection. Given the growing evidence in support of such applications, the integration of laser-based technologies into everyday clinical practice is likely to grow over the coming years. A wide range of lasers have been used successfully in endodontics, and this opens the pathway for laser systems which offer more than one wavelength, delivered through separate delivery systems or the one delivery system.

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Lasers in Implant Dentistry

Suchetan Pradhan

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Core Message

Dental lasers can be employed during all procedures for implant dentistry. Incisions and contouring of soft tissue, along with impression procedures for restorations, can all be accomplished with any laser wavelength. When the laser is used properly, hemostasis, precision tissue removal, and increased patient comfort are some of the benefits. Certain lasers may also assist in the osseous procedures necessary to prepare the implant fixture site. In areas of peri-implant disease, lasers can remove granulomatous tissue as well as decontaminate implant surfaces and can aid in establishing a more favorable healing environment.

10.1 Introduction

Implant dentistry has become a viable and predictable treatment alternative for oral rehabilitation. Dental implants are now considered an essential component of treatment planning for edentulous areas in every dentist's armamentarium of treatment modalities. Dental lasers are slowly being integrated into clinical dental practice, and they have enabled dentists to enhance and simplify patient-centric treatment concepts.

Lasers can be used very beneficially in implant dentistry in a large variety of ways. They include all the procedures from presurgical planning to postsurgical continuing care. The different wavelengths have unique absorption characteristics and effects on dental tissues. Thus it is important to understand the characteristics of those wavelengths and their tissue interactions with peri-implant tissues.

This chapter will describe the various uses of available laser wavelengths for dental implant procedures.

10

10.2 Different Laser Wavelengths Used in Implant Dentistry

The currently available dental laser wavelengths, their tissue interaction, and optimum parameters have been discussed in other chapters in this book, and the reader should consult those for further information. The following is a more focused discussion about laser use for implant dentistry.

10.2.1 Diode Lasers

The currently available dental surgical diode wavelengths are 810, 940, 980, and 1064 nm, delivered in a contact mode. They have a very small-sized footprint, resulting in good ergonomics and portability.

Wavelength	Target tissue	
810, 940, 980, 1064 nm	Hemoglobin, melanin	High absorption
	Water	None to very low absorption
	Carbonated hydroxyapatite	No absorption

The absorption in hemoglobin and melanin makes them ideally suited for soft tissue procedures [1], and the general indications for use are:

- Incision
- Excision
- Coagulation
- Hemostasis
- Debridement and detoxification of inflammatory tissue in the periodontal pocket

Specifically, diode lasers are utilized in implant dentistry for the following procedures:

- Preparation of the implant bed prior to implant placement
- Increasing the width of attached gingiva
- Incision before flap reflection
- Debridement of the socket prior to immediate implant placement
- Second-stage surgery, to uncover the implant fixture
- Creation of an emergence profile
- Adjunctive treatment of peri-implant mucositis

The infection seen in peri-implant tissue is similar to infection seen in periodontitis [2–6]. Diode lasers are also used for decontamination of diseased tissue around ailing dental implants.

In a study done by Bach et al., the laser groups had significant reduction of dark pigmented anaerobic gram-negative rods, the most relevant being *Fusobacteria*, *Prevotella*, and *Porphyromonas* species. These pathogens have been assigned a predominant role in the breakdown of the supporting periodontal tissue [7]. Hence, a diode laser is ideal for bacterial reduction, debridement of diseased soft tissue around implants, and hemostasis during implant surgery.

10.2.2 Nd:YAG Laser

Wavelength	Target tissue	
1064 nm	Hemoglobin, melanin	High absorption
	Water	No absorption
	Carbonated hydroxyapatite	No absorption

The Nd:YAG laser operates at a wavelength of 1064 nm. It is well absorbed in tissue pigments such as hemoglobin and melanin. The Nd:YAG is a free-running pulsed laser, with very short duration pulses and an emission cycle of <1% and of corresponding very high peak power per pulse (in the order of 100–1000+Watts). Thus the Nd:YAG generates high heat energy at the target tissues [8]. Nd:YAG lasers in vitro have produced undesirable results such as melting and increasing the roughness of implant surfaces. Although Nd:YAG lasers significantly decrease bacteria, they can alter implant structure along with a significant increase in temperature [9].

Romanos et al. [10] and Schwarz et al. [11] suggest that the free-running pulsed Nd:YAG laser is contraindicated for treatment of titanium implant surfaces because the high peak power, as well as the moderate reflection rate of this laser from titanium metal, easily causes melting of the metal surface. However, Gonçalves et al. [12], in an in vitro study, used an Nd:YAG laser in non-contact mode with a longer pulse duration and demonstrated no damage to these titanium surfaces.

The Nd:YAG laser is hence not ideally suited for soft tissue procedures in implant dentistry where there is a high likelihood of direct implant contact and must be used with caution by the clinician.

10.2.3 CO_2 Lasers

Wavelength	Target tissue	
9300–10,600 nm	Carbonated hydroxyapatite	Very high absorption
	Water	High absorption
	Collagen	Good absorption

Carbon dioxide (CO_2) employs photonic energy in the far-infrared spectrum (wavelength 9300–10,600 nm) and is usually delivered in a non-contact mode. Some models have extremely short pulse durations, and one instrument with a wavelength of 9.3 microns can produce a 5 microsecond pulse. Compared to any other dental wavelengths, they have the highest absorption in dental minerals, such as hydroxyapatite and calcium phosphate, and must be used with caution during periodontal soft tissue procedures in order to avoid direct contact with hard tissue. The penetration depth into soft tissue is relatively shallow (approximately 0.2–0.5 mm.). In addition to being effective against bacteria such as *Porphyromonas gingivalis* [13], the CO_2 lasers provide disinfection and bacterial reduction without any significant changes to the implant surface.

Hence, the CO_2 laser is a good option for:

- Soft tissue surgical incisions
- Disinfection and debridement of diseased tissue in pockets around implants
- Healthy clot formation
- Second-stage implant exposure
- Osseous surgery (9300 nm wavelength micropulsed instrument only)

10.2.4 Erbium Family of Lasers: Er:YAG and Er,Cr:YSGG

Wavelength	Absorption	
Er:YAG 2940 nm Er,Cr:YSGG 2780 nm	Water	Very high absorption
	Carbonated hydroxyapatite	High absorption
	Collagen	Good absorption

Erbium lasers (Er:YAG and Er,Cr:YSGG lasers) have water as a primary absorption target and mineral as a secondary target. They emit in the mid-infrared range at wavelengths of 2940 nm for Er:YAG and 2780 nm for Er,Cr:YSGG and can be delivered in a contact or non-contact mode. Similar to Nd:YAG, they have a free-running pulse emission with very short pulse durations and correspondingly high peak powers. With the very high absorption in water, their penetration depth can be as shallow as 5 microns [14]. Erbium lasers offer ablation with minimal thermal-related side effects.

As mentioned, erbium photonic energy is very well absorbed primarily by water within the enamel, dentin, bone, and soft tissue. The absorbed energy causes rapid explosive expansion of water in those tissues, resulting in ablative tissue removal. Hemostasis in soft tissue is adequate, but not nearly as effective as other wavelengths. In osseous surgery, the resulting bone surface is devoid of a smear layer and has good bleeding, without thermal damage or coagulation. Coaxial water spray is essential to prevent thermal damage and delayed postoperative healing.

The erbium lasers are useful for the following in implant dentistry:

- Raising surgical flaps.
- Debridement of surgical sites prior to immediate implant placement. Since laser surgery is bactericidal, infected implant sites can be relieved of pathogenic bacterial load and apical granulomas.
- Laser-assisted osteotomy.
- Bone harvesting and donor site preparation.
- Creation of the window in lateral sinus lift procedure.
- Uncovering of implant fixtures in second-stage surgery.
- Recontouring gingival tissue and sculpting emergence profile for prosthodontic components.
- Ablating diseased junctional epithelium.
- Removing calculus and plaque from implant surfaces without damaging the implant fixture or components.
- Treatment of peri-implantitis—debridement of soft and hard tissue.

Clinical studies by Kreisler and associates concluded that even at low energy densities, the Er:YAG laser has a high bactericidal potential on common implant surfaces. Also at these energy densities, no excessive temperature elevations or morphological implant surface alterations were detected [15].

Other authors found that Er,Cr:YSGG laser irradiation can be used successfully to decontaminate the surface of the titanium implant [16, 17].

10.2.5 Lasers for Photobiomodulation

Photobiomodulation therapy (PBM), which is also known as low level laser therapy (LLLT), has been shown to both reduce pain and accelerate healing of tissue [18]. PBM can be a useful therapy after implant fixture placement and after second-stage exposure. It should be noted that certain lasers produce a direct PBM effect, while some surgical lasers can offer similar beneficial results, although those are not true photobiomodulation. ▶ Chapter 7 describes the details of this phenomenon.

10.3 Laser Applications in Implant Dentistry

Dental implant procedures can be divided into three main divisions: presurgical, surgical, and postsurgical.

Laser Applications in Implant Dentistry

1. The presurgical therapy utilizing a laser includes:
   - Maintaining healthy attached gingiva or increasing the width of attached gingiva prior to implant placement with procedures such as a frenectomy, vestibuloplasty, gingival grafting, or apically repositioned flap
   - Preparation of surgical site prior to implant placement
2. The laser surgical procedures consist of:
   - Disinfection of the implant site in case of immediate extraction and implant placement
   - Incision and debridement using lasers
   - Laser-assisted osteotomy
   - Sinus lift used in the creation of the window in the direct sinus lift procedure
   - Preparation of the donor site prior to bone augmentation
3. Postsurgical treatment can employ lasers for:
   - Implant fixture exposure
   - Retraction and management of tissues prior to making impressions
   - Creation of attached gingiva prior to final restoration
   - PBM therapy during healing after the implant placement for pain relief and accelerated wound healing

In addition, lasers can be used for peri-implant disease therapy.

10.4 Presurgical Procedures

10.4.1 Use of Lasers to Create Attached Gingiva or Increasing the Width of Attached Gingiva Prior to Implant Placement

One of the factors in successful implant retention in the oral cavity is the width of keratinized gingiva surrounding dental implants. The implant-mucosa interface differs from the interface between mucosa and natural teeth. These differences can contribute to the susceptibility of implants to infection. Natural teeth have a periodontal ligament supporting them which helps to defend against bacterial infection. However, dental implant lacks a periodontal ligament. In addition, Lindhe and Berlungh [18] suggested that the ability of the peri-implant mucosa to regenerate itself is limited by its compromised number of cells and poor vascularity. Also, peri-implant and periodontal tissue may differ in their resistance to bacterial infection [19–21]. Hence, the necessity of a zone of keratinized tissue adjacent to dental implants has been suggested [22]. A decreased zone of keratinized tissue could be attributed to aberrant frenal attachments or a generalized tissue pull.

The release of frenal attachments around a dental implant can alleviate any tension to the tissue around the implant site. Hence aberrant frenal attachments around an implant site must be checked for.

The surgical procedures to increase width of keratinized gingiva and achieve a stress-free and tension-free closure around implants include frenectomy and vestibuloplasty.

Figure 10.1 Frenectomy increasing the length of attached gingiva prior to implant placement

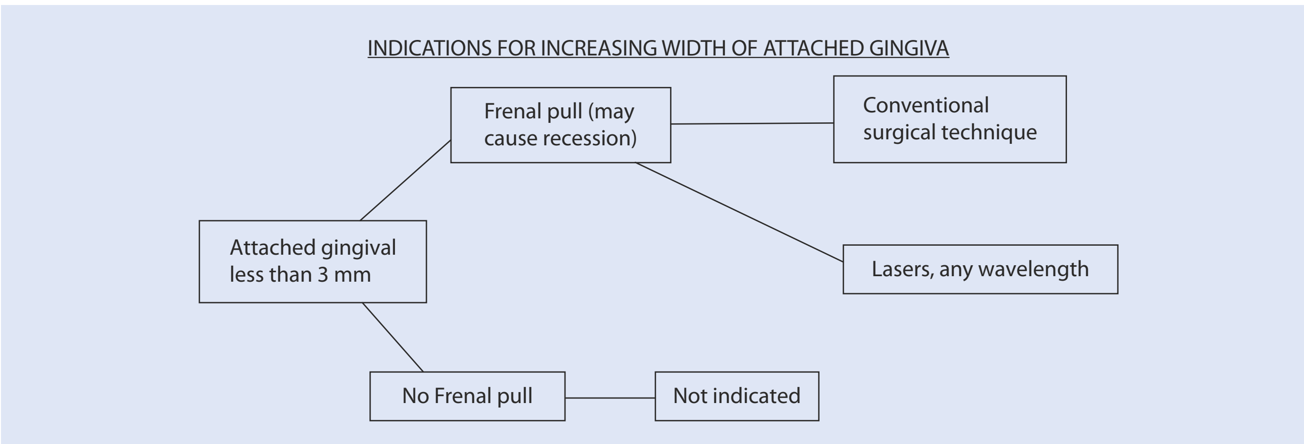


Fig. 10.1 a Preoperative view showing the maxillary anterior frenum insertion at the apical border of the attached gingiva. **b** A 980 nm diode laser was used with an average power of 0.7–1 W delivered with a 300-diameter micron tip. **c** Immediate postoperative view showing frenum revision and sutured extraction sites of the right central and lateral teeth. **d** Three-month postoperative view showing increased width of attached gingiva

10.4.2 Preparation of Surgical Site Prior to Implant Placement

One of the most critical aspects of implant dentistry is preoperative disinfection of the surgical site. This reduces the microbial count of the oral cavity as well as prevents any contamination of the surgical site. Traditionally this is done with antimicrobial rinses such as chlorhexidine. The emergence of bacterial resistance to antibiotics, owing to frequent doses of antibiotics, is a matter of concern. In this context, there is significant interest in the development of an alternative antimicrobial treatment modality. Lasers have excellent bactericidal properties and hence can be used successfully. The soft tissue can be disinfected more effectively with a laser than with rinsing or swabbing. The literature reports that erbium and diode wavelengths can accomplish decontamination if the photonic energy covers every square millimeter of the target surface [23, 24].

10.5 Surgical Uses

10.5.1 Decontamination of Surgical Site During Implant Placement

Decontamination of the surgical site is essential for the successful integration of immediate dental implants. The goal prior to immediate implantation is to ensure that the post extraction surgical site is free of debris and granulation tissue. The failure rate of immediate implants is higher because of pre-existing disease in the teeth and periodontal areas being replaced. Two examples are the tissues with periapical infection or periodontal disease in a molar furcation area. The protocol would be to remove gross amount of soft tissue with a curette and then use the laser to remove any visible tissue tags. The entire inner wall of the extraction socket can then be decontaminated with a laser.

All laser wavelengths are antibacterial in nature and can be used to varying degrees to disinfect the surgical site [25, 26].

The lasers can be broadly classified based on the tissue to be decontaminated, either soft or hard tissue.

Diode Lasers for Soft Tissue

Diode lasers should be used with caution near osseous tissue, since the photonic energy can scatter in soft tissue. However, when used judiciously with lower average power (approximately 1 W), they can aid in disinfecting the soft tissue site prior to grafting or implant placement. Moritz et al. studied the reduction of bacterial pathogens in periodontal pockets after irradiation with a diode laser. A comparison between the initial and the final bacterial counts revealed that irradiation with the diode laser facilitates considerable bacterial elimination, especially of *Actinobacillus actinomycetemcomitans*, from periodontal pockets [27]. It follows that diode lasers can be used with the same result on soft tissue flaps around dental implants prior to implant placement.

Nd:YAG Laser (For Soft Tissue)

The Nd:YAG laser is commonly used in periodontal therapy to incise and excise soft tissues as well as for the curettage and disinfection of periodontal pockets [28–30]. The high peak power produced by this free-running pulsed mode laser can cause deep tissue penetration. This possible thermal effect of this laser on tissues lying below the irradiated area is a matter of concern during periodontal treatment [31]. Hence caution must be exercised before using the Nd:YAG laser for decontamination of the surgical sites.

Carbon Dioxide Lasers (For Soft Tissue)

The CO_2 laser can be used for decontamination of soft tissue tags and granulation tissue. Kato et al. reported a very high reduction of *S. Sanguis* and *P. gingivalis* bacteria using the 10.6 μ CO_2 laser [32].

Erbium Family of Lasers (Soft and Hard Tissue)

Erbium lasers are antibacterial and can be used to remove both calculus and biofilm around tooth structure and implant surfaces [33, 34].

The Er:YAG laser possesses suitable characteristics for both oral soft and hard tissue ablation. Contouring and cutting of bone can be achieved with minimal damage and faster healing [35]. In addition, irradiation with the Er:YAG laser has a bactericidal effect with reduction of lipopolysaccharides [36]. These are a major component of the outer membrane of gram-negative bacteria, and they play an active role in the pathogenesis of periodontal tissue breakdown. The properties of the photonic energy from the Er,Cr:YSGG laser also verify its effectiveness for decontamination of hard and soft tissue [34].

Figure 10.2 depicts the various steps of immediate implant fixture placement while using a diode laser to disinfect the extraction site.

Figure 10.3 shows the degranulation of the peri-implant area along with disinfection of the socket with an Er,Cr:YSGG laser prior to bone grafting.

10.5.2 Incision Using Lasers

Traditionally a scalpel has been used to make an incision prior to flap opening for implant placement. Most of the commercially available dental lasers are effective in making incisions almost replacing the scalpel.

The advantages of using the laser versus the scalpel are numerous. A laser incision cannot spread infection, and there is also no subsequent cascade of inflammation. The laser's use also seals off the lymphatic and blood vessels. There is also a clinically measurable reduction in pain swelling and other postoperative complications. If the swelling is

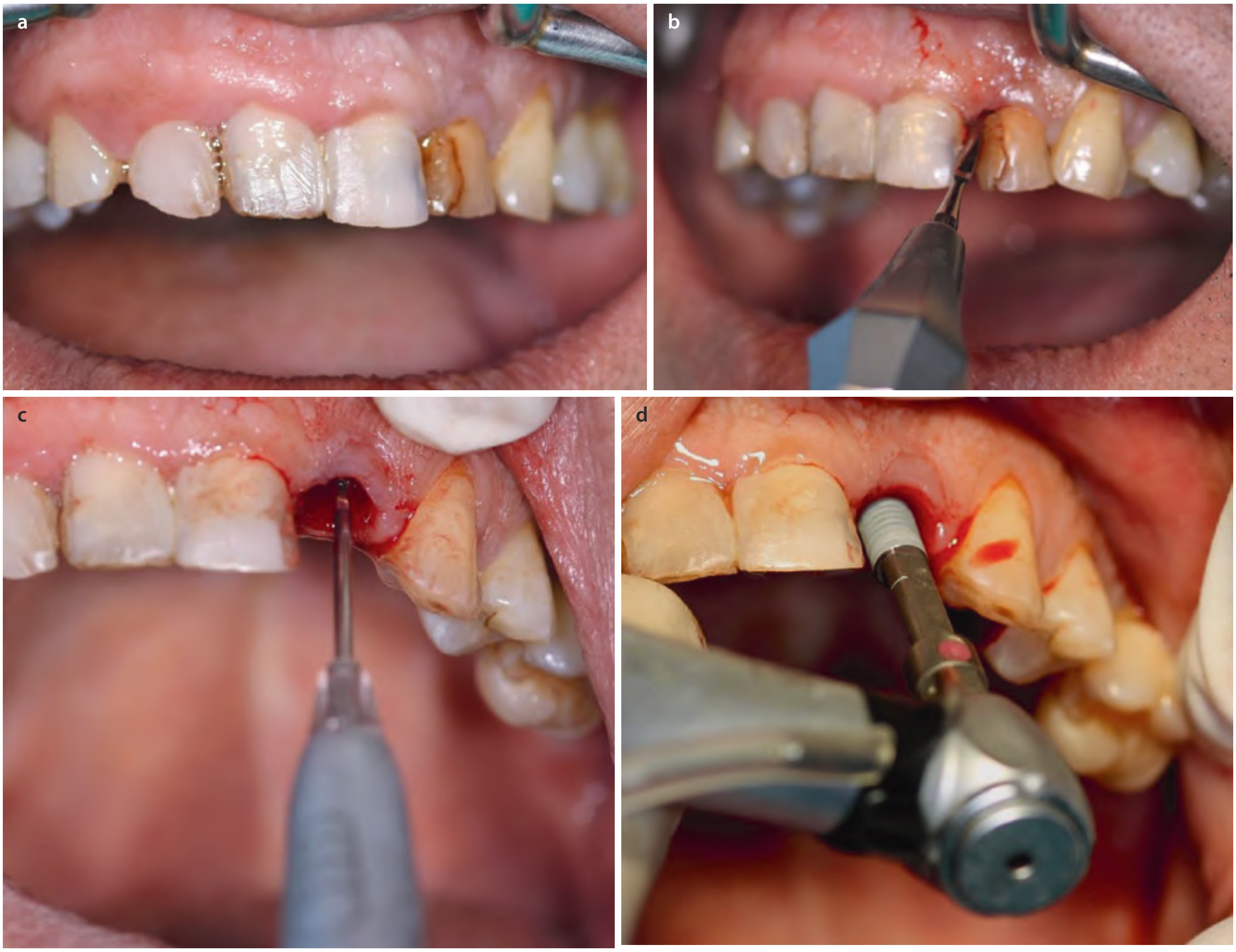


Fig. 10.2 **a** Preoperative view of maxillary anterior segment. The upper left lateral incisor will be replaced with an implant crown. **b** A periosteal elevator is carefully positioned for an atraumatic extraction. **c** A 940 nm diode laser with an average power of 1 W delivered with a 300-diameter micron tip is used for disinfection of the extraction socket. **d** The implant fixture is being placed in the decontaminated osteotomy

reduced, sutures will not pull through the tissue and are less likely to come undone. There is a reduced need of postoperative pain medication and antibiotics. Laser incisions have only a few myofibroblasts that are injured compared to scalpel incision. Hence there is superior tissue healing and a more precise control of depth of tissue damage [37, 38].

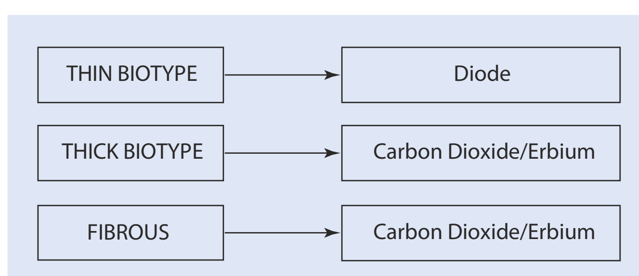
The choice of laser is determined by the existing thickness of the soft tissue. Thicker tissues can be challenging to incise with the diode wavelengths and would require more efficient cutting, which CO_2 and the erbium family can provide.

One of the most important advantages of the laser is the decreased bleeding. For patients taking anticoagulant therapy such as aspirin, clopidogrel, and warfarin, a laser incision should be the ideal choice. The diode, Nd:YAG, and CO_2 instruments provide excellent hemostasis, whereas erbium lasers do not control bleeding as efficiently as the other wavelengths. Unobstructed vision, excellent hemostasis, and efficient cutting through all tissue biotypes make CO_2 lasers most suitable for these procedures [39].

To conclude laser incisions are precise, disinfecting, and provide the operator with a clear field of vision. Due to excellent hemostasis, they additionally provide favorable healing with minimal inflammation.

Decision Chart for Laser Incision

The laser wavelength selection is based on the soft tissue characteristics.



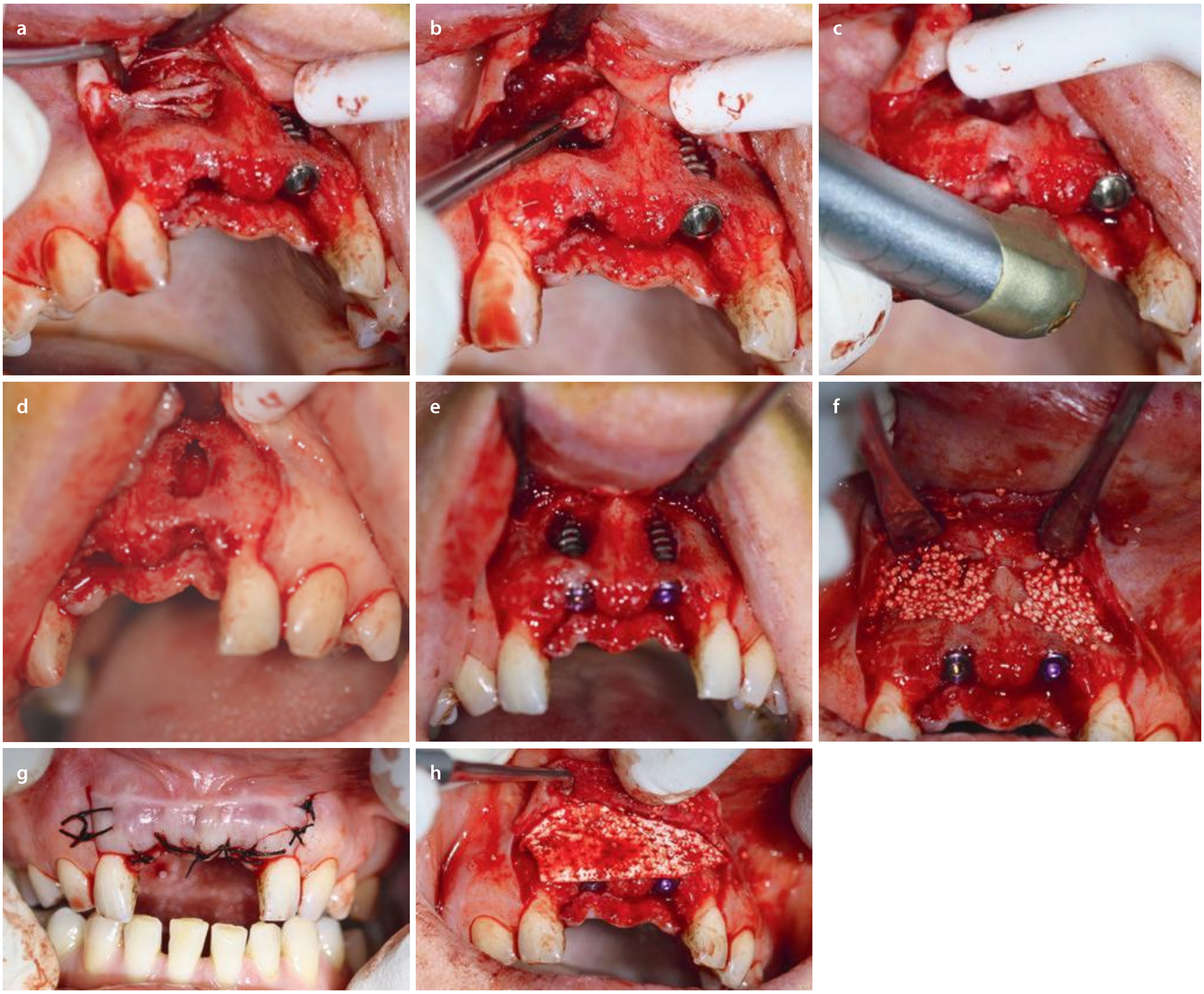


Fig. 10.3 **a** Perioperative view of maxillary anterior area, while a curette is used to access infected granulation tissue. **b** The curette removes the diseased tissue segments. **c** An Er,Cr:YSGG laser is used at an average power of 2.5 W with the parameters: 50 Hz H mode, air 20%, and water 20% delivered with a MT4 tip. **d** Photo showing the site after degranulation and disinfection are complete. Note the vascularity and the sound osseous surface. **e** The implant fixtures are inserted. **f** Bone grafting material in place and is covered with a membrane **g**, **h**. The immediate postoperative view with the flap repositioned and sutured

Figure 10.4 demonstrates an Er,Cr:YSGG laser flap incision for implant placement.

Note

If the patient is on anticoagulant medication, the diode and Nd:YAG lasers are ideal choices for the incision.

10.5.3 Laser Use in Osteotomy for Implant Placement

The current standard protocol for osteotomy site involves the use of burs which are either internally or externally irrigated and are operated at an adjusted speed in order to minimize thermal temperature rise in the hard tissue [40]. They allow for implants to be tapped or torqued into position with a torque wrench or a 20:1 reduction handpiece. The osteotomy of bony structures is sometimes challenging, since thin and fragile bone segments of the maxilla and mandible are prone to fracture due to massive contact pressure and vibration caused by mechanical instruments. A laser osteotomy offers a viable and beneficial alternative.

As noted above, both erbium laser wavelengths (Er:YAG at 2940 nm and Er,Cr:YSGG at 2780 nm) are efficient for dental hard tissue ablation. Studies on healing of laser-ablated

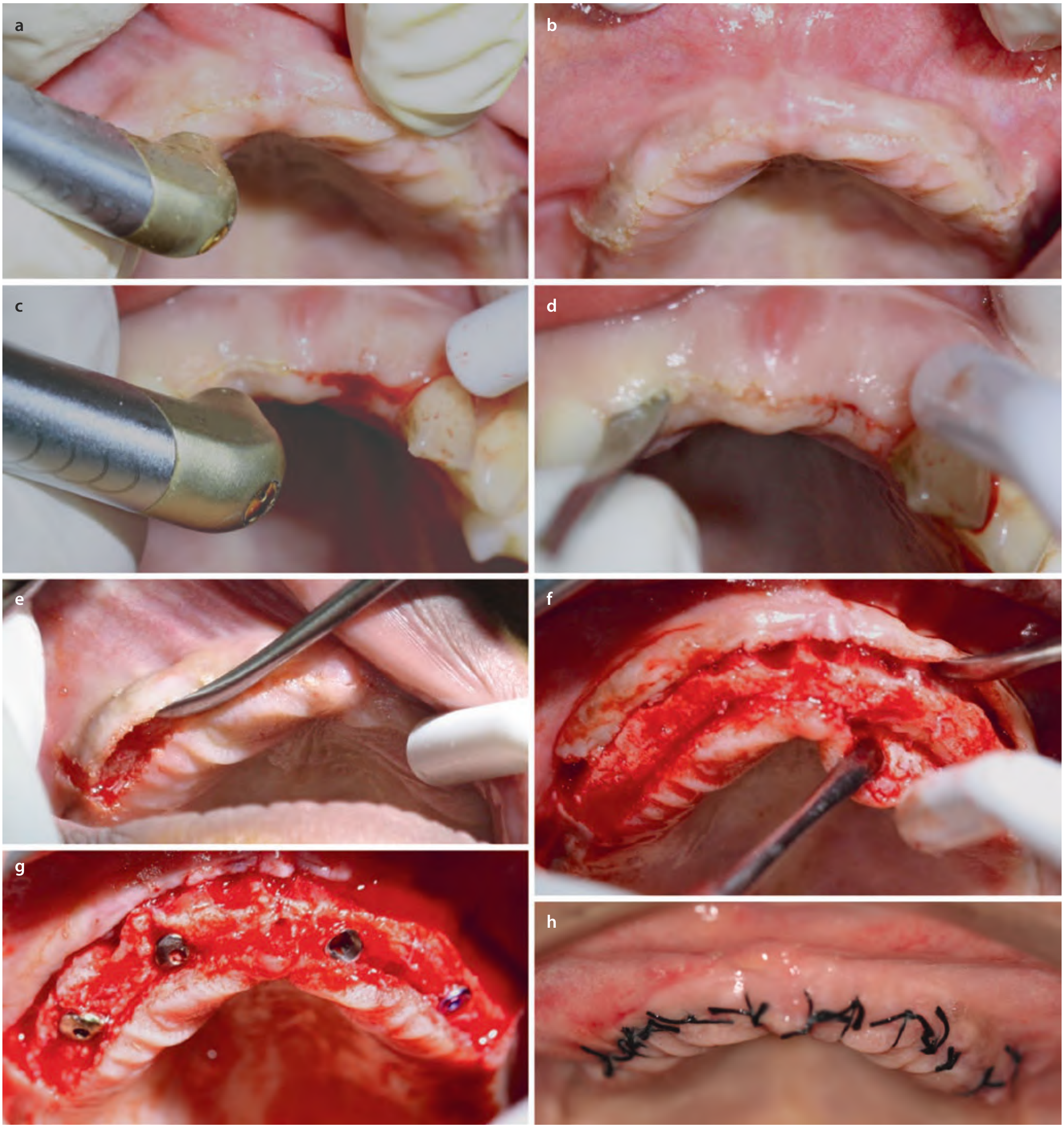


Fig. 10.4 **a** An Er,Cr:YSGG laser is used at an average power of 2.75 W with parameters of 75 Hz delivered through a 75 Hz H mode, air 20%, and water 20% delivered through a MT4 tip. **b** The incision produced with the laser shows favorable tissue interaction with excellent hemostasis. **c**–**e** A periosteal elevator is used to reflect the flap. **f** The edentulous ridge is exposed. **g** The implant fixtures are placed. **h** Immediate postoperative view of the flap repositioned. The edges of the laser incision were easily approximated and sutures were placed.

bone support the argument that the postoperative reduction in effects such as physical trauma, tissue heating, and bacterial contamination may lead to uncomplicated healing, when compared to conventional use of a surgical bur for osteotomy [41–43].

Microanalysis of the surface of the bone ablated using lasers shows little evidence of thermal damage, with a minimal char layer 20–30 µm in depth [44, 45]. Moreover, some animal studies have shown favorable osseous healing with laser use [46, 47].

Further Reading
Maybe some comment on BIC studies:
References missing!!

And effect of PBM on bone:
Sasaki et al. [76]
Bouvet-Gerbettaz et al. [77]
Dörtbudak et al. [78]

Drawbacks and Future of Lasers in Osteotomy

Generally, the application of laser systems is very advantageous when it offers new and beneficial therapeutic possibilities in contrast to commonly accepted conventional methods [48–50]. The healing advantages however are overshadowed by three major drawbacks currently:

1. The time required is lengthy, much more than when traditional instruments are used.
2. There is a lack of calibration for the size of the fixture.
3. There is a lack of control of the depth of the osteotomy.

In addition, producing a predictable cylindrical laser cavity without the use of a surgical template is not feasible, especially in the apical end of the implant preparation. This is due to deviations in the laser beam angulations.

Due to the crucial lack of depth control, laser osteotomy is still assessed to be inferior to other bone cutting techniques that utilize high-speed drills or piezoelectric devices. Even though the contact-free mode is highly beneficial for arbitrarily cut geometries, the lack of a tactile feedback is a striking restriction. Therefore, achieving accurate bone removal depth is difficult. Only visual inspection and intermittent application of gauges enable the surgeon to assess and guarantee a certain amount of tissue volume ablation and depth.

Research is currently focused on making laser osteotomy more accurate. A recent approach is concentrated on the creation of defined geometries by navigated laser ablation based on volumetric three-dimensional (3-D) data [51–53]. A different approach was described by Rupprecht et al. [54, 55] using a special feedback system to control laser drilling of cortical bone with an Er:YAG laser under water spray cooling.

Certainly, the combined therapy of conventional bur osteotomy site preparation and laser irradiation within the osseous tissue can be of benefit.

With further developments like special miniature laser systems, depth control feedback systems, and robotic guidance, new clinical indications and applications will undoubtedly arise. The current rate and intensity of research will soon propel the use of laser implant placement osteotomy as a routine procedure.

10.5.4 Laser Sinus Lift for the Creation of a Window in Direct Sinus Lifts

Two serious limiting factors in the placement of implants in the posterior maxilla are the anatomical shape and location of the maxillary sinus and quantity of bone. To ensure successful implant placement in the posterior region, a minimum of 6–8 mm of sound bone structure is mandatory.

Additionally bone density in the posterior maxilla is often poor, which could lead to complications during implant fixation. To improve placement outcomes, maxillary sinus lift surgery was developed as a method to increase the amount of bone available for the implant. This has now become a routine surgery to address deficient maxillary posterior bone.

The different methods for a sinus lift procedure include:

- Lateral window technique
- Crestal core elevation
- Osteotome technique (Summers technique)
- Balloon sinus elevation

The lateral window sinus lift is a direct sinus lift procedure which allows for direct visualization and accurate bone placement. Also, tearing of the membrane can be easily treated, minimizing contamination of the graft during healing.

The lateral approach involves a modified Caldwell-Luc operation to gain access to the sinus cavity. A bony window is created in the lateral maxillary wall; the Schneiderian membrane is elevated, and bone grafting material which may be a combination of autogenous bone and allograft is placed between the membrane and the maxilla. An absorbable collagen membrane may sometimes be placed between the bone graft and the membrane as well as over the bony window to prevent the graft from migrating.

The surgical instruments conventionally used to perform sinus grafting are rotary handpieces [56, 57]. In the past decade, piezoelectric-ultrasonic devices have replaced rotary instruments because of the reduced risk of membrane rupture [58].

The development of Er:YAG and Er,Cr:YSGG wavelengths has enabled bone ablation to be carried out with minimal adjacent damage. The use of erbium lasers in dentoalveloar surgery represents a less traumatic experience for the patient when compared to the intense vibration of the slow-speed surgical bur. However, to prevent overheating of the bone, it is important to maintain a sufficient coaxial water spray.

In the maxilla, the speed of the laser ablation is comparable with that of the bur due to the cancellous structure of the osseous tissue. However, it is important to set appropriate power settings to minimize blood spatter and to reduce the stall out effect caused by bone shavings that may have gathered at the tip or near the laser orifice.

Procedure

A full thickness flap must be raised, and the outline of the bony window must be predetermined. After the location for the window has been identified, a bony window corticotomy is initiated by placement of the laser beam at 30–45-degree angulations to the cortical surface in a non-contact mode (with 0.5–1 mm distance from the target tissue). Lasing should be performed with slow movements until the darkness of the underlying Schneiderian sinus cavity is visualized. Ablation should be stopped after completing the predetermined window border decortications; and, at that point, there should be only a few very thin bony bridges remaining on top of the membrane.

The rest of the surgery is completed following conventional surgical procedures.

The Schneiderian membrane must be kept intact so it can help to contain the graft material as well as to prevent migrations of the graft particles in the sinus cavity. If the membrane is cut and damaged, the graft material may become infected and lead to a failed sinus lift procedure.

There still are technical drawbacks in the unrestricted use of lasers in lateral access osteotomy. One major drawback is the missing depth control which can cause significant destruction of the membrane. Therefore, case selection is important for the use of lasers in osteotomy procedures.

Figure 10.5 depicts the creation of a window with an Er,Cr:YSGG laser in a direct sinus lift procedure.

10.5.5 Laser Use for Bone Removal for Autogenous Augmentation

For some bone augmentation procedures, native osseous material can be harvested from the patient. This is termed an autogenous bone graft. There are some possible sites for obtaining this material, and one example is from a torus. The erbium lasers are ideal for this procedure, and the

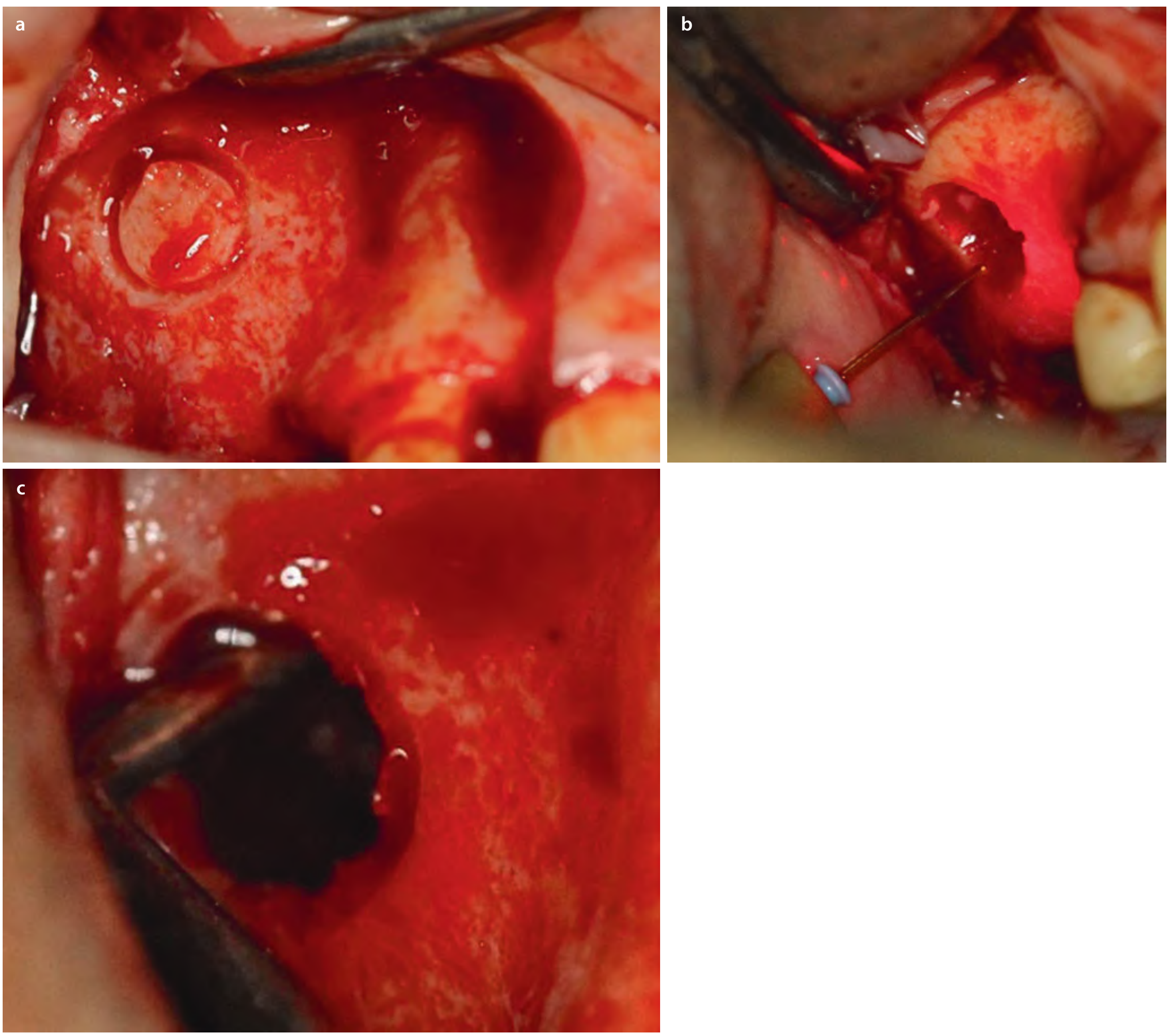


Fig. 10.5 **a** Preoperative view of the area where the direct sinus lift will be performed. **b** The Er,Cr:YSGG laser is used at an average power of 6 W with the following parameters: 25 Hz H mode, air 80%, and water 80% delivered with an MZ6 tip. The corticotomy proceeds with slow movements of the laser tip. **c** The membrane is then gently elevated

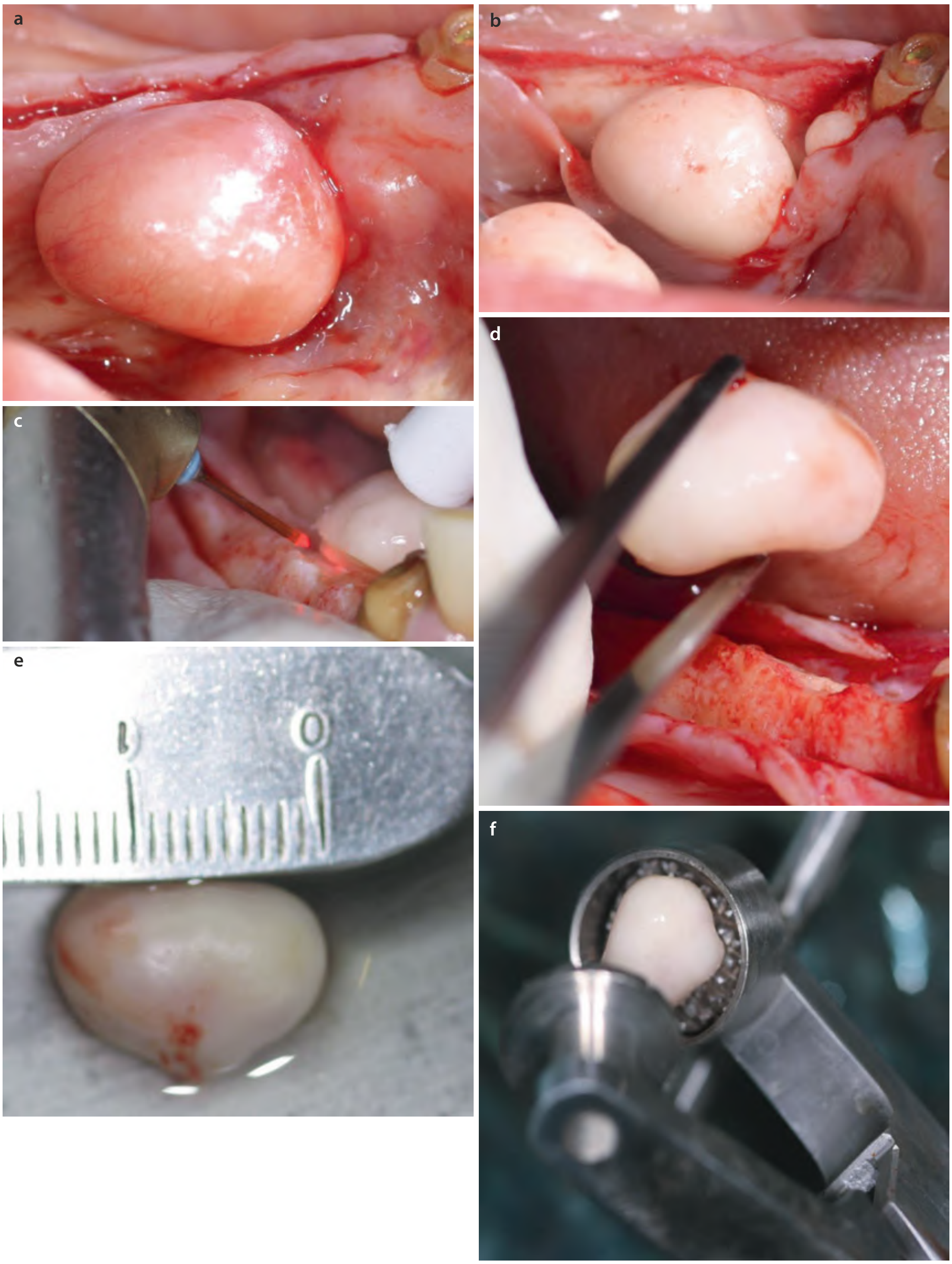
procedure is similar to an osteotomy, described in ▶ Sect. 10.5.3. ◘ Figure 10.6 demonstrates how the laser is utilized.

◘ Figure 10.6 depicts use of an Er,Cr:YSGG laser to harvest bone for an autogenous augmentation procedure.

10.6 Postsurgical Laser Utilization

10.6.1 Second-Stage Implant Surgery

The second-stage implant surgery involves uncovering the implant cover screw to facilitate and evaluate the site for



◘ **Fig. 10.6** **a** The preoperative view of a torus that will be excised. **b** A flap is reflected to expose the extent of the osseous structure. **c** The Er,Cr:YSGG laser is used at an average power of 6 W with the following parameters: 25 Hz H mode, air 80%, and water 50% delivered with an MZ6 tip. The laser excision proceeds with minimal thermal damage to the bone while preserving its vascularity. **d** The osseous segment is removed and the site is closed **e** and **f.** The harvested bone segment is measured and treated abutment placement. Conventional modes for second-stage implant recovery include scalpel blade, tissue punch, and electrocautery, although the latter has since been contraindicated.

The efficiency and visual advantages of using the laser are unsurpassed in second-stage implant recovery and are now becoming routine. The benefits include precision, hemostasis (which may vary depending on the wavelength), and immediate postoperative protection through a coagulum surface [59, 60]. In addition, there is a reduced need for anesthesia.

Procedure

It is essential to accurately assess the position of the implant site relative to the edentulous ridge. This may be done through radiographs, model mapping, and using natural landmarks. Exposure of the cover screws allows an impression to be taken from which the prosthodontic infrastructure can be made.

Local anesthetic may or may not be used, depending on patient and operator preference. Some analysis of the form, thickness, and vascularity of the tissue should be made, which will define the choice of laser wavelength and the operating parameters. The photothermal tissue interaction will be dependent on those two factors [61].

A small cone of tissue must be removed till near contact with the screw is made. From this, the tissue opening must be extended to the diameter of the cover screw. Typical laser average power values should be in the range of 1–1.5 W. All wavelengths work well, although studies offer contraindications for Nd:YAG [62, 63]. Although the diode lasers are very popular for this procedure, it is not the ideal choice if the tissue is thicker than 1–2 mm or the implant is deeply submerged. As mentioned, the CO_2 laser is efficient in removing thicker tissue.

On some occasions, there is an inadequate amount of gingival tissue surrounding the integrated implant. Similar to the presurgical scenario described above, lasers can create additional attached gingiva by performing a vestibuloplasty or frenectomy.

If bone has formed over the implant, the choice of laser wavelengths is more limited. The CO_2 laser could affect a thin layer of bone and facilitate removal of the bone with a hand instrument [39]. Generally speaking, the erbium lasers will ablate osseous tissue very efficiently and will safely accomplish the uncovering process.

Figure 10.7 shows the Er,Cr:YSGG laser uncovering the implant fixture and contouring the gingiva to establish the emergence profile.

Figure 10.8 depicts an inadequate zone of attached gingiva surrounding the integrated implants. The Er,Cr:YSGG laser performs a frenectomy and contours the vestibular tissue to create additional attached gingiva.

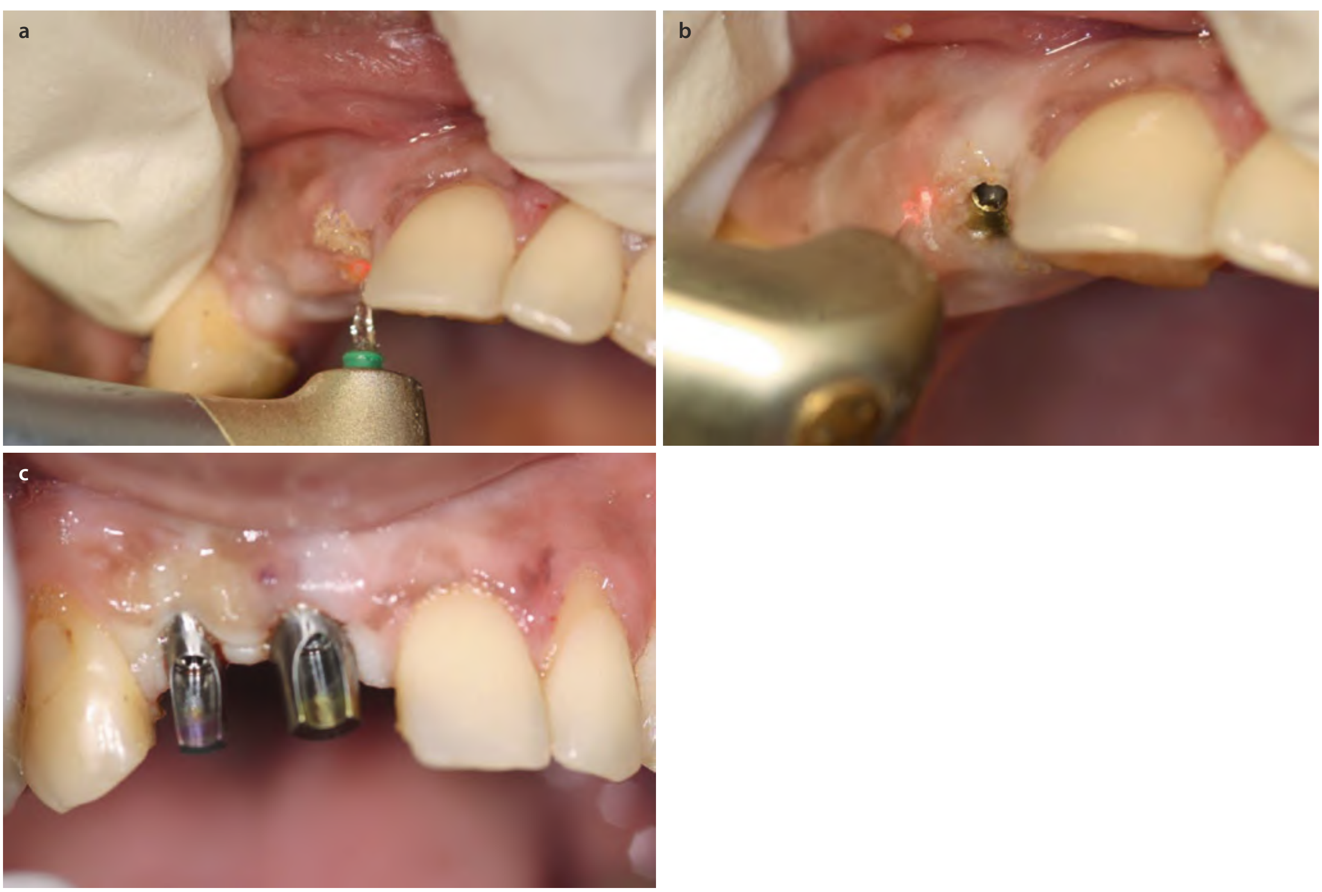


Fig. 10.7 **a** The Er,Cr:YSGG laser is used at an average power of 2.75 W with the following parameters: 75 Hz S mode, air 20%, and water 40% delivered with an MZ5 tip. An incision is made through the tissue at the location of the implant fixtures in the upper right incisor area. **b** The laser is used to contour the gingiva to establish an emergence profile. **c** The abutments are placed. Note the healthy tissue tone and sculpting, which will contribute to the success of the final restoration

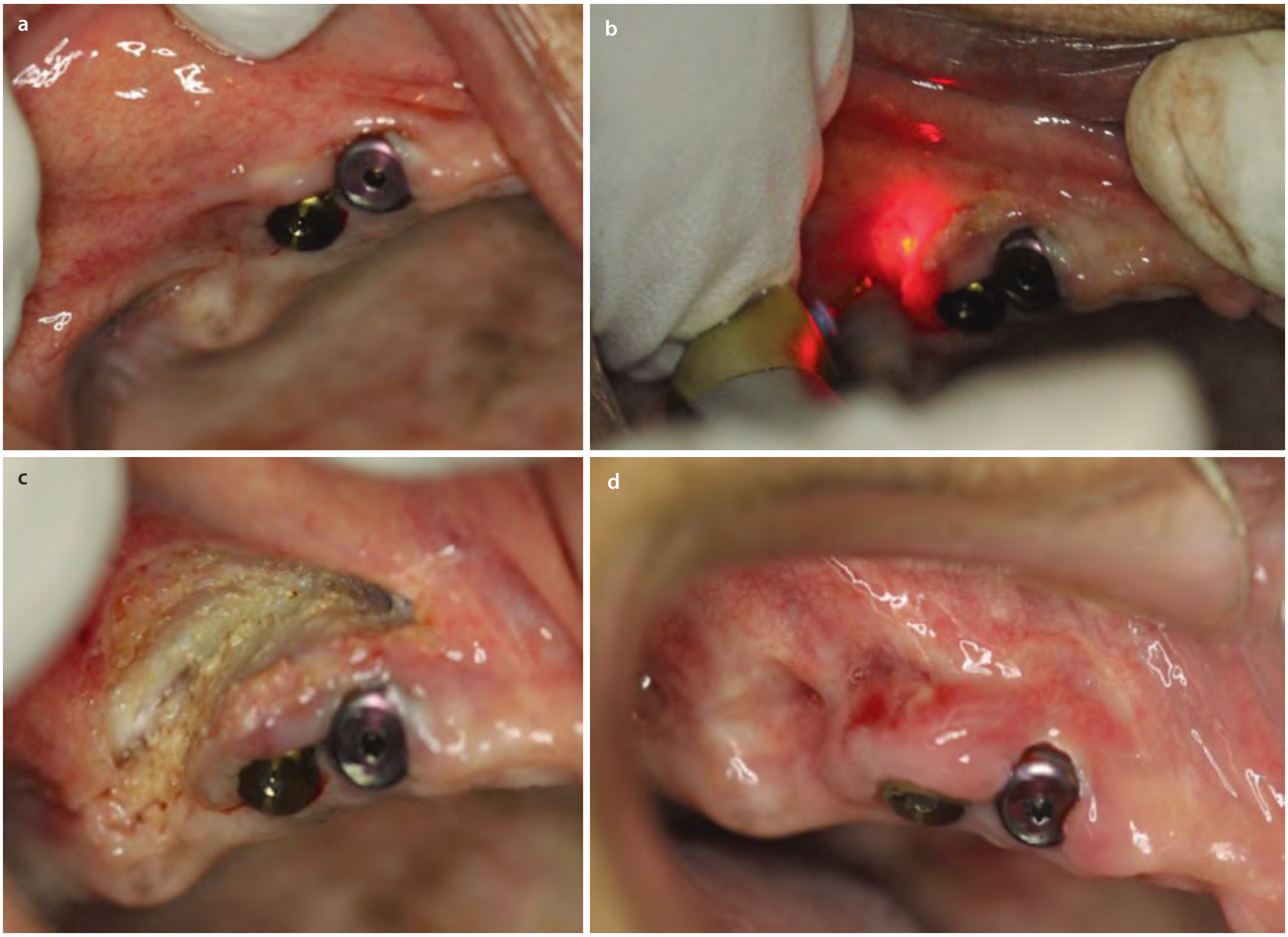
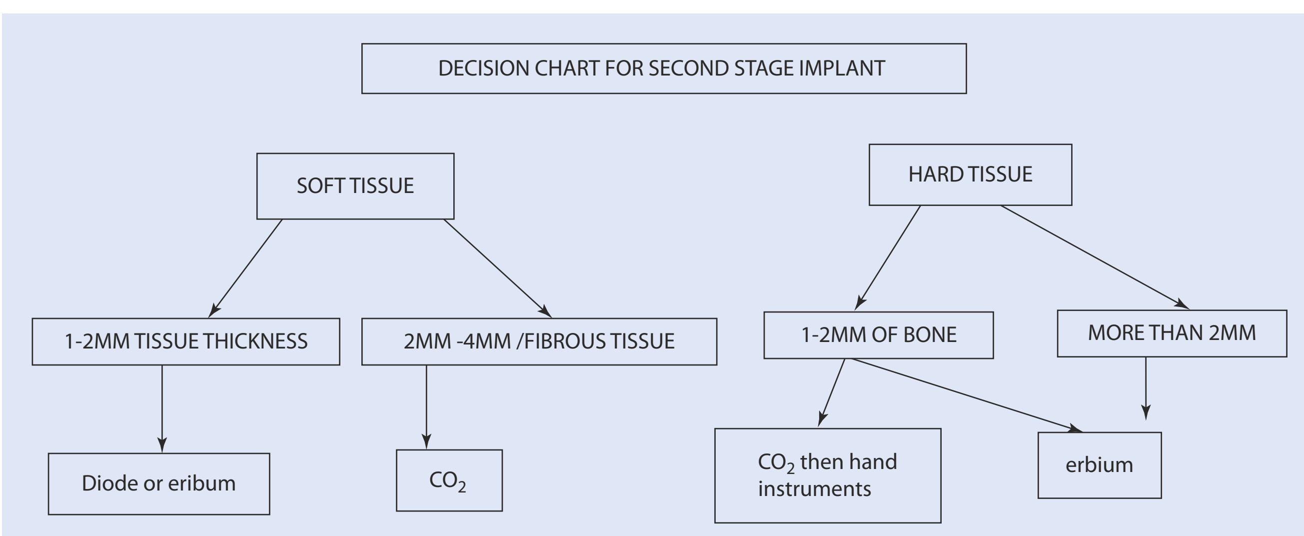


Fig. 10.8 **a** Preoperative view of integrated abutments with healing screws with a thin amount of surrounding gingival tissue with a frenum insertion. **b** The Er,Cr:YSGG laser is used at an average power of 2.75 W with the following parameters: 50 Hz S mode, air 20%, and water 40% delivered with an MZ5 tip to revise the frenum and increase the vestibular depth. **c** Immediate postoperative view shows the apical extension of the surgery. Note the excellent hemostasis. **d** A 15-day postoperative photo shows creation of a large zone of attached gingiva in the healing tissue



10.6.2 Laser Troughing Prior to Impression

In implant dentistry, the margin of the abutment may be subgingival in some instances. To prepare the gingival tissues for an accurate impression for the final restoration, a «sulcus» or space must be created; and the procedure is often referred to as troughing.

For non-implant restorative procedures, this is accomplished with retraction cords, the scalpel, or electrosurgery. Electrosurgery is contraindicated around implants, but retraction cord or a scalpel is an option. However, the retraction cord technique is time-consuming with potential to injure the gingiva as well as to cause postoperative discomfort. Use of a scalpel may result in reduction in the width of attached gingival postoperatively and also some amount of postoperative discomfort.

In contrast to conventional techniques, laser troughing allows for clear clean visualization of gingival margins. Most lasers are excellent coagulation devices with minimal to no bleeding. Lasers usually require 30–60 s to achieve retraction which does not rebound because lasers remove the internal epithelial lining of the gingival sulcus. Also another advantage of laser troughing is that it promotes the ideal environment for current impression scanning devices. All of the currently available wavelengths can perform this procedure; however, Nd:YAG should be used with caution next to an implant fixture.

Figure 10.9 demonstrates how the Er,Cr:YSGG laser is used for gingival troughing around an immediately loaded implant and the crown preparations on the adjacent teeth.

Figure 10.10 shows how a diode laser is used for troughing the gingiva around the implant abutments.

Fig. 10.9 **a** Preoperative view of the anterior maxillary area. The upper left central incisor will be extracted and replaced with an immediately loaded implant. **b** The implant fixture is placed. **c** A zircon abutment is attached to the fixture. **d** The Er,Cr:YSGG laser is used at an average power of 2 W with the following parameters: 100 Hz H mode, air 10%, and water 10% delivered with an MZ5 tip to trough the gingiva around the abutment and the prepared teeth. **e** The immediate postoperative view with excellent tissue contour

Fig. 10.10 **a** The preoperative view of abutments on the maxillary right anterior incisors. **b** and **c** A 940 nm diode laser is used with an average power of 0.7–1 W delivered through a 200-diameter micron tip. The photonic energy creates a «sulcus» while uncovering the margin of the abutment. **d** The immediate postoperative photo shows a clean, dry field for the impression. Note the excellent bleeding control afforded by the laser. **e** 1 week postoperative healing

10.6.3 Photobiomodulation

As mentioned, photobiomodulation (PBM) offers clinical benefits for reducing pain and inflammation while stimulating wound healing [18]. It would therefore follow that PBM would be very useful after surgical implant procedures. Many in vivo studies of animal models with implants and laser therapy have demonstrated their efficacy [10, 64, 65]. At present, protocols and dosing parameters are needed for clinical dentistry applications [66].

10.7 Peri-implant Disease

Dental implants are now becoming the most widely and commonly used treatment modality to replace missing teeth. However, even after successful osseointegration, dental implants can also lose supportive bone [67, 68]. There are various causes related to early and late implant failure.

Peri-implant diseases are one of the most common reasons for implant failure. These infectious diseases are defined as inflammatory lesions of the surrounding peri-implant tissues and include two different entities: peri-implant mucositis and peri-implantitis. *Peri-implant mucositis* describes an inflammatory lesion that resides in the mucosa, while *peri-implantitis* also affects the supporting bone.

10.7.1 Diagnosis of Peri-implant Disease

Peri-implant mucositis may be identified clinically by redness and swelling of the soft tissue, but bleeding on probing is currently recognized as the important feature. In peri-implantitis, the mucosal lesion is often associated with suppuration and deepened pockets, but always accompanied by loss of supporting marginal bone [69].

Several studies demonstrate the tendency for implants to develop peri-implant disease. The range of 10–50% has been reported up to 10 years after placement [70]. Based on the Consensus Report of the Sixth European Workshop in Periodontology, Lindhe and Meyle reported an incidence of mucositis of up to 80% and of peri-implantitis between 28 and 56% [71]. Zitzmann et al. quantified the incidence of the development of peri-implantitis in patients with a history of periodontitis almost six times higher than in patients with no history of periodontal inflammation [72].

The visual signs of peri-implantitis include:

- Increased probing pocket depth
- Suppuration from the pocket
- Draining fistulous tract
- Peri-implant mucosal swelling/hyperplasia
- Radiographic evidence of bone loss such as crater bone formation

The microflora that cause peri-implantitis are similar to those that cause periodontal infection [73, 74].

- *Aggregatibacter actinomycetemcomitans*
- *Porphyromonas gingivalis*
- *Bacteroides forsythus*
- *Prevotella intermedia*
- *Peptostreptococcus micros*
- *Fusobacterium nucleatum*

10.7.2 Peri-implantitis Can Be Further Classified into Early and Late Peri-implantitis: A Consequence of Early Disease Usually Is Incomplete Osseointegration, While Late Disease Is a Possible Failure of an Existing Implant and Its Restoration

Early peri-implantitis can be caused by any or all of the following:

- Improper preparation of the recipient site which results in undue hard tissue damage such as necrosis of bone
- Bacterial contamination and extensive inflammation of the wound that may delay healing of the soft and hard tissues
- Improper mechanical stability of the implant following its insertion
- Premature loading of the implant
- Cementation residues between abutment and prosthesis

Late peri-implantitis can be a result of any or all of the following:

- Excessive load force from poor design or malocclusion
- Chronic infection in the tissue
- Poor oral hygiene
- Lack of keratinized gingival tissue
- Patient's systemic factors, such as diabetes

10.7.3 Treatment of Peri-implant Disease

Firstly the clinician must assess whether the peri-implantitis is treatable. Twenty five years ago, two terms were applied to help in this decision. The ailing implant has bone loss that could respond to regeneration therapy. The ailing implant has progressing osseous defects with mobility and peri-implant radiolucency. Any implant which is mobile has failed. This must be removed [75].

The conventional treatment for peri-implant disease can be divided into a nonsurgical and a surgical approach. ► Chapter 14 discusses the role of all available laser wavelengths for adjunctive and standalone treatment. Peri-implant mucositis would respond well to nonsurgical therapy, and surgical procedures would be necessary for treatment of peri-implantitis.

The nonsurgical approach includes scaling and polishing debridement and adjunctive locally applied antimicrobial photodynamic therapy.

The surgical protocol involves raising a flap and surgical debridement. Application of antimicrobial agents, local and systemic antibiotics, air or abrasive polishing, guided tissue regeneration, or a combination using tetracycline, citric acid, and guided tissue regeneration can also be performed.

Figure 10.11 demonstrates how the Er,Cr:YSGG laser can be used adjunctively for treatment of peri-implantitis around ailing implants.

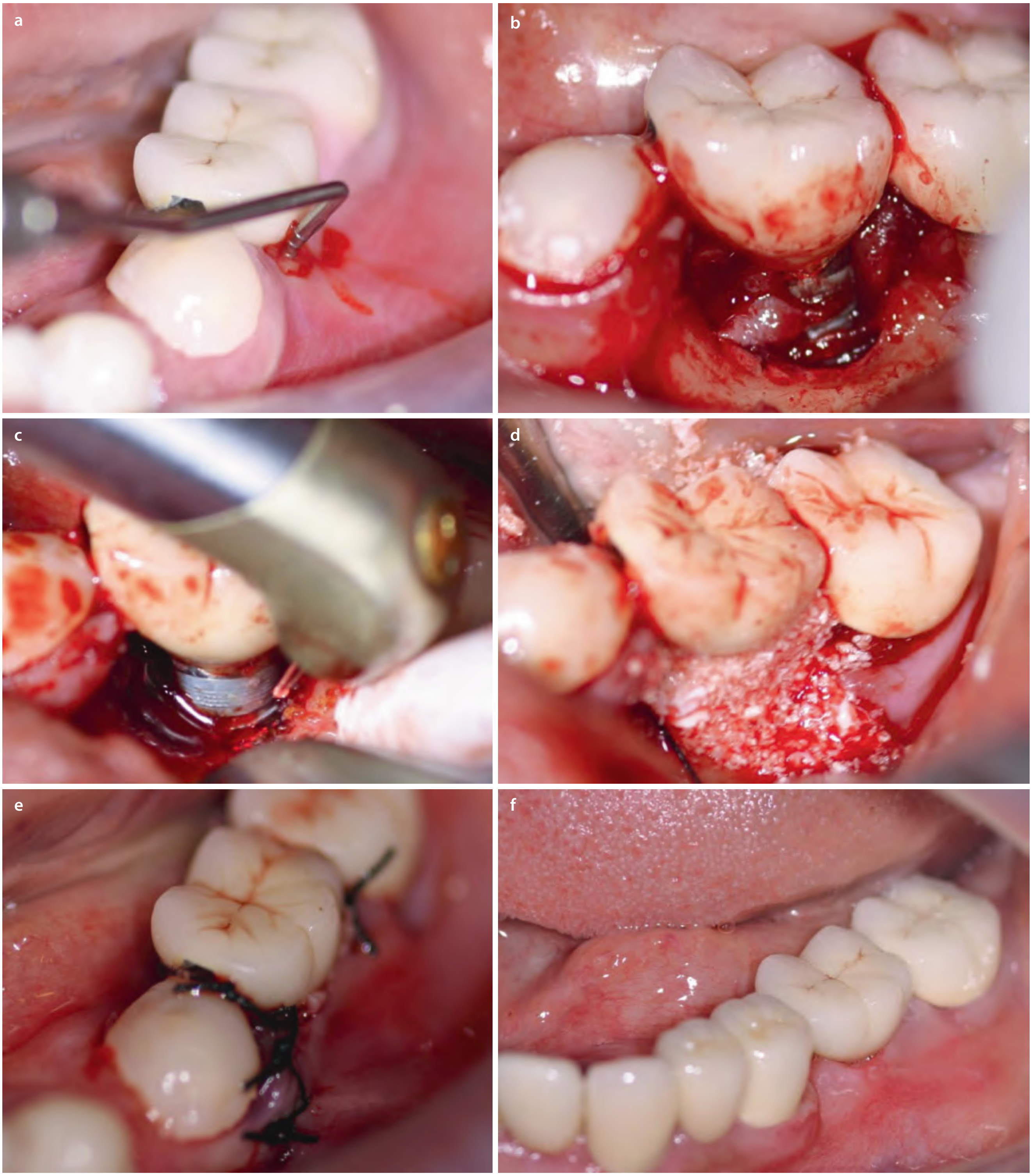


Fig. 10.11 **a** Photo of bleeding and inflammation in a deep pocket surrounding the lower left molar implant crown. A diagnosis of peri-implantitis was established. **b** A flap was reflected and a large amount of granulation tissue is present around the implant fixture. **c** The Er,Cr:YSGG laser is used at an average power of 2.75 W with the following parameters: 75 Hz H mode, air 20%, and water 40% delivered with an MZ5 tip is used to remove the granulation tissue from the implant threads and offer disinfection of the site. **d** Bone graft material is placed in the site. **e** The flap is sutured in place. **f** A 15-day postoperative photo that shows good tissue healing and resolution of the peri-implantitis is expected

Conclusion

As has been described, lasers are useful in all aspects of implant dentistry from preoperative to postoperative applications. As more research and further long-term longitudinal studies are conducted, the results should confirm the effectiveness of various wavelengths.

Lasers in dentistry have significantly enhanced the concept of patient centered care, and this is especially true of their use in implant dentistry. Laser-assisted treatments result in less pain, swelling, and inflammation as compared to conventional treatments. This has afforded more comfort and therefore increases patient acceptance. The clinician who desires excellent patient care with implant dentistry should include lasers in the dental armamentarium.

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Laser-Assisted Pediatric Dentistry

Konstantinos Arapostathis

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Core Message

The progress of laser application in dentistry is continuous. There are many debates between researchers, clinicians, and scientists who try to carry on research within and with respect to clinical everyday dental practice. The American Academy of Pediatric Dentistry acknowledges using lasers as scientifically documented, alternative, and/or adjunctive treatment provision methods of soft and hard tissue management for infants, children, adolescents, and persons with disabilities. The aim of this chapter is to describe the indications for their use in various therapeutic procedures in pediatric dentistry and to analyze the advantages and disadvantages compared to traditional techniques. Together with the appropriate child's psychological management, proper presentation and approach with the laser is crucial. The technological evolution of dental lasers offers the possibility of completing several therapeutic procedures, such as removing carious dental tissue in permanent and deciduous teeth, usually with less or no anesthesia, performing laser-assisted pulpotomy and pulpectomy, soft tissue interventions, dental trauma, etc. Depending on the treatment procedure and the targeted chromophores, all laser wavelengths could be used (e.g. KTP, diodes, Nd:YAG, erbium family lasers, CO_2).

11.1 Laser-Assisted Pediatric Dentistry

Pediatric dentistry is a demanding part of dentistry because of its nature to deal with children from birth through adolescence as well as with their parents' compliance. It requires from the clinician a high level of knowledge regarding the stomatognathic system conformation, the special anatomical figures, and the prevention, cure, and the prognosis of dental pathologies found in children, but above all, it requires expertise in treating the child itself. Pediatric dentistry practitioners are not only responsible for providing and promoting good oral and dental health for their patients but also to educate parents that oral health is an integral part of general health with continuous informative sources.

In general, the occurrence of oral diseases in children and adolescents includes dental caries, periodontal diseases (mainly in the form of gingival inflammation), developmental disturbances (morphological or numerical variations in both permanent and deciduous dentition), erosions, malocclusions, cranio-mandibular disorders, oral mucosal lesions (mainly aphthous ulcers, herpes simplex and other virus infections, or oral candidiasis), and, of course, dental trauma [1]. Over the past few years, traditional dentistry has been innovated with the embracement of more microinvasive techniques, moving from the era of «extension for prevention» to «prevention for extension» model of modern dentistry. In this technological-dental evolution with micro-abrasion, the application of topical fluoride, the use of sealants, and the general adhesives techniques, laser technology has started to become more popular to the pediatric dental world. The widespread use of lasers in dentistry can be employed for both diagnosis and treatment and as stated by the American Academy of Pediatric Dentistry (AAPD): «the use of lasers is an alternative and complementary method of providing soft and hard tissue dental procedures for infants, children, adolescents, and persons with special health care needs» [2].

11.2 Behavior Management and Laser Application

Dental specialists are trained to diagnose and treat dental diseases according to evidence-based dentistry with the behavior guidance to be the priority of the dental treatment. The dental practitioner interacts with the patient and their parents and through that procedure identifies appropriate or not behaviors, understands the emotional state of each person, and promotes empathy and compassion. The goal is to achieve communication, eliminating dental fear and anxiety in order to build a circle of trust between the child, the parent, the dentist, and the dental staff.

Earning child/parent's trust before managing to achieve high patient cooperation is the ultimate issue in pediatric dentistry. This is a difficult and demanding task, because many children perceive a visit to the dentist as stressful. This is an expected reaction, since an appointment includes several stress-evoking components, such as strange sounds and tastes, having to lie down, meeting unfamiliar adult people and authority figures, discomfort, and even pain. Even though laser therapy sounds promising and well accepted by the parents due to the possibility of better therapeutic results for their children and the assumption of no pain treatment (anesthesia may be necessary), the use by the dentist of the new technology still requires a degree of compliance by the child patient. Although a dental practice may have several modern and friendly devices, it remains an unknown and peculiar environment for the young child and may provoke negative emotions and stress during child's first visit. Therefore, the practitioner should choose and offer dental treatment with the appropriate methods and instruments that are suitable for each patient. Sometimes laser treatment is preferable, especially for young children who refused the traditional dental treatment (Fig. 11.1a–e). Laser treatment can be used to introduce dentistry, gain the trust of the child, and perform needle-free and also no painful procedures. Through this, oral laser applications may also offer an alternative strategy in behavior management (Fig. 11.2a–g). A positive experience during dental treatment is of paramount significance for a lifelong confiding relationship between the child and the dentist, which may also lead to better oral health in the adulthood.

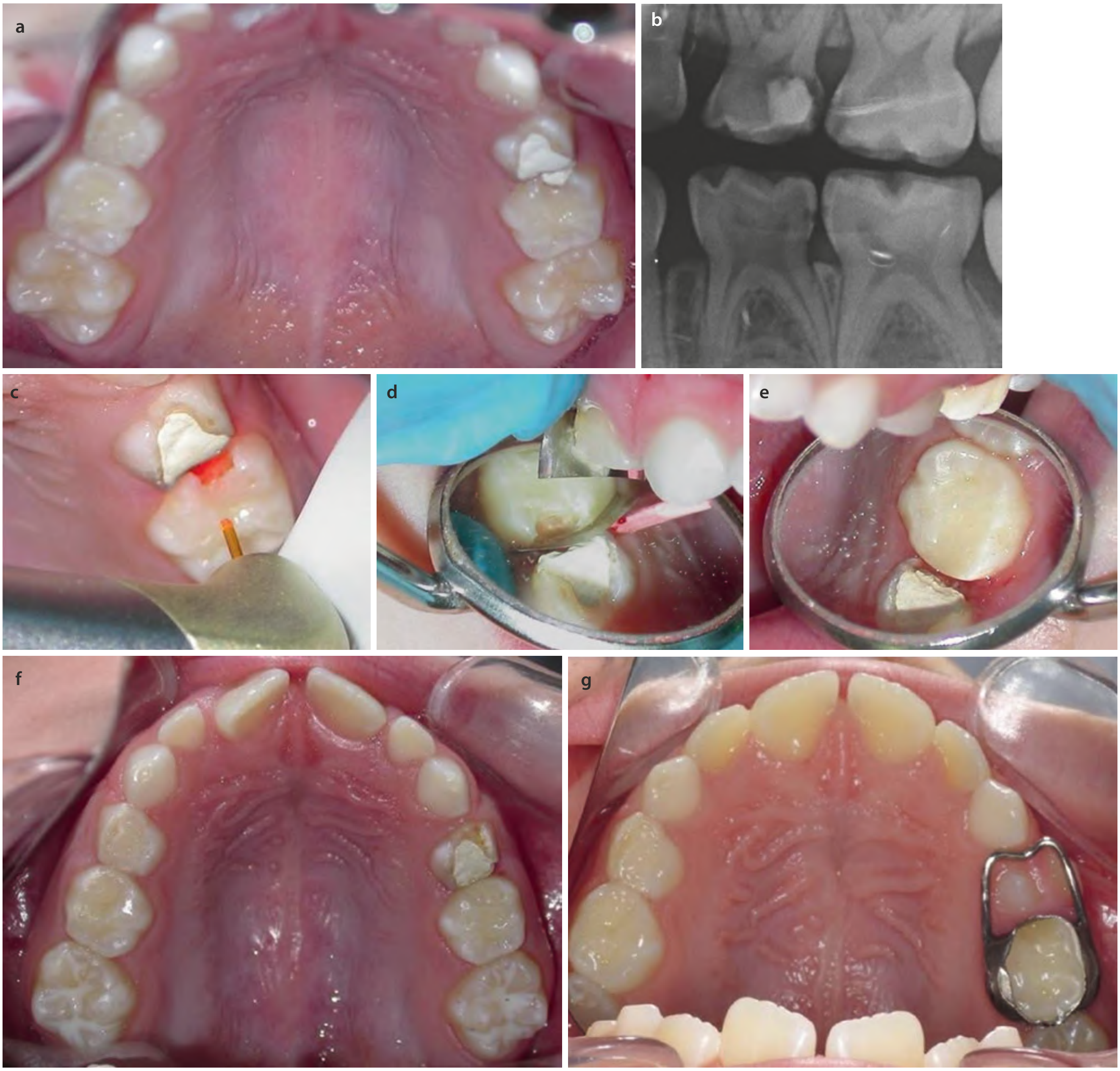
Either way, for its successfulness and the child's acceptance, a well-prepared presentation, training, and education on that have to be proceeded before the use. The pediatric

■ **Fig. 11.1** **a**–**e** Resin-modified glass ionomer (RMGI) restorations on the primary second molars, without the use of local anesthesia, of a 3-year-old uncooperative girl with primary molar hypomineralization (PMH). **a** Preoperative intraoral view. According to the traditional treatment recommendations, stainless steel crowns (SSC) should be placed on teeth #75 and 85 under local anesthesia. **b** Laser analgesia (starting with 50 mJ, 10 Hz, 82% water (16 ml/min), 70% air, distance 6 to 10 mm from the tooth, for 40 to 60 s, and continuing with 80 to 100 mJ for 60 more seconds before tooth preparation) and cavity preparation (see ■ Table 11.2 for energy parameters) by Er,Cr:YSGG (2780 nm, gold handpiece, 0.6 mm MZ tip, H tissue mode). **c** After laser preparation. The cavity was well extended into dentin. The child revealed no pain and no complain and cooperation was relatively good. **d** Final RMGI restoration. **e** Intraoral view 24 months after treatment. Restorations are still in place and there are no caries lesions. The patient is now 5 years old and cooperative, and it is the practitioner's decision if and when he/she will provide a more permanent rehabilitation

dentist may use some of the basic behavior techniques to introduce laser to the child. One of the most powerful techniques is «tell, show, do» in which the practitioner explains verbally the consecutive stages of the dental treatment (tell), demonstrates the equipment and shows the different tools/instruments on the hand/finger (show), and executes the procedure (do) [3]. Laser technology can be introduced using friendly, familiar, and easy-to-understand words like «special flashlight», «magic light», «colored light», etc. The sound of the laser could be like «making popcorn», «playing metal music», etc. The special glasses are going to make you look like «a ninja», «a princess», etc. In conjunction with the technique «tell, show, do» positive reinforcement (e.g. use of phrases like «great job» or a reward at the end of the session) and distraction techniques (e.g. television, movies, music) should be adopted. Children who do not cooperate or the mental status does not allow them to comply cannot be candidates for laser therapy.

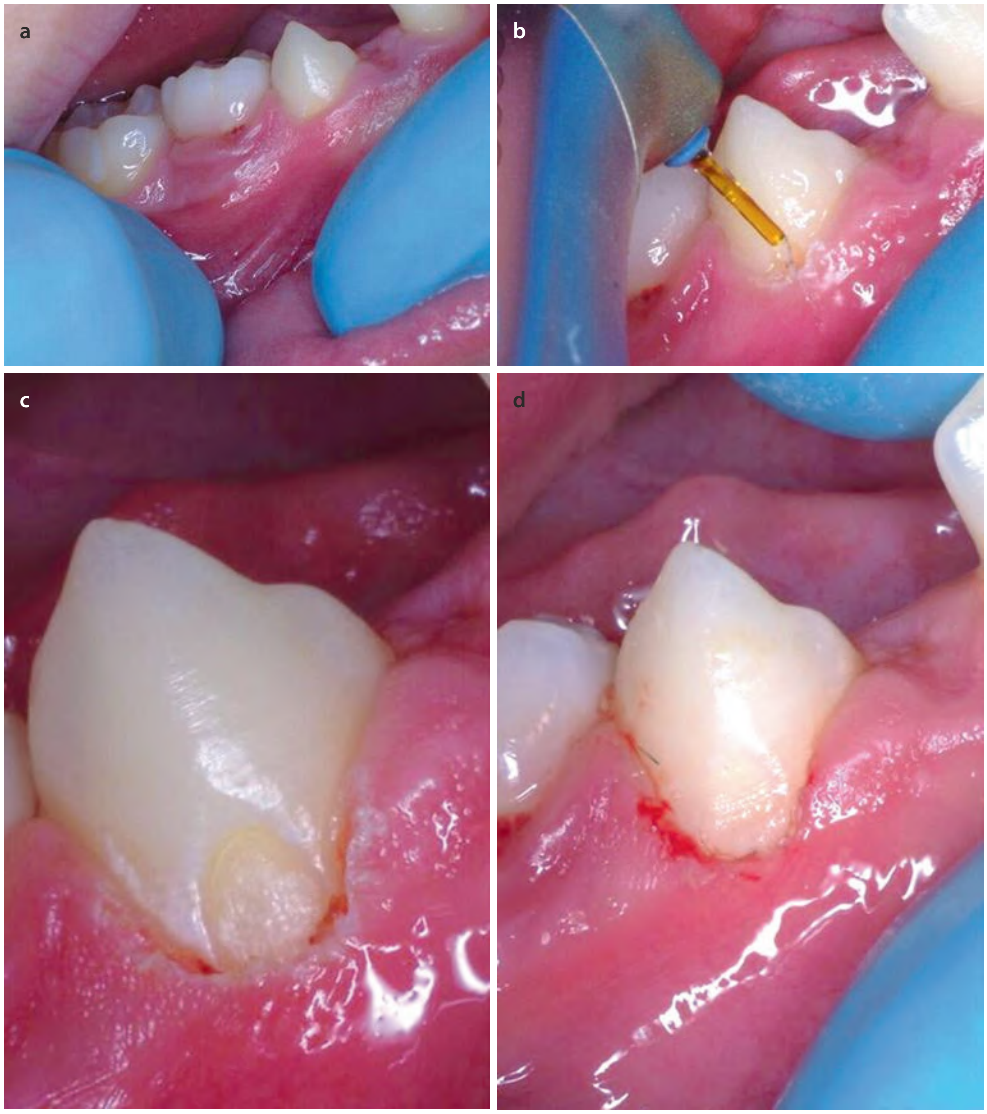
11.3 Local Anesthesia and Laser Application

Local anesthesia is the basis in controlling pain during dental treatment, but, at the same time, one of the most common and major fears for the patient. Traditionally most of the dental treatment procedures need to be performed under local anesthesia. Laser analgesia provides an extra tool for the dentist to avoid or reduce the use of local anesthesia, in some cases. It should be stated that analgesia is not really anesthesia, but a way to reduce sensitivity, needing a more intensive stimulus for the patient to feel pain. Studies using infrared wavelengths (diode, Nd:YAG) conclude that low-level energy doses (LLLT) can suppress the excitation of unmediated C-fiber afferents of the pulp. Also, there are studies regarding the potential analgesic effect of erbium family lasers irradiation and the mechanism resulting in this effect. Many clinicians report that they have been successful in performing a variety of dental procedures, in pediatric dentistry too [4, 5].



◘ **Fig. 11.2** **a**–**g** Behavior shaping using laser for the completion of dental treatment of a referred 7.5-year-old needle-phobic girl with low cooperation at the dental office. Laser treatment is used to introduce dentistry, gain the trust of the child, perform needle-free and also no painful procedures, and «desensitize» the patient through gradual exposure to dental treatment: perform first sealants, needle-free restorations (laser analgesia and preparation), and finally the extraction. **a** Initial intraoral view of the upper arch. **b** Left bite wing radiograph. Tooth #64 had to be extracted due to abscess and root resorption. Note that caries was well extended into dentin on #65. **c** Cavity preparation on #65 (see ◘ Table 11.2 for energy parameters). No local anesthesia but laser analgesia (see text and ◘ Fig. 11.1b for laser parameters) and preparation by Er,Cr:YSGG (2780 nm, gold handpiece, 0.6 mm MZ tip, H tissue mode). **d** After laser preparation of #65. The child revealed no pain and no complain and cooperation was good. **e** After RMGI placement on #65. **f** Intraoral view of the upper arch after 2 months. The patient presented for extraction of tooth #64 with the administration of local anesthesia (4% articaine, 1:200,000 epinephrine). Cooperation was excellent. **g** After 20 months. The permanent successor is erupting and space maintenance has to be removed. Restoration on #65 remains intact

In all clinical cases presenting in this section, laser analgesia was applied using the Er,Cr:YSGG (2780 nm) laser with the following parameters: starting with 50 mJ, 10 Hz, (0.5 W), 82% water (16 ml/min), 70% air, distance 6 to 10 mm from the tooth, for 40 to 60 s, and continuing with 80 to 100 mJ for 60 more seconds before tooth preparation (gold handpiece, 0.6 mm MZ tip, H tissue mode) (◘ Figs. 11.1a–e, 11.2a–g, and 11.3a–d). There are no studies reporting any analgesic effect of CO_2 wavelength. Theoretically, the ideal laser wavelength choice would be the one that has an analgesic effect and that can be used in all of those treatment procedures at the same time.



■ **Fig. 11.3** **a**–**d** Minimal gingivoplasty and subgingival composite resin restoration, in a single visit and without administration of local anesthesia, on tooth #83 of a 7-year-old boy. **a** Initial clinical view. Placement for 3 min only EMLA cream (lidocaine 2.5% and prilocaine 2.5%) on dry gingiva. **b** Minimal gingivoplasty using Er,Cr:YSGG (2780 nm) at 50 mJ, 20 Hz, (1.0 W), 30% water (6 ml/min), 70% air, tip distance 1 mm (close contact), tip parallel to the long axis of the tooth (gold handpiece, 0.6 mm MZ tip, H tissue mode). **c** After gingivoplasty and cavity preparation by Er,Cr:YSGG (2780 nm) (see ■ Table 11.2 for energy parameters). **d** Final composite resin restoration

The performance of laser analgesia using erbium family lasers could be a useful tool to overcome behavioral problems, especially for needle-phobic children seeking dental treatment (■ Fig. 11.2a–g). Also, only the application of topical anesthetic gel on dry gingival or mucosa for 3–5 min [e.g. EMLA cream (lidocaine 2.5% and prilocaine 2.5%, each gram of EMLA cream contains 25 mg lidocaine and 25 mg prilocaine)], without the administration of injected local anesthesia, is efficient in performing minimal gingival interventions in several clinical cases by erbium family lasers (■ Figs. 11.3a–d and 11.4a–f).

It should be noticed that a prerequisite for achieving cooperation with the child and complete dental treatment is the minimization of disturbance and the absence of pain. Completion of dental treatment with children is directly related to the absence of pain. There is always a possibility of pain during dental treatment after laser analgesia, and, in this case, laser energy parameters should be altered, or local anesthesia should be delivered. Adult patients can communicate their feelings with the dentist and may tolerate the pain to some extent and to remain cooperative, but children are frightened, lose trust to the dentist when their teeth ache, and then do not cooperate. It is the dentist's responsibility, after evaluating the child's maturity and providing adequate psychological preparation to reach a high degree of cooperation, to decide if local anesthesia should be administered before laser-assisted dental treatment. In general, if there is a possibility of pain, it is preferable to deliver local anesthesia before the start rather than during the dental treatment in children with low cooperation. Examples of such cases are shown at ■ Figs. 11.5a–e and 11.7a–i. These patients were not cooperative (one had extremely high gagging reflex which is very often associated to «hidden» dental anxiety). Laser analgesia could be used but it was decided that block anesthesia was more appropriate for these patients.

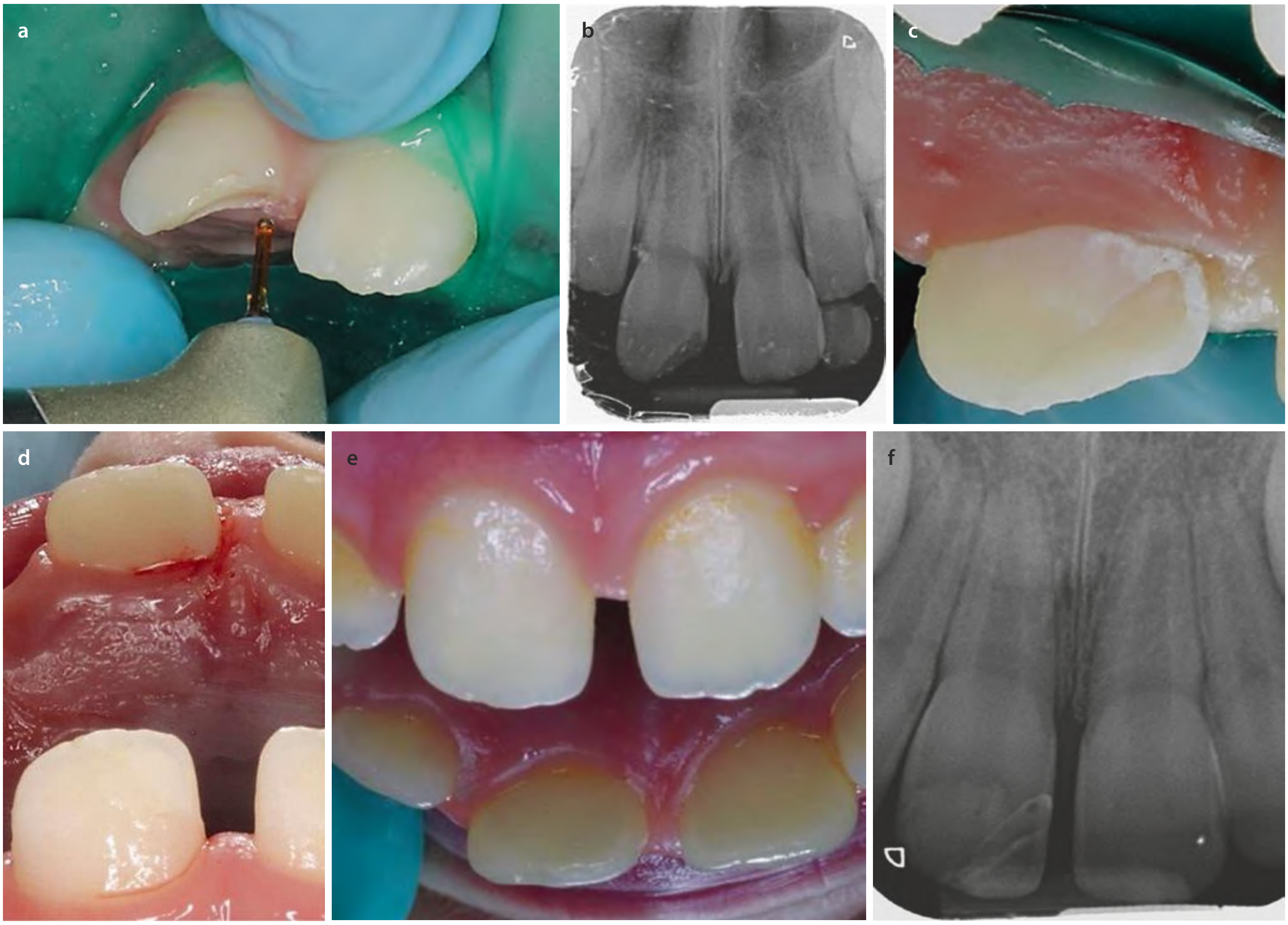


Fig. 11.4 **a**–**f** Minimal gingivoplasty using Er,Cr:YSGG and reattachment of tooth fragment, in a single visit and without local anesthesia, following enamel-dentine subgingival (no pulp involvement) crown fracture on a permanent incisor of a 7.5-year-old boy. **a** Rubber dam placement, EMLA cream (lidocaine 2.5% and prilocaine 2.5%) for 3 min. Minimal gingivoplasty using Er,Cr:YSGG (2780 nm) (see laser energy parameters on Fig. 11.3b). **b** Initial radiographic image (no complete root formation). **c** After minimal gingivoplasty and before tooth fragment reattachment using composite resin. There is no gingival bleeding and tooth structures have been exposed. **d** Final restoration. **e** and **f** Clinical and radiographic views 30 months after treatment showing root formation

11

11.4 Types of Lasers Used in Pediatric Dentistry

Caries management includes prevention (fluoride application, dietary instructions, everyday oral hygiene), detection, and treatment management. Treatment includes the removal of the infected dental tissue, the cavity preparation, and, depending on the case severity, indirect or direct pulp capping, pulpotomy, and pulpectomy, followed by tooth restoration. At this time, erbium family lasers are the ones that can be commonly used on both hard tissues, for caries removal and cavity preparation, and soft tissues too. The targeted chromophore for this wavelength is primarily water and secondarily hydroxyapatite. This, and in combination with the mid-infrared wavelength (less penetrative compared to shorter wavelengths), results in its superficial effect on tissues, minimizing the risk for collateral thermal damage. The remaining laser wavelengths can be used successfully on the rest of the procedures, especially regarding hemostasis achievement in pulp or gingiva before restoration and decontamination, since the targeted chromophore in soft tissues is hemoglobin and melanin (for KTP, diodes, and Nd:YAG), with respect to their more penetrative wavelength (except for the CO_2 which, due to its longer wavelength and high absorption in water, is the less penetrative of all) [6]. Regarding caries prevention, CO_2, erbium family lasers, and Nd:YAG (due to their high power values emitted and ability to photothermally melt enamel) have been tested alone or in combination with fluoride, especially through in vitro studies. Infrared irradiation (diode lasers), due to its high penetration (and low absorption on hard tissue), is used widely in detecting caries.

Periodontal diseases in children usually include minimal-severity gingivitis infections, usually due to poor everyday oral hygiene, and hyperplastic gingivitis with the formation of pseudo-pockets (not completely erupted teeth). In

Fig. 11.5 **a**–**e** Minimal gingivoplasty and treatment of subgingival caries, in a single visit, on teeth #83, 84, and 85 after preparation by Er,Cr:YSGG (2780 nm) of a 7.5-year-old girl. Also treatment of occlusal caries on #46. **a** Intraoral initial clinical view. **b** and **c** Block anesthesia (4% articaine, 1:200,000 epinephrine) and placement of rubber dam. Using Er,Cr:YSGG (2780 nm), [1] remove caries from #46 (enamel 4 W, 20 Hz, (200mj) 82% (16 ml/min) H_2O, 70% air) (RC restoration and sealant) [2]. Minimal gingivoplasty on teeth #83, 84, and 85 (see laser energy parameters on Fig. 11.3b) and [3] caries removal from teeth #83, 84, and 85 (see Table 11.2 for energy parameters for primary teeth). **d** Placement of SSC on #84 and #85 and buccal RMGI restoration on #83. **e** Clinical view after 26 months. The girl is almost 10 years old; #83 is movable and #84 has been normally exfoliated. Restoration on #83 is intact

addition, gingival and periodontal changes may be seen during or following orthodontic treatment, due to difficulties in maintaining good oral hygiene and/or the periodontal tissues following the teeth movement during the orthodontic treatment. All laser wavelengths can be used in these instances, for laser decontamination, and, if needed, removal of hyperplastic gingival tissue.

Apart from tooth decay, tooth injuries represent the most frequent pathology encountered in pediatric dentistry. Around 20% of children suffer a traumatic injury to their primary teeth and over 15% to their permanent teeth [7]. Dental trauma is a stressful and challenging emergency situation for the child, the parents, and the dentist. Accurate diagnosis in combination with immediate intervention is required, so that any risk of sequel problems or healing complications is minimized. Mid-infrared wavelength lasers could be used to reduce acute pain, to improve and speed up tissue healing (photobiostimulation effect), to provide decontamination and inflammation control, and to help control bleeding.

Among the other advantages, the use of lasers can often make it easier for the dentist to perform several procedures in the same appointment (Figs. 11.3a–d, 11.4a–f, 11.5a–e, and 11.7a–i).

11.5 Restorations on Primary Teeth

Dental caries is one of the most common diseases in childhood, and several well-established restorative methods and materials have been used for replacing the carious dental tissues of primary teeth. Lasers can be used as alternative instruments to completely or partly substitute traditional instruments and techniques or to help and contribute to traditional dental treatment. The erbium family lasers are used for caries removal and cavity preparation on primary teeth. Enamel and dentine in primary teeth have compositional and structural differences from those of permanent teeth. Primary tooth enamel is less mineralized and more porous, and prisms do not have an orderly spatial organization. Primary tooth dentine has more water, less in number, and narrower dentinal tubules. Therefore, lower laser energy parameters than those for permanent teeth should be used for caries removal and cavity preparation on primary teeth (Tables 11.1 and 11.2). Water flow is given both in percentage and ml/min. The percentage of water given means the percentage of the maximum possible amount of water the specific laser unit could provide. For example, 70% (7 out of 10) for Fotona LightWalker (Er:YAG, 2940 nm) is water flow of 32 ml/min, while 82% for Er,Cr:YSGG (Waterlase MD, 2.780 nm) is 16 ml/min.

All dental restorative materials [composite resin (CR), compomers (C), resin-modified class ionomer (RMGI), glass ionomer (GI)] could be placed after laser cavity preparation on primary teeth (Figs. 11.1a–e, 11.3a–d, and 11.5a–e). There are no long-term randomized clinical trials about restoration of primary teeth using lasers. However, there are several studies concluding that laser abrasion is a safe and useful alternative method for caries removal and cavity preparation on primary teeth [8–11]. Studies on bond strength restorative materials after preparation of primary teeth by laser or traditional method showed lower or equal results [12–16]. The results on marginal microleakage are controversial but most of the studies report good results (similar or better than the diamond bur), for both laser wavelengths of the erbium family. The restorative materials studied include several types of CR, C, RMGI, and GI. In the case of CR and C, several etching (total etch, self-etch) and adhesive systems (one-step adhesive, two-step adhesive, self-etching adhesive) are studied [17–26]. Also, a study showed no statistical significant difference on marginal microleakage between Er:YAG and Er,Cr:YSGG lasers for any of CR, RMGI, and GI restorations [26]. The main advantages of laser use in restorative pediatric dentistry are patient and parent's acceptance, the administration of no or less local anesthesia, the absence of vibration, the cavity decontamination effect, and the selectivity of dental caries.

Table 11.1 Parameters for cavity preparation with Er:YAG laser (2940 nm) on primary teeth. Tip diameter 600 µm, 70% water (32 ml/min for Fotona LightWalker), 1 mm tip to tissue distance, (1) enamel preparation, (2) dentine preparation, (3) dentine finishing-conditioning and removal of dental caries, (4) enamel finishing-conditioning, and (5) decontamination (based on Professor Wayne Selting's laser parameter calculation sheet)

Energy per pulse (mJ)	Average power (watts)
1. 160–200 mJ, 10 pps	1. 1.6–2
2. 80–100 mJ, 10 pps	2. 0.8–1
3. 40–60 mJ, 10 pps	3. 0.4–0.6
4. 35–50 mJ, 20 pps	4. 0.70–1
5. 50 mJ, 20 pps, defocus for 15 s	5. 1

Table 11.2 Parameters for cavity preparation with Er,Cr:YSGG (Waterlase MD, 2.780nm) on primary teeth. Tip diameter 600 µm, 82% water (16 ml/min), 1 mm tip to tissue distance, (1) enamel preparation, (2) dentine preparation, (3) removal of dental caries, (4) dentine finishing-conditioning, (5) enamel finishing-conditioning, and (6) decontamination (based on Professor Wayne Selting's laser parameter calculation sheet)

Average power (watts)	Energy per pulse (mJ)
1. 2.0 W, 10 pps	1. 200
2. 1.5 W, 10 pps	2. 150
3. 1 W, 10 pps	3. 100
4. 0.5 W, 10 pps	4. 50
5. 0.75 W, 20 pps	5. 37.5
6. 1 W, 20 pps, defocus for 15 s	6. 50

11.6 Pulp Treatment in Primary Teeth

Pulp treatment in primary teeth is usually required due to deep dentine caries or dental trauma. Indirect pulp capping, direct pulp capping, and pulpotomy are the treatment options for vital teeth, while pulpectomy is the recommended treatment for necrotic or irreversible pulpitis in primary teeth. The treatment choice is based on well-known clinical and radiographic criteria: history of pain and signs or symptoms of pulp degeneration are indications of necrotic pulp or irreversible pulpitis [27]. The use of the erbium family laser is beneficial for cavity preparation, especially in cases of teeth with deep dentin caries, because of (a) the selective and minimal tooth structure removal aiming to avoid unnecessary mechanical pulp exposure and (b) the facility of dentine decontamination and smear layer removal (see Tables 11.1 and 11.2 for energy parameters). In many cases, no local anesthesia is required when erbium family lasers are used. In addition, for all the above reasons, when interim therapeutic restoration (ITR) [28] is the choice of contemporary treatment in order to prevent the progression of dental caries on uncooperative patients, the use of lasers could be beneficial.

11.6.1 Indirect Pulp Capping

The goal of the technique is to preserve the integrity of the vital pulp and also activate the repairing mechanism for the formation of tertiary dentine. All decayed enamel and dentine except the decayed dental tissue located next to the pulp has to be removed. The pulpal wall is covered with a biocompatible protective base (usually mineral trioxide aggregate (MTA) or Portland cement (PC) or biodentine or calcium hydroxide or glass ionomer), and the final restoration follows (glass ionomer restorative material or resin-modified glass ionomer or composite resin or preformed crowns). It has the same indications to pulpotomy on primary teeth [29], presenting success rates up to 83–100% using the traditional preparation techniques [30, 31], but there is no clinical study involving the use

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of laser at the indirect pulp capping on primary teeth. However, it is speculated that the laser-assisted technique (erbium family or/and near-infrared laser wavelengths) could be more predictable and successful due to decontamination of the cavity, the remaining carious dentine, and the positive effect on pulpal tissue healing and recovery [32]. See ◘ Tables 11.1 and 11.2 for laser wavelength parameters for deep dentine removal (erbium family) and decontamination.

11.6.2 Direct Pulp Capping

When the vital pulp is exposed because of mechanical caries removal or trauma, direct pulp capping could be performed. However, direct pulp capping is not recommended for primary teeth [27]. The success rate of the traditional techniques is 70–80%, using MTA or PC or biodentine or calcium hydroxide as pulp dressing material, while usually there is acute edema and pain after 7–15 days in case of failure [33]. Therefore, there is a general recommendation to avoid direct pulp capping in primary teeth and perform pulpotomy, in case of any size of pulp exposure [27, 33]. Successful laser-assisted direct pulp capping cases have been reported [32], but there is no clinical study involving the use of any laser wavelength in such a treatment on primary teeth. Following cavity preparation using a diamond bur or a laser from the erbium family, the laser-assisted technique (erbium family, diode, Nd:YAG, CO_2) is introducing pulp tissue coagulation (erbium family: 50 mJ, 10 Hz, no water, 40% air, defocus for 5–10 s) along with decontamination before the placement of pulp dressing [32]. After laser-assisted direct pulp capping, it is expected that better pulpal healing occurs than with the traditional technique; the pulp will retain its vitality and perform the formation of tertiary dentine. See ◘ Tables 11.1 and 11.2 for laser wavelength parameters for decontamination.

11.6.3 Pulpotomy

The traditional technique of pulpotomy has clinical success rates up to 98–100% [MTA/PC/biodentine or ferric sulfate (FS)] and is the most common technique performed after pulp exposure on vital primary teeth with deep carious dentine lesions. The technique involves the removal (amputation) of the coronal pulp tissue with burs and spoon excavator, achievement of hemostasis using sterile cotton pellets, and placement of MTA/PC/biodentine or FS over the pulp stumps [27]. When the bleeding from the pulp stumps could not be controlled, it is an indication of irreversible pulpitis beside the absence of clinical and radiographical symptoms, and pulpectomy is indicated. Formocresol had been used for several years (before the wide use of FS) with great success, but its use is not currently recommended due to possible carcinogenic effect. The MTA/PC/biodentine is covered by glass ionomer, while in the case of FS, a fast setting zinc oxide and eugenol paste (IRM) is placed over the pulp stumps before the placement of the final restoration. FS forms a ferric ion and protein complex on contact with blood, providing a bridge between the vital root canal pulp tissues, and the paste contains eugenol (IRM), while the biocompatible and also bioinductive MTA/PC/biodentine has to be in contact with the pulp tissue.

Alternatively, instead of using medicaments like FS, laser (erbium family, diode, Nd:YAG, CO_2) could be used for the pulp tissue coagulation over the pulp stumps before the placement of IRM (◘ Fig. 11.6a–g). Clinical studies show that either there is no significant difference in success rate (clinical or radiographically) between laser-assisted and traditional pulpotomy, or the result is in favor for the laser-assisted method [34–41]. After coronal pulp was removed with burs and spoon excavator and hemorrhage was controlled, a type of laser [diode (five studies), Er:YAG (one study), Nd:YAG (one study), CO2 (one study)], using a variation in laser application parameters (power, frequency, exposure time) and capping materials (MTA, zinc oxide eugenol, IRM), reports success rate of laser-assisted pulpotomy (follow-up period from 1 to 66 months) which ranged from 71.4% to 100% clinically and 71.4% to 100% radiographically. The amputation through vaporization of the coronal pulp tissue using lasers (erbium family, diode, Nd:YAG, CO_2) is not recommended because they create coagulation and necrotic tissue which may camouflage possible inflammation or necrosis of the root canal pulp. See ◘ Tables 11.1 and 11.2 for laser wavelength parameters for decontamination (erbium family).

11.6.4 Pulpectomy

Pulpectomy is the endodontic treatment for primary teeth and is indicated for teeth without or with minimal pathological (internal or external) root resorption due to irreversible pulpitis or necrotic pulp. The traditional technique involves the removing of all coronal and root pulp tissue, limited mechanical instrumentation, root canal disinfection using the appropriate irrigants, and filling the root canals with resorbable material (pure zinc oxide-eugenol paste or iodoform-calcium hydroxide paste). Several protocols have been developed using lasers (erbium family, diode, Nd:YAG,) with great results for better decontamination of the main and the lateral canals on permanent teeth [42–46]. These same protocols for permanent teeth, using the same parameters, are also recommended for primary teeth but there are only four studies (one in vivo, one in vitro, and two case reports) for deciduous teeth, all using photodynamic therapy, leading to satisfactory results [47–50]. In addition to the traditional technique, a laser-assisted disinfection method could be performed before the final conclusion of the endodontic treatment (◘ Fig. 11.7a–i). Laser-assisted disinfection could have better results on primary teeth where there are more complex, with variable morphology root canals making instrumentation and disinfection complicated. Irrigation with sodium hypochlorite should be avoided, especially when the laser-activated irrigation protocol is used, because if extruded from the open or resorbed root apex, it could be an irritant to the surrounding tissues.

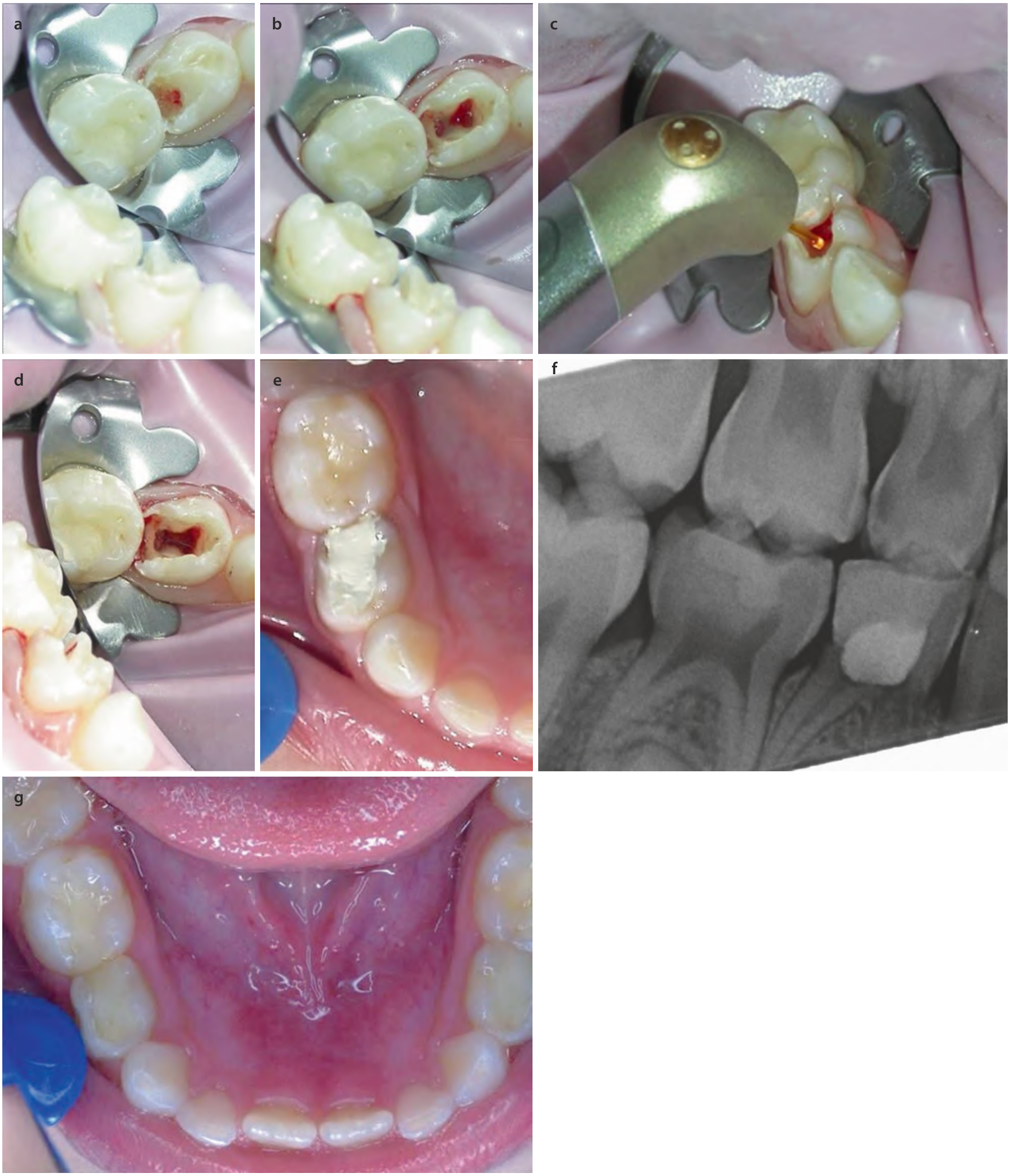

Fig. 11.6 **a–g** Laser-assisted pulpotomy on a first primary molar of a 5.5-year-old girl. Block anesthesia (4% articaine, 1:200,000 epinephrine) and placement of rubber dam. **a** Pulp exposure during caries removal. **b** Removal of the coronal pulp tissue (diamond bur and spoon excavator). Hemorrhage was controlled. **c** Er,Cr:YSGG (2.780 nm) was applied at 50 mJ, 10 Hz, (0.5 W), no water, 40% air; defocus for 5–10 s (gold handpiece, 0.6 mm MZ tip, S tissue mode) over the canal orifices. **d** Complete coagulation after laser application. **e** The cavity was filled up with IRM (fast setting zinc oxide and eugenol paste). Clinical view after 15 days. The placement of RMGI restoration was followed. **f** and **g** Radiographic and clinical pictures 16 months after treatment

Fig. 11.7 **a–i** Laser-assisted pulpectomy and gingivoplasty on a first primary molar of a 6.5-year-old boy. Endodontic therapy of #84 due to abscess. The patient returned 10 days after the initiation of treatment with a subgingival crown fracture. **a** Intraoral view of lower teeth. **b** Block anesthesia (4% articaine, 1:200,000 epinephrine) and placement of rubber dam. Occlusal view of #84. **c** Laser-activated irrigation (Er,Cr:YSGG 2.780 nm) was applied at 33 mJ, 30 Hz (1.0 W), no water, no air, tip inside the tooth chamber, saline solution for 5 s each root canal (gold handpiece, 0.6 mm MZ tip, H tissue mode). **d** Obstruction of the root canals with pure zinc oxide and eugenol paste and filling the tooth chamber with fast setting zinc oxide and eugenol paste (IRM). Gingivoplasty (see laser energy parameters on Fig. 11.3b) and cavity preparation followed (see Table 11.2 for energy parameters). **e** After gingivoplasty and cavity preparation and decontamination. **f** Final restoration with RMGI. **g** Pulpectomy and restoration after 3 months. SSC was placed on #84 at that visit. **h** and **i** Periapical radiograph and clinical views 16 months after treatment

Conclusion

All dental laser wavelengths (KTP, diode, Nd:YAG, erbium family, CO_2) could be used as alternative and/or complementary treatment methods of soft and hard tissue management for the pediatric dentistry patients. The main advantages of laser use in pediatric dentistry are (a) patient and parent's acceptance, (b) the administration of no or less local anesthesia, (c) the absence of vibration during cavity preparation, (d) the selectivity of dental caries, (e) the decontamination effect, and (f) making it easier for the dentist to perform several procedures in the same appointment. In addition to these advantages, the use of lasers can often offer an alternative strategy in children's behavior management along with the appropriate child's psychological management. Laser treatment can be used to introduce dentistry, gain the trust of the child, and perform needle-free and also no painful procedures using laser analgesia, especially for children who refused traditional dental treatment. However, children who do not finally cooperate or the mental status does not allow them to comply cannot be candidates for laser therapy.

Laser-assisted treatment in pediatric dentistry includes, among others, the removal of the infected dental tissue, the cavity preparation, and, depending on the case severity, indirect or direct pulp capping, pulpotomy, and pulpectomy, followed by tooth restoration. Several studies concluded that laser abrasion is a safe, useful, and highly accepted by patients alternative method for caries removal and cavity preparation on primary teeth (erbium family). All dental restorative materials (composite resin, compomers, resin-modified class ionomer, glass ionomer) could be placed after laser cavity preparation on primary teeth revealing high success. Laser-assisted indirect and direct pulp capping techniques for primary teeth (erbium family or/and near-infrared laser wavelengths) could be more predictable and successful, than the traditional techniques, due to decontamination of the cavity, the remaining dentine, and the positive effect on pulpal tissue healing and recovery in order to form tertiary dentine. Instead of using medicaments (like ferric sulfate) during primary teeth pulpotomy, laser (erbium family, diode, Nd:YAG, CO_2) could be used, with great clinical and radiographical success, for the pulp tissue coagulation over the pulp stumps before the placement of the fast setting zinc oxide and eugenol paste (IRM).

Laser-assisted disinfection, before the final root canal obstruction, could have better results on primary teeth pulpectomy where there are more complex, with variable morphology, root canals making instrumentation and disinfection complicated.

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Laser-Assisted Oral Soft Tissue Management

Contents

Lasers in Orthodontics

Ali Borzabadi-Farahani and Mark Cronshaw

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12.1 Applications of Lasers in Orthodontics for Soft Tissue Procedures and Photobiomodulation

Core Message

Scientific literature reports an exponential growth in the number and variety of laser applications in orthodontics. This paper reviews the available laser wavelengths and will discuss some adjunct application of diode lasers for soft tissue procedures. These include photobiomodulation, laser gingivectomy to improve oral hygiene or bracket positioning, aesthetic laser gingival recontouring and laser exposure of the superficially impacted teeth. Selected treated cases will be presented throughout.

Ali Borzabadi-Farahani

12.1.1 Soft Tissue Procedures Introduction

The healthy gingival margin is located 1–2 mm coronal to the cemento–enamel junction [1]. However, this gingival architecture does not always present smile aesthetics during or after orthodontic treatment. Mucogingival surgery on the other hand, is a periodontal treatment to correct the defects in the morphology, position and/or amount of soft tissue and underlying bone support around teeth and implants. Laser incision/excision definitely has a place in modern mucogingival surgery [2]. Compared with a scalpel, a laser beam or the initiated fiberoptic tip of laser device can more easily cut, ablate and reshape the oral soft tissues in the oral cavity, with no or reduced bleeding and less pain, as well as with no or less need for suturing [2]. This represents a range of tissue interactions, such as tissue warming, welding, coagulation, protein denaturation, drying and finally vaporisation (ablation) and carbonisation, where soft tissues are evaporated or incised [2–7]. This process also provides haemostasis, microbial inhibition and destruction and photobiomodulation (PBM) [2–7]. In particular, there is increasing evidence that the appropriate use of lasers is associated with reduced intraoperative and post-operative pain and enhanced wound healing or tissue regeneration, compared to conventional use of scalpel or electrosurgery [2–4]. Electrosurgery can be used for incising soft tissues with good haemostasis [2–4], but comes with a risk of delayed wound healing due to unwanted thermal damage [2, 6] and necrosis of the underlying periosteum and alveolar bone.

12.1.2 Advantages of Laser Excision vs. Scalpel Surgery

Dental lasers have been widely used for soft tissue procedures, such as gingivectomy, gingivoplasty and frenectomy, and, in particular, for aesthetic gingival procedures, such as recontouring or reshaping of gingiva, crown lengthening and depigmentation [2]. For instance, compared to conventional scalpel surgery, the diode laser cut is more precise and more visible due to the laser ability to seal off blood vessels and lymphatics, leaving a clear dry field [2, 7]. The laser also contributes to significant pathogen reduction as it cuts; and residual bacteria are evaporated, destroyed or denatured by laser irradiation [2]. Laser incision with high-level laser therapy (HLLT) excises (ablates) the diseased tissues, with simultaneous provision of low-level laser therapy (LLLT) that penetrates or scatters into the surrounding tissues during high-level laser treatment and stimulates tissues and cells without producing irreversible changes (Fig. 12.1).

LLLT promotes periodontal wound healing of the adjacent tissues as a desired effect [2, 8, 9], a process known as photobiomodulation (PBM) of tissues and cells following laser irradiation [2]. LLLT generates an array of extremely transient biochemical intermediates that result in cascading biological reactions in favour of tissue healing [10–12]. This process works by altering the cellular redox state [10] and production of reactive oxygen species (ROS) in mitochondria, such as superoxide ($O_2^{\bullet -}$) and hydrogen peroxide (H_2O_2), which mainly affect and stimulate cells in a low redox state [12]. Cells in a low redox state are acidic, but after laser irradiation, the cells become more alkaline and are able to perform optimally, inducing the activation of numerous intracellular signalling pathways [12]. Photoabsorption by mitochondrial chromophores, in particular *cytochrome c oxidase*, leads to dissociation of the binding between *nitric oxide* (NO) and *cytochrome c oxidase*, allowing mitochondria to increase ATP production and *nitric oxide* (NO) release [10–12]. The produced ATP modulates a wide range of biological responses, including activation or synthesis of DNA, RNA, enzymes and other cellular components necessary for optimal performance and repair/regeneration of tissues [11]. The LLLT-mediated NO release leads to vasodilatation, involving cGMP-mediated activation of Ca-sensitive K (Kc) channels [11], as well as promotes keratinocyte and tenocyte proliferation, endothelial migration and lumenisation, macrophage function, angiogenesis in ischemic limb injuries and stem cell differentiation [11]. Overall, PTM positively affects each of the four phases of wound healing [11, 13] (Table 12.1).

Within the progressive stages of wound stabilisation and healing, the many cellular and biochemical pathways are potential recipients of sub-ablative (low-level) laser photonic energy between approximately 600 and 1,400 nm wavelength. Outside this range, similar induced effects may be attributable to low thermal rise and consequent tissue stimulation.

PBM can promote changes at the cell level and expression of cytokines that can collectively promote wound healing, by increasing collagen production, reduction of inflammation and pain relief [2, 10–53]. LLLT has been effective in pain reduction [15, 18], wound healing [19–24], bone repair and remodelling [25–33], nerve repair [34–39], angiogenesis [40, 41], as well as increased cell proliferation and biomodulation

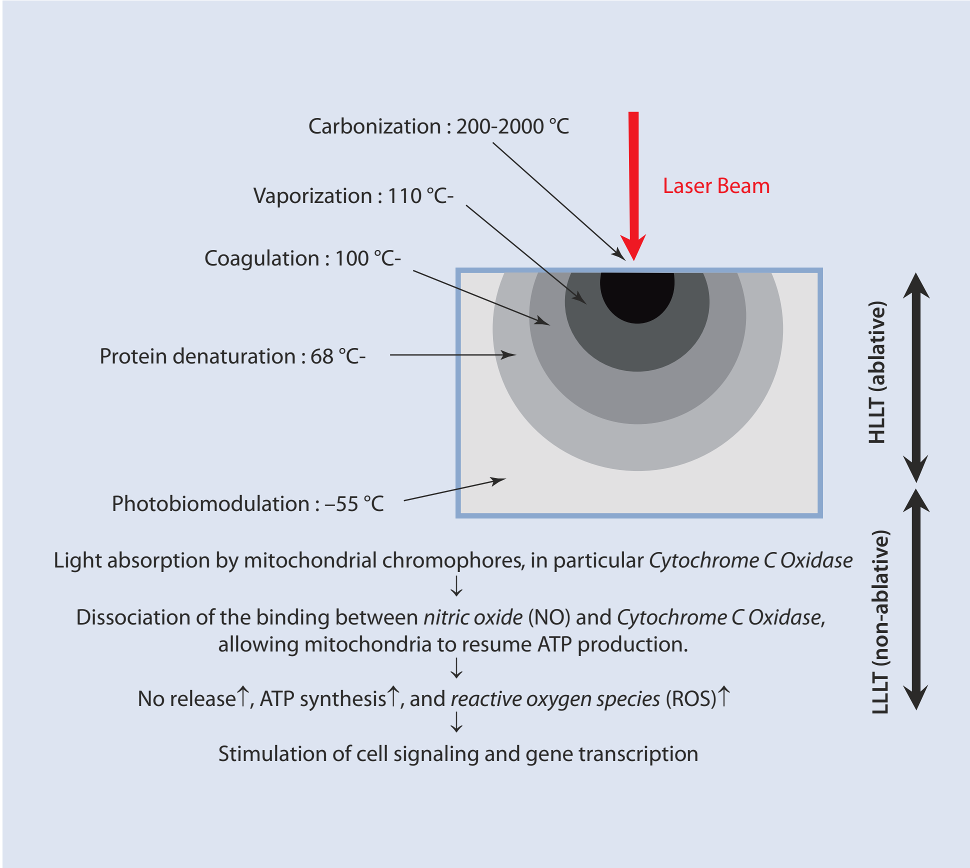

Fig. 12.1 Diagram showing the simultaneous work of high-level laser therapy (*HLLT*) and low-level laser therapy (*LLLT*). HLLT initiates various thermal effects on tissues, such as carbonisation, vaporisation, coagulation and ablation of soft tissue, as well as sometimes removal of the hard tissue (erbium lasers). Simultaneously, a low level of energy (*LLLT*) penetrates or scatters into the surrounding tissues during high-level laser treatment, which stimulates tissues and cells without producing irreversible thermal changes in the tissues, resulting in activation or stimulation (photobiomodulation, PTM) of wound healing in the surrounding tissues (Partially adopted from Aoki et al. [2])

Table 12.1 Effects of photobiomodulation (PTM) on four phases of wound healing [11, 13]

Four phases of wound healing	Effects of PTM on wound healing
Haemostatic phase	Promotes platelet aggregation and activation
Inflammatory phase	Promotes proliferation and degranulation of mast cells
Proliferative phase	Promotes proliferation of fibroblasts, keratinocytes, osteoblasts and chondrocytes as well as induces matrix synthesis
Maturation phase	Improves reorganisation and remodelling of wounds, aids improved tensile strength and restoring functional architecture of the repaired tissues

for cell lines such as fibroblasts [20, 42], keratinocytes [43, 44] and osteoblasts [45]. LLLT predominantly stimulates macrophages and fibroblasts [46–48] and collectively modulates secretion of vascular endothelial growth factor (VEGF), platelet-derived growth factor (PDGF), fibroblast growth factor (FGF) and tumour necrosis factor alpha (TNF-α) by macrophages, neutrophils, endothelial cells and fibroblasts, stimulating cell proliferation, cell differentiation and neoangiogenesis, as well as synthesis of extracellular matrix components such as types I and III collagen fibres [46–53]. Less wound contraction and oedema also occur during mucosal healing; scars tend not to develop as less damage occurs to adjacent tissues, and there is rarely a need for periodontal dressing [7, 54]. This phenomenon can be attributed to the low-power (PBM) zones that surround the high-power surgical laser site [11].

These qualities allow faster or more favourable wound healing, needing less pain medication, as well as less postoperative discomfort, compared to usual scalpel surgery [2]. This can lead to reduction in the orthodontic treatment time, when there is a need for soft tissue procedures that otherwise need referral to other specialties such as periodontist or oral surgeon, in particular for fee-paying patients who demand optimal results with minimal effort as quickly as possible [55].

12.1.3 Overview of Lasers Used for Soft Tissue Procedures

Various laser systems have been used for soft tissue procedures, which work by ablating, incising and excising the soft tissue, as well as providing the much-needed coagulating effect. The frequently used soft tissue lasers include the carbon dioxide laser (10,600 nm), erbium lasers [erbium-doped yttrium-aluminium-garnet (Er:YAG) laser (2,940 nm) and erbium chromium-doped yttrium-scandium-gallium-garnet (Er,Cr:YSGG) laser (2,780 nm)], neodymium-doped yttrium-aluminium-garnet (Nd:YAG) laser (1,064 nm), the diode group of lasers (800–980 nm) and, the potassium, titanium and phosphate ($KTiOPO_4$, KTP) laser (532 nm) [2, 3].

12.1.4 The Shallow or Deeply Penetrating Lasers and Haemostasis

The soft tissue lasers can be categorised into two broadly acting types: the deeply penetrating-type lasers (visible and near-infrared spectrum, 532–1,100 nm) that are essentially transmitted through water, showing a lower absorption coefficient in water [56] such as KTP green laser. This explains their deep penetration into healthy soft tissue, such as Nd:YAG and diode lasers, in which the laser light penetrates and scatters deeply into tissue [56]. However, they are selectively absorbed in areas of inflammation by blood components and tissue pigment [56]. There is also minimal to no interaction of Nd:YAG and diode lasers with healthy (not covered by calculus) dental hard tissue, which makes them suitable for soft tissue procedures [56]. The Nd:YAG laser is often used in free-running pulsed mode, with very-short-duration pulses and an emission cycle (ratio of "on" time to total treatment time) of <1% and very high peak power per pulse (100–1,000 W) [56]. The Nd:YAG laser is a deeply penetrating type of laser and produces a relatively thick coagulation layer on the lased soft tissue surface, exhibiting strong haemostasis. Therefore, the Nd:YAG laser is effective for ablation of potentially haemorrhagic soft tissue. Diode lasers represent a shallower penetration depth compared to Nd:YAG lasers and are less likely to cause pulpal damage after use [55]. The diode lasers can be used in a continuous-wave or gated-CW mode [7] and are the ideal choice for the use in orthodontic set-up because of the smaller size ("footprint") of the laser device and relatively lower cost involved [57] .

The second category highlights the superficially absorbed lasers (CO_2, Er:YAG and Er,Cr:YSGG lasers), in which the laser beam is absorbed in the superficial layer and does not penetrate or scatter deeply [2, 58, 59]. These lasers have higher absorption coefficient in water, and due to the high water content of oral mucosa (>90%), they are very effective soft tissue lasers [55]. However, what make them unattractive for the orthodontic set-up are the relatively high cost and the portability and movement issues [55]. Soft tissue penetration depth for CO_2 laser is approximately 0.2 mm [56, 60] and for erbium lasers (Er:YAG and Er,Cr:YSGG lasers) can be as shallow as 5 μm [56, 58]. CO_2 lasers have the highest absorption in hydroxyapatite and calcium phosphate and must be used with care during soft tissue procedures to avoid direct contact with hard tissue [56]. The CO_2 laser beam is absorbed at the tissue surface with very little scatter or penetration [2] and is associated with relatively thin layer of coagulation around the ablated site. The ablation for CO_2 laser is basically caused by heat generation (carbonisation) [2]. Erbium lasers have the highest absorption into water and target molecular water or the hydroxide ion as primary targets and mineral as a secondary target and therefore are used for ablation of both hard and soft tissues [56]. Erbium lasers provide the most rapid, favourable and uneventful wound healing due to their precise ablation with minimal thermal effects as well as low inflammatory response [60]. However, haemostasis is less effective with the erbium lasers because of the minimal tissue denaturation, which guarantees subsequent sufficient bleeding and blood clot formation in the ablated defects and thereby induces favourable wound healing [6]. Overall, erbium lasers provide the highest absorption into water, minimizing the thermal effects on the surrounding tissues during irradiation, but the cost, laser portability and movement and less clear-cut incision morphology compared to CO_2 and diode lasers [60] are the potential drawbacks in orthodontic practice.

12.1.5 Tissue Ablation: Non-contact or Contact Cutting Mode

As has been seen elsewhere (▶ Chap. 3), laser-tissue interaction is the result of electromagnetic (photonic) energy being absorbed and converted into other (predominately thermal) energy. Three forms of energy transfer can be observed:

Radiation
Where the photon stream is delivered through a short air space with no contact between delivery tip and target tissue. This may be commonly referred to a "non-contact mode".

Conduction
Where enhancement of the energy conversion can be achieved through direct contact between the delivery tip and the tissue. This may be commonly referred to a "contact mode".

Convection
Transfer of energy within the body of the tissue through fluid movement or circulation. This may occur regardless of either contact or non-contact modes.

Most surgical lasers produce a photothermal effect on soft tissue, evaporating soft tissues through rapid thermal rise. The non-contact lasers such as CO_2 or erbium lasers (Er:YAG and Er,Cr:YSGG) directly and easily evaporate soft tissues by photothermal effects that vaporise interstitial water. However, the non-contact mode is associated with less precise cut and lack of proprioceptive feedback compared to contact mode lasers.

When lasers are used in contact mode to make an incision or excise soft tissue, they often need "initiation" of the laser tip end. In this process, part of the emitting light in the

Fig. 12.2 A typical initiated fibre-optic laser tip will be used for laser excision

Nd:YAG and diode lasers is converted into heat by refraction or diffused reflection at the tip end, or in simple terms the laser tip end gets initiated, creating a condition called "hot tip". This initiation produces secondary thermal effects at the heated tip end that can cut or incise soft tissue as well as offer coagulation of the tissue as a result of contact with the overheated tip rather than by the laser energy itself [2, 3]. Figure 12.2 shows an initiated fibre-optic tip prior to laser exposure of an ectopic lower left canine. Diode and Nd:YAG lasers produce a relatively thicker coagulation layer on the treated surface than superficially absorbed lasers [4]. Diode lasers are considered to be ideal for daily practice of orthodontic soft tissue procedures owing to sufficient haemostasis and precise incision margins [61, 62]. For the purpose of this paper, the use of diode lasers for soft tissue procedures will be discussed in more detail due to their ease of use in orthodontics and lower operating cost.

12.1.6 Soft Tissue Diode Lasers

Since their introduction in 1962 [63, 64], the diode laser family has grown considerably and diode lasers with wavelengths in the range of 445-2200 nm have been used for treatment of various medical conditions [55, 57, 65–67]. However, reports on the use of the 810–830 nm, 940 nm, 980 nm and 1,064 nm wavelengths are more frequent in the literature [55, 57, 69]. They have high absorption coefficients in water and haemoglobin and particularly in oxyhaemoglobin, therefore rendering different soft tissue effects. However, diode laser light is poorly absorbed by the hydroxyapatite and enamel [54, 55], and therefore, it is an excellent soft tissue surgical laser for incising, excising and coagulating gingiva and mucosa. The active media of semiconductor (diode) lasers are varied and can include aluminium (Al), gallium arsenide (GaAs) and, occasionally, indium (In) [55, 68, 69]. Examples are gallium-aluminium-arsenic (Ga-Al-As), arsenic-gallium (As-Ga) and indium-gallium-aluminium-phosphorus (In-Ga-Al-P) lasers. The diode lasers are portable (<5 kg), small, relatively inexpensive and simple to use [68]. There is also a stable power output, long lifetime and low installation and maintenance costs [68].

12.1.7 Fibre-Optic Tip Size, Power Output and Continuous/Gated-CW Mode for Diode Lasers

The soft tissue diode lasers usually work in a 'contact mode' and the laser beam is delivered by a fine glass optic fibre, with a fibre system tip that can be angled, so that the dentist holds it in a pencil-like holder for accurate manipulation of the areas that are difficult to handle [68]. For surgical incisions and excision, a 400-μm diameter fibre-optic tip is recommended, as smaller diameter fibres tend to be more friable and liable to fracture [69]. The fibre-optic tip needs initiation prior to performing surgical excision, often by tapping the initiated tip on a thick blue articulating paper and use of black ink, a solid colour in a magazine page or a piece of cork – each with varying degrees of success [55, 70]. Diode lasers with power outputs of <500 mW are used in *low-level laser therapy* (LLLT) to provide photobiomodulation (PBM) and associated wound repair and pain relief [55]. However, for excision there is often a need for a continuous power output of 1.0–1.5 W [70], depending on the fibrotic nature of the tissue. In order to decrease the carbonisation and thermal damage and allow for thermal recovery of the tissue, a gated-CW mode (with repetitive "on–off" cycles of varying length and frequency depending on the make of the laser) has been suggested and implemented in many contemporary diode laser units [69, 71].

12.1.8 Provision of Anaesthesia and Basic Soft Tissue Guidelines

Lower pain sensation and less need for analgesia have been reported when diode laser with superpulsed mode [72] or with gated-CW of one millisecond pulse duration (on/off cycle of 50/50) [73] was used for soft tissue surgery, as compared to continuous wave diode laser. Diode laser soft tissue surgery is often performed using local infiltration (e.g. 2% lidocaine) approximately 5 min before procedure, but literature also reports using topical lignocaine anaesthetic gel, applied for 3 min, particularly with the gated-CW mode [69, 74], or compound topical anaesthetics such as TAC Alternate for 3 min (20% lidocaine, 4% tetracaine and 2% phenylephrine) [69, 70, 75]. Given enough time, topical anaesthetics often provide enough analgesia for laser exposure of buccally superficially impacted teeth; if enough analgesia is not achieved, additional topical dosage can be applied [69]. Palatal mucosa; however, is thicker and local infiltration is often necessary [69]. In order to confirm adequate anaesthesia prior to laser soft tissue surgery, gently probing the soft tissue will confirm that the patient feels pressure only or feels anything sharp that indicates the need for added dose of local anaesthesia.

During laser ablation, vaporised tissue, water, bacteria and organic chemical residues are liberated; this is known as the “laser plume”, and the use of a high-speed suction is recommended to remove this plume and objectionable charred odour, as well as provide a degree of safety against inhalation by patient and attending clinicians [69, 70]. Following the surgical excision, the soft tissue margins can appear dark and charred (carbonised), and the remnants of carbonised tissue at the surgical margins can be removed using sterile gauze dampened with saline [74] or a micro-applicator brush soaked in 3% hydrogen peroxide solution [70].

Various manufacturers present different arrangements for diode laser with respect to output power, diameter of fibre and wavelength. Although these parameters may influence collateral tissue damage, there is currently lack of standardisation in setting the best operating parameters of diode laser for orthodontic soft tissue procedures, which needs to be investigated in future studies [76].

Diode lasers are useful in recontouring the gingiva to gain access to the clinical crown, where there is gingival overgrowth or in case of partially erupted teeth, which prevent the proper positioning of a bracket. When planning laser soft tissue procedures, the general guideline is to leave at least 1.0 mm of pocket depth and to preserve at least 2.0 mm of keratinised tissue to avoid further soft tissue complications such as gingival recession [55]. The aforementioned guidelines are based on the “biologic width” concept, as measured from the free gingival margin to the crestal bone, which is approximately 3 mm, consisting of, on average, 1 mm of junctional epithelium, 1 mm of connective tissue attachment, as well as a gingival sulcus depth of approximately 1 mm [55, 69]. In order to decide between the conventional flap approach and laser gingivectomy, the gingivectomy location should be probed, and the amount of attached gingiva, the location of the crest of bone and the desired amount of crown lengthening should be looked into based on the limitations of the biologic width. In general, an average of 3 mm of soft tissue will rebound (regrow) coronal to the alveolar crest in about 3 months [77].

12.1.9 Laser Gingivectomy to Improve Oral Hygiene or Bracket Positioning

Difficulties in cleaning approximal tooth surfaces and reduction in aerobe/anaerobe ratio of sub- and supra-gingival flora [78, 79] may contribute to the gingival hyperplasia and pseudo-pocketing. This is common following fixed orthodontic therapy and can be seen in about 10% of orthodontic patients [76, 80]. Gingival enlargement often impedes the maintenance of oral hygiene, causing aesthetic and functional problems, and has been reported to compromise orthodontic tooth movement [76, 81, 82]. Conventional treatment for gingival enlargement often includes oral hygiene instruction, scaling, root planing and prophylaxis, but extensive and often fibrotic gingival enlargement compromises the self-care and may necessitate gingivectomy to maintain oral health [76, 83]. The adjunct use of diode laser gingivectomy can produce a greater and faster improvement in gingival health of patient with gingival enlargement [76].

In addition, laser gingivectomy can be performed to remove excess soft tissue and expose the crown of the partially erupted teeth, allowing brackets to be placed properly, ideally in the centre of the teeth, allowing maintenance of an improved level of hygiene during treatment [55, 84].

12.1.10 Aesthetic Laser Gingival Recontouring

Following active orthodontic treatment, it is not unusual to “debond” – remove – adherent orthodontic brackets and come across unsightly gingival margins not conforming to the principles of smile aesthetics, presenting with short or uneven crown heights, disproportionate tooth proportionality ratios and unaesthetic enlarged and fibrotic interdental papillae and gingival margins [7]. Aesthetic procedures such as aesthetic crown lengthening or papilla flattening can be technically demanding tasks in that the gingival margins sometimes need very minor recontouring that needs a higher degree of precision than that achieved with a scalpel blade, regardless of the operator’s skill level [85]. Diode lasers offer the precise incision control because of less bleeding and a clear dry field during surgery. ◘ Figures 12.3a–c show a patient who has undergone gingival recontouring of the maxillary left central incisor and lateral incisor.

12.1.11 Laser Exposure of the Superficially Impacted Teeth

One of the most interesting applications of diode laser is for exposure of superficially impacted teeth, in particular for maxillary permanent canines, which are the most frequently impacted teeth after third molars (0.92–4.3%) [86, 87]. The conventional approach is to wait for the tooth to erupt, which could delay treatment for months and affect treatment efficacy adversely, or to refer for the placement of an apically positioned flap or mucoperiosteal flap [70]. The flap procedures are relatively aggressive in nature. Accurate

◘ **Fig. 12.3** (**a**) A preoperative image of a patient with gingival hyperplasia at the maxillary left lateral incisor (UL2) region. (**b**) Immediate post-operative appearance following local infiltration (2% lidocaine). Laser operating parameters used were the continuous-wave 940 nm diode (InGaAsP) laser (Epic 10, Biolase, Irvine, CA), with a 400-μm diameter fibre-optic tip, in a contact mode after initiation (power output = 1 W). Some carbonisation is evident at the laser gingivectomy site. (**c**) Immediate post-operative close-up view after gingivectomy

localisation of the impacted tooth prior to laser exposure is vital to establish if the impacted tooth is positioned superficially and not covered completely by bone, or needs referral to an oral surgeon or periodontist for surgical exposure. The presence of a labial bulge does not guarantee access to crown after soft tissue exposure as clinical crown might be fully covered by alveolar bone. The localisation should be based on both clinical (blanching of tissue with finger pressure) and, if in doubt, by radiographic examination [88]. Approximately, 85% of canine impactions occur palatally and 15% buccally [88–90].

Diode laser exposure is not applicable in cases of full impaction of teeth covered by cortical bone. In such cases, a conventional full-thickness mucoperiosteal flap (palatal impaction) or an apically positioned flap (buccal impaction) and removal of cortical bone until the crown portion of the retained tooth is exposed are recommended. When superficially impacted teeth are present, it is recommended to create sufficient space before the surgical laser exposure to facilitate bonding an eyelet or bracket and apply orthodontic forces right after laser exposure.

◘ Figures 12.4a–c demonstrate a male patient with a buccally impacted maxillary right canine, which has undergone laser exposure right after exposure and at 24 h follow-up. Note that the amount of post-operative inflammation is minimal.

◘ Figure 12.5a shows a buccally impacted maxillary left canine, right after laser exposure (◘ Fig. 12.5b), bonding (◘ Fig. 12.5c) and applying orthodontic force (◘ Fig. 12.5d) as well as at 2 weeks (◘ Fig. 12.5e) and 11 months follow up (◘ Fig. 12.5f).

◘ Figures 12.6a–d illustrate the remarkable healing process in a male patient with a palatally impacted maxillary right canine, after palatal laser exposure.

◘ Figures 12.7a–j show another patient with a buccally impacted maxillary right canine and a partially erupted maxillary left canine. The gated-CW mode and pulse duration of 1m second was used, which led to minimum post-operative discomfort and excellent healing at

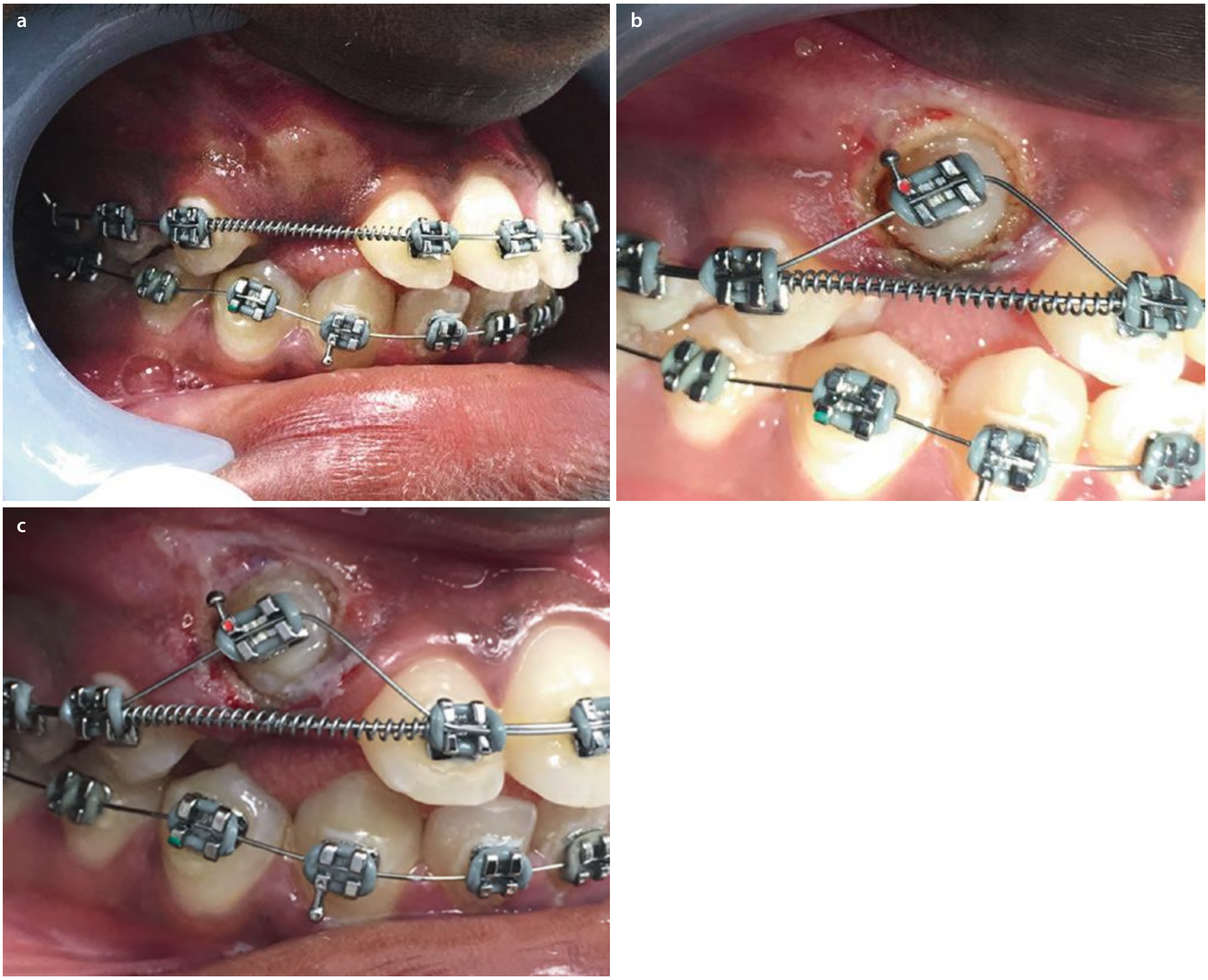

Fig. 12.4 (**a**) A male patient with a buccally impacted maxillary right canine. (**b**) Immediate post-operative view of laser-assisted exposure through soft tissue ablation. The bloodless field facilitates the bonding process and placement of orthodontic brackets. Laser operating parameters were the 940 nm diode laser (Epic 10, Biolase, Irvine, CA), with an initiated 400-µm diameter fibre-optic tip, in a contact mode (gated-CW mode, average power output = 1 W, pulse duration = 1 ms, time on/time off = 50%). Time spent for the laser exposure was approximately 10 mins. (**c**) Appearance at 24 h follow-up. Note that the amount of inflammation is minimal. The patient reported very minimal pain and discomfort during the first 24 h

subsequent follow-ups. The diode laser in this case clearly provided bloodless site that allowed immediate orthodontic bonding of the maxillary canines and reducing the treatment time.

Compared to laser tooth exposure, a patient with a similar superficially palatally impacted canine usually is usually referred for full-thickness mucoperiosteal flap, which can be very aggressive and often needs placement of a protective dressing (pack) over the surgical site whilst it heals [91]. The use of scalpel usually involves suturing with stitches during surgical procedure that need to be removed 1–2 weeks post-operatively. [92] All demonstrated cases were performed using the 940 nm diode (InGaAsP) laser (maximum power output = 10 W, Epic 10, Biolase, Irvine, CA), using a 400-µm diameter fibre-optic tip, in a contact mode and after initiation.

12.1.12 Other Applications of the Laser Soft Tissue Procedures in Orthodontics

Diode lasers have been used to uncover temporary anchorage devices (TADs), in frenectomy where highly attached frenum impedes tooth movement in diastema cases, in removal of operculum on mandibular second molars that prevents banding, or to improve healing of minor aphthous ulceration following placement of fixed orthodontic braces [7, 55, 70].

12.1.13 Post-op Instruction

Literature review indicates suggestions such as keeping the area clean, using soft-bristle toothbrush (or cotton swab), rinsing the

Fig. 12.5 (**a**) A female patient with a buccally impacted maxillary left canine. (**b**) Immediately after laser-assisted exposure. A 940 nm diode laser (Epic 10, Biolase, Irvine, CA) with an initiated 400-µm diameter fibre-optic tip, in a contact mode, was used (gated-CW mode, average power output = 1 W, pulse duration = 1 ms, time on/time off = 50%). Time spent for the laser exposure was approximately 10 min. (**c**) After bonding the bracket, please note that the bloodless exposure site facilitates immediate placement of orthodontic bracket. (**d**) Applying orthodontic force immediately after exposure reduces the treatment time. (**e**) At 2 weeks follow-up. (**f**) at 11 month follow-up, note the adequate amount of keratinised tissue at the maxillary left canine buccal aspects

mouth with salt water three or four times daily for several days and removing any remaining tissue with a wet cotton swab [7, 55], rubbing vitamin E gel over the healing area (to aid in healing and keeping the treated area moist), as well as taking over-the-counter analgesics such as acetaminophen (500-mg tablet qid prn 3 3/7) that have been suggested for pain control [55, 76].

Fig. 12.6 (**a**) Preoperative appearance with the patient wearing the safety protective glasses. The palatal canine bulge is clinically evident. (**b**) Palatal view. (**c**) Immediately after palatal laser exposure. Laser operating parameters were the 940 nm diode laser (Epic 10, Biolase, Irvine, CA), with an initiated 400-µm diameter fibre-optic tip, in a contact mode (gated-CW mode, average power output = 1 W, pulse duration = 1 ms, time on/time off = 50%). Time spent for the laser exposure was approximately 15 min. An aggressive conventional full-thickness mucoperiosteal flap often needs placement of a protective dressing (pack) over the surgical site whilst it heals and is associated with significant bleeding in the exposure site that can compromise the bonding process. (**d**) At 2 weeks follow-up. Please note the excellent healing without signs of inflammation

12.1.14 Laser Photobiomodulation in Orthodontics

As previously mentioned, lasers with power outputs of <500 mW are used in *low-level laser therapy* (LLLT) to provide biomodulation, wound repair and pain relief [55]. This application involves two main uses including the acceleration of orthodontic tooth movement and the reduction of orthodontic pain.

12.1.15 Lasers for Orthodontic Pain Reduction

There is body of evidence confirming that placement of orthodontic separators and initial aligning archwires induce pain that reaches peak intensity at approximately 24 h [91, 93, 94–97]. This pain caused by orthodontic treatment can affect patient's compliance and even force them to terminate treatments prematurely [98].

Two recent systematic reviews that included meta-analysis of the previous randomised controlled trials (RCTs) investigated the effects of diode LLLT on orthodontic pain [99, 100]. One stated that the comparison of laser versus placebo demonstrated that LLLT reduced the pain score significantly compared with placebo groups *($P < 0.00001$)* [99]. Furthermore, a trend of earlier pain termination in laser versus control and placebo groups was detected, but without statistical significance *($P > 0.05$)* [99]. The other study revealed that diode LLLT significantly reduced orthodontic pain by 39% in comparison with placebo groups *($P = 0.02$)* [91]. Diode LLLT was shown to significantly reduce the maximum pain intensity amongst parallel-design studies ($P = 0.003$ versus *placebo groups*; $P = 0.000$ versus *control*

■ **Fig. 12.7** (**a**, **b**) A male patient with a buccally impacted maxillary right canine and a partially erupted maxillary left canine (**c**–**f**) Immediate postoperative view after laser-assisted exposure and bonding and following placement of orthodontic wire. Laser operating parameters were the 940 nm diode laser (Epic 10, Biolase, Irvine, CA), with an initiated 400-μm diameter fiber-optic tip, in a contact mode (gated-CW mode, average power output = 1 W, pulse duration = 1 ms, time on/time off = 50%). Time spent for the laser exposure was approximately 15 mins. Appearance at one week (**g**, **h**) and at 4 month (**i**, **j**) follow- up groups) [100]. Authors of both systemic reviews concluded that the use of diode LLLT for orthodontic pain appears promising. However, due to methodological weaknesses, there was insufficient evidence to support or refute LLLT's effectiveness [99, 100]. Therefore, RCTs with better designs and appropriate sample power are required to provide stronger evidence for diode LLLT's clinical applications and identify the appropriate laser parameters such as irradiation dose, power output, fluency and continuous/pulsed mode.

12.1.16 Lasers for Acceleration of Orthodontic Tooth Movement

This area of investigation is quite recent, and new studies are emerging. Receptor activator of nuclear factor kappa-B ligand (RANKL) and its receptor RANK are members of the tumour necrosis factor (TNF) and TNF receptor superfamilies and present a regulatory function in bone homoeostasis [101]. The available limited evidence suggest that LLLT increases the expression of RANK and RANKL [102] and may have a rule in accelerating orthodontic tooth movement [103–109]; however, identifying the ideal parameters of the LLLT needs more investigations, such as the most effective laser wavelength, power output, energy density, irradiation dose and ideal time interval between them, as well as the method of delivery.

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Summary
The use of diode lasers for soft tissue procedures and photobiomodulation introduced alternative adjuncts for gingivectomy, to improve oral hygiene or bracket positioning and gingival recontouring, to enhance gingival aesthetics, and for laser exposure of the superficially impacted teeth, to reduce the treatment time as well as for reducing the orthodontic pain or potentially decreasing orthodontic treatment time. The diode laser incision/excision is usually performed in a contact mode, and the use of a 400-μm diameter fibre-optic tip is recommended. Compared to scalpel surgery, diode lasers offer a clean and bloodless surgical site, with an added benefit of photobiomodulation that enhances the wound healing and reduces the patient discomfort. There is obviously a strong argument for laser safety that can be addressed with proper training. However, there is paucity of data regarding the most effective wavelength (810, 940 or 980 nm) for performing diode laser gingivectomy or tooth exposure, as well as other laser parameters such as continuous or pulsed/gated mode of delivery, and the optimum power output that requires further research.

12.2 Photobiomodulation Concepts Within Orthodontics

Mark Cronshaw

Lasers and LED phototherapy appliances have been the subject of many scientific in vitro, in vivo animal and more recently clinical studies for a variety of non-surgical effects. The possibility of applying photonic energy as a treatment modality to biomodulate cellular, humoral, vascular and neuronal tissue behaviour has been subject to many studies over the past 45 years. The potential applications of lasers and LED phototherapy for orthodontics include pain relief as well as the possibility of shortening treatment time by accelerating the rate of orthodontic tooth movement. Pain associated with standard orthodontic treatment is a common problem, and along with protracted treatment times, these issues represent a significant problem reducing patient compliance and acceptance of treatment. Initial investigations studied the observable effects of laser devices to influence pain and discomfort experienced by patients associated with the forces applied to teeth to achieve movement. The mechanisms underlying orthodontic pain are discussed here along with a discussion of the problem and an analysis of the current literature.

12.2.1 Background

At present the consensus opinion is that further studies are required to strengthen the evidence base and define the optimum methodology; however, the published studies to date are encouraging and indicate some positive clinical benefits. In respect of the acceleration of orthodontic tooth movement, there has been considerable interest as reflected in the volume of published studies attempting to use both in surgery laser devices and more recently the use of patient home-use LED phototherapy appliances to shorten treatment time. A description and discussion of the various animal and clinical studies are presented here. Due to the highly heterogeneous nature of the various studies, there is at present no consensus on appropriate treatment strategies, although this is clearly an area worthy of continued investigation. The current evidence base is inadequate. However, there are some interesting animal and clinical studies which support this topic as worthy of further in-depth evaluation. The most recent clinical trials use a patient home-LED therapy device which could potentially represent an entirely new approach to shorten treatment time and overcome a major obstacle to the uptake of orthodontics.

A variety of light sources have been investigated for possible therapeutic gain in orthodontics for a range of non-surgical applications. Of the optical sources investigated, a variety have been applied, the majority of which are diode semiconductor lasers or LED lights in the waveband range of 650–980 nm A variety of clinical applications have been proposed, for instance, as an adjunct to the possibility of reducing the frequency of incidence, duration and intensity of pain associated with standard orthodontic therapies. Also, researchers have evaluated the potential of phototherapy to accelerate orthodontic tooth movement (OTM) or conversely enhance anchorage. Many of the published studies have used in-surgery laser equipment, although more recently home application devices for patient self-administration of home-based phototherapy have been developed using transdermal or intra-oral LED devices [110–112].

The potential clinical gain to treat orthodontic patients taking advantage of the known physiological properties of light is an intriguing area. There are many in vitro, in vivo animal studies and some clinical trials and reports in the current scientific literature. As a product of over 40 years of research, quite a lot is known about how light can interact with biological tissues which can result in a variety of possible beneficial effects. More bone, enhanced repairs, reduced inflammation, vasodilatation and analgesia are amongst a long list of possible effects [113, 114].

At the time of writing, there have been, within the past 3 years, over 10 systematic and narrative reviews on various aspects of orthodontic phototherapy, assessing animal and clinical studies that have been published during the preceding 20 years. This high level of recent activity is indicative of the considerable interest surrounding the claims of proficiency in the literature. This is an area shrouded in confusion, and notwithstanding the volume of publications, this is still a subject with a developing scientific evidence base. It is the intention here to offer an overview of the subject along with a critical analysis and description of some of the various suggested treatment strategies [110, 111, 115–122].

It is worthy of note to examine the reasons for the current level of clinical interest and scientific endeavour. Every year, many millions of children and adults worldwide receive orthodontic treatment with a trend towards the increasing uptake of this type of therapy by adults. A typical course of orthodontic treatment can take between 12 and 24 months to complete with a variable amount of post-treatment time for retention with appliances or fixed splints. Orthodontic treatment can frequently be associated with a variety of side effects, including variable degrees of pain and discomfort, alveolar bone resorption, root resorption, caries and a variety of periodontal issues. Due to the protracted nature of orthodontic treatment and the various possible associated complications, there can be a loss of patient motivation. Also, extended treatment results in increased costs, due to time away from school, work, extracurricular and recreational activities. Particularly for adults the commitment to time is a prime deterrent to patients to commit to this type of therapy. All of these issues result in a reduction in treatment uptake as well as failures in treatment compliance. Any assistance that can improve patient comfort and shorten treatment length consequent to the acceleration of the rate of OTM can help to alleviate these risk and challenges [123–130].

12.2.2 Pain Studies

It is accepted that orthodontic tooth movement involves a complex cascade of processes consequent upon the creation of tensile and compressive areas in the periodontium. An inflammatory response is essential in the remodelling of alveolar bone and periodontal ligament during orthodontic tooth movement. As a response to the acute inflammation, there is increased osteoclastogenesis and an upregulation of matrix metalloproteinases associated with tissue remodelling [131].

In response to the application of load, there is mechanical stimulation as well as some damage of cells and tissues and associated changes in blood flow. This is a trigger to a complex pro-inflammatory cascade of cytokines including histamine, bradykinin and prostaglandins amongst others. The nervous system contributes to the physiology of the resultant peripheral inflammation mediated via neuropeptides such as substance P, neurokinin A and calcitonin gene-related peptide. These potent mediators induce vasodilatation, increased vascular permeability and the activation of nuclear factor kappa B. The overall resulting biological response is to produce so-called aseptic inflammation which results in the stimulation of C-nerve and A-delta nerve fibres producing pain symptoms. These symptoms can vary in intensity and duration and are most normally seen during the first hours after the application of forces. Pain usually reaches a peak after around 18–36 h with a gradual decline over the following week. This pain/discomfort experience is commonly associated with fixed and removable appliances, separator and band placement, bracket debonding and wire displacement. The consequent deterioration in patient comfort can in prevalence affect the majority of patients and is recognised as a key barrier to the completion of orthodontic treatment [128–131].

Strategies to manage orthodontic pain have been proposed, including the application of transcutaneous electrical nerve stimulation, vibratory appliances and other methods such as chewing gum or plastic wafers. The most common option has been to prescribe non-steroidal anti-inflammatory drugs (NSAIDS). These are effective in pain relief; however they are associated with the hindering of osteoclastic activity due to the inhibition of the production of prostaglandins via COX2 suppression. Also, NSAIDs can be associated with serious adverse effects such as gastric bleeding, ulcers and allergy. Studies in experimental animals have demonstrated a reduction in the rate of OTM in conditions where inflammation has been suppressed, and it is apparent that induced acute inflammation is a necessary component associated with OTM bone remodelling [115, 117, 118, 132–137].

Laser phototherapy has been applied for the management of acute and chronic pain for a wide variety of conditions, including various arthropathies and neuropathies, as well as to ameliorate the pain and discomfort associated with cancer chemotherapy- and radiotherapy-induced oral mucositis. The precise mode of operation of laser-induced analgesia is still the subject of continued investigation. It is thought to operate on a variety of local and systemic pathways including the inhibition of axonal depolarisation; the selective reduction of acute inflammatory mediators such as prostaglandins, IL1-B, IL-6 and TNF-α; vasodilatation and improved lymphatic drainage; as well as systemic effects mediated through humeral and peripheral neural pathways [138–144].

A variety of laser wavelengths have been found to be useful in producing analgesia including the helium-neon laser, the diode laser, the Nd:YAG laser, the Er:YAG and ErCr:YSGG lasers as well as the CO_2 [114, 121, 138–140, 143, 145] (see also Table 12.2). Due to the potential for deep tissue penetration, consequent upon the low absorption of the incident photonic energy by tissue chromophores such as water, the wavelengths that may be best suited for this purpose are the diode lasers as well as the Nd:YAG. Lasers differ from broader spectrum light sources such as LEDs by virtue of narrow waveband in comparison to the LEDs, as well as by being a coherent light source, whereby all the photons are in the same phase and space. This physical phenomenon can result in the generation of areas of interference and amplification; in turn, this can result in laser sources having deeper penetration into tissues, compared to a noncoherent light source – hence facilitating the delivery of an adequate dose. In addition, a free-running pulsed laser such as the Nd:YAG can have very high peak power (albeit for a very short pulse duration) which could, in principle, cumulatively permit sufficient energy to reach deeper tissue layers to precipitate the photochemical and photophysical changes associated with analgesia. The choice of wavelength and type of laser applied, however, has not been subject to a meta-analysis, and at this stage, it is premature to make an evidence-based determination [114, 138, 159].

In respect of the orthodontic literature, two types of diode laser have been used most frequently: the InGaAlAs laser (λ 630–700 nm) and the GaAlAs laser (λ 780–890 nm).

A recent review by Ren et al. [121] included a total of 14 eligible studies. It was noted that the output power and energy delivered varied greatly between studies (0.18–9 J per treatment point). There were marked differences in the methodology of application as some studies used a single-point method, whereas others used multiple points of application along the root in contact with the mucosa. There was also a range of application frequency from a single time through to multiple additional irradiation within 1 week of orthodontic treatment. Although the majority of studies included supported the beneficial effects of laser irradiation, it was a highly heterogeneous set of studies. Also, regrettably, there was incomplete reporting of the parameters as important information concerning beam size and energy density was missing in some of the studies. In consequence, it was not possible for the authors to draw conclusions as to the merits of diode laser therapy for orthodontic pain control. It was, however, noted that in respect of the prevalence of pain that of a synthesis of two studies [150, 151] by meta-analysis, the pain was reduced by 39% at a significant level compared with the placebo. The time course of pain was investigated in two studies which revealed that pain subsided significantly earlier in the laser-treated group compared to the placebo. Also, this interesting review paper noted that in the parallel-type studies, there was a marked reduction in pain severity, whereas in the split-mouth studies, this was only slightly reduced. This may be explained by the possibility of cross-over effects and photo-contamination of the test sites as well as the proposal that laser-induced analgesia may, in part, be mediated systemically, hence the different outcomes between the two types of study.

A more recent systematic review by Sonesson et al. [110] reported that of the 13 studies included, all reported a significant reduction in pain amongst the treated patients. This outcome was consistent with two previous systematic reviews. Sonesson's group applied strict measures for inclusion and a high level of assessment to score the clinical trials following the guidelines of The Swedish Council on Technology Assessment in Health Care [160]. Sonesson et al. identified inconsistencies in design of the studies, reporting and different outcome parameters (acute pain as opposed to delayed pain). The overall quality of the evidence was regarded as poor, largely consequent upon inconsistencies in study design and conformity of laser method applied. The fact remains, however, that notwithstanding strict guidelines, it was accepted that this is an evidence-based approach; the significance of the level of pain reduction compared to the placebo/control group was questioned.

There is the need to further develop the scientific understanding of the mechanisms underlying laser-induced analgesia which has been found clinically useful in restorative dentistry as well as in a variety of unrelated pain studies. The orthodontic modulation of pain by laser is clearly an emerging area which shows some promise, and perhaps as the evidence base further matures, this may in time turn into a useful management approach for a highly significant clinical problem.

12.2.3 Acceleration of Orthodontic Tooth Movement

Many methods to accelerate tooth movement have been attempted, including surgical corticotomy, pulsed electromagnetic fields, ultrasound, electrical stimulation and the use of a variety of drug injections. For example, increased rates of OTM have been reported following the administration by

Table 12.2 Summary of data from recent clinical studies on acute pain [146–158]

Study	Subjects	Study design (laser/placebo/control)	Pain measure	Wavelength	Power	Time	Frequency	Result
Lim [146] (1995)	39/39	Double-blind placebo RCT (split mouth)	VAS	830 nm GaAsAl	30 mW	15 s–5 min	1/d 5d	Null
Harazaki [147] (1997)	20/20/44	Single-blind RCT	NRS (1–5)	632.8 nm He-Ne	6 mW	30 s–24 min	1	↓Onset
Harazaki [148] (1998)	20/20	Single-blind CCT	NRS (1–5)	632.8 He-Ne	6 mW	30 s–5 min	1	Pain 48.4%↓
Fujiyama [149] (2008)	60/60/30	Single-blind CCT (split mouth)	VAS	10,600 CO2	2000 mW	30s–1 min	One	Pain 40%↓
Tortamano [150] (2009)	20/20/20	Double-blind RCT	NRS (1–5)	830 nm GaAsAl	30 mW	16 s–37min	One	↑Resolution
Doshi-Mehta [151] (2012)	20/20	Single-blind RCT	VAS	800 nm AlGaAs	0.7 mW	30 s–∞	Day 0/3/7/14	↓25% d3 ↓38% d30
Kim [152] (2012)	28/30/30	Single-blind RCT	VAS	635 nm AlGaInP	6 mW	30 s–28 min	2×/d 1wk	↓45% av
Artés-Ribas [153] (2012)	20/20	Single-blind RCT (split mouth)	VAS	830 nm GaAlAs	100 mW	20–300 s	One	↓45%
Domínguez [154] (2013)	60/60	Single-blind RCT (split mouth)	VAS	830 nm GaAlAs	100 mW	22–44 s	One	↓52%
Eslamían [155] (2013)	37/37	Single-blind RCT (split mouth)	VAS	810 nm AlGaAs	100 mW	20–300 s	Two	↓VAS d3 ↓22%
Nóbrega [156] (2013)	30/30	Double-blind RCT	VAS	830 nm AlGaAs	40.6 mW	25–125 s	One	↓88%
Abtahi [157] (2013)	29/29	Single-blind RCT (split mouth)	VAS	904 nm GaAs	200 mW	7.5–30 s	1×/d, 5d	↓40%
Heravi [158] (2014)	20/20	Single-blind CCT (split mouth)	???	810 nm GaAlAs	200 mW	30–240 s	Day: 4/7/11/15/28 32/35/39/43/56	Null

Adapted from Sonesson et al. [110]
The majority of studies demonstrated a reduction in pain following orthodontic procedural visits

local injection of biomodulators such as prostaglandins, vitamin D, corticosteroids, osteocalcin or parathyroid hormone. However, these agents are rapidly flushed from the tissues, and daily injections are required for the delivery of some of the pharmacological agents, such as corticosteroids. Although these methods may confer advantages in shortening treatment time, they also have some drawbacks as they may call for the use of specialist apparatus. The application of chemicals can have negative effects on bone metabolism or contribute to root resorption, and surgery in the form of corticotomy can be an unpleasant experience for the patient. Surgical approaches are by nature invasive requiring some surgical skill, or the administration of frequent painful injections may be required with drug injections which may reduce patient acceptance.

By contrast, phototherapy is not associated with any negative side effects. Other than the need for good optical protection whilst applying intense light sources, there are no common complications or safety concerns in relation to phototherapy. Indeed, should in future the technique become an evidence-based standard, there is the possibility of supplying the patient with an appropriate home therapy appliance which, if proven effective, could significantly reduce the burden on resources and improve patient compliance [117, 122, 132–136].

Orthodontic treatment consists of directed tooth movement and an associated cycle of bone apposition and resorption. Forces applied to teeth produce areas of compression and tensile pressure in the periodontal apparatus, which results in a change in osteoblast and osteoclast activity. An extended duration of orthodontic treatment is associated with an increased risk of root resorption, periodontal disease and caries [122, 161].

On the application of an orthodontic force, a rapid acute inflammatory tissue response is elicited. The subsequent application of phototherapy apparently optimises the cellular response permitting an increase in bone metabolism. It is recognised, however, that higher doses of phototherapy can have an inhibitory effect on cellular metabolism. However this will not result in tissue damage, providing the applied energy is kept below the level required to significantly heat the tissues to the point of protein degradation [114, 162].

As OTM requires the trigger to bone remodelling of acute inflammation, it would appear counterproductive to apply lasers which have been found to have selective anti-inflammatory properties. Cytokines associated with the acute inflammatory response such as TNF-α, IL-1 and IL-6 are known to be downregulated by red to near-infrared phototherapy. Also, PGE2 is selectively downregulated along with NFKB, and there is evidence of the selective apoptosis of pro-inflammatory cells. However, there are many animal studies demonstrating an increase in bone resorption and apposition associated with the application of laser or LED phototherapy. It is known that cellular physiology is significantly affected by phototherapy, and depending on dose, a variety of effects can be seen. For example, there is a change in the redox status of the cells such that there is a strong increase in the manufacture of ATP by mitochondria. In addition, there is the release and increased production of nitric oxide which is a potent vasodilator. There is a small but significant increase in the production of reactive oxygen species (ROS) which are recognised as being a potent trigger for mitosis at low levels, whereas at higher levels ROS can be associated with the activation of the heat stress protein (HSP) cascade which can slow cellular metabolism. At even higher levels, ROS can trigger cellular toxicity and apoptosis [162–165].

Downstream effects of phototherapy include signs of increased cellular activity such as increased motility, migration, differentiation and phagocytosis plus there is a considerable increase in the rate of cell division (mitosis). Studies in bone metabolism have found a sustained increase post irradiation in alkaline phosphatase, which is a key enzyme involved in bone deposition as well as an increase in platelet-derived growth factor (PDGF) [166, 167].

Studies conducted in animal models using rats, dogs and rabbits have shown promise that laser and LED phototherapy can improve OTM. Measures applied in the animal studies have included histology assessing bone density and volume, the proliferation of osteoclasts and osteoblasts, the number of capillaries and changes in the number of inflammatory cells. By using monoclonal antibodies, there have been immunohistochemical measures for important cytokines involved in bone remodelling, such as osteoprotegerin (OPG) and the receptor activator of nuclear factor kappa-B ligand (RANKL). Animal studies have used metrics on movement of the adult first molar in rats and dogs, although perhaps controversially a few of the studies used movement of the rat incisor as the experimental model. There are studies looking at the effects on the mid-maxillary suture in rapid maxillary expansion augmented with laser or LED phototherapy. Animal studies showed that the application of lasers in the wavelengths of 650–940 nm increased the rate of tooth movement 2–3x compared to control groups. In addition, this outcome was supported by histological evidence of increased cellular activity and significant signs of an increase in bone remodelling compared to control [168–176].

In a recent animal study by Suzuki et al. [177], laser phototherapy was found to increase the number of osteoclasts present on the pressure side, whilst there was a corresponding increase in the number of osteoblasts on the tension side. Aside from the histomorphometric analysis, this interesting study applied an immunohistochemistry analysis of RANKL/OPG and tartrate-resistant acid phosphatase (TRAP) activity. This further correlated the histological findings of increased osteoclast activity in the test group on the pressure side (elevated levels of RANKL and TRAP) and increased bone apposition and osteoblast activity on the tension side (an increase in OPG). Furthermore, the rate of OTM was found to be increased by around 40% compared to the control.

Animal studies represent a substantial body of evidence-based research [111]; however, there is no agreement on laser or LED wavelength, duration of treatment, frequency of treatment, energy density applied or total dose (fluence). Faced with a heterogeneous set of experimental studies based on a variety of animal models ranging from rats, to dogs, to rabbits, it is not possible to extrapolate the results to human subjects. The animal studies are, however, highly supportive of a possible future role for photobiomodulation as an effective tool in accelerated bone metabolism in relation to OTM.

12.2.4 Clinical Trials

In respect of clinical trials, there are published anecdotal case reports, case series, pilot studies and at present a relatively few well-constructed randomised controlled trials.

The table below (Table 12.3) summarises the clinical trials that have been included amongst the many recent reviews and systematic reviews on phototherapy and OTM.

As can be seen from the table of clinical studies [151, 158, 178–182], there is no agreement in respect of choice of wavelength, parameters or frequency of application. It is, however, apparent that in the studies with a positive outcome, there is a trend towards a dose in the range of 2–8 J/cm^2 and that frequent applications of phototherapy are required. Also studies which used high doses returned a null result (Herravi, Limpanichkul [158, 179]). The issue of standardised therapy delivery is a key problem yet to be properly overcome as effective phototherapy requires the administration of photonic energy within a narrow range. Too little energy results in a zero response as does an excessive dose, perhaps consequent to photobioinhibition, as higher doses are associated with cellular stasis rather than stimulation of cellular metabolism [162].

Conventional wisdom suggests that the therapeutic target for the beneficial effects of photobiostimulation falls in a therapeutic dose delivered at tissue level of around 2–8 J/cm^2 [183]. There are, however, many compounding factors which may affect tissue penetration, not least of which is the depth at which the target rests. Incident visible red to near-infrared wavelength photonic energy is absorbed by a variety of tissue chromophores including protein, haemoglobin and melanin. At a target depth of 5–10 mm from the surface of the tissues, the amount of light that penetrates can range from 2 to 10% depending on the wavelength chosen as well as local tissue characteristics, such as the presence of pigments or dense layers of highly keratinised epithelium. Further complicating factors that can make accurate dosimetry difficult include beam divergence (distance from the surface), beam profile (typically it is Gaussian in distribution) and spot size at the tissue surface (which may have a marked effect on energy density). As the very many laser and LED devices are not the same, it is not at present possible to make anything but highly tentative proposals on treatment and management practices [113, 114](Fig. 12.8).

Amongst the significant drawbacks to the use of laser phototherapy for accelerated OTM is that the equipment is expensive to purchase and training is required to develop the necessary clinical skills. There are also safety implications as, due to the potential for serious optical damage, appropriate eye protection is required. A further problem is that the treatment strategies adopted to date require frequent re-care attendance by patients, which has important implications for the logistics of the availability of appropriately trained personnel.

12.2.5 Current Trends

More recently, clinical studies have tested the use of LED phototherapy as an alternative to lasers to modulate the rate of OTM [184–187]. LED devices are relatively inexpensive compared to laser equipment. In addition, the output power and the absence of optical coherence which is inherent to lasers reduce the potential optical hazards. Finally, in a departure from previous surgery-based equipment, devices have become available which are intended for self-administration at home. This has important advantages over office-based systems, as it can reasonably be anticipated to improve patient access to treatment. Potentially this may have an impact on compliance whilst reducing the need for repeated visits to the operatory over a period of many months. The use of a handheld laser by a skilled operator is time-consuming and requires frequent applications.

The first of this type of appliance was a transdermal device which used a near-infrared wavelength of 850 nm. The initial reports on a retrospective cohort study by Kau, Kantarci and Shaughnessy et al. [184] assessed a treatment time of 20 or 30 min on a daily basis or a single 60 min treatment (Fig. 12.9), once a week by the patients at home. The surface of the cheek was irradiated at a power density of 60 mW/cm^2, and the 73 test subjects were compared to a control group treated by another centre without the intervention. Tooth movement was assessed by Little's Irregularity Index (LII) which is a quantitative measure of five contact points. The technique involves measurement directly from the mandibular cast with a calliper (calibrated to at least tenths of a millimetre), held parallel to the occlusal plane. The linear displacement of the adjacent anatomic contact points of the mandibular incisors is determined, the sum of the five measurements representing the Irregularity Index value of the case. Assessments were conducted at baseline, then every 2 weeks for a 6-week period and then every 4 weeks until alignment was achieved. The average results appeared to demonstrate that the mean rate of change in LII was 0.49 and 1.12 mm/week for the control and test groups implying an increase in the rate of OTM by two- to threefold. There are, however, issues related to the design of this groundbreaking study, as the intervention was not a randomised controlled or blinded trial. In addition, different operators were involved in placing the fixed appliances which may have used different bracket systems. The test group is noted by the authors to have at the outset a higher LII, and the authors acknowledge that there was the need for a larger and longer clinical trial to assess the long-term stability of the outcome. The study was sponsored by the manufacturer of the appliance, and this study can at best be viewed indicative of the need for further independent and better designed studies.

The same appliance was subsequently subject to an independent hospital-based controlled clinical trial by Chung et al. [185]. This was a split-mouth randomised controlled

Table 12.3 Summary of clinical trials included in recent systematic reviews

No	First author (publication year)	*N*	Laser					Application			Result velocity
			Laser type	Wave-length	Power, time	Dose (J/cm [2])	Total energy (j)	Irradiation interval	Applied tooth	Force (g)	
70	Cruz [178] (2004)	11	Diode laser	780 nm	20 mW, 10 s 0.04 cm^2	5/point 50/ session	0.2/point 2.0/session	4 days of each month	Canine	150	Increase 34% (2 months)
71	Limpanichkul [179] (2006)	12	Diode laser	860 nm	100 mW, 23 s 0.09 cm^2	25/point 200/ session	2.3/point 18.4/ session	First 3 days of each month	Canine	150	No effect (3 months)
72	Youssef [180] (2008)	15	Diode laser	809 nm	100 mW, 10/20/10s	No informa-tion	8.0/session	0,3,7, 14 days	Canine	150	2 × Increase (6 months)
73	Sousa [181] (2011)	13	Diode laser	780 nm	20 mW, 10s 0.04 cm^2	5/point 50/ session	0.2/point 2.0/session	0,3,7 days of each month	Canine	150	2 × Increase (4 months)
74	Genc [182] (2013)	20	Diode laser	808 nm	20 mW, 10s 0.28 cm^2	0.71/ point 7.1/ session	0.2/point 2.0/session	0,3,7,14, 21,28 days	Upper lateral incisors	80	20–40% increase (1 month)
44	Doshi-Mehta [151] (2012)	20	Diode laser	800 nm	0.25 mW, 10s 0.04 cm^2	8 J 10/ session	2.5 mJ/ point 8.0 J/ session	0,3,7,14, 29,44 days	Canine	150	Increase 30%
51	Herravi [158] (2014)	20	Diode laser	810 nm	200 mW, 30s 0.28 cm^2	21.4 J 10/ session	6 J/point 60 J	0,4,7,11, 15,28, 32, 35,39,43, 56 days	Canine	150	No effect

Adapted from Kim et al. [110]
High-dose regimes were not beneficial, whereas low doses of 2–8 J/cm [2] increased movement by 20–40%

clinical trial, which assessed closure of single tooth extraction sites. LED phototherapy was applied to one side for 21 min/day, and the LED array was inactive on the contralateral side which acted as the control. The output power was set by the manufacturer at 150 mW/cm^2 (from private correspondence to the authors) resulting in a sum total of 189 J/cm^2 delivered daily. Measurements from casts were taken by two independent and blinded assessors on a sum total of 17 dental arches from 11 orthodontic participants – all of whom required bilateral symmetrical extraction of premolars. Three measurements were taken at the outset (T0), at 3–7 weeks after the initiation of space closure (T1) and again at a further 3–7 weeks (T3) after T1. Compliance of home use was measured by the device as well as a record maintained by the participants. The results were that there was no discernible difference in outcome between the test and control sites. It is worthy of note that the rate of compliance by the subjects was reported at around 80% over the study period. This well designed and conducted study followed the CONSORT statement guidelines, and there were no declared conflicts of interest. The authors recognise that there was the potential for photo leakage to the contralateral side. In private correspondence, the authors stated that they sought in their analysis to detect any indication of either stimulation in either or both the control and test sites. However, both sites were found to be the same and also that the outcome was comparable to patients treated with conventional fixed appliance therapy.

The transdermal LED appliance required high output power, to compensate for the high absorption and scatter of the incoming photonic energy. It is debatable whether a meaningful dose can be reliably delivered at depth to

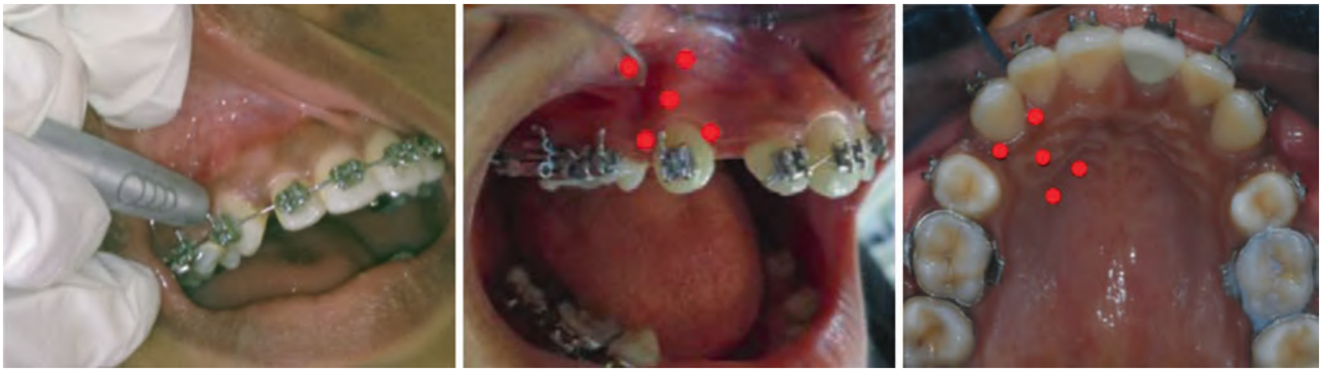

Fig. 12.8 Images illustrating points of application using in this case a 940 nm diode laser in contact with the mucosa at 5 points buccal and palatal to the canine undergoing retraction (Courtesy of Dr Premila Suganthan)

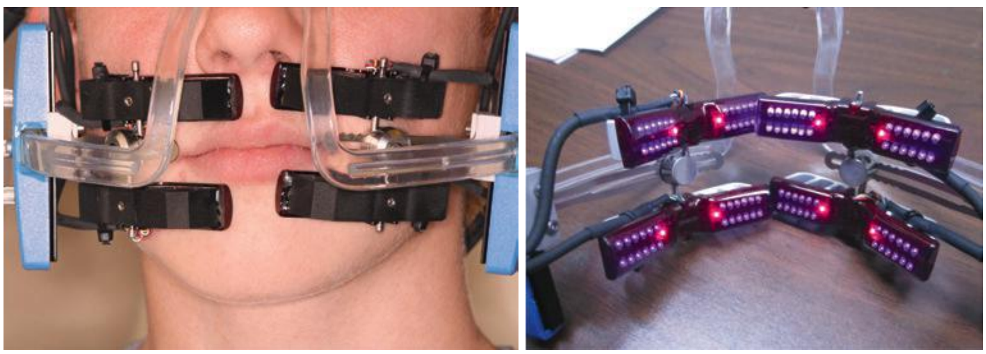

Fig. 12.9 An initial model of the LED extra-oral transmucosal phototherapy appliance for patient home use. Reproduced with permission from Biolux Research Ltd.

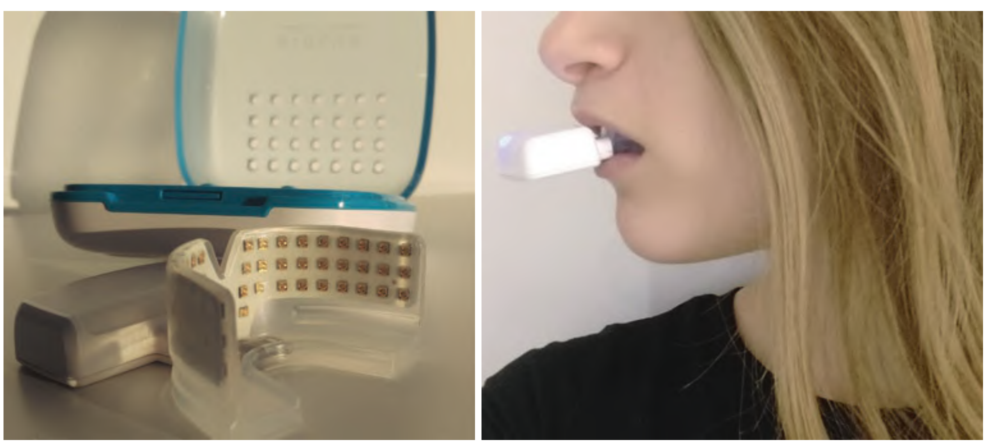

Fig. 12.10 The latest version of the patient home-use LED phototherapy device uses an intra-oral tray lined with arrays of 850 nm LEDs. This appliance is intended for daily home use, and it meters frequency and duration of use. Images reproduced by permission of Biolux Research Ltd.

the target tissues, as the administered light had to cross three layers of highly keratinised epithelium to reach the target tissues. Anatomical variations in cheek thickness between individuals and issues, such as superficial skin pigmentation, effectively prohibit a reliable and reproducible protocol.

In a recent pilot clinical trial conducted by Shaughnessy, Kantarci and Kau et al. [112], a further design of LED home-use appliance was tested (Fig. 12.10). This time, the device was placed intra-orally, and the 850 nm LED arrays are built into an intra-oral applicator tray with a declared output power density of 42 mW/cm^2, used for 3.8 min/day for each arch treated. Nineteen patients were conscripted into the study with the first eight patients being enrolled as the control group of ten arches (three upper and seven lower). The next 11 patients were the test group who provided a total of 18 test arches (ten upper and three lower arches). As in the previous study, the unit of measurement was Little's Irregularity Index, and measurements were taken from casts by a blinded technician. Measures were taken from casts at the outset (T0) and at a second point at which by visual assessment supported by photographs, LII was estimated to have reached ≤1 mm. The outcome reported was that the average period to achieve alignment was 48 and 104 days for the test and control groups.

The authors recognise some limitations to the study as there was no sham device used. The sample size was small, and there were some inconsistencies in the type of bracket applied. Again, this was a company-sponsored study, and it is noteworthy that the control group had a preponderance of lower arches compared to the test group. In addition, as recognised by Chung et al., there can be differences in parallel-type studies between participants; there can be variation in jaw and tooth positions and growth patterns between individuals, which can make comparisons between test and control unreliable especially in small study group sizes. Shaughnessy et al. conclude that overall treatment time in the test groups was significantly reduced, although the authors recognise the need for a larger randomised sham-control clinical trial to further assess the effects of daily patient-administered intra-oral phototherapy.

Most recently, Shaughnessy et al. [186] have published anecdotal clinical reports appearing to support the value of LED intra-oral phototherapy. There is a remarkable case report from Ojima et al. which describes a patient treated with the LED intra-oral appliance, Invisalign clear aligners for upper and lower anterior crowding, an anterior open bite and a lateral incisor crossbite with a v-shaped maxillary arch. Usually a patient would require a new pair of upper and lower aligners once every 2 weeks over a period forecast, in this case to be 21 months. The device was used by the patient for 5 min for each arch daily. Ojima et al. [187] report that following the adjunctive daily use of the LED intra-oral device, the aligners were changed every 3 days and that the whole course of treatment was completed in 6 months.

However, clinical reports and poorly controlled non-randomised case series, in the absence of adequate blinding, are at the lowest level of evidence base and can at best only be viewed as indicative of the need for further well-designed assessments by controlled randomised clinical trials. It can only be concluded that there is at present no adequate scientific base to support the integration of this highly innovative technique of patient self-administered therapy.

Conclusion

Based on in vitro, in vivo animal studies and a limited scientific clinical evidence base, the prospects for the use of clinical phototherapy in orthodontic case management look promising. However, there is much that is still not known about the dosimetry of phototherapy and the consistent delivery of photonic energy to the correct target tissue depth. Significant efforts are needed to standardise the clinical dosing and delivery protocols of phototherapy, to ensure the maximal efficacy to achieve analgesia and manipulate the cellular and molecular processes associated with bone remodelling. In addition, as in many other areas of clinical practice, more high-quality research is required, prior to general acceptance of this method as an evidence-based approach.

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Laser-Assisted Soft Tissue Oral Surgery: Benign Soft Tissue Lesions and Pre-prosthodontic Procedures

Claus Neckel

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Core Message
The initial experimentation and early clinical practice of laser use have been reported in the mid-1960s [1], and one of the first initial clinical surgeries was documented in 1977 [2]. Nowadays, a laser procedure is defining the standard of care for many oral surgeries, offering many advantages for both the surgeon and the patient. The purpose of this chapter is to explain those therapies and to demonstrate those benefits.

13.1 Introduction

In 1960 Maiman published his pioneering work on the ruby maser [3]. This was based on the theoretical statements of Einstein dated in 1917 [4] and the work of Schawlow and Townes in 1958 [5]. Based on this breakthrough, many groups working on different laser types published their studies in the 1960s. Those articles led to the development of the main laser types in use today such as the CO_2 laser, the Nd:YAG laser, or the diode laser [6–11]. For dentistry, the long sought-after goal was to replace the pain and vibration of the drill with a laser. This quest for the drill substitute held up the introduction of lasers in the dental field as it took till 1989 for the Er:YAG laser [12, 13] to be studied and then developed for practice a few years later. At this time lasers had been in widespread use in medicine working mainly on soft tissue. Beginning in the 1990, laser therapy began to establish its place in dentistry.

Prior to lasers, there were three main methods of oral surgical treatment available:

- The conventional scalpel
- Electrosurgery [12]
- Cryotherapy (in use since the mid-1970s) [13]

For treatment of dental hard tissue, there are only a few wavelengths that may be used (Er:YAG, Er, Cr:YSGG, CO_2). However, in soft tissue surgery, up to ten different wavelengths are applicable. The surgeon has a choice of a fiber-based delivery system (Nd:YAG, diode lasers) or a noncontact optical system (CO_2, erbium family).

- *Diode lasers (445–1064 nm)* are best used on pigmented tissue. They are small, compact instruments whose portability can be an advantage for short procedures. They are delivered through a small-diameter flexible optical fiber with an optional tip that can access small areas of tissue. Using a gated mode with digitally modulated pulse width and high-output-power diode laser has become very much more efficient than the early generations.
- *Nd:YAG (1064 nm)* has similar interaction with soft tissue although the free running pulse mode can produce very high peak powers for efficiency. Its delivery system is the same as the diode.
- The *KTP laser* emits at 532 nm and can be used similar to diode and Nd:YAG laser.
- *Ho:YAG laser (2100 nm)* is mostly used in soft tissue surgery. It utilizes an articulated delivery system and noncontact application.
- The *argon laser (488, 514 nm)* has its indications in the use for pigmented lesions or vascular malformations.
- The *carbon dioxide lasers (9300 and 10,600 nm)* have been used traditionally in oral surgery, the latter wavelength having a very long history of clinical success. Higher average power than diode is readily available with very rapid tissue cutting speed, but there is a possibility of more tissue carbonization when used in continuous wave. Noncontact mode and the use of an articulated arm make the application more demanding.
- The *Er:YAG (2940 nm)* and the *Er, Cr:YSGG(2780 nm)* lasers are readily absorbed in water. Their main indication is hard tissue (bone) surgery. Soft tissue surgery is also possible but much slower. Hemostasis is not as prominent due to poor absorption in pigmented chromophores. Depending on the particular laser, there is a choice of either contact or noncontact mode with the tissue, using delivery tips or a tipless handpiece.

Main Indications in Selecting a Laser for Use in Oral Surgery

- Hemostasis
- Maintaining a decontaminated operation field
- Controllable penetration depth of laser-tissue interaction
- Minimal need for wound dressing/sutures
- Less need for local anesthetic
- Less postoperative pain
- Less wound contraction and scarring
- Faster wound healing

Hemostasis is one of the most sought-after advantages that the laser provides. Depending on the target tissue and the type of laser used, an almost totally dry operation field is produced. This can also be achieved in patients with hemorrhagic diatheses [42]. The use of adequate energy for cutting will produce little carbonization leaving the wound unchanged in color and structure. This makes orientation during the procedures easier even for the surgically inexperienced dentist. When using the laser, not only is the wavelength important but also parameters like temporal emission mode (continuous wave or pulsed), pulse duration, emission cycle, exposure time, and the speed of the incision [14, 15]. All this in the right proportions will lead to a clean cut with little carbonization and contraction of proteins resulting in scarring [16–19].

As mentioned, all of the dental wavelengths currently available can be used for soft tissue oral surgery. As mentioned in ▶ Chap. 3, the laser-tissue interaction can vary because of the different absorption characteristics of the photonic energy. However, with careful technique and prudent

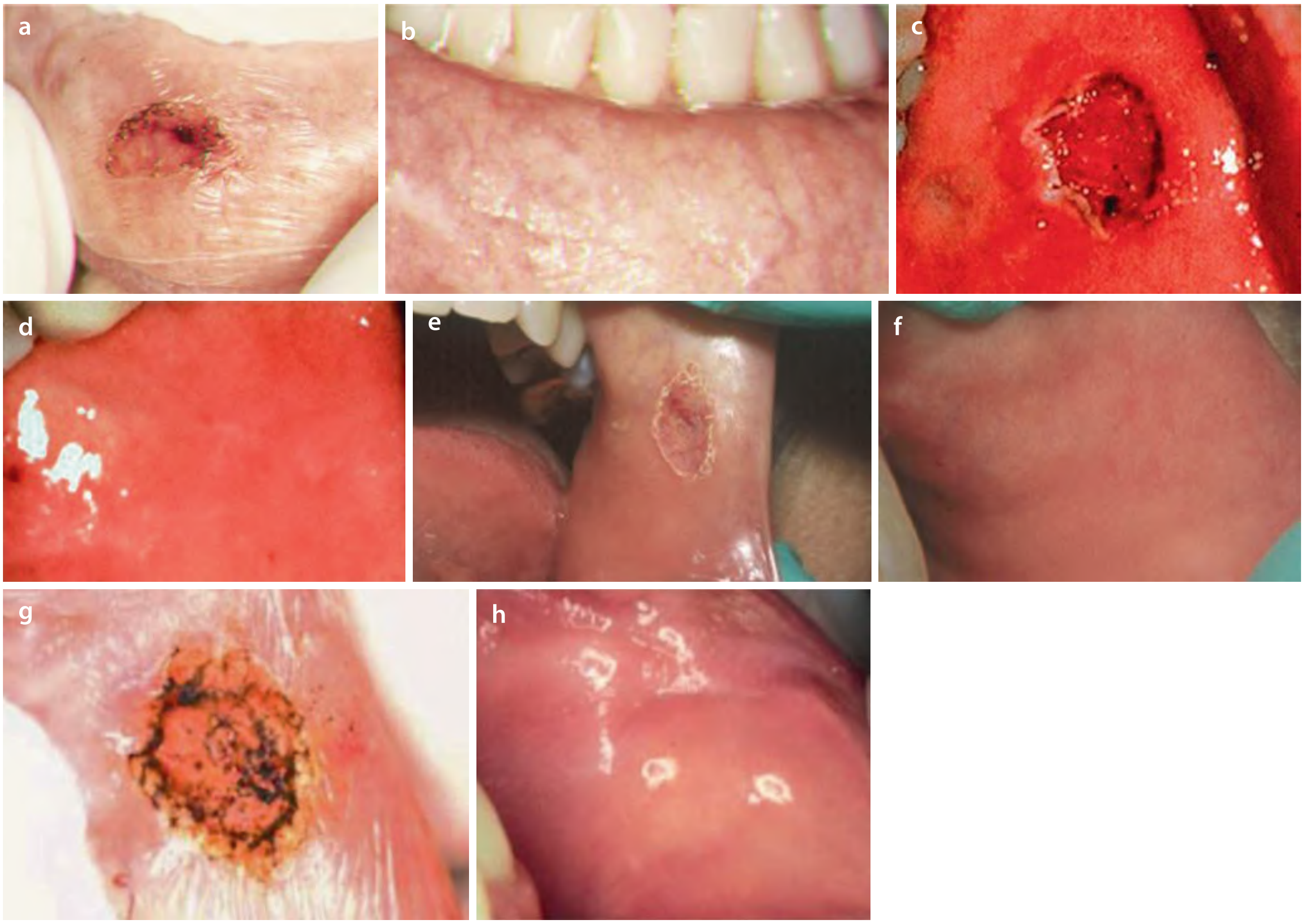

Fig. 13.1 **a** An immediate postoperative view of an excision of an irritation fibroma on the lower lip. An 810 nm diode was used with a 400 μm glass fiber in contact with the tissue at 1.2 W continuous wave. Fluence 149 Joules/cm^2. **b** A 3-week postoperative view of the healed area. **c** An immediate postoperative view of an excision of an irritation fibroma on the buccal mucosa. An Nd:YAG laser was used with a 320 μm glass fiber in contact with the tissue at an average power of 3 W (100 mJ, 30 Hz.) Fluence 915 Joules/cm^2. **d** A 3-week postoperative view of the healed area. **e** An immediate postoperative view of an excision of an irritation fibroma on the inner lip mucosa. An Er:YAG laser was used with a 600 μm glass tip in contact with the tissue at an average power of 2.4 W (80 mJ, 30 Hz, without water spray.) Fluence 263 Joules/cm^2. **f** A 2-week postoperative view of the healed area. **g** An immediate postoperative view of an excision of an irritation fibroma on the buccal mucosa. A 10600 nm carbon dioxide laser was used with a 0.8 mm diameter hollow tubular tip that was focused on the lesion at 5 W continuous wave. Fluence 146 Joules/cm^2. **h** A 3-week postoperative view of the healed area (Courtesy of Dr. Donald Coluzzi)

choice of operating parameters, healing from laser surgery should be uneventful. Figure 13.1 depicts examples of an excisional procedure performed with four different wavelengths.

13.2 Benign Lesions and Tumors of the Oral Cavity

13.2.1 Leukoplakia

A color change from normally light red oral mucosa to white is one of the most often discovered abnormalities in the oral cavity. Failure to identify and recognize the cause of this alteration can be an omission with serious consequences, since early squamous cell carcinomas may appear in early stages as a white lesion.

Clinically the term leukoplakia has been used differently by many authors that it now presents a “white patch that cannot be rubbed away” [20]. As defined by the World Health Organization, leukoplakia is “a white patch or plaque that cannot be characterized clinically or pathologically as any other disease” [21, 22]. As such, leukoplakia should be used only as a clinical term; it has no specific histopathological connotation and should never be used as a microscopic diagnosis. Recently, WHO (2005) changed the definition of leukoplakia to a white plaque of questionable risk having excluded (other) known diseases or disorders that carry no increased risk for cancer.

In clinical practice, the Malmö protocol of 1983 [23, 24] has been helpful in differentiating between potentially precancerous and benign lesions. The distinction of these is purely clinical, based on surface color and morphological (thickness) characteristics, and does have some bearing on the outcome or prognosis. Since leukoplakia has been and still is an exclusion diagnosis, it is mandatory to perform a biopsy to verify the diagnosis. There are two types of leukoplakia: homogeneous and nonhomogeneous. Homogeneous lesions are uniformly flat and thin and exhibit shallow cracks of the surface keratin. The risk of malignant transformation in the homogeneous type lesion is similar to any other normal mucosa tissue, whereas for nonhomogeneous lesions, the risk factor is reported to be up to 50%, depending on the dysplasia rate of the histology [25–28]. In the therapeutic treatment protocol of leukoplakia, it is mandatory to excise all areas of the lesion that showed surface morphology that could warrant dysplasia. In conventional surgery, a flap procedure is usually employed and the result can be scarring and prolonged and painful healing. The introduction of laser technology, for example, using the CO_2 laser [29–31], offers the option of vaporizing the lesion and leaving it to heal with no to minimal scar formation. However, the ability to analyze the submitted laser-excised specimen for pathology was soon questioned. Conventional excision produces a serial section of the whole specimen, and spot biopsies were criticized as insufficient. In the eyes of traditional surgeons, the pathologic evidence was being vaporized. The standard of care is still to biopsy suspicious lesions, and fortunately today's pathologists readily accept laser surgical specimens.

As mentioned previously, the greatest advantage of the laser in this kind of surgery is that there is an almost total lack of scar formation even with secondary wound healing. This is also true in functional zones where the excision will crossover anatomical structures like the parotid papilla in the buccal plane or the caruncula sublingualis in the floor of the mouth. With conventional techniques, scarring can lead to saliva retention with the risk of infection and pain. As an aside, when continuous wave mode is used during laser surgery, the resulting higher tissue temperature can lead to a small scar formation. An equally important benefit is the laser's ability to provide hemostasis. For example, after excision of a leukoplakia on the tongue, there is no excessive bleeding. During the healing phase of a wound adjacent to teeth, the patient will not suffer any bleeding problems even when swallowing.

Recurrence of a white lesion is a serious development. Studies show that the use of laser treatment has at least a similar if not better outcome than the conventional therapy [32, 33]. In functionally sensitive regions as the lips, a laser excision showed significant improvement of the outcome [34, 35].

Most of the studies about laser treatment of oral leukoplakia were performed with the 10,600 nm carbon dioxide wavelength. However, it is also possible and in some cases advantageous to use a fiber-based delivery system of an Nd:YAG laser or a diode laser, depending of the accessibility of the lesion [36].

Figure 13.2 shows a case of leukoplakia on the lateral border of the tongue. A 50-year-old female presented with an inconspicuous medical history except for smoking. An Nd:YAG vaporized the lesion. Six months later, a small area has recurred.

Figure 13.3 is a case of a large area of leukoplakia on a 65-year-old male who smokes. His medical history consisted of hypertension and diabetes which were controlled with medication. A diode laser performed the excisional biopsy. Healing should proceed well with some chance of recurrence.

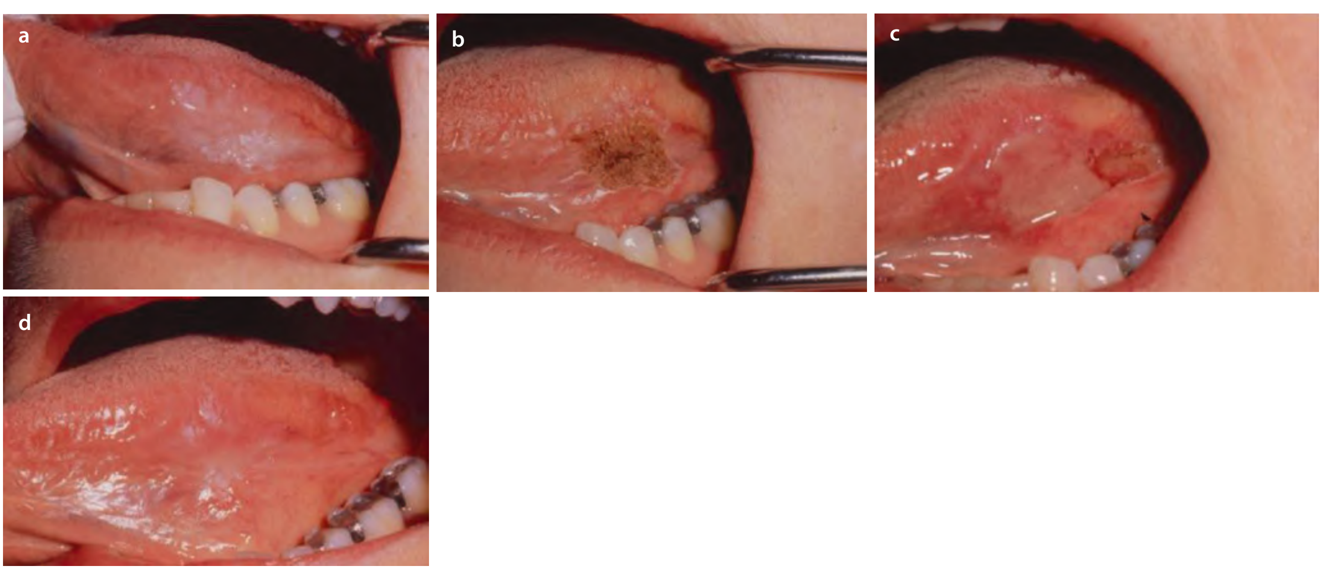

Fig. 13.2 **a** Preoperative view of leukoplakia of the lateral area of the tongue. **b** An Nd:YAG laser was used with a 600 µ glass fiber, in contact with the tissue at an average power of 6 W (150 mJ, 40 Hz.). Fluence 812 Joules /cm^2. **c** One-week postoperative view showing healing. **d** Six-month postoperative photo shows some partial recurrence

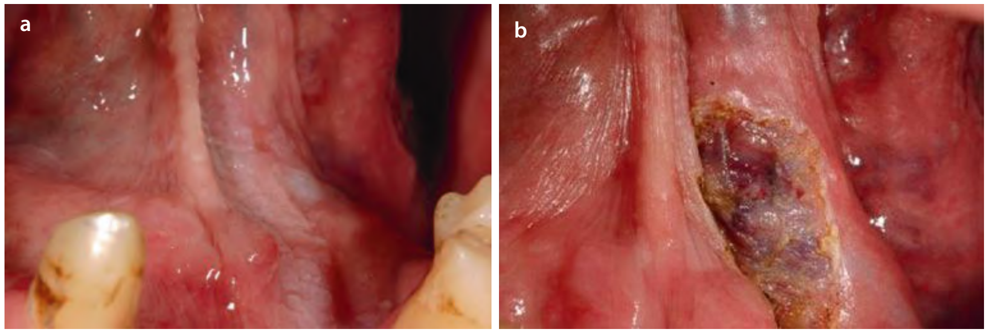

Fig. 13.3 **a** Preoperative view of extensive leukoplakia of the floor of the mouth with inclusion of the submandibular papilla. **b** Immediate postoperative view of the lesion's excision. An 810 nm diode laser was used with 200 µ glass fiber in contact with the tissue at 30 W, 12,500 Hz, and a 9 µsec pulse duration. Average power 3.38 Watts. Fluence 554 Joules/cm^2. Note the minimal thermal damage

13.2.2 Lichen Ruber Planus

The lichen ruber planus is a specific disease of the oral mucosa and is in some cases associated with the dermal lichen. However, two thirds of the dermal lichen patients have mucosal lesions, and 70% of the patients are female older than 50 years of age. Lichen planus usually appears as an irregular, lacelike whitening of the buccal mucosa, but other regions of the oral cavity may be affected. The clinical appearance also can be bullous or erosive, and those patients often experience painful sensations during mastication. The clinical diagnosis normally is evidence-based on the morphology of the whitening, termed Wickham's striae [37–39]. The etiology of lichen planus is unknown.

Oral lichen planus is a chronic inflammatory disease that affects the mucous membrane of the oral cavity. It is a T-cell-mediated autoimmune disease in which the cytotoxic CD8+ T cells trigger apoptosis of the basal cells of the oral epithelium. Several antigen-specific and nonspecific inflammatory mechanisms have been proposed to explain the accumulation and homing of CD8+ T cells subepithelially and the subsequent keratinocyte apoptosis [40]. All therapy modalities that are used are not curative, but rather offer relief of severe pain and discomfort. Conventional medication with corticosteroid ointments is still used in the treatment of the lichen planus. An alternative noninvasive therapy with low-dose laser radiation showed a successful outcome in one study [41]. Recurrence in all these patients with lichen ruber planus mucosa is normal and is independent of the therapeutic regimen [42].

13.2.3 Fibroma

The lesion most commonly found in the oral cavity is the fibroma. It occurs as a discrete, superficial, pedunculated mass commonly found on the buccal mucosa. It is usually of nonneoplastic nature and arises as a response to mechanical, chemical, and inflammatory agents. It is composed of collagenous, fibrous connective tissue covered with keratinized or parakeratinized squamous epithelium. In the lesion, there can be myxomatous degeneration or pathological weakening of the connective tissue along with bone formation and in growth of fatty tissue. The patients often notice the lesion only after masticating on the area and then experiencing post-traumatic pain and swelling. At this point, the fibroma will have grown to at least 2–3 mm in size depending on the region and would be visible in a mirror. The lesion will generally continue to grow, becoming a nuisance, and should be removed. When a scalpel is used, postoperative bleeding often makes the procedure difficult, especially if the lesion is inflamed with increased vascularization. Moreover, suturing is often necessary. Laser surgery allows both excision and hemostasis simultaneously. The wound is normally left open for free secondary granulation [19, 43, 44].

Figure 13.4 is a case of an asymptomatic fibroma present on a 45-year-old female patient, nonsmoker, with an

Fig. 13.4 **a** Preoperative view of a fibroma in the buccal vestibule. **b** Immediate postoperative view of the excision. An 810 nm diode laser was used with a 200 µ glass fiber in contact with the tissue at 30 W, 12,500 Hz, and a 9 µsec pulse duration, 200 µ glass fiber, contact mode. Average power 3.38 Watts. Fluence 554 Joules/cm^2. **c** A 4-week postoperative photo shows complete healing

Fig. 13.5 **a** Preoperative view of a fibroma on the inner mucosal tissue of the lip. **b** A perioperative view of the excision. A 10600 nm carbon dioxide laser was used in SP mode at 1.5 W of average power with a 600 µ beam size in noncontact. Fluence 135 Joules/cm^2. The lesion was kept under tension with a suture, gently pulling it away from its base. The total surgical time was 1 min. **c** The 10-day postoperative photo shows almost complete healing (Case courtesy of Dr. Steven Parker)

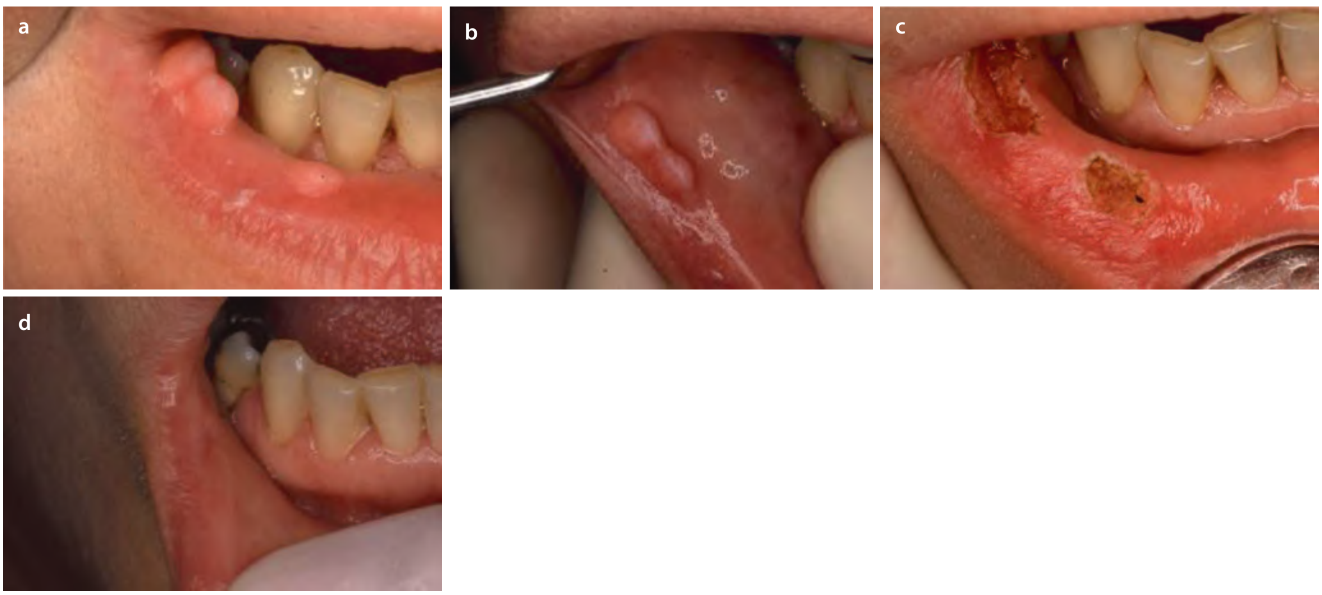

Fig. 13.6 **a** Preoperative view of multiple fibroma lesions on the lower right lip. **b** A similar view showing that the lesions are contained in the keratinized portion of the tissue. **c** An immediate postoperative view of the excision areas. An Nd:YAG laser was used with a 320µ glass fiber in contact with the tissue at an average power of 4 W (100 mJ, 40 Hz.). Fluence 637 Joules/cm^2. **d** A 4-week postoperative photo showing complete healing with no residual lesion present

inconspicuous medical history. A diode laser performed the excisional biopsy, and the tissue healed without any scarring or residual lesion.

Figure 13.5 depicts an irritation fibroma present inner mucosal lining of the lip of a 50-year-old female patient with a noncontributory medical history. A superpulsed 10,600 nm carbon dioxide laser performed the excision, while a suture kept tension on the lesion (Clinical case courtesy of Dr. Steven Parker).

Figure 13.6 is that of a 38-year-old female, nonsmoker, presented with multiple areas of fibromas. Her medical history included hypertension and cardiac dysrhythmia, which are drug controlled. She has a bruxism habit which could contribute to the presence of the lesions.

13.2.4 Papilloma

A papilloma presents as an arborescent growth of numerous squamous epithelial fingerlike projections. Each branch contains a well-vascularized fibrous connective tissue core. It can be seen throughout the oral cavity with a preference on the tongue and the periuvular region. The etiology of the lesion is generally viral and is thought to be induced by the human papillomavirus [45, 46]. Treatment of an oral papilloma consists of excision of the whole lesion [36, 47, 48]. A recurrence can occur even though laser treatment has shown lower reappearance rates than conventional therapy. However, any therapy could be limited since the virus as such is not eliminated.

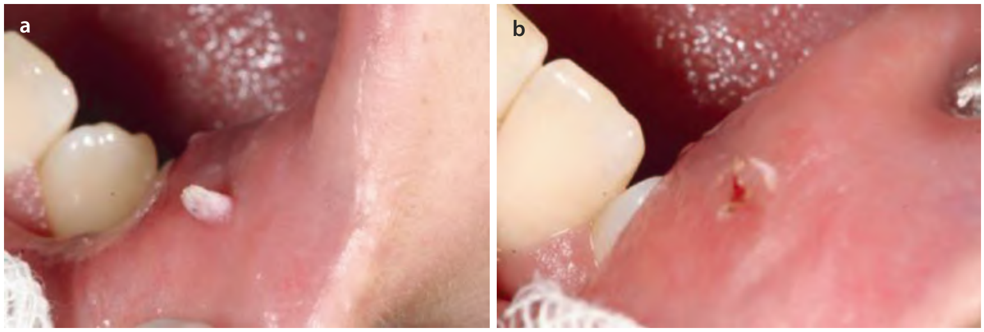

Fig. 13.7 **a** Preoperative photo of a small oral papilloma on the buccal mucosa. **b** An immediate postoperative view of the excision of the lesion. An 810 nm diode laser was used with a 200 µ glass fiber in contact with the tissue at 30 W, 12,500 Hz, and a 9 µsec pulse duration. Average power 3.38 Watts. Fluence 554 Joules /cm^2. Complete healing is expected

Figure 13.7 is a clinical case of an oral papilloma. The patient is a 36-year-old male, smoker with an inconspicuous med history. A diode laser performed the excision and excellent healing is anticipated.

13.2.5 Lipoma

Lipomas are the most common benign tumors of the human body. They can be solitary or in multiple clusters. They vary highly in size from minute to large growths with weight in the kilograms. They occur mostly between 40 and 50 years of age. In the oral cavity, they appear as soft, slightly elastic, and painless lesions and usually are noticed by the patients if they are a large dimension. They are normally found in the buccal, submandibular, and vestibular region. The development of a lipoma is not necessarily hereditary although hereditary conditions, such as familial lipomatosis, can stimulate its growth [49, 50]. Genetic studies support prior epidemiologic data in humans showing a correlation between high-mobility group proteins (HMG I-C) and mesenchymal tumors [51]. When the patient's complaint is the size of the lesion, or to verify the diagnosis, the treatment is excision. The laser's ability to achieve instant hemostasis offers a good view of the site which is important in some areas of the mouth, for example, in direct proximity to the mental nerve. While any wavelength will perform the surgery, a fiber-delivered laser that has better maneuverability could be an advantage in the depth of the wound. Depending on the dimension of the lesion, sutures would be placed to avoid food impaction.

Figure 13.8 is that of a 48-year-old male patient, nonsmoker with a noncontributory medical history presented with a

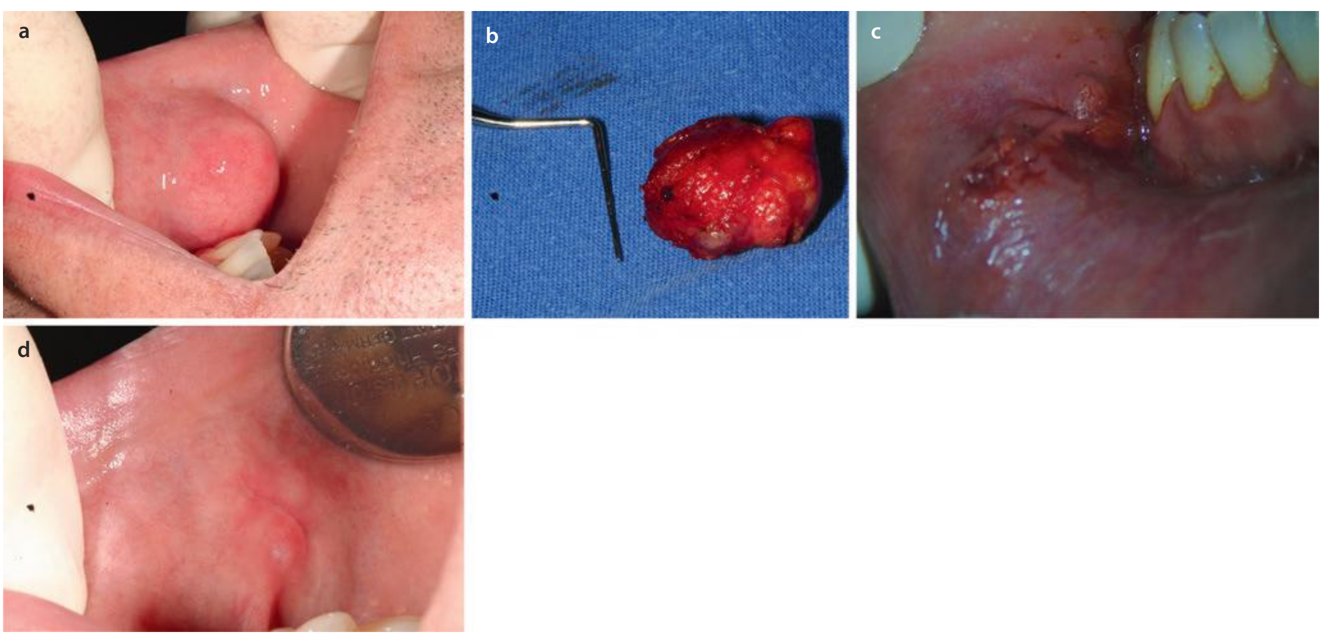

Fig. 13.8 **a** Preoperative photo of a lipoma lesion in mandibular vestibule. It is soft and elastic, but firmly attached to the underlying and covering tissue. There is no sign of any inflammatory process. An 810 nm diode laser was used with a 300 µ glass fiber in contact at 30 W, 13,000 Hz, and a 9 µsec pulse duration. Average power 2.93 Watts. Fluence 967 Joules/cm^2. **b** The excised specimen has an irregular lobular surface, and the histologic diagnosis was that of a common lipoma. **c** Immediate postoperative view showing closure of the deep wound with sutures. **d** One-week postoperative view depicts good healing

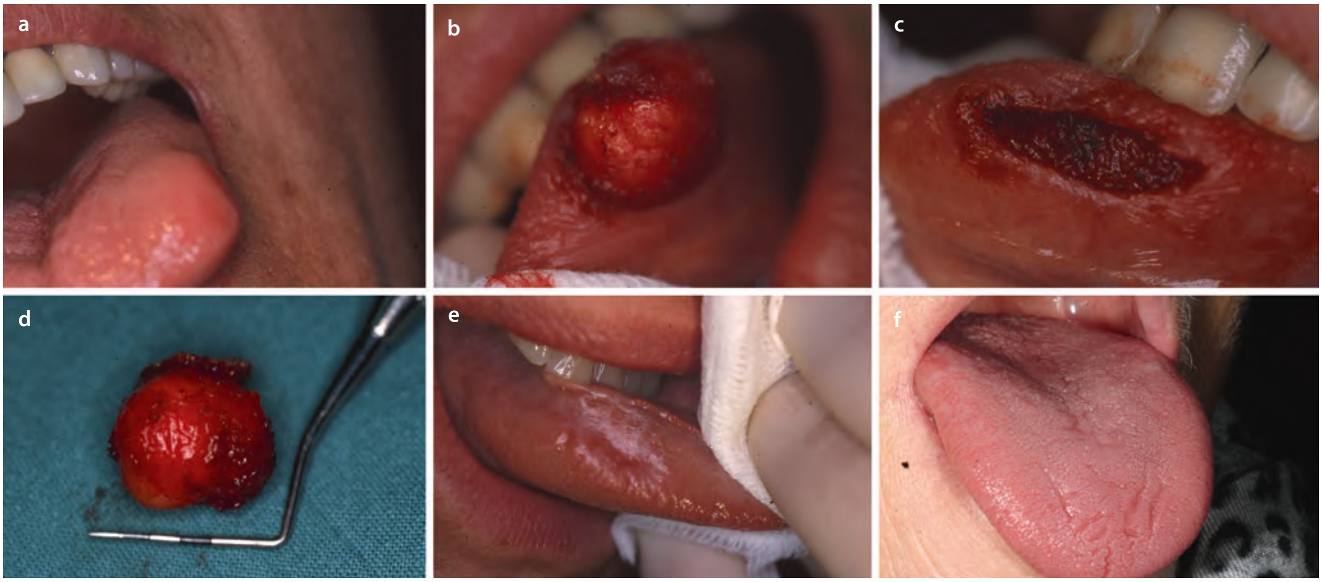

Fig. 13.9 **a** A preoperative view of the swelling in the left portion of the tongue. **b** The tissue overlying the area is excised and the mass can be seen. It is adhered deeply in the underlying tissue. **c** An immediate postoperative view of the excision area. An 810 nm diode laser was used with a 400 µ glass fiber in contact with the tissue at 1.6 W continuous wave. Fluence 199 Joules/cm^2. The lesion does show some carbonization because of the emission mode, but the hemostasis is excellent. **d** A photo of the large sized lesion. **e** Three-week postoperative photo shows healing with a substantial tissue defect. **f** Fifteen-year postoperative view of the completely healed area with no sign of recurrence or a functional defect

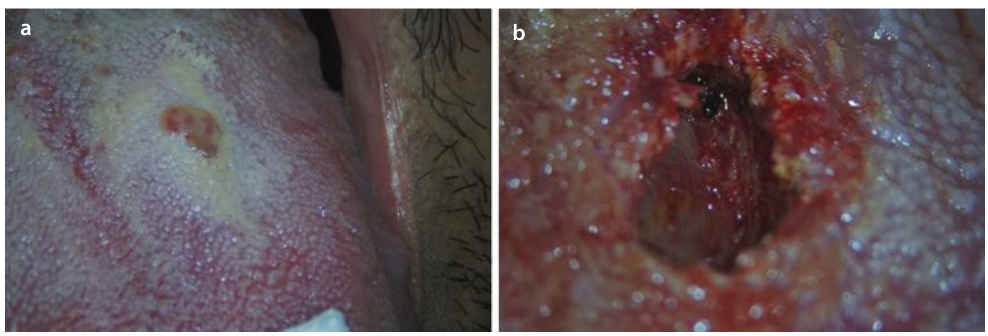

Fig. 13.10 **a** A preoperative view of a small lesion on the dorsal surface of the tongue. It bleeds easily on contact without pain. **b** A closeup immediate postoperative photo of the excision. An 810 nm diode laser was used with a 400 µ glass fiber in contact with the tissue with 30 W, 12,500 Hz, and a 10 µsec pulse duration. Average power 3.75 Watts. Fluence 928 Joules/cm^2. Normal healing is expected

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slow-growing mass in the mandibular vestibule. It was beginning to annoy the patient. A diode laser was used for an excisional biopsy and a diagnosis of lipoma was confirmed. Sutures were placed because of the large size of the excised tissue and the depth of the wound. Healing proceeded uneventfully.

Figure 13.9 is a clinical case of a lipoma on the lateral border of the tongue. The 58-year-old male patient presented because of his concern with the growing size of the tumor, although it has not yet caused any functional impairment. His hypertension and diabetes are controlled with medication. A diode laser was used for the excision. A 15-year postoperative photo shows excellent healing and no recurrence.

13.2.6 Pyogenic Granuloma

Pyogenic granuloma is a vascular lesion of the skin and oropharyngeal mucosa. It appears as reddish overgrowth due to mechanical, physical, chemical, or hormonal trauma [52]. It is generally located in the anterior of the maxilla and can be painful if it is constantly irritated. The lesion can grow rapidly and will often bleed profusely after little or no trauma, and it has the appearance of a highly vascular granulation tissue with inflammation on histologic examination. Special variants of the pyogenic granuloma are the epulis granulomatosum and the granuloma gravidarum. Treatment is not necessary except in cases of excessive bleeding or pain and ulceration. After pregnancy, the lesion normally regresses. Recurrence is in a range of 8% for laser surgery and 15% for conventional treatment [1, 53]. As expected, any surgical laser that achieves good control of bleeding may be used [54, 55]. A biopsy must be taken for histological verification of the lesion.

Figure 13.10 is that of a 28-year-old female with an inconspicuous medical history, presented with a red-colored area on the rear dorsal surface of her tongue. The clinical diagnosis is a pyogenic granuloma. It is not painful, but easily bleeds with light contact, and she reports that volume of

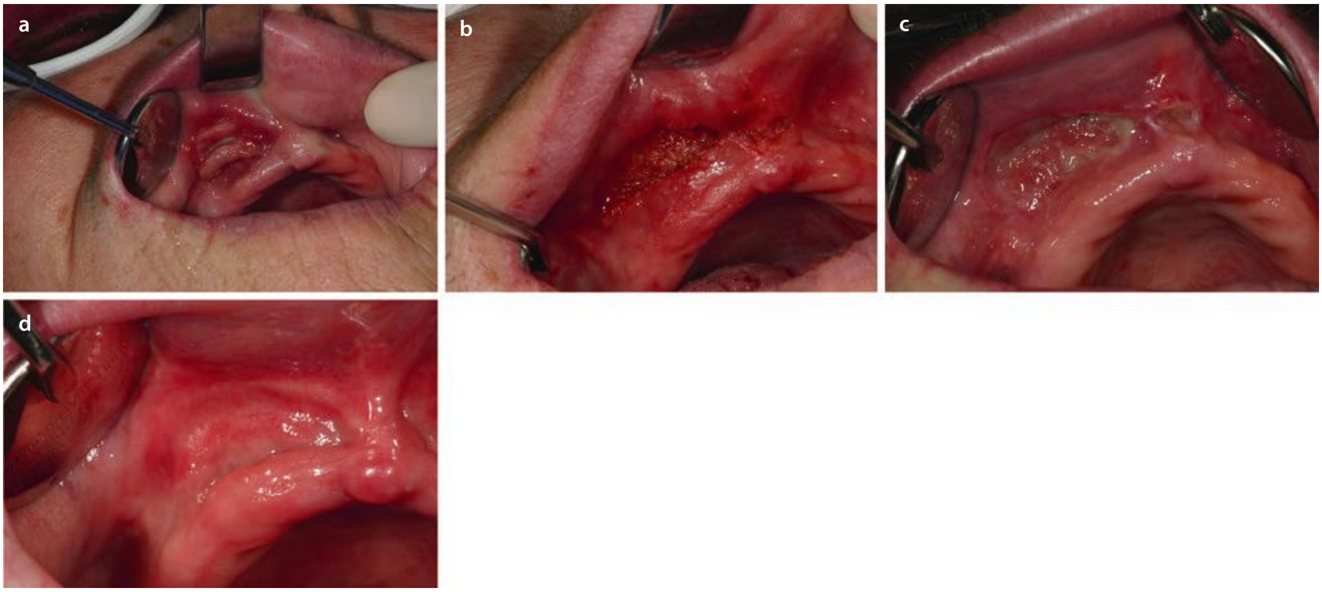


Fig. 13.11 **a** The preoperative view of a painful epulis fissuratum lesion in the maxillary vestibule due to the ill-fitting denture. **b** An immediate postoperative view of the tissue excision. An 810 nm diode laser was used with a 400 μ glass fiber at 30 W, 12,500 Hz, 10 μsec pulse duration. Average power 3.75 Watts. Fluence 928 Joules/cm^2. There was no significant bleeding. **c** The 1-week postoperative photo shows the secondary intention healing progressing with the fibrin layer covering the wound. There is no pain. **d** A 4-week postoperative photo depicts good healing, and the tissue is free of inflammation

blood continues to increase. A diode laser excised the lesion and afforded excellent hemostasis. The healing should be uneventful.

13.3 Pre-prosthetic Surgery

13.3.1 Epulis Fissurata and Pre-prosthetic Vestibuloplasty of the Edentulous Patient

The epulis fissuratum or denture-induced fibrous hyperplasia is a trauma- or inflammation-caused lesion in patients with partial or full dentures. Ill-fitting and overextended dentures can irritate the mucosal tissue and create a hyperplastic tissue flap that can develop signs of secondary inflammation [56]. Due to constant irritation, the lesions can progressively grow, compromising the support for the denture, which in turn causes more irritation. Often these epulides are combined with alveolar ridge atrophy and diminished or missing vestibular depth. During conventional surgery, hemostasis is difficult to achieve, especially for patients with bleeding problems. Furthermore, in most cases, suturing the incision can result in a diminished vestibular depth. Since laser-produced wounds show a reduced number of myofibroblasts, there will be a diminished contraction of the tissue when healing by secondary intension [57]. Secondary wound healing is ordinarily uneventful and significantly less painful than with a conventional surgical protocol. Therefore, excision of the epulis fissurata should be performed with a laser to achieve adequate hemostasis even in patients with bleeding disorder. If there are very large tissue flaps, a fiber-delivered laser can easily undercut them for excision.

Figure 13.11 is that of a 68-year-old female patient, nonsmoker, who presents with an ill-fitting denture and a very painful epulis fissuratum lesion in the maxillary vestibule. Her medical history is significant for hypertension, cardiac dysrhythmia, and coumarin anticoagulant medication. A diode laser excised and contoured the tissue. Four weeks later the area has healed.

Vestibular depth can be very challenging with elderly patients, and a vestibuloplasty can be planned. After losing their teeth at young age, many of these patients show a profound progressive atrophy of the skeletal bone. This atrophy has anatomical limitations in the mandible due to the structure of the self-supporting bone; thus, the patient seldom presents with less than 8 mm of residual bone height. In the maxilla, the limitations are the nasal cavity with apertura piriformis and the floor of the maxillary sinus. If the alveolar ridge is lost, the bony configuration of the maxillary sinus takes over to function as the ridge. In the anterior segment, the alveolar ridge can recede and disappear. Considering these anatomical situations, experience has shown that, in a mandible with a residual height of approximately 10 mm, it is impossible to expect a satisfactory prosthodontic outcome. In the maxilla, a vestibular extension in the premolar and molar region is possible. However, the vestibule can only extend to a certain height without compressing the residual soft tissue, so relapse can occur. It is possible to stabilize the wound healing by inserting a free gingival graft [58].

Figure 13.12 is that of a 68-year-old male with a medical history of cardiac insufficiency, hypertension, and nephrolithiasis who presents with insufficient vestibular depth. A diode laser was used for a vestibular excision and a free gingival graft was inserted. The border of the existing denture was extended apically to aid the graft in healing. Six months postoperatively, the vestibular depth is now adequate.

Atrophy of the alveolar ridge leads to the appearance of preexisting frenula that can subsequently interfere with the denture flange or the periodontal tissue. Laser surgery offers benefits for frenum revision and vestibuloplasty and suturing, such as for conventional Z- or VY-plasty procedures, is not necessary [59].

Gingival recession is normally located in the anterior mandible, due to a high insertion point of the mandibular frenulum and a misaligned mental muscle with mobility of the periodontal soft tissue under function. Treatment of this recession accompanied by a malalignment of the mental muscles should be carefully planned ahead of time so that patient can care for the healing edentulous area. The objective of the surgery is to divert the muscle movement away from the periodontium and establish a neutral zone in the affected anterior vestibule [60]. One option is called the Kazanjian technique. An incision line is made on the mucosa in the lip from canine to canine, or it can be extended to the premolar region, depending on the patient's muscle activity zone. A thin mucosal flap is prepared to the periosteum at the mucogingival border by using a laser with a 200 micron fiber. Then the mental muscle is excised off of the periosteum into the vestibule. When sufficient vestibular depth is achieved, the mucosal flap is placed back onto the periosteum and fixed there with two or three absorbable sutures to spread out the flap. The muscle and wound in the lip are prone to secondary granulation. The postoperative outcome is generally uneventful, and patients report minimal bleeding with tolerable discomfort which is eased with mild oral pain medication. Some swelling could occur. Over time, a relapse of recession can occur; however, good oral hygiene measures can produce some stable reattachment. If the recession persists, a connective tissue graft can be placed to reestablish an adequate zone of attached gingiva.

Figure 13.13 shows the revision of the maxillary frenum of a 65-year-old male with no significant medical

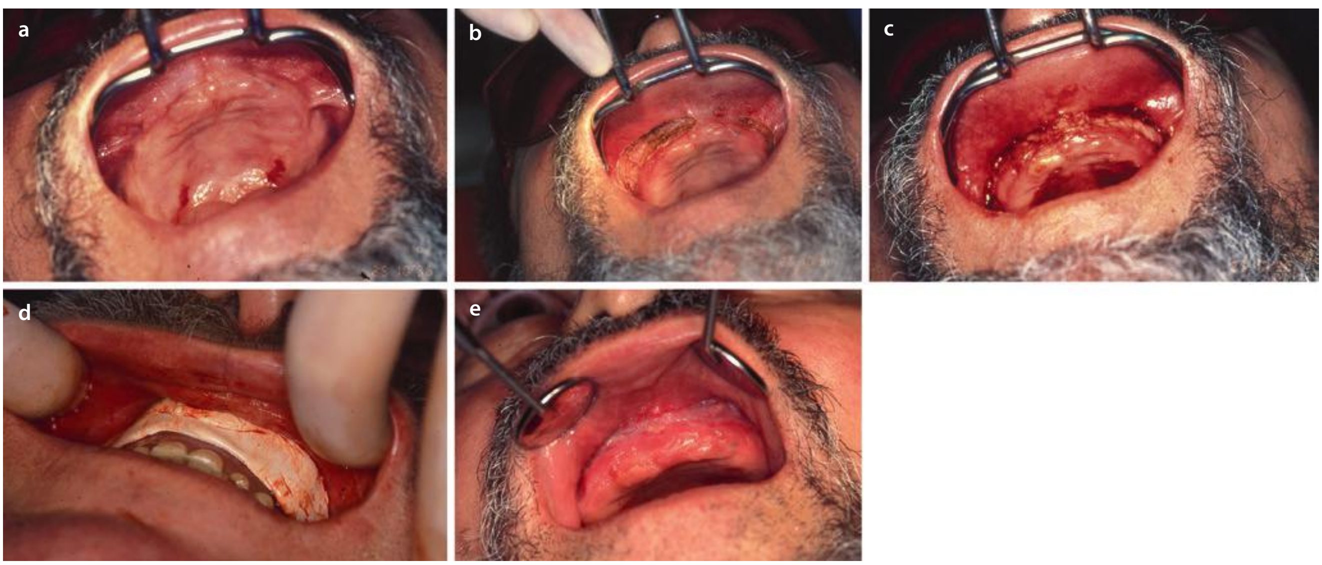


Fig. 13.12 **a** Preoperative view of the very short maxillary anterior vestibule extension, which is inadequate for a stable denture. **b** An incision was made to the periosteum with 810 nm diode laser employing a 400 µ glass fiber in contact with the tissue at 1.6 W continuous wave. Fluence 199 Joules/cm^2. **c** A free gingival graft is placed, covering the periosteum. **d** An extension was placed on the denture border for a scaffold enabling the graft material to adapt and heal. **e** A 6-month postoperative view shows the new vestibular depth with healed tissue

Fig. 13.13 **a** Preoperative view of a maxillary anterior frenum whose attachment is embedded in the gingiva. **b** Immediate postoperative photo of the completed frenum revision. A 10600 nm carbon dioxide laser was used in the SP mode at an average power of 1.5 W with an 800 µ beam diameter in noncontact mode. Fluence 135 Joules/cm^2. The incision's extension was well into the gingival tissue to eliminate the muscle pull. No sutures were placed. **c** Postoperative view of the revised frenum, showing completely healed tissue

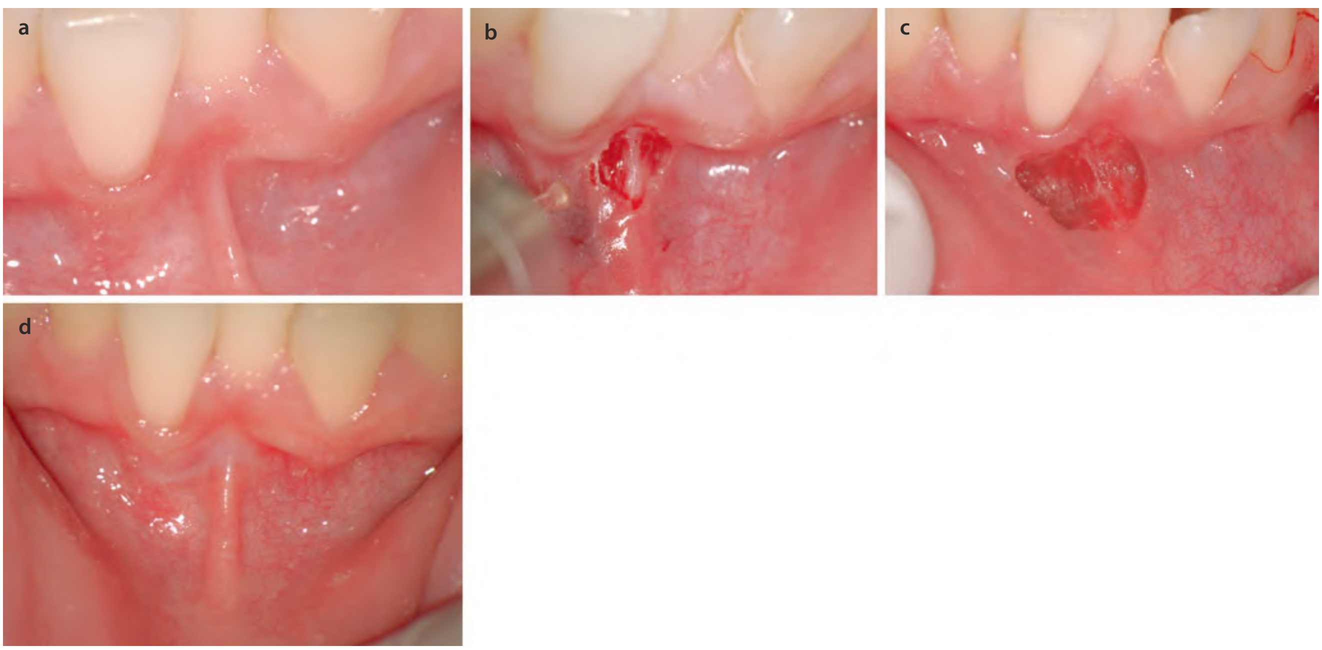
history. The maxillary anterior frenum attachment must be revised to allow improved periodontal health and further treatment planning for tooth restoration, which may involve a maxillary denture. Clearly, the revised frenum would also allow an adequate extension of the denture flange. A carbon dioxide laser in superpulsed mode was used for the surgery. A 2-month postoperative photo shows total healing and a stable position of the frenum's attachment (Clinical case courtesy of Dr. Charles Hoopingarner).

13.4 Frenulae Revisions for Children and Adults

A frenulum attachment positioned within the attached gingiva can lead to gingival recession and accompanying periodontal problems. The revision of this attachment can be easily performed with a laser. The wound is usually not sutured and the secondary intention healing generally proceeds uneventfully. This same treatment method can be performed on children with no negative influence on the development of the mucogingival complex [61].

◘ Figure 13.14 depicts a mandibular anterior frenum of a 35-year-old female patient with no significant medical history. The frenum inserts at the base of the gingiva and is causing a developing loss of clinical attachment to the anterior teeth. One month postoperatively, the frenum's attachment has been repositioned on the mucosa to eliminate the muscle pull on the gingival tissues (Clinical case courtesy of Dr. Donald Coluzzi).

◘ Figure 13.15 shows the case of a 13-year-old female patient who was referred by her orthodontist for a developing periodontal problem with her frenum. A diode laser was used for the excision, and 1 week later the tissue is healing normally with the revised frenum releasing its pull on the gingiva.



◘ **Fig. 13.14** **a** Preoperative photo of a mandibular anterior frenum causing the beginning of clinical attachment loss. **b** A perioperative view. An Er:YAG laser (2940 nm) was used with a 400 u contact tip at an average power of 2 W (40 mJ, 50 Hz) with a water spray for the incision. Fluence 57 Joules/cm^2. **c** Another perioperative view showing the final incision dimensions. Subsequent to this photo, the same laser tip and parameters were used to score the underlying periosteum. No sutures were placed. **d** One month postoperatively, the tissue is completely healed and the frenum is attached into the mucosal tissue

◘ **Fig. 13.15** **a** A view of the frenal insertion, impinging on the periodontal tissues. **b** An immediate postoperative view of the incision to release the frenum attachment. An 810 nm diode laser was used with a 400 μ glass fiber in contact at 1.6 W, continuous wave. Fluence 199 Joules/cm^2. **c** One week later, the tissue is healing and the frenum is no longer compromising the gingival health

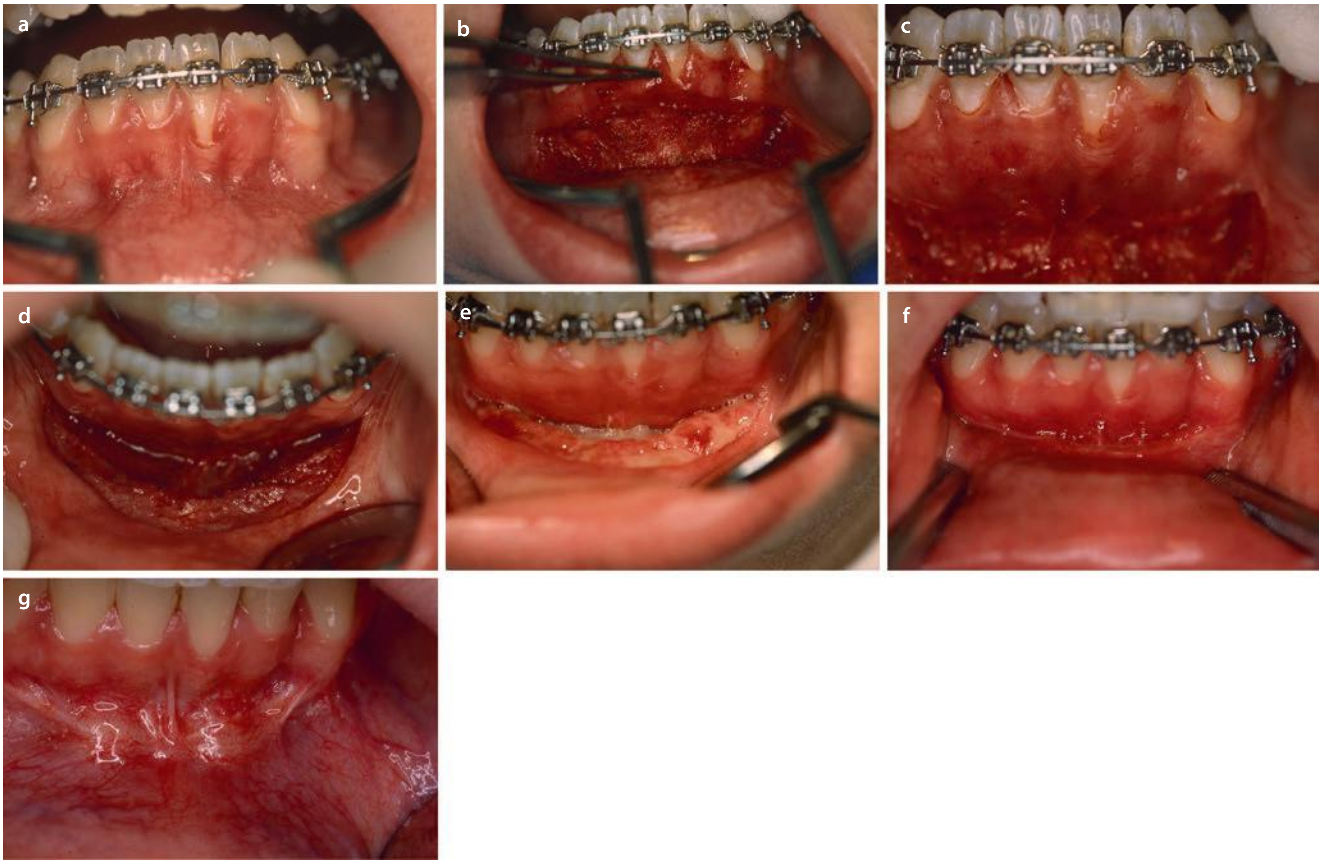


Fig. 13.16 **a** A preoperative view of gingival recession of the lower central incisor caused by the mandibular anterior frenum's attachment. **b** An 810 diode laser was used with a 400 µ glass fiber in contact with the tissue at 1.6 W continuous wave for an incision in the mucosa for a flap procedure. Fluence 199 Joules /cm^2. **c** The flap is completed and adequate vestibular depth is created as shown in **d**. **e** A one-week postoperative view shows fibrin covering the wound as it heals by secondary intention granulation. **f** A three-week postoperative photo depicts good healing. **g** One-year postoperative view shows complete healing with a healthy frenal attachment revision and resolution of the gingival recession

Figure 13.16 shows a clinical case of a 15-year-old female patient undergoing orthodontic treatment presented with the anterior impinging mandibular frenulum causing gingival recession. An incision for a mucosal flap procedure was performed with a diode laser and tissue was repositioned. One year postoperatively, the attached tissue has regenerated and periodontal health is restored.

13.5 Other Conditions

13.5.1 Vascular Malformations

Over the last 35 years, the term hemangioma has evolved to describe any number of vasoformative tumors thanks to Mulliken and Glowacki [63] who produced the classification scheme that is generally accepted today. However, it is important to note that the different clinical entities named hemangioma have little in common other than they all involve blood vessels. The classification differentiates between the group of hemangiomas and other vascular malformations. Hemangiomas are tumors characterized by rapid endothelial cell proliferation in early infancy, followed by involution over time. Everything else is a vascular malformation with a normal endothelial growth. A hemangioma develops in the first months after birth and subsequently grows rapidly. It usually regresses over time, and only 10% are treated in adolescence. Conversely, a vascular malformation, such as a venous lake, shows little to no regression and very slow, stable growth. It is treated when it becomes a functional impairment or for esthetic reasons. These lesions can be excised conventionally, which easily produces a biopsy specimen. The main disadvantage of that procedure is that a defect and scarring can result, especially on the lip. An alternative technique is to use the laser in a noncontact mode, aiming the photonic energy at the lesion, starting on the circumference and working toward the center, until there is blanching and induration of the malformation [64–66]. There will be a tissue temperature rise during lasing to achieve coagulation, and, with careful technique, thermal damage to the surrounding structures should be minimal. One protocol employing the deeply penetrating diode or Nd:YAG wavelengths includes using an ice cube to cool the tissue while lasing through the ice [67]. The postoperative outcome of the noncontact treatment of vascular malformations shows an extremely high success rate and little postoperative discomfort [68].

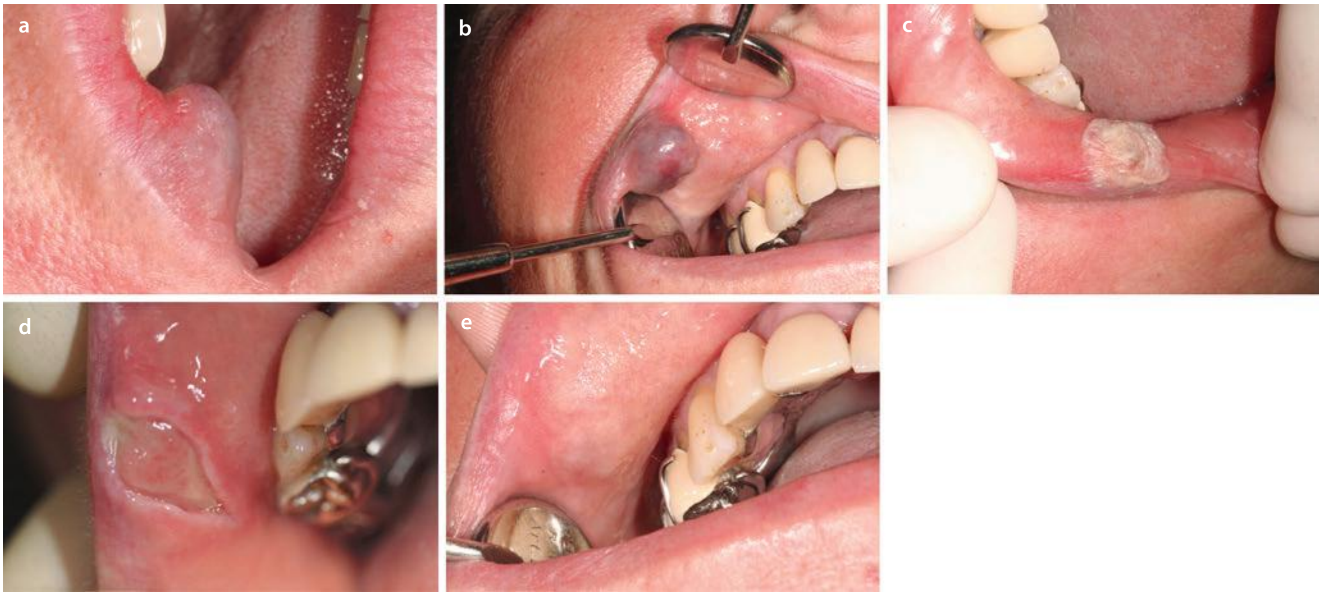


Fig. 13.17 **a**, **b** Two preoperative views of a vascular malformation on the upper right lip. **c** Immediate postoperative view. An 810 nm diode laser was used with a noninitiated 600 µ glass fiber out of contact with the tissue at 2.5 W continuous wave. Fluence 128 Joules/cm^2. The laser was activated until the tissue appeared blanched, and then the laser was turned off. **d** A 1-week postoperative view shows granulation is proceeding. **e** Four weeks postoperatively, the area is healed and the lesion disappeared

Fig. 13.18 **a** A preoperative view of a large vascular malformation lesion on the lower lip. **b** An 810 nm diode laser was used with a 400 µ glass fiber in contact with 30 W, 12,500 Hz, and a 10 µsec pulse duration. Average power 3.75 Watts. Fluence 928 Joules/cm^2. **c** A 5-day postoperative photo shows normal wound healing

Figure 13.17 depicts a clinical case of a large vascular formation that was present on the lip of a 72-year-old female patient with an inconspicuous medical history. The patient reported that the lesion had been slowly growing over a period of 10 years, but she was given medical advice to not treat it. A diode laser was used in a noncontact mode, and 4 weeks postoperatively, the lesion has disappeared.

Figure 13.18 is that of a 78-year-old patient with a medical history consisting of hypertension, cardiac insufficiency, and cardiac dysrhythmia was who taking coumarin for anticoagulation therapy. A diode laser performed an excisional biopsy and the tissue was determined to be a nonmalignant vascular malformation. A 5-day postoperative photo shows the wound healing satisfactorily and that is expected to continue.

Figure 13.19 shows a 65-year-old female patient with a medium-size vascular lesion on the central part of her lower lip. Her medical history is noncontributory. The patient recalls biting her lip several months ago, and she is concerned about the esthetic appearance. A carbon dioxide laser was used for an excision. One month later, the tissue is healed (Clinical case courtesy of Dr. Rick Kava).

Figure 13.20 depicts a nonaesthetic hemangioma on the lower lip of a 72-year-old female, with a noncontributory medical history. The large lesion extends from the vermillion border to the mucosa. A diode laser was used in a noncontact mode to allow the laser radiant energy to penetrate into the lesion. A 3-month postoperative view shows complete healing (Clinical case courtesy of Dr. Giuseppe Iaria).

13.5.2 Retention Cyst

Retention cysts are lesions often found in older children or young adults. They normally are not true cysts since the epithelial lining is absent, unlike true cysts. They are located in the body of the salivary gland and do not exceed 8 mm in diameter. They regress in most cases without need of treatment. Of much more frequent occurrence is the extravasation

Fig. 13.19 **a** Preoperative view of the hemangioma on the central area of the lower lip. **b** Immediate postoperative view of the lesion ablation. A 10600 nm carbon dioxide laser was used with an average power of 2 W in SP mode with a 400 μ noncontact tip. Fluence 289 Joule/cm². **c** A 6-week postoperative photo showing complete resolution of the vascular lesion

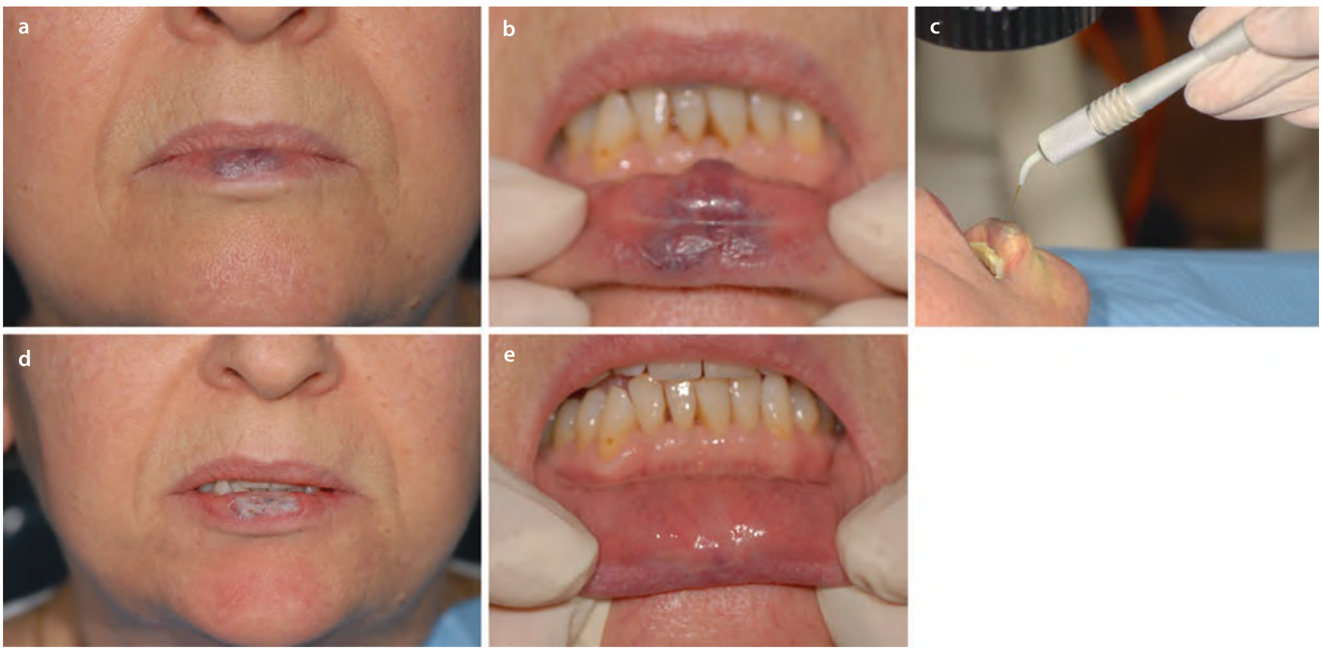


Fig. 13.20 **a** Preoperative view of a hemangioma on the lower lip from the extraoral view. **b** The intraoral view showing the extent of the lesion to the inner mucosa. **c** An 808 nm diode laser was used with a 400 u noninitiated fiber in noncontact, approximately 2 mm from the tissue surface. Average power 3.0 Watts CW. Fluence 154 Joules/cm². The handpiece was in constant movement with a circular motion, covering the extent of the lesion. No anesthesia was used, and the patient was comfortable. **d** The immediate postoperative view after 1 min shows the tissue is light gray in color. Ice was applied for 2 min to reduce edema of the surrounding tissues. **e** Three-month postoperative view shows complete tissue healing

cyst, in which a mucous gland duct ruptures due to trauma or inflammation. That lesion can grow to 4–5 cm in diameter. It can be painless but troublesome depending on its location and size. In some cases, the cyst can regress and vanish without recurrence. Treatment is only necessary when the patient's function is impaired, and the goal is to eliminate the cyst and involved gland while minimizing the chance of recurrence. Excision can be performed by scalpel which can be challenging, since there is no true cystic capsule. Similarly, a laser can also lacerate the lesion, but, with a fiber delivery, it is possible to weld the injured and now overlapping wound edges together. This can conserve some of the form of the cyst and gland without blindly dissecting too much tissue. In deep excisions, two or three sutures are placed to avoid food impaction and allow healing to occur. Patients report very little pain or loss of function. Wound healing is in secondary intention.

Figure 13.21 is that of a 31-year-old female nonsmoker patient presenting with a noncontributory medical history. She was concerned about a lesion on her lower lip that had been growing for 3 months. It appeared bluish and was 1 cm in diameter. A diode laser was used to excise it and it was determined to be a retention cyst. A 3-month postoperative photo shows good healing.

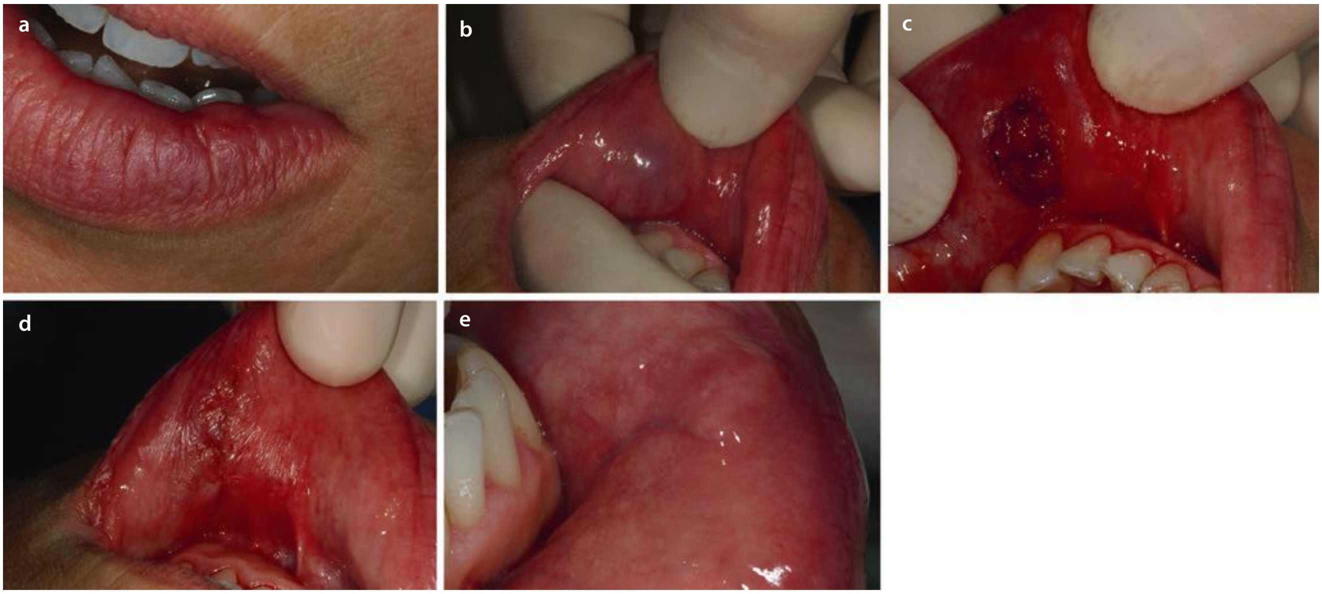


Fig. 13.21 **a** The preoperative extraoral view of a discrete swelling of the left side of the lower lip. **b** An intraoral view of the lesion. **c** The immediate postoperative view of lesion excised with an 810 nm diode laser using a 200 µ glass fiber in contact with the tissue at 30 W, 12,500 Hz, and a 10 µsec pulse duration. Average power 3.75 Watts. Fluence 928 Joules/cm^2. The excision was sutured to prevent food impaction (**d**) One week postoperatively, the wound is healing adequately. (**e**) A 3-month postoperative view of complete resolution of the lesion

13.5.3 Sialolithiasis

Sialolithiasis is the occurrence of a salivary stone or calculus and is a frequent cause of inflammatory changes within the large salivary glands. Statistics show that over 78% of salivary stone formation affect the submandibular gland and 81% appear in the parotid gland, but is a rare occurrence in the sublingual gland, though not totally unknown [69]. Clinical practice detects signs of stone formation in one out of 10,000 patients. The incidence in male patients is two to three times higher than in females. The greatest presence can be found in the age range of 50–70 years, but sialiths have been reported in children. Some reports assume a correlation between sialolithiasis and other stone diseases as urinary or biliary stones, but large multicenter studies show no correlation at all [70].

The typical symptoms include a painful swelling of the affected salivary gland which is intensified by chewing and at mealtimes. The diagnosis is based on the clinical symptoms, ultrasound examination, radiographic imaging, and endoscopic evaluation [69]. Other symptoms can be due to an obstruction such as one in Wharton's duct in the floor of the mouth resulting in an infection of the gland. Chronic inflammation may lead over time to an atrophic replacement of the acinar cells by scar and fatty tissue [71]. An acute inflammation is often the first sign of a sialolithiasis even in the presence of an extensive calculus formation. Instead of extirpating the gland, a different therapeutic concept has been developed nowadays which analyzes the location and size of the stones. In cases of normally small-size parotid stones, a basket extraction shows promising results. Also extracorporeal sonographically controlled lithotripsy plays a major role in therapy. Endoscopic techniques can more precisely locate the stones. Although extra- and intracorporeal lithotripsy shows excellent results, that method is not often used due to accessibility and cost of the apparatus.

A trans-oral approach has been established as an alternative; as a result, more than 90% of all submandibular stones can be removed preserving the gland. After sounding the duct to locate the stone, it is easy to incise the tissue and locate the stone which can be mobilized and removed. Conventional instrumentation offers no control of bleeding, and with the flow of saliva, visibility can be extremely difficult during the surgery. A laser ensures good hemostasis and therefore a good overview of the operation site. Sutures are not usually placed and the healing is uneventful with little scaring.

Figure 13.22 shows a clinical case of a 48-year-old male smoker who presented with a painful swelling submandibular which intensifies during chewing and eating. His medical history includes hypertension and hyperlipidemia. A radiograph was taken and the diagnosis was made as sialolithiasis. A diode laser preformed the incision, and the stone was removed. No sutures were placed and the healing is expected to be normal.

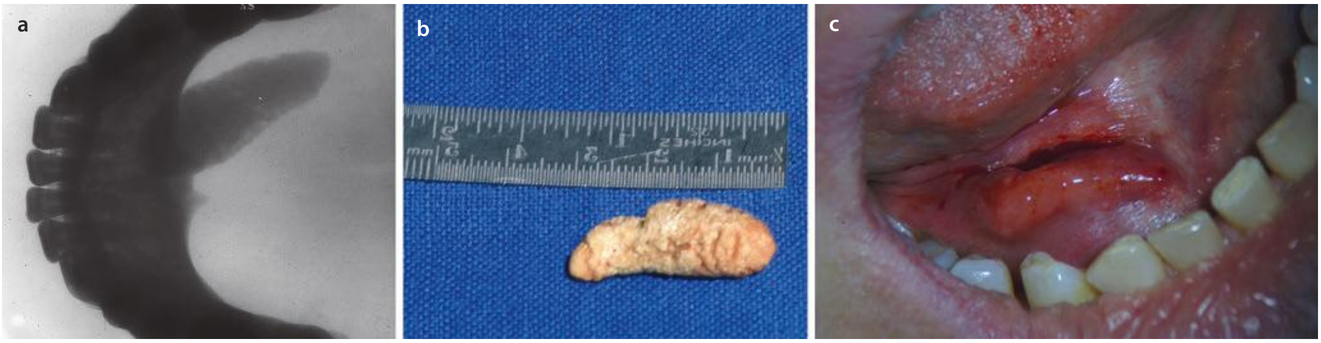


Fig. 13.22 **a** A radiograph of the area showing a large sialolith in the Wharton's duct. X-ray shows a large sialolith in the Wharton's duct. **b** A photo of the excised sialolith. An 810 nm diode laser was used for the incision with a 200 μ glass fiber in contact with the tissue at 30 W, 12,500 Hz, and a 9 μsec pulse duration. Average power 3.38 Watts. Fluence 554 Joules/cm^2. **c** Immediate postoperative view shows good hemostasis. No sutures were placed and healing is expected to be normal

Conclusion

The use of lasers in oral soft tissue surgery is beneficial for patient and surgeon. The good hemostasis provided offers a better view of the operation site and can help to make the procedure more straightforward and even easier for both the accomplished and the novice surgeon. Treatment for patients with bleeding problems becomes possible. Wound healing is mostly uneventful. Conventional biopsies, so necessary for histological verification, can be easily taken. Depending on the choice of parameters, soft tissue surgery can be performed with all available wavelengths. On some instruments, a fiber-based delivery system facilitates accessibility in areas with challenging anatomy, such as undercuts. All told, for many indications, laser treatment is superior to conventional therapy in many instances and can help to deliver safe and effective dental care.

13

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Laser-Assisted Oral Multi-Tissue Management

Contents

Laser Treatment of Periodontal and Peri-implant Disease

Donald J. Coluzzi, Akira Aoki, and Nasim Chininforush

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Core Message

Therapy for periodontal and peri-implant disease continues to evolve with new methodologies, medications, and instrumentation added to the conventional armamentarium. Dental lasers have been used both adjunctively and alone in the protocol. Clinical studies and basic investigations have shown that laser photonic energy has been a useful addition to increase the effectiveness and outcomes of treatment of the disease.

14.1 Introduction

The periodontium is essential for optimal oral function and health. Any inflammation will affect both soft and hard tissue and could lead to loss of those structures. Periodontal disease is an infection whose primary etiologic factor is the oral pathogens existing in the plaque biofilm. Initially the gingiva will become inflamed without attachment loss, and the disease is thus termed gingivitis. With increasing pathogen invasion, there will be loss of connective tissue attachment as well as apical migration of the epithelial tissue with subsequent infection and resorption of the alveolar bone. Chronic periodontitis is a slowly progressing disease and one of the most commonly occurring diseases in middle-aged adults [1].

Moreover, periodontal disease has been linked with other systemic diseases. Oral pathogens can migrate through the inflamed and ulcerated gingival epithelium into the rest of the body. There are suggested clinically important associations between periodontal bacteria and conditions ranging from peripheral artery disease, liver cirrhosis, and chronic kidney disease to other systemic disorders including cardiovascular, respiratory, and osteoarticular problems. These connections highlight the importance of treating this disease because of its implication on general medical health. Interestingly, the reverse association is also important: the patient's age, smoking habits, and the presence of diabetes can worsen chronic periodontal inflammation.

Putative periodontal pathogens, such as *Aggregatibacter actinomycetemcomitans* and *Porphyromonas gingivalis*, have long been considered the primary contributors to the disease. However, the red complex especially three species—*Porphyromonas gingivalis*, *Tannerella forsythia*, and *Treponema denticola*—are now regarded as the most pathogenic and are prevalent in biofilm. Unfortunately, determining which organisms are important can be a daunting task: there can be several species of pathogens in any one site; some can be more opportunistic than others and may proliferate subsequent to the initial inflammation rather than cause it; and the patient's immune response can vary.

Peri-implant disease shares the same etiology—pathogenic microorganisms—and the literature is beginning to report significant statistics that indicate many implant sites will develop the disease [2]. For clarity, soft tissue inflammation is termed peri-implant mucositis, whereas implant bone loss is termed peri-implantitis.

The general understanding is that the gold standard for successful treatment of these diseases is gain in clinical attachment level. The root surface should be restored to biocompatibility to reestablish that attachment without the presence of inflammation [3, 4]. There are however other clinical creditable endpoints such as lack of bleeding on probing, complete removal of root accretions, and measureable regeneration of bone, periodontal ligament, and cementum. Of course, the patient's oral hygiene improvement and reduction of other risk factors can also be considered and are crucial for maintenance of a stable periodontium.

This chapter will be divided into three modalities of treatment utilizing lasers in nonsurgical, surgical, and antimicrobial photodynamic modalities. These methods are separate therapies, but may be combined to produce the best result. A nonsurgical protocol is the first approach, but surgery may follow to help unresolved problems. Photo-activated medications can be a useful addition for either procedure. Since periodontal disease can have episodic progression, one or more of these treatments may be employed for the current stage of the disease.

14.2 Nonsurgical Periodontal and Peri-implant Disease Laser Therapy

14.2.1 Description of Non-surgical Therapy

The term «nonsurgical therapy» is defined as a protocol to remove as much calculus as possible, to disrupt or eliminate the biofilm and accompanying microbes, and to reduce inflammation contributing to periodontal and peri-implant disease as initial therapy. After this phase of treatment, the patient's periodontal condition will be evaluated. Two possibilities then exist: one, the patient will receive periodontal maintenance, and two, a surgical procedure must be performed as a next step.

During initial nonsurgical therapy, it is essential that root/implant accretions be thoroughly removed; indeed conventional periodontal treatment begins with calculus and biofilm removal, using scaling instruments on the tooth surfaces while using carbon fiber or plastic curettes on the implant fixture. For the patient with gingivitis or beginning peri-implant mucositis, that procedure is very straightforward with ease of access. As the severity of the disease increases, root/implant debridement becomes more difficult. Studies have shown that some calculus remains, despite careful root planing or implant debriding; and treatment outcomes may not always be successful with deeper pockets [5–7]. Thus surgery would be necessary to access those areas, along with placing regenerative materials.

Another consideration is that conventional ultrasonic and sonic scalers used for subgingival debridement may not be effective to produce a bactericidal effect [8].

This initial therapy is usually performed in the general dentist's clinic, if immediate referral to a periodontist is not indicated. Within that office setting, a dental hygienist may deliver all or part of the treatment in accordance with the scope of practice and other regulations governing his/her license. During any therapeutic session, the patient must be instructed in an effective oral hygiene regimen. Several appointments may be necessary to complete the initial nonsurgical protocol, and adequate evaluation periods will determine how successful the patient compliance and the practitioner's efforts have been.

14.2.2 Laser Wavelengths That Can be Used

Dental lasers are generally used adjunctively for the above-described initial nonsurgical therapy [9]. For purposes of this section, the laser instrument described will have a minimum output of approximately 0.5 W of average power. This is to distinguish it from other lasers used for antimicrobial photodynamic therapy, described in the next section.

Any of the commercially available dental lasers can be utilized for nonsurgical periodontal or peri-implant disease therapy. At this date, the generic types and nominal emission wavelengths include diode (810, 940, 980, and 1,064 nm), Nd:YAG (1,064 nm), Er,Cr:YSGG (2,780 nm), Er:YAG (2,940 nm), and CO_2 (9,300 and 10,600 nm.). For treatment of periodontal and peri-implant diseases, all of the above wavelengths can be used for debridement of the soft tissue side of the periodontal pocket; both erbium wavelengths are also currently indicated for calculus removal on the tooth structure. With the exception of Nd:YAG, there are no general contraindications for use of these wavelengths around implant fixtures. Studies have shown that the high peak power emission of the Nd:YAG laser with microsecond pulses caused melting on sand-blasted, acid-etched, and titanium plasma-sprayed surfaces of titanium implants [10]. The details are described in Table 14.1.

Table 14.1 Details of dental wavelengths used in adjunctive nonsurgical therapy

Laser type	Nominal wavelength in nm.	Periodontal tissue target for laser photonic energy used in nonsurgical therapy	Precautions
Diode	810, 940, 980, 1,064	Debridement and detoxification of inflammatory tissue due to selective absorption in areas of inflammation by soft tissue pigments and blood components, including pigmented bacteria. Very good hemostasis of blood in the sulcus	1. For periodontitis, prolonged contact with dark colored calculus, root surface, and osseous tissue should be avoided 2. For peri-implant mucositis, no implant surface damage has been reported
Nd:YAG	1,064	Same as diode	1. For periodontitis, prolonged contact with dark colored calculus, root surface, and osseous tissue should be avoided 2. For peri-implant mucositis, the beam should be placed parallel to the long axis of the implant fixture so that any interaction will be minimized
Er, Cr:YSGG Er:YAG	2,780 2,940	Debridement of inflammatory soft tissue due to the absorption in water of sulcular fluid and organic components of soft tissue inflammation along with the cellular water of pathogens Removal of root accretions due to the primary absorption in the water component of dental calculus and secondarily absorbed in the mineral component. Good hemostasis of blood in the sulcus	1. For periodontitis, care should be used to avoid excessive removal of cementum during calculus removal. Water spray must be used 2. For peri-implant mucositis, low average power should be used
CO_2	9,300 10,600	Debridement and detoxification of inflammatory soft tissue due to the absorption of water and organic components of sulcular fluid and soft tissue inflammation along with the cellular water of pathogens. Very good hemostasis of blood in the sulcus	1. For periodontitis, prolonged contact with tooth surface should be avoided[a] 2. For peri-implant mucositis, low average power should be used

[a]*Note*: the potential exists for 9,300 nm CO_2 lasers to be used for calculus removal. Currently, there is no indication for use in this procedure

14.2.3 Adjunctive Laser Use

The general principle of adjunctive laser use for periodontal and peri-implant disease therapy is to supplement conventional instrumentation in removing or disrupting the biofilm and calcified deposits. Conventional mechanical therapy of periodontal pockets does not necessarily achieve complete removal of bacterial deposits and toxins. Employing a laser has the potential to improve therapeutic results [11].

All dental lasers produce a temperature rise in the target tissue, which would affect the pathogens and the resulting inflammation. In general, most non-sporulating bacteria, including periodontopathic anaerobes, are readily deactivated at temperatures of 50 °C [12]. Coagulation of the inflamed soft tissue wall of a periodontal pocket and hemostasis are both achieved at a temperature of 60 °C [13]. It should be noted that surgical excision of soft tissue occurs at 100 °C; thus using a laser at these lower temperatures defines a nonsurgical therapy. When erbium lasers are used for calculus removal, the primary interaction occurs when the photonic energy vaporizes the interstitial water of the mineralized matrix at a minimum temperature of 100 °C. However, the rapid pulsing of those lasers used with water spray minimizes any significant temperature rise in the surrounding tissues.

Considering the microbial component, it follows that laser irradiation would have significant potential as an adjunct to traditional scaling instrumentation used on teeth and implants. All of the lasers listed in Table 14.1 use the photothermal effect capable of strong bactericidal and detoxification effects [14]. In addition, the infected soft tissue in the pocket can be debrided; the lymphatic and blood vessels can also be coagulated to enable healing.

14.2.4 General Protocol [15]

Following the examination and diagnosis, the clinician should refer to the periodontal charting and perform initial nonsurgical therapy. A suggested protocol is:

1. Prior to any other instrumentation, laser irradiation at low average power is used to reduce the microbial population in the sulcus [16]. This will lower the risk of bacteremia and reduce the aerosolized contaminants during conventional instrumentation. When using the diode, Nd:YAG, and CO_2 wavelengths, care should be taken to avoid prolonged laser contact with subgingival calculus and root surfaces. For implant surfaces, care should be exercised with the Nd:YAG beam placement. When using erbium lasers, calculus removal is occasionally performed at the same time with the initial laser irradiation.
2. Appropriate conventional instrumentation is used to perform calculus removal of the tooth or implant surface. Erbium lasers can be used primarily or adjunctively.
3. Decontamination of the pocket epithelium is performed with laser irradiation. The photonic energy interacts with different components of the inflamed soft tissue to disrupt the biofilm and microbial components. The parameters employed produce an average power below that used for excisional surgery, and the clinician should refer to the laser's operating manual to verify the average power settings. The treatment objective is to aim the laser beam toward the soft tissue with overlapping strokes to ensure that the entire area of the pocket is irradiated. The time needed for this portion of the protocol depends on the pocket anatomy—its shape, depth, and width. Visible debris will accumulate on the contact tip of some lasers or will be flushed out of the pocket with others. Decontamination is complete when fresh bleeding emanates from the pocket.
4. To ensure coagulation and sealing of the blood capillaries and lymphatic vessels, laser energy is used. Generally this occurs in a short time, and the last beam placement will be at the entrance to the pocket. In more shallow pockets, the decontamination procedure may produce the desired hemostasis without any additional irradiation. After the laser is turned off, digital pressure will help readaptation of the tissue to the tooth, especially in deeper pockets. In more shallow pockets, the decontamination procedure may this step will help the initial healing.
5. The patient is given postoperative and oral hygiene instructions. There should be minimal tissue manipulation of the treated area so that the fibrin clot is not disrupted. Very gentle brushing and flossing should be performed for 2 days. Spicy and crunchy foods should be avoided for at least 1 day. Gentle rinsing with warm salt water three times a day should soothe the tissues in a short period of time, and only mild discomfort should be expected. Subgingival irrigation must be avoided.

14.2.5 Treatment Planning

The above protocol of initial therapy should be followed for every patient manifesting periodontal or peri-implant disease. The extent of the disease will be determined during the periodontal exam, charting, and diagnosis. When planning treatment, several points should be considered:

- The patient's physical limitations such as posture or temporomandibular joint disease
- The patient's pain sensitivity during the procedure and medications necessary to control it, ranging from topic and local anesthetics to sedation
- The patient's systemic health along with any risk factors that would affect the treatment outcome

- The number of pockets to be treated and the anatomy of each
- The amount and tenacity of debris and biofilm to be disrupted/removed
- Any restorations or occlusal problems that need attention and could compromise access or success of the therapy
- The patient's ability to continue adequate oral hygiene techniques

The severity of the disease will determine the appointment schedule both for therapy and the patient's tolerance for treatment. Most importantly, the treatment plan must be customized for each patient. Some cases of gingivitis may only require full-mouth debridement and disinfection and can be accomplished in two appointments, including polishing. Other advanced conditions with excessive deposits and biofilm may necessitate that only a few teeth are to be treated in each visit.

The length of each appointment can also vary. Generally speaking, moderate generalized disease would be treated with hourly visits in each area of the disease. Some clinicians divide the mouth into quadrants for therapy; others choose to treat all of the deeper pockets first. The latter approach has an advantage in that those pockets with more disease can be retreated with steps 3 and 4 on subsequent appointments, especially if some inflammation remains after the first session. To ensure those pockets receive maximum debridement, the laser can be used again during the other therapy visits.

Locally delivered chemotherapeutic agents, such as minocycline hydrochloride, doxycycline hyclate, and chlorhexidine gluconate, may be placed in pockets to help biofilm suppression. They are most effective after the biofilm has been disrupted by the debridement procedure. As such, those additions should be performed after the last laser treatment. Antimicrobial photodynamic therapy should also be considered, as discussed in the next section of this chapter.

The patient's oral care skills must be continually assessed and reinforced in this protocol. If the presence of biofilm is not minimized, the intended healing will not progress. An assessment appointment should be scheduled approximately 4 weeks after the completion of the initial therapy.

Following the initial nonsurgical therapy, the next appointment 3 months later will assess both the patient's home care and the periodontal status. Expected outcomes are inflammation reduction or absence, healthier tissue tone, and reduced pocket depths without bleeding. Minimum force should be used during probing in this period, since the attachment apparatus is easily disrupted. Normal detailed probing can be performed at the 6-month post therapy appointment. Reevaluation can continue at 3-month intervals, with careful assessment of how the disease is resolving. Supportive therapy to preserve the improved clinical attachment and minimum inflammation can continue. This will probably include additional debridement and laser decontamination, along with the patient's daily oral hygiene regimen.

14.2.6 Clinical Cases

Figure 14.1 shows a diode laser used in a shallow-inflamed periodontal pocket. Figure 14.2 depicts the adjunctive use of an Nd:YAG laser. Figure 14.3 shows the adjunctive use of an Er,Cr:YSGG laser for initial treatment of periodontitis (clinical case courtesy of Dr. Rana Al-Falaki). Figure 14.4 demonstrates the use of a diode laser for adjunctive treatment of peri-implant mucositis.

Fig. 14.1 **a** Preoperative view of an inflamed shallow gingival sulcus. **b** An 810 nm diode laser with a 300 µm bare fiber and 0.4 W CW emission directed toward the soft tissue side of the sulcus. **c** Six-month postoperative view showing no inflammation

Fig. 14.2 **a** Preoperative view of a 6 mm pocket wit bleeding on probing. **b** After hand and ultrasonic scaling, an Nd:YAG laser is used with a 400 µm fiber and an average power of 1.8 W (30 mJ/pulse and 60 Hz) and directed toward the soft tissue side of the pocket. **c** Three-month postoperative view showing pocket depth reduction and lack of inflammation

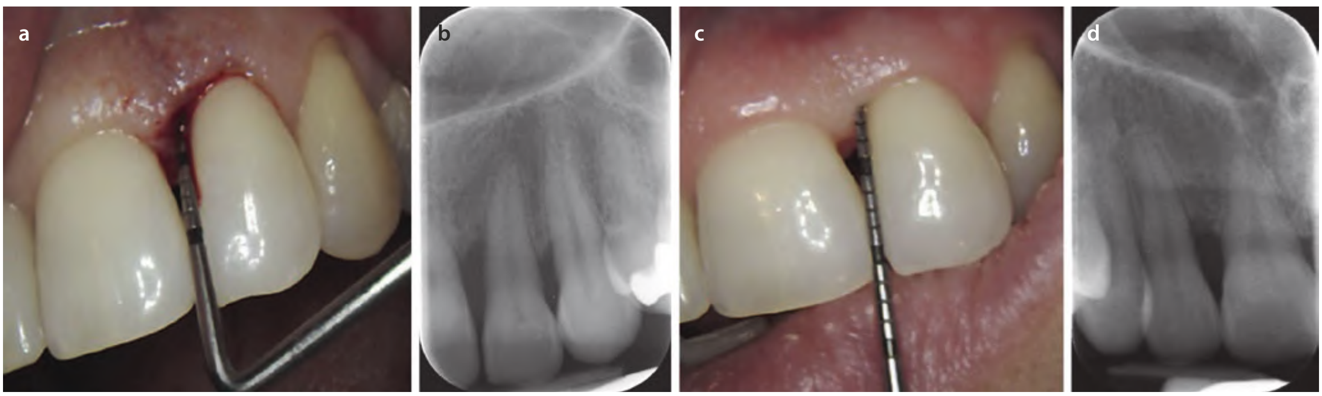

Fig. 14.3 **a** Preoperative view of an 8 mm pocket with bleeding on probing. **b** Preoperative radiograph of the pockets. After ultrasonic removal of the calculus, an Er,Cr:YSGG laser was used with a 500 micron diameter radial firing tip at an average power of 1.5 W (50 mJ, 30 Hz) with a pulse duration of 60 microseconds for debridement. **c** Seven-month postoperative probing shows significant pocket depth reduction without bleeding on probing. **d** Seven-month postoperative radiograph depicts a more stable periodontium (Clinical case courtesy Dr. Rana Al-Falaki)

Fig. 14.4 **a** Preoperative view of a 7 mm pocket with bleeding on probing around an implant. **b** After careful conventional debridement of any calculus, an 810 nm diode laser with a 400 micron tip was used with an average power of 0.4 CW emission directed toward the soft tissue and away from the implant fixture. **c** Six-month postoperative view showing pocket depth reduction and lack of inflammation

14.2.7 Considerations About Laser Use in Initial Nonsurgical Therapy

In any laser-tissue interaction, the absorption of the photonic energy depends on many factors, as discussed in Chap. 3. For periodontal and peri-implant therapy, those same factors are at work in a very limited space—the periodontal pocket and surrounding structures. Therefore, the following points are important:

- Each wavelength will have different interaction on the various tissue components. For example, the near-infrared wavelengths are easily scattered and are only absorbed by inflammation. Their depth of penetration in sulcular fluid can be significant, which means that the energy could travel beyond the intended target tissue [17]. On the other hand, erbium lasers can be used efficiently to remove subgingival calculus, although it is not very selective; and cementum on the root surface can also be removed [18].

- The current literature indicates that lasers are generally safe for treatment of peri-implant mucositis, but some precaution should be exercised [19, 20]. As mentioned previously, Nd:YAG laser usual emission mode produces very short pulse durations and a very high peak power per pulse. Those high powers have been known to damage titanium surfaces. Erbium lasers have the same pulse durations but produced no surface alterations with low energy density use. Understanding of those differences is necessary for the clinician to choose the appropriate wavelength for beneficial treatment.
- The laser parameters must produce low average power to minimize ablation of healthy tissue. Each laser instrument has specific operating instructions for this procedure with suggested settings, and these should be used as a guide to begin the therapy.
- Each laser has a specific handpiece and emission device—for example, an optical fiber tip or a small tube. The clinician should ensure that the laser beam is aimed as precisely as possible toward the intended target tissue. For example, diode photonic energy will be readily absorbed by dark calculus causing a significant temperature rise; so, the tip should be angled toward the soft tissue. Likewise, when using an erbium laser for calculus debridement, the tip should be as parallel to the tooth axis to avoid excessive cementum removal.
- As granulation tissue is removed, it may accumulate around the laser tip or tube. Those should be checked and cleaned often to avoid concentration of the energy in the debris.
- Proper case selection is important and continuing evaluation must be performed. If areas of disease do not respond to the nonsurgical approach, then subsequent surgical therapy will be necessary.

14.2.8 Acronyms for Nonsurgical Initial Periodontal and Peri-implant Therapy

Clinicians may find various acronyms in the operating manuals of different laser instruments or in scientific literature. The intent of these terms is the same—to provide the first phase of treatment. Such terms as LAD/LABR (laser-assisted decontamination/laser-assisted bacterial reduction), LAPT (laser-assisted periodontal therapy), and LCPT (laser-assisted comprehensive treatment) can give specific additional details about the protocol. Some companies have legally protected their acronyms:

- *REPaiR* (regenerative Er,Cr:YSGG periodontitis regimen) uses the company's Er,Cr:YSGG laser for sulcular debridement and root surface cleaning.
- *WPT*™ (wavelength-optimized periodontal therapy) uses the company's Nd:YAG and Er:YAG to remove the diseased epithelial lining and to debride the root surface calculus, respectively.

Whichever terminology or abbreviations are used, various laser wavelengths can add beneficial results for the treatment of periodontal and peri-implant disease.

14.2.9 Selected Literature Review for Lasers in Nonsurgical Therapy

The following is a sampling of the literature describing various wavelengths used adjunctively for nonsurgical therapy:

- Qadri et al. [21] showed that the adjunctive use of a diode laser (800–980 nm) with scaling and root planing (SRP) is more effective in treatment of moderate chronic periodontitis than when SRP is used alone.
- Lerario et al. [22] used mechanical debridement with the adjunctive use of a diode laser (810 nm) for peri-implant disease and demonstrated greater reduction of probing depth and bleeding on probing than conventional treatment.
- Martelli et al. [23] showed that adding Nd:YAG laser to conventional treatment found significant and long-term effectiveness in improving clinical and bacteriological measurements.
- Al-Falaki et al. [24] assembled case report series and reported pocket depth and inflammation reduction in the nonsurgical treatment of peri-implant disease using the Er,Cr:YSGG laser.
- Schwarz et al. [25] reported that the Er:YAG therapy resulted in significant reduction of the BOP score and improvement of the clinical attachment gain in the nonsurgical treatment of periodontitis.
- Zhao et al. [26] in a meta-analysis highlighted a significant attachment gain using the Er:YAG laser and SRP when compared to SRP alone.
- Yan et al. [27] in a meta-analysis showed that the Er:YAG laser as an alternative to mechanical debridement could provide some short-term additional benefit.

Summary: Nonsurgical Laser Therapy

In summary, the adjunctive use of lasers for initial, nonsurgical periodontal therapy must follow specific protocols, and the treatment must be continually evaluated to determine if surgery is necessary. This therapy is well accepted by patients, and it may contribute to their improved home care. Well-designed scientific studies are always required to support the evolving reported benefits of the procedure.

Table 14.2 Details of wavelengths used in surgical therapy

Laser type	Nominal wavelength in nm.	Periodontal tissue target for laser photonic energy used in surgical therapy	Precautions
Diode	810, 940, 980, 1,064	Incision and excision of gingival tissue along with hemostasis. Good absorption in pigmented tissue and hemoglobin, likewise in areas of acute inflammation	1. For gingival surgery or debridement of granulation tissue, prolonged contact with dark colored calculus, root surface, and osseous tissue should be avoided 2. For peri-implantitis, no implant surface damage has been reported when low average power irradiation is used
Nd:YAG	1,064	Same as diode	1. For gingival surgery and granulation tissue debridement prolonged contact with dark colored calculus, root surface, and osseous tissue should be avoided 2. For peri-implantitis, the beam should be placed parallel to the long axis of the implant fixture so that any interaction will be minimized
Er, Cr:YSGG Er:YAG	2,780 2,940	Excellent incision and excision of soft tissue with minimal depth of cut due to the very high absorption in the water content of that tissue. Good hemostasis. Excellent cutting and shaving of osseous tissue	1. For osseous surgery and calculus removal, water spray must be used 2. For peri-implantitis, low average power should be used near the implant fixture
CO_2	9,300 10,600	Excellent incision and excision of soft tissue due to the high absorption in the water content of that tissue. Very good hemostasis Excellent cutting and shaving of osseous tissue (9,300 nm wavelength ONLY)	1. For osseous surgery with 9,300 nm, water spray must be used 2. For peri-implantitis, low average power should be used near the implant fixture. Care should be taken to minimize reflection from the metal implant toward surrounding tissue

14.3 Surgical Therapy for Periodontal and Peri-implant Disease

14.3.1 Description of Surgical Therapy and Laser Wavelengths That Can be Used

After initial therapy is completed, periodic evaluations and maintenance appointments follow. There can be challenges to complete debridement and disinfection of periodontal or peri-implant pockets which range from anatomic complexity of the defects to the patient's inability to maintain good oral hygiene. Moreover, the clinical attachment level and pocket depth produced by initial therapy may still be inadequate for optimum health. Thus, some surgical intervention will be occasionally necessary.

Table 14.2 lists the details of laser wavelengths that can be used for surgical therapy. The small diameter delivery system including curved tips can especially aid in access to infrabony and furcation pockets.

In this section, surgical therapy will be divided into two sections. The first is a flapless technique and the second is the more conventional protocol where a flap is reflected and then repositioned.

14.3.2 Flapless Periodontal And Peri-implant Surgery

Description of Flapless Surgery

There are two current flapless techniques that are considered to be surgical but without employing any open flap technique for debridement. These fulfill the concept of a minimally invasive procedure, but could have limitations because of limited access to the entire diseased area of the periodontium around the root or the implant. One, termed LANAP® is an acronym for laser-assisted new attachment procedure and uses a proprietary Nd:YAG instrument. The other is termed laser-assisted comprehensive pocket treatment (LCPT) where any erbium laser can be employed.

Laser Assisted New Attachment Procedure (LANAP®)

The LANAP® protocol entails a specific step, single session treatment, shown in Fig. 14.5. After verifying the pocket depth, the laser selectively removes the pocket's epithelial lining. The root surfaces are debrided with conventional scaling instruments, and then blunt dissection is performed at the osseous crest. The laser is then used to

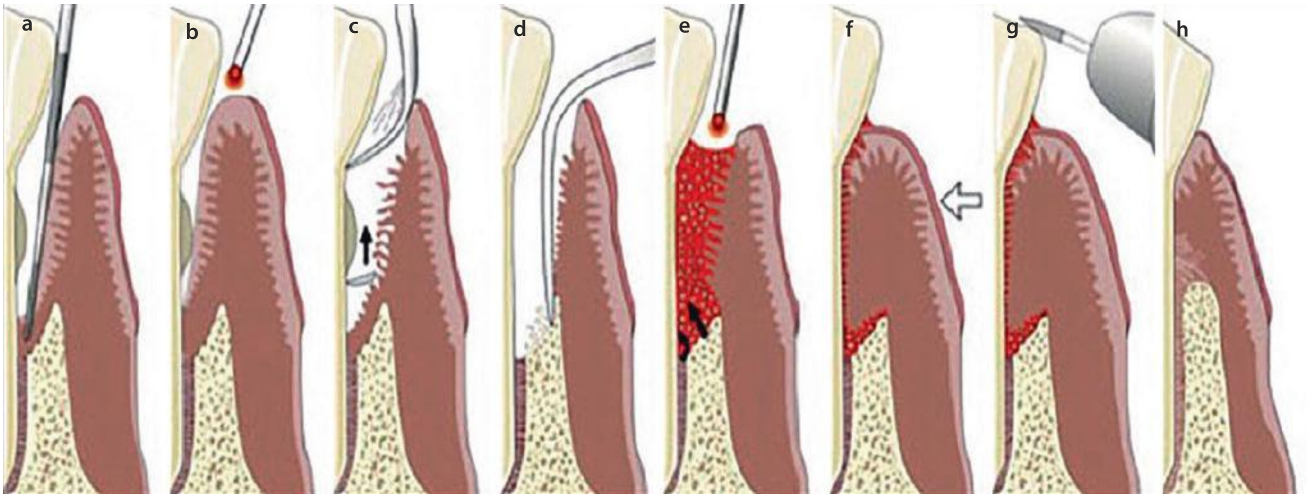

Fig. 14.5 Graphic depiction of LANAP® using the pulsed Nd:YAG laser. **a** Bone sounding to determine pocket depth. **b** Under local anesthesia, typically a 360 μm optic fiber delivers 3.6–4.0 W average power at a pulse duration of 100–150 μsec to selectively remove the diseased epithelial lining of the pocket, denature pathologic proteins, and create bacterial antisepsis. **c** The root surface accretions are removed with piezo ultrasonics and conventional instruments. **d** Blunt dissection with a conventional dental instrument is used to modify the osseous contour at the alveolar crest and perform intra-marrow penetration to gain access to stem cells and growth factors. **e** Using the same fiber but with a pulse duration of 550–650 μsec, the laser energy performs hemostasis; establishes a thick, stable fibrin clot; activates growth factors; and upregulates gene expression. **f** The gingival tissue is pressed toward the tooth to secure it without sutures. **g** Occlusal adjustments are performed to eliminate improper contacts and to allow for passive eruption. **h** Shows anticipated healing in an environment conducive to true regeneration of new cementum, new periodontal ligament, and new alveolar bone (LANAP® is a patented and registered trademark of Millennium Dental Technologies, Inc., Cerritos, Calif., USA) (Graphic reproduced with permission from Millennium Dental Technologies)

obtain hemostasis and to form a fibrin clot so that the loose gingival tissue can be approximated back to the tooth. Occlusal adjustments are performed and postoperative instructions given. This procedure has generated case report studies that offer histologic evidence of new connective tissue attachment, new cementum, and new alveolar bone [28, 29]. The Nd:YAG wavelength (1,064 nm) is usually safe when using appropriate parameters for pocket irradiation. However, the photonic energy has a potential of deep tissue penetrability, so care must be taken to avoid thermal damage to the underlying tissues.

Figure 14.6 shows a clinical case of moderate periodontitis in the maxillary anterior sextant. The LANAP® protocol is used for successful treatment (Clinical case courtesy of Dr. Raymond Yukna)

The same company has an identical procedure for treatment of peri-implant disease, termed LAPIP™ (laser-assisted peri-implantitis protocol.) The laser emission is reduced so that much less average power is applied around the implant structure. The fiber is aimed as parallel as possible to the long axis of the fixture to avoid the metal absorbing the energy and thus overheating as well as to minimize any reflected photons off the surface.

Laser-Assisted Comprehensive Pocket Therapy (LCPT)

LCPT (laser-assisted comprehensive pocket therapy) uses erbium lasers with wavelength emissions of 2,870 or 2,940 nm [30]. As noted previously, these lasers can be used for soft tissue and calculus removal. In addition, they are indicated for use in contouring osseous tissue. Thus they can be useful for debridement of both granulation tissue and bone defects in moderate to deep periodontal pockets, depending on the accessibility. The procedural steps are shown in Fig. 14.7. After assessing the pocket, the laser and hand instrumentation is used for root surface debridement. That is followed by removal of the epithelial and diseased connective tissue of the lining of the gingival pocket as well as diseased osseous tissue. The treatment objective is thorough decontamination of the whole pocket as well as enhance of bleeding from bone surface, including bone marrow-derived cells which are a major source of mesenchymal stem cells. The parameters used will not affect hemostasis in the bone; on the contrary, the procedure should enhance bleeding which would be advantageous for tissue regeneration. There may also be some biostimulatory effects from the low-level laser penetration into the surrounding tissues. The next step is laser ablation of the external gingival tissue at the pocket entrance. The

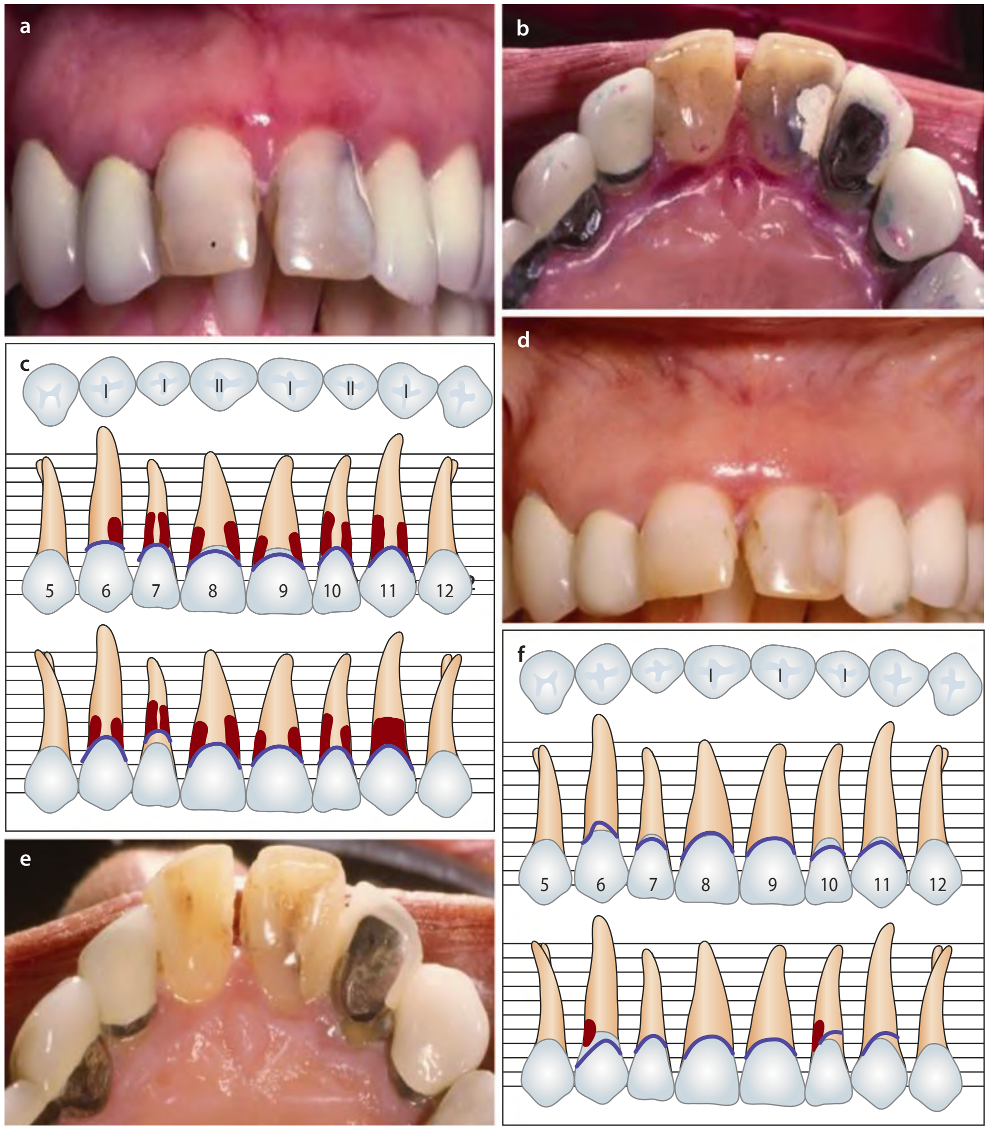

Fig. 14.6 **a** Clinical view of the anterior facial region of a patient with acute moderate periodontitis. **b** Clinical view of the lingual anterior region. **c** Pretreatment periodontal probe chart showing pockets and mobility on all the anterior teeth. Each horizontal line represents a 2 mm increment, and the red markings indicate bleeding on probing. Mobility is indicated with Roman numerals on the incisal view icon at the top of the chart. The patient was treated with the LANAP® protocol as described in Fig. 14.4. **d** Three-year facial postoperative view. **e** Three-year lingual postoperative view. Note the reduction in inflammation. **f** Three-year postoperative periodontal probe chart shows significant pocket depth and mobility decrease (Clinical case courtesy Dr. Raymond Yukna)

epithelium and occasionally a layer of connective tissue are removed. The pocket depth is automatically reduced with this small-dimension gingivectomy, and the exposure of the connective tissue will delay the migration of the epithelium into the pocket while the attachment is being reestablished. That procedure will cause some gingival recession, but the primary benefit of pocket healing will be realized. The last step is to ensure adequate coagulation for a stable blood clot to seal the pocket entrance. The erbium laser is used in a non-contact mode without water spray to achieve this.

This procedure can also be used for the treatment of peri-implant mucositis or the initial stages of peri-implantitis.

Figure 14.7 is a clinical case of Er:YAG (2,940 nm) laser-assisted LCPT shown in Fig. 14.6. Deep pockets and an infrabony defect are treated. There is radiographic evidence of osseous healing and new attachment at 1-year post-operatively (Fig. 14.8).

14.3.3 Osseous Periodontal Surgery Employing a Flap

Osseous surgery, during which bone is removed, recontoured, and/or reshaped, is one of the major periodontal surgical procedures. Optimum bone anatomy will help establish and maintain clinical attachment, shallow pockets, and physiologic gingival architecture—all of which are critical for long-term stability of periodontal tissue.

At the time of writing, no studies are available for the 9,300 nm wavelength, but there are manuscripts showing that both the Er,Cr:YSGG (2780) and Er:YAG (2,940 nm) [31, 32] wavelengths are effective in ablation of bone tissue with minimal thermal damage. In addition, the healing assessment of those lasers performing an osteotomy is at least comparable to conventional instrumentation [33] and may be advantageous for faster and improved outcomes [34, 35].

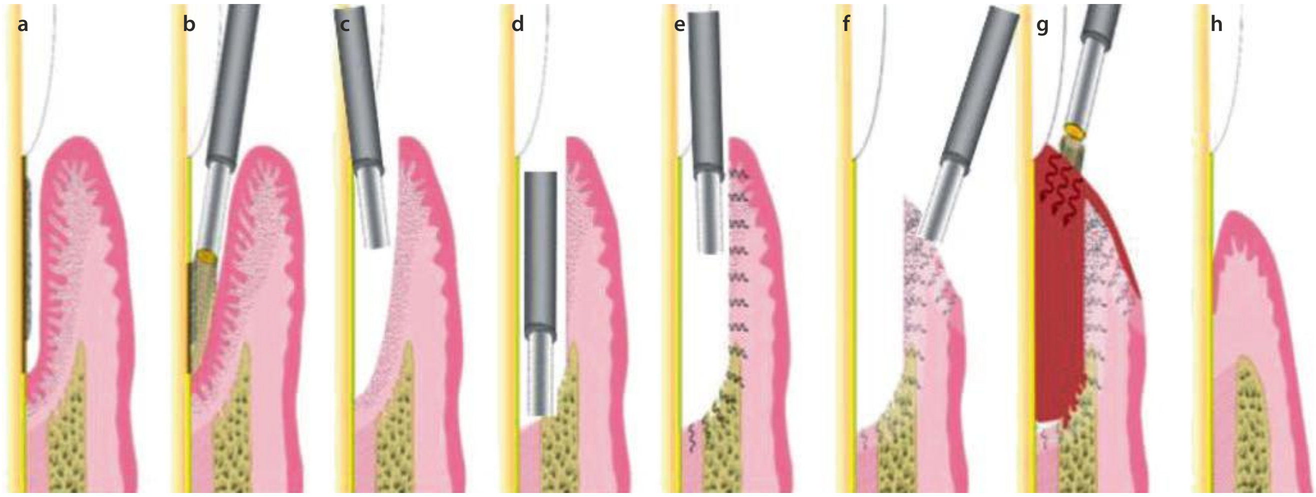

Fig. 14.7 A graphic depiction of LCPT (laser-assisted comprehensive pocket therapy) using an Er:YAG laser. **a** The pocket depth is assessed. **b** Subgingival calculus is removed with both the laser (utilizing a water spray) and conventional instrumentation so that the diseased root surface is decontaminated and detoxified. **c** The laser is used to remove the diseased epithelial and connective tissue lining of the pocket. **d** The osseous tissue is also debrided by the laser using a water spray to promote bleeding from the bone, and the resulting healthy tissue is shown. **e** Some of the laser irradiation can offer biostimulation to the surrounding intrasulcular tissue. (**f**) The outer epithelium and some connective tissue are removed to delay epithelial migration into the healing pocket. This gingivectomy does produce some gingival recession. **g** The laser is used in a noncontact mode without a water spray to ensure hemostasis and to produce a stable blood clot to protect the entrance to the pocket, as well as to stimulate the outer surface of the periodontium. **h** Shows the new attachment and pocket depth reduction (Graphic modified from Aoki et al. [30] with permission © copyright 2015 John Wiley and Sons A/S)

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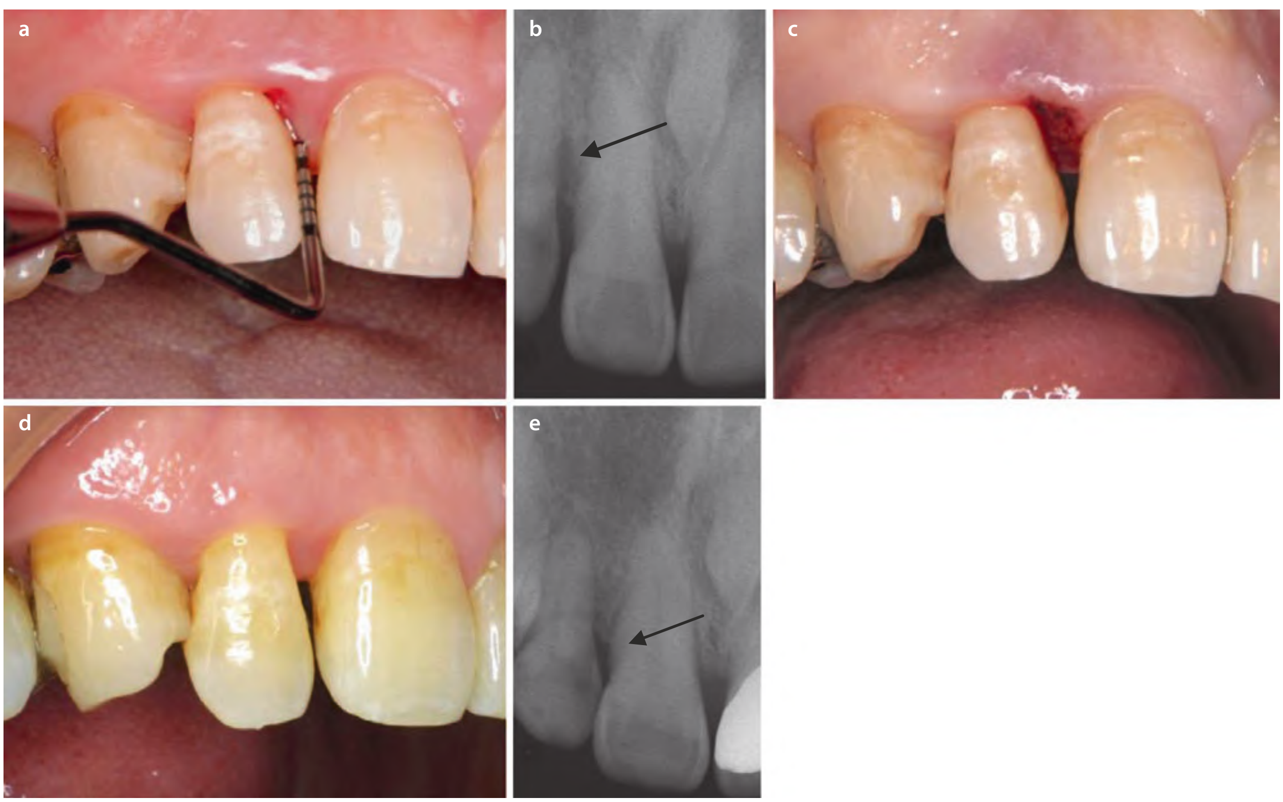


Fig. 14.8 **a** Deep pockets are present on the lateral incisor. The one measures 8 mm with bleeding on probing. **b** The radiograph shows the vertical bony defect (*black arrow*). **c** Immediate postoperative view showing a stable blood clot. The Er:YAG laser was used with an 600 μm curved tip at 1.0 W average power (50 mJ/pulse at 20 Hz) with a water spray to remove the inflamed soft tissue in the pocket and adjunctively with a curette to debride the root surface. Then the inner epithelial wall and the osseous defect were also debrided. The outer epithelium was recontoured to delay gingival down growth and a stable clot was formed. The latter procedure was performed without a water spray. **d** One-year postoperative view shows good healing with a slight loss of the gingival papilla. **e** The radiograph confirms the osseous defect has filled in (*black arrow*) (Clinical case and details courtesy of Dr. Koji Mizutani, and modified from citation [9] with permission © copyright 2016 John Wiley and Sons A/S)

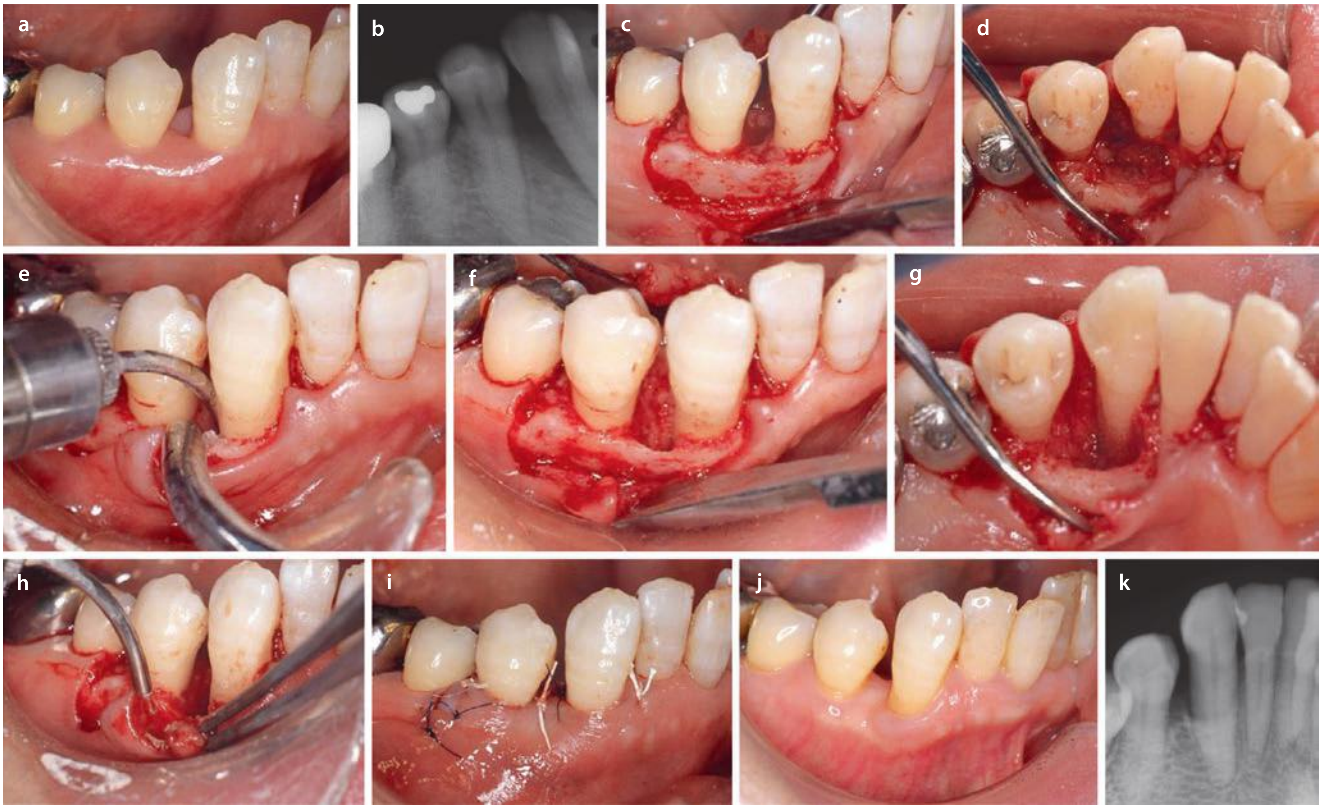


Fig. 14.9 **a**, **b** After initial therapy, a 9 mm pocket with bleeding on probing remains on the distal of the mandibular right cuspid shown clinically and radiographically. **c**, **d** A flap is elevated and granulation tissue fills the pocket when viewed from the buccal and lingual aspects. **e** An Er:YAG laser is used with an 80 degree 400 micron tip at 1.2 W average power (40 mJ per pulse at 30 Hz) with a saline water spray for debridement. **f**, **g** Shows the clean vertical bone defect with no thermal damage from the laser energy. No bone augmentation material was placed. **h** The laser is used with the same parameters to decontaminate and stimulate the gingival flap tissue. **i** The flap is sutured in place. **j** Eight-year postoperative view showing healthy gingival tissue with some recession. In fact, there was 7 mm of pocket depth reduction and 5 mm of clinical attachment gain. **k** Eight-year postoperative radiograph (Case photos and details modified from Aoki et al. [30] with permission © copyright 2015 John Wiley and Sons A/S)

The correct laser wavelength delivered through a small diameter tip can offer more precision and better access than mechanical instruments. Conventional surgical instruments usually need a wider area of access compared to the laser with its irradiation confined to the end of the tip. Thus more precision is possible.

Bone grafting procedures with appropriate membranes may be used in areas where the defect cannot be properly contoured. A laser produces minimal thermal damage resulting in a new osseous surface with good vascularity and a lack of smear layer, which should aid in successful bone augmentation [32].

Figure 14.9 shows the use of an Er:YAG laser for open flap surgery on a 9 mm deep pocket on the distal of the mandibular right cuspid. This pocket remained after initial therapy. The flap was elevated and the laser was used to remove the granulation tissue and debride the root surface. The osseous defect was also debrided, and no grafting material was placed. The inner surface of the flap was irradiated for debridement, and sutures were placed. Eight-year postoperatively there was significant pocket depth reduction and clinical attachment gain.

Figure 14.10 demonstrates a similar open flap procedure where the Er,Cr:YSGG laser was used on a 11 mm pocket on the mesial of the maxillary right first premolar that did not respond to initial therapy. After raising a flap, the laser was used to debride the root surface, the pocket epithelium, and the osseous defect. No bone graft material was placed and the flap was sutured. An 8-month analysis showed pocket depth reduction and attachment gain with slight gingival recession (clinical case courtesy of Dr. Rana Al-Falaki).

Surgical Therapy for Peri-implantitis

Debridement and detoxification of the implant surfaces as well as the diseased tissues surrounding implant fixtures is the primary objective for the treatment of

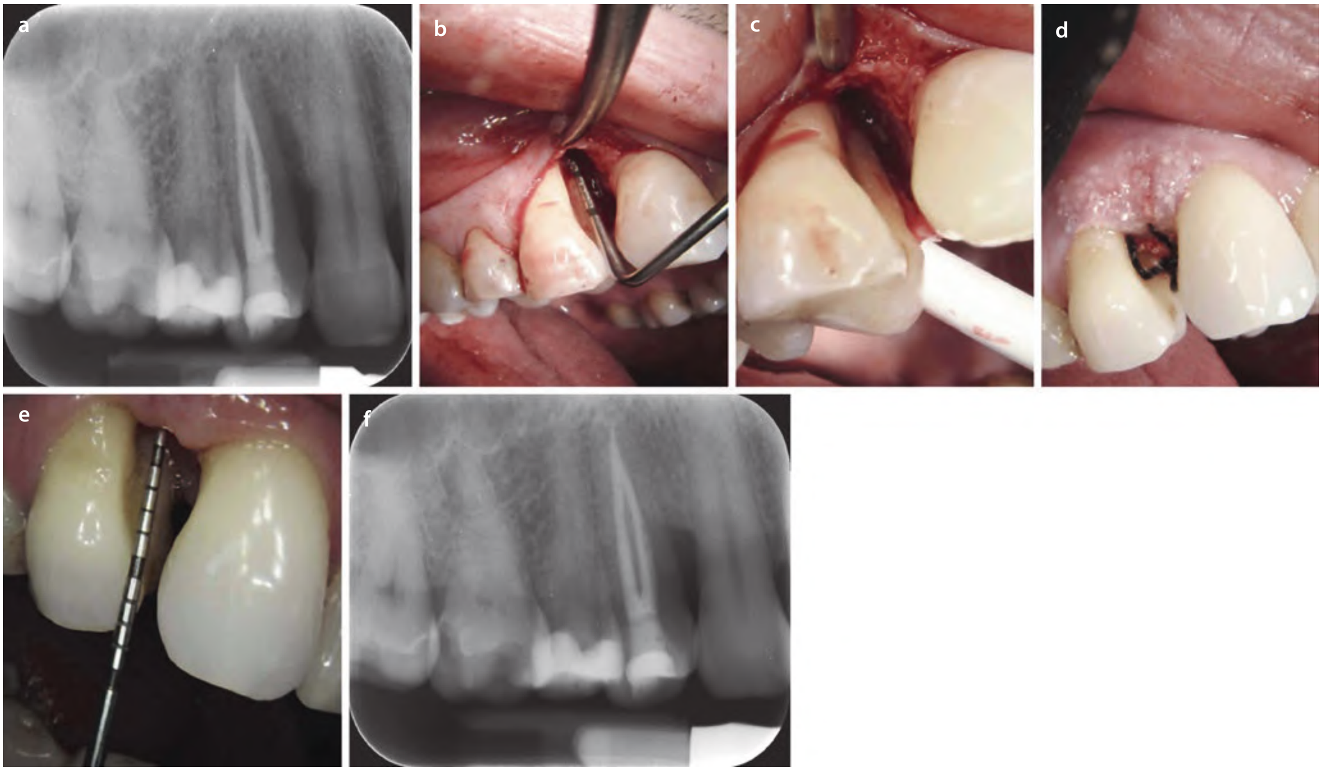


Fig. 14.10 **a** Radiograph showing 11 mm pocket on the mesial of the maxillary first premolar that remained after initial therapy. **b** After the subgingival calculus was removed with ultrasonic instrumentation, a flap is raised and the osseous defect is explored with the periodontal probe. **c** Immediate postoperative view of the debrided infrabony pocket. An Er,Cr:YSGG laser was used with a 600 micron diameter contact tip. To remove the granulation tissue from the soft and hard tissue, an average power of 1.5 W (50 mJ, 30 Hz) was used with 50% air and 40% water spray in the short pulse mode. Subsequently, the smear layer was removed from the root surface and osseous tissue with an average power of 0.75 W (15 mJ, 50 Hz) with 50% water and 40% air. **d** View of the sutured flap. **e** Eight-month postoperative photo with periodontal probe, demonstrating good reattachment with slight gingival recession. **f** Eight-month postoperative radiograph showing a more stable periodontal condition with bone regeneration (Clinical case courtesy of Dr. Rana Al-Falaki)

peri-implantitis. Many laser wavelengths have been studied for their ability to efficiently debride implant surfaces. The diode, carbon dioxide, and erbium instruments generally do not cause any surface damage to implants [36–38]. The precaution is that high average power settings can generate heat on the peri-implant tissues and/or directly affect the titanium fixture. Thus appropriate parameters and techniques must be employed during the surgical session.

After debridement of the surrounding tissues and decontamination of the implant itself, bone augmentation materials and appropriate membranes can be placed in the defect to enhance regeneration. Clearly, good bone vascularity is important to achieve, and proper laser parameters can accomplish this. As mentioned, lasers should allow for beneficial bone healing following surgery along with a biocompatible implant fixture.

Figure 14.11 demonstrates how an Er,Cr:YSGG laser for peri-implantitis therapy. After reflecting a flap, the osseous defect was filled with granulation tissue, and the laser debrided the soft and hard tissues in the area. A bone graft and membrane were placed and the flap was sutured in place. Six months later, the periodontal health was restored (clinical case courtesy of Dr. Rana Al-Falaki).

Figure 14.12 shows the use of an Er:YAG laser for treatment of severe peri-implantitis. The implant fixture shown had no mobility despite the significant lack of labial supporting bone. A decision was made to attempt regenerative therapy although the prognosis was extremely guarded. The large defect contained large amounts of granulation tissue along with underlying infected bone. The Er:YAG laser debrided all of the tissues, and then bone grafting material and a membrane were placed. The flap was sutured. A 3-month radiograph shows new bone growth with a lack of inflammation.

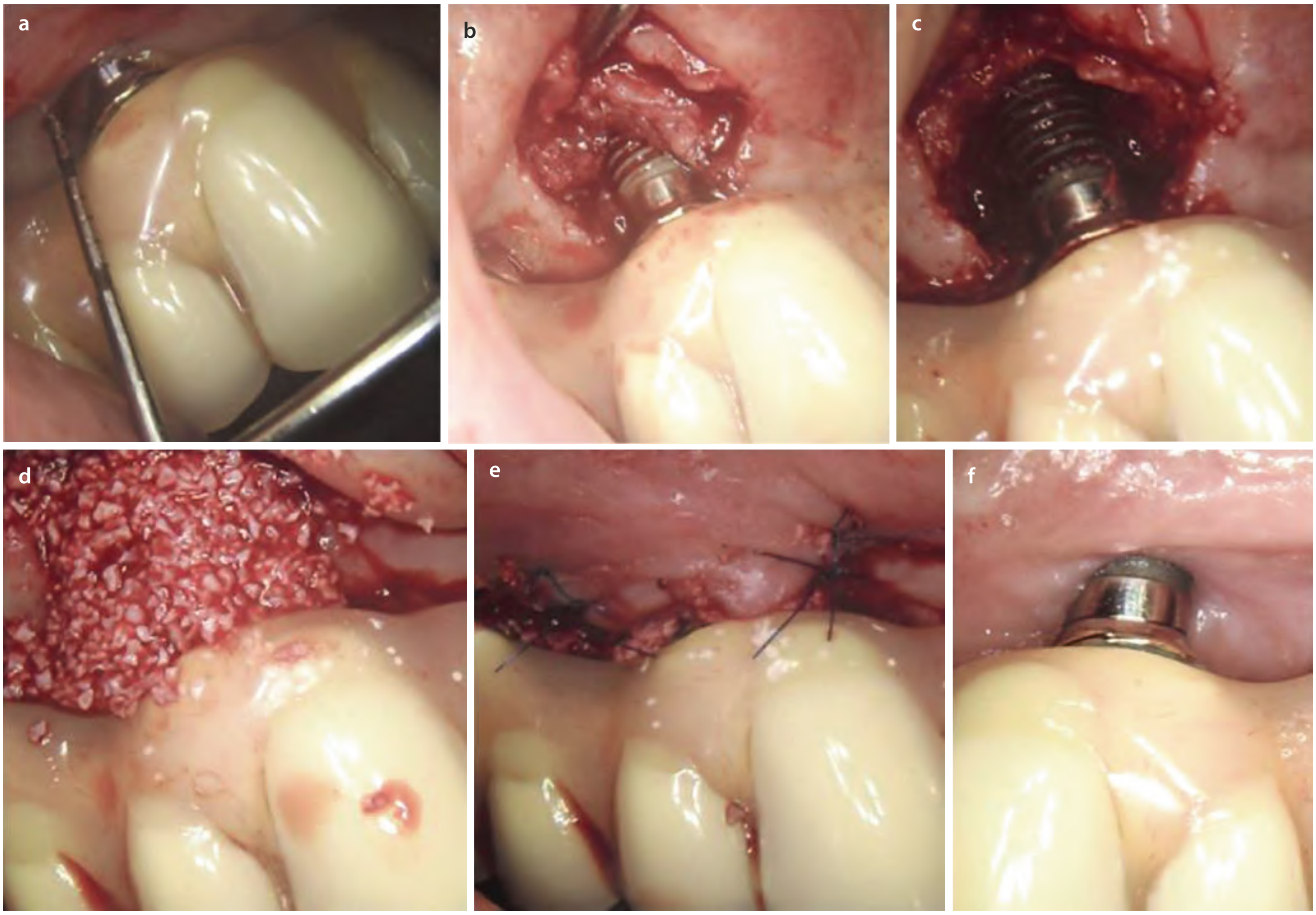
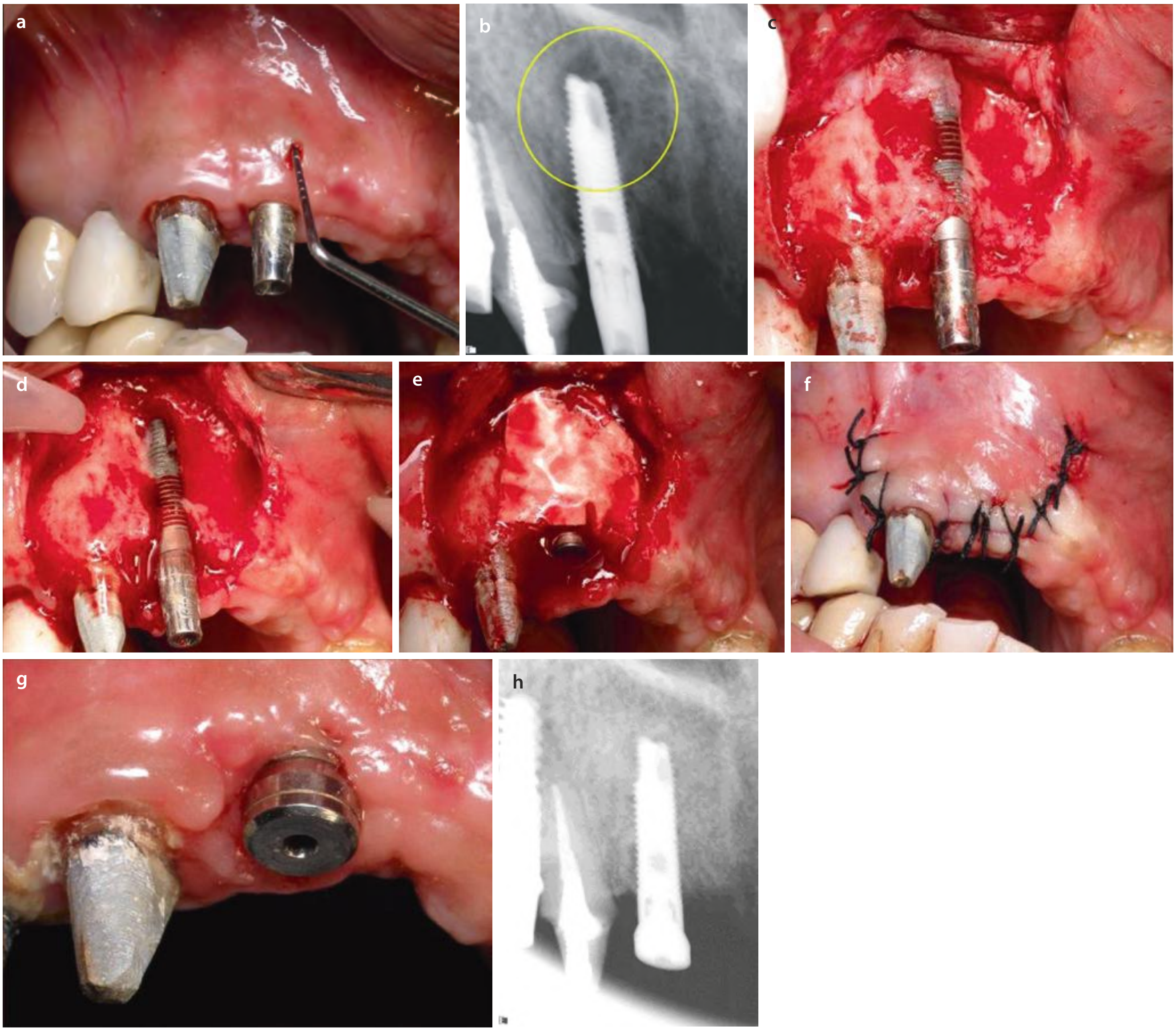


Fig. 14.11 **a** Preoperative view of peri-implantitis around a maxillary posterior implant with an 8 mm pocket. **b** After the flap is reflected, the extent of the defect, filled with granulation tissue, can be seen. **c** Immediate postoperative view of the debridement therapy. An Er,Cr:YSGG laser was used with a 600 micron diameter contact tip. The granulation tissue was removed from the soft and hard tissue with an average power of 2.0 W (66 mJ, 30 Hz) with 70% water and 50% air, angling the tip away from the implant surface. Then the implant was debrided at an average power of 1.25 W (25 mJ, 50 Hz) with 70% water and 50% air. Lastly, the internal surface of the flap was decontaminated at any average power of 0.75 W (15 mJ, 50 Hz) with 50% water and 40% air. Note the good vascularity of the osseous tissue. **d** Bone grafting material is placed immediately to fill the area. **e** The flap is sutured in place. **f** Six-month postoperative view of the healed periodontium with no inflammation (Clinical case courtesy of Dr. Rana Al-Falaki)

Summary: Flapless Periodontal and Peri-Implant Surgery

In summary, dental lasers can be used in a surgical approach for treatment of periodontal and peri-implant diseases with benefits such as precision and enhanced visibility during debridement. In addition, osseous tissue can be predictably ablated and contoured. Future research should emphasize proper power settings and describe the details of the protocol. Laser application for bone ablation is becoming a very useful modality for developing the various usages on periodontal and implant therapy. Preventing thermal damage during following laser treatment is critical for optimal wound healing.



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■ **Fig. 14.12** **a** Preoperative view of a draining fistula from an area of peri-implantitis. **b** The radiograph shows extensive disease including a large area of apical bone loss (*yellow circle*). **c** A flap is raised showing the extent of the inflammatory granulation and infected osseous tissue. **d** The Er:YAG laser was used with a 1,300 micron sapphire tip with an average power setting of 8.4 W (700 mJ per pulse at 12 Hz) with a water spray directed at the granulation tissue. Then, using the same tip and water spray, the parameters were changed to an average power of 3 W (150 mJ per pulse at 20 Hz) for debridement of the implant surface and removal of the infected bone. **e** The site was filled with a xenograft bone substitute and covered with an absorbent bilayer membrane. **f** The flap was sutured. **g** A healing cap was placed 2 weeks postoperatively. **h** The 3-month radiograph shows good bone regeneration and stable bone tissue (Some case details courtesy Dr. Avi Reyhanian)

14.4 Antimicrobial Photodynamic Therapy in Management of Periodontal and Peri-implant Disease

14.4.1 Photodynamic Therapy

Photodynamic therapy (PDT) is a new approach in killing or eliminating pathogens and uses light of a specific wavelength to activate a nontoxic photoactive dye (photosensitizer) in the presence of oxygen to produce cytotoxic products [39, 40]. Various terms are used for PDT such as photoactivated chemotherapy (PACT), photodynamic disinfection (PDD), light-activated disinfection (LAD), photodynamic inactivation (PDI), and photoactivated disinfection (PAD) and antimicrobial photodynamic therapy (aPDT) in different studies and literature. Among these terms, aPDT is the most accepted one for antimicrobial purposes [41, 42].

The successful outcome of PDT critically depends on three elements: photosensitizer, light source, and oxygen (■ Figs. 14.1 and 14.13).

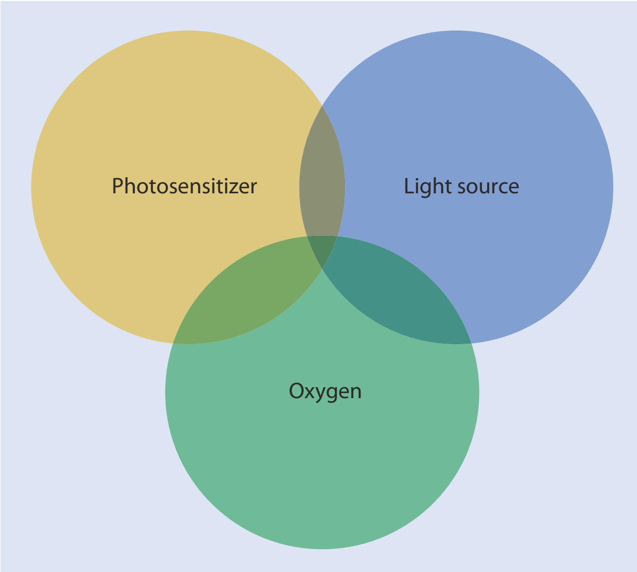

Fig. 14.13 The basic elements of PDT

14.5 Photosensitizer

A photosensitizer is a chemical compound, which, when activate by an appropriate wavelength, forms a highly reactive oxygen species which results in cell death.

The photosensitizers should have some characteristics including:

- Existing as nontoxic and chemically pure compound
- Having the ability to stain the target
- Be economical and easily available
- Possess a short interval between administration of the drug and peak accumulation in the tissue
- Have a short half-life
- Be rapidly eliminated from normal tissue
- Have activation at specific wavelength
- Possess the ability to produce the huge amount of cytotoxic products
- Have the ability to act on a wide range of microorganism [43, 44]

The most applicable photosensitizers which used in dentistry for antimicrobial procedures are described below.

14.5.1 Toluidine Blue O

Toluidine Blue O (TBO) is a cationic blue coloring agent used for histological staining. It can also be applied for differential diagnosis between benign and malignant precancerous leukoplakia. It can be activated by wavelength of 635 nm. It can act on both gram-positive and gram-negative bacteria due to its physical and chemical properties and hydrophilic characteristics, and it showed attraction to the mitochondria which has negative charge. TBO can bind to LPS of the outer cell envelope in gram-negative bacteria and the teichuronic acid residues of the outer wall in gram-positive bacteria [45–47].

14.5.2 Methylene Blue

Methylene blue (MB) is used for selective coloring in histology. It is a hydrophilic compound with positive charge. This photosensitizer can be applied for both gram-positive and gram-negative bacteria. It can penetrate through the porin channels in the outer membrane of gram-negative bacteria and interacts with the anionic macromolecule lipopolysaccharide creating MB dimmers which have role in the photosensitization process. It has a peak absorption at wavelength of 660 nm [48, 49].

14.5.3 Indocyanine Green

Indocyanine green (ICG), a green coloring agent, has recently been introduced as photosensitizer. The mechanism of this photosensitizer is somehow different from other ones. The effect of ICG is mainly that of photothermal therapy (PTT) rather than photochemical reaction. This anionic photosensitizer can be activated by 810 nm but its absorption critically depends on the dissolving medium, the chemical bonds of plasma proteins, and its concentration [44, 50].

14.5.4 Curcumin

Curcumin is a yellow-orange pigment isolated from *Curcuma longa* L. which is mostly used as a spice. It has some therapeutic effects on liver diseases, wounds, and inflamed joints, as well as for blood purification and microbial effects. Curcumin has shown no toxic effects on a number of cell cultures and animal studies. It has a broad absorption peak in the 300–500 nm range (maximum 430 nm) and produces strong phototoxic effects. Therefore, curcumin has the capability to be used as a photosensitizer. Easy handling, low cost, and efficacy make this photosensitizer more popular [51–53].

14.6 Light Source

In photodynamic therapy procedure, the light source coincides with maximum absorption of the photosensitizer used. The light source for aPDT can be classified into three types:

1. Broad-spectrum lamps
2. Light-emitting diode lamps (LED)
3. Lasers

Among the different sources, lasers have some characteristics that make them superior compared to other sources. Monochromaticity which allows the laser to interact with photosensitizer due to matching with its peak absorption results in elimination of unnecessary tissue heating by bandwidths not effective in PDT reaction [54, 55].

In dentistry, most of the photosensitizers are activated by wavelengths between 630 and 700 nm. Currently, with the introduction of new photosensitizer such as ICG, infrared wavelength like 810 nm is also used which has more penetration depth. On the other hand, blue light LED (400–500 nm) which coincidences with curcumin can be a suitable option due to its availability in all dental offices for curing of dental resin composites and capability in creating free radicals more efficiently compared to red light. LEDs are more cost effective and compact in comparison to lasers [56, 57].

14.7 Mechanism of Photodynamic Therapy

When a photosensitizer is activated by an appropriate wavelength, electrons are transferred from a lower level of energy to a higher one which is called the triplet state. Then, the energy is transferred to a biomolecule or to oxygen which leads to the production of cytotoxic species. These products damage the cellular plasma membrane or DNA. Both consequences lead to cell death [58, 59].

The transfer of electrons in activated photosensitizer can be done in two pathways including transfer to the neighboring molecule (type-1 reaction) or to oxygen (type-2 reaction) to produce reactive oxygen species (ROS) like singlet oxygen and other radicals like hydroxyl radical. Although, the two pathways can have a role on bacterial killing, type 2 by producing highly reactive singlet oxygen is detected as the main pathway in killing bacteria (Figs. 14.2 and 14.3). This mechanism is totally different from that of antibiotics; hence, the resistance of bacterial strain is not likely, due to acting on multiple targets inside the bacteria [60, 61] (Figs. 14.14 and 14.15).

It's important to note that antioxidant enzymes produced by bacteria may protect against some oxygen radicals but not singlet oxygen which makes aPDT more effective procedure. Singlet oxygen has a short lifetime in biological

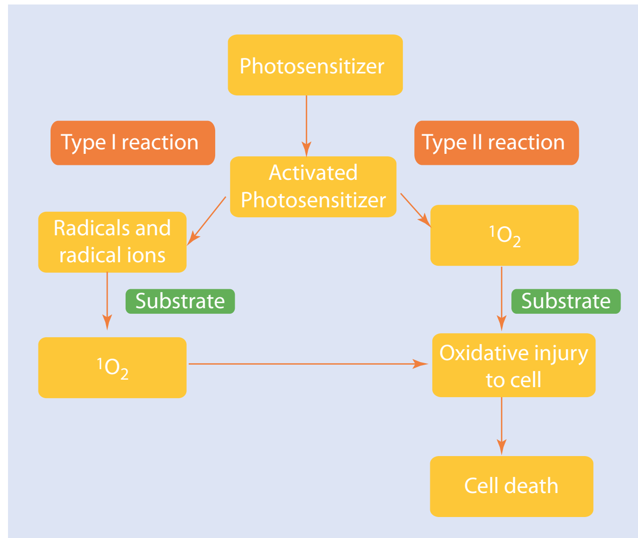

Fig. 14.15 Two pathways in function mechanism of PDT are shown in the flow chart

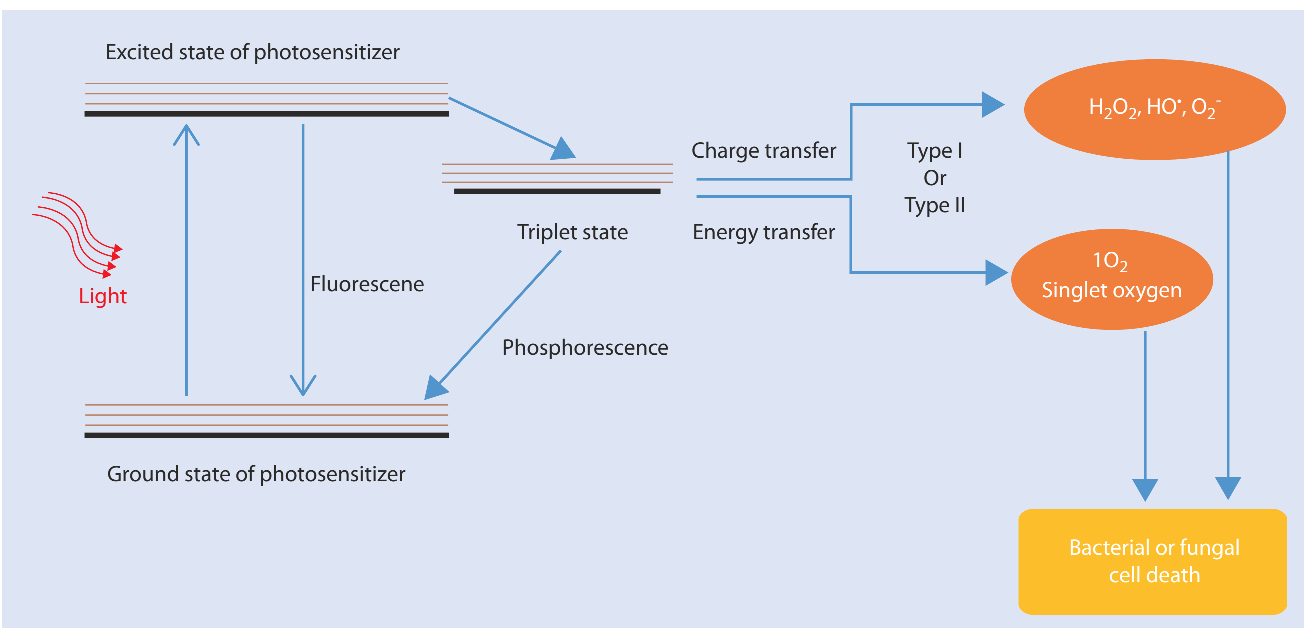

Fig. 14.14 The mechanism of PDT. The photosensitizer is raised to an excited state by absorbing photonic energy and a triplet state is created. Its energy is transferred to create either a hydroxyl radical or a singlet oxygen. The latter is thought to be the main toxic agent for pathogens

system (≤0.04 μs) and a short radius of action (0.02 μm) that make its action localized without affecting distant cells [62, 63].

One of the main concerns during photodynamic therapy is the photosensitivity of bacteria which seems mainly related to the charge of the photosensitizer used. The neutral or anionic sensitizer binds effectively to gram-positive bacteria. It also binds to some degree to the outer membrane of gram-negative bacteria [64]. The porous layer of peptidoglycan and lipoteichoic acid outside the cytoplasmic membrane of gram-positive species allow the photosensitizer to cross into the cell. On the other hand, gram-negative bacteria have an inner cytoplasmic membrane and an outer membrane separated by the peptidoglycan-containing periplasm which acts as a physical barrier between cells and its environment [65]. The binding of negatively charged photosensitizer to gram-negative bacteria may be improved by linking the photosensitizer to a cationic molecule [66] .

The success rate of photodynamic therapies depend on the type, dose, incubation time, and localization of the photosensitizer, the availability of oxygen, the wavelength of light (nm), the light power density, and the light energy fluency. Limitations of this treatment which should be taken into account are the low-oxygenated environment and the diffusion ability of the photosensitizer and light to be used [67].

14.8 aPDT in Periodontital and Peri-implant Disease

It is now established that the application of lasers in management of periodontal diseases can offer some benefits. Using a high-powered laser for antimicrobial purposes raises some concerns like irreversible thermal damage to surrounding periodontal tissues, thermal coagulation, carbonization, and root necrosis [68]. Therefore, aPDT was developed, which is a noninvasive method which uses low power to overcome these limitations. In this technique, the bacteria are selectively targeted without damaging the neighboring tissue [69].

14.8.1 Procedure

- *Assessing periodontal clinical parameters:*
  - The clinical parameters are collected before treatment. The record of parameters were as follows: (a) bleeding on probing (BOP), (b) clinical attachment level (CAL), (c) plaque index (PI), (d) probing pocket depth (PPD), (e) full-mouth plaque score (FMPS), and (f) full-mouth bleeding score (FMBS).
- *Treatment:*
  - After educating oral hygiene instructions, the patients receive full-mouth scaling and root planing (SRP), and the photosensitizer solution is applied to the bottom of the periodontal or peri-implant pocket and gingival sulcus with the use of syringe. Following this, the pocket is exposed to the laser light due to protocol moving from bottom of pocket to coronal. Special safety glasses are provided to the patients, operator, and dental assistant to prevent possible eye damage by the laser irradiation. The procedure can be repeated in the same manner for following weeks due to treatment plan.

Bacteria can penetrate into epithelial cells and connective tissue during periodontal diseases. *P. gingivalis* and *A. actinomycetemcomitans* can infiltrate the epithelial barrier in to periodontal tissues in this case; aPDT can be a solution for eliminating them [70]. Sulcular epithelium has increased penetration of photosensitizer due to non-keratinized pattern. The uptake of photosensitizer in epithelial cells is dependent on incubation time (the interval between applying photosensitizer and laser irradiation). So, there should be a few minutes waiting time after applying photosensitizer before starting laser irradiation [71, 72].

Photodynamic therapy has some advantages like detoxification of endotoxins such as lipopolysaccharides which inhibit the production of pro-inflammatory cytokines. Also, it can reach to deep or limited access sites without the need for flap surgery in some cases; there is no need to anesthetize the area, and there is no need to prescribe antibiotics. In addition there is a low risk of bacteremia, which is useful for at-risk patients (those with cardiovascular diseases, diabetes, and immunosuppression) [73].

Furthermore, aPDT increases tissue blood flow in microcirculatory system and reduces venous congestion in gingival tissues.

In assessing different studies, controversial results are obtained due to the different wavelengths of laser and the type of photosensitizer type used.

Bassir et al. assessed photo-activated disinfection using LED and TBO as an adjunct in the management of patients with moderate to severe chronic periodontitis. The study concluded that at 1 and 3 months, PDT showed significant improvements with regard to all clinical parameters compared to baseline but did not have additional effects on clinical parameters in patients [74].

On the other hand, Prasanth et al. in evaluation of aPDT by methylene blue and 655 nm diode laser in management of chronic periodontitis concluded that aPDT has an important role in improving clinical outcomes obtained by SRP, and single application of aPDT resulted in effective gingival inflammation and pocket depth reduction over a period of 6 months. The group also suggested that the procedure be repeated at frequent intervals [75].

Monzavi et al. tried to test the efficacy of adjunctive aPDT with ICG compared with scaling and root planing (SRP) alone in chronic periodontitis treatment (Fig. 14.5). The

PDT group yielded higher improvements in bleeding on probing (BOP) and full-mouth bleeding score (FMBS) rather than the control group after 1- and 3-month follow-up examinations. After 3 months, the patients that received PDT showed 0% of BOP score, while the control group displays 48% of BOP positive [76]. Boehm and Ciancio found that rapid and significant uptake of ICG into periodontal pathogens that are activated by 810 nm diode laser resulted in significant killing of *A. actinomycetemcomitans* and *Porphyromonas gingivalis* [77].

The effect of ICG is mainly photothermal therapy rather than photochemical (80% photothermal and 20% photochemical). In addition, the peak absorption of ICG is close to available soft tissue diode lasers (808 nm), compared to the peak absorption of methylene blue and toluidine blue O which are at 660 nm and 635 nm, respectively. The higher penetration of 810 nm diode laser compared to other wavelengths with an easy insertion of the fiber-optic applicator allows an easier access into deep pockets. Besides, the photothermal effects of ICG accompanied by photochemical effects make this photosensitizer important for eradication of pathogens in deep periodontal pockets or in the periodontal treatment of non-reachable sites (i.e., furcation or invaginations). Therefore, ICG with an 810 nm diode laser can be considered as a promising candidate for adjunctive periodontal treatment [78].

14.8.2 Clinical Cases

Figure 14.16 illustrates the use of Toluidine Blue O for treatment of a periodontal pocket. A LED source of photonic energy activates the chemical.

Figure 14.17 depicts the use of indocyanine green for treatment of a periodontal pocket. An 810 nm laser was used to activate the photosynthesizer.

Figure 14.18 illustrates the use of methylene blue for the treatment of a periodontal pocket. A proprietary visible red laser (632 nm) was used to activate the photosynthesizer. Clinical case courtesy of Dr. Steven Parker.

Figure 14.19 shows the application of antimicrobial photodynamic therapy for management of peri-implantitis in a 50-year-old woman. In this case, 7 mm pocket depth and bleeding on probing were observed. After manual debridement, the phenothiazine chloride as photosensitizer was applied in the implant sulcus. After 3 min, the excess

Fig. 14.16 **a** Application of TBO inside the pocket. **b** Irradiation of papilla by blunt tip of LED. **c** Irradiation of the pocket by intra-pocket tip of LED

Fig. 14.17 **a** Clinical aspect of treatment site. **b** ICG was applied inside the pockets. **c** The view of treatment site after ICG application. **d** Irradiation of pockets by diode laser at wavelength of 808 nm

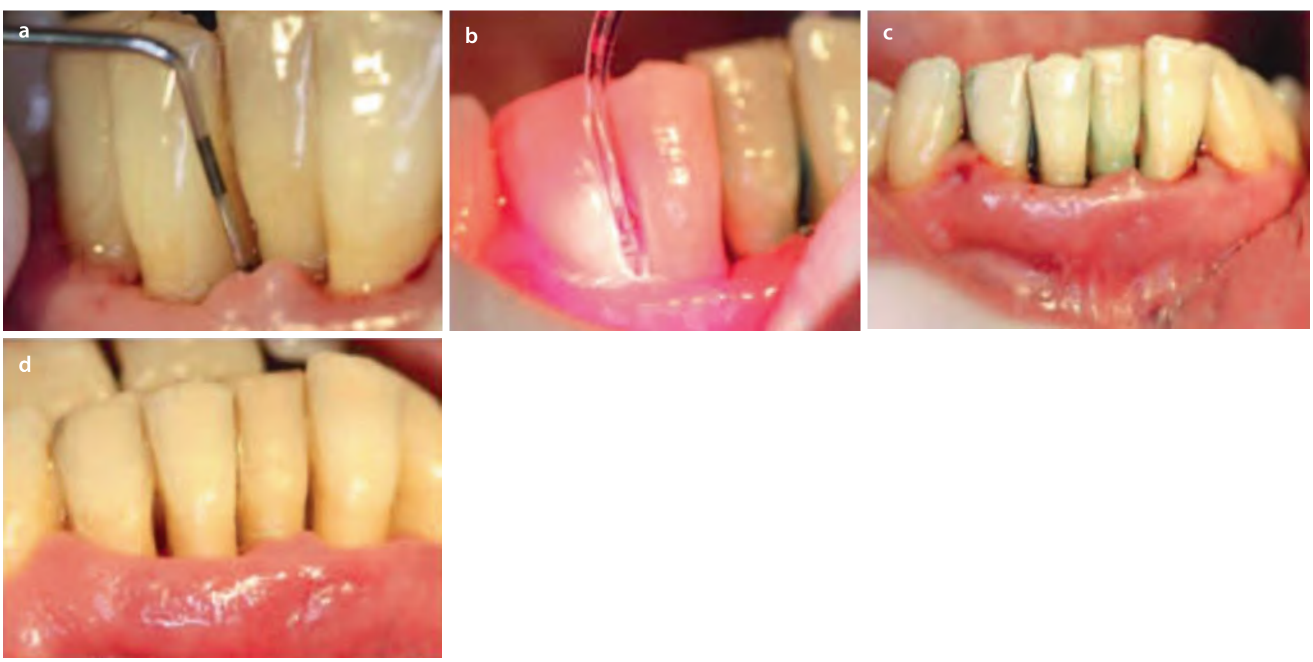

Fig. 14.18 **a** Facial view of the periodontitis condition of the lower anterior area. **b** After scaling of the pockets, the methylene blue solution is applied. A visible diode laser activates the photosensitizer. **c** Immediate posttreatment view of the site. **d** A 1-month posttreatment photo showing tissue health with no inflammation (Clinical case courtesy of Dr. Steven Parker)

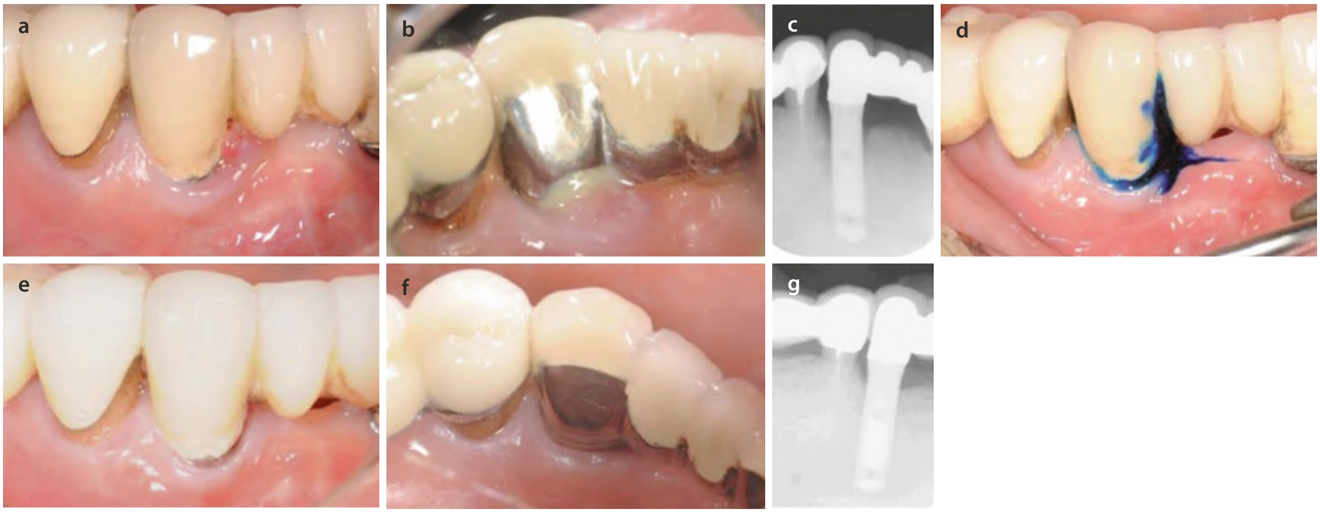

Fig. 14.19 **a** Facial view of peri-implantitis of the lower right cuspid. **b** The lingual view of the implant area with a discharge of exudates. **c** Preoperative radiograph showing the periodontal defect. **d** The application of phenothiazine chloride inside the pocket. **e** Facial view 31 months later showing excellent periodontal health. **f** Lingual view 31 months later of the healed area. **g** Radiograph of the treated implant, 31 months later (Clinical case courtesy of Dr. Chen-Yeng Wang, modified from citation [9] with permission © copyright 2016 John Wiley and Sons A/S)

photosensitizer was rinsed, and diode laser (670 nm) with output power of 75 mW was irradiated for 1 min. In follow-up of 8 months, pocket depth of 3 mm and absence of bleeding on probing were observed.

Angular bony defects at both mesial and distal parts were observed before treatment, but 8 and 19 months later, bone gain at both sides was detected, and 31 months later, maintenance of the bone level at mesial and distal aspects was approved (case details provided by Dr. Chen-Ying Wang) [9].

14

14.9 Considerations During a PDT Therapy

The effective treatment of periodontal problems must include proper oral hygiene instructions, which consist of a combination of daily tooth brushing, interdental cleaning, and, when necessary, use of chemotherapeutic agents [e.g., mouthwash]. Thus, the patient's compliance with those instructions is fundamental for the success of the treatment of periodontal and peri-implant disease.

Summary: Antimicrobial Photodynamic Therapy

In summary, there are still limited data from clinical studies with controversial results in application of PDT as an adjunctive treatment for management of periodontitis and peri-implantitis. In patients with chronic periodontitis, SRP and PDT have shown higher short-term clinical improvements like probing depth or bleeding on probing compared to SRP alone. But in aggressive periodontitis, there is not sufficient evidence to replace systemic antibiotic by PDT. Also, limited evidence exists to consider PDT as an alternative to local antibiotics in peri-implantitis.

Moreover, the application of some photosynthesizers like methylene blue can stain the teeth if the appropriate concentration is not used. It was suggested that MB in concentrations below 100 µg/ml reduces the chance of tooth discoloration [79]. Pourhajibagher et al. in evaluation of antimicrobial photodynamic therapy with indocyanine green and curcumin on human gingival fibroblast cells came to this conclusion that to avoid cytotoxicity, the concentration of the sensitizers and laser irradiation time are essential for aPDT. They also observed that the optimum concentration of ICG as photosensitizer for aPDT should be at least 1,000 µg/ml with 30 or 60s irradiation time by 810 nm diode laser [80].

Conclusion

Clinicians continue to search for and learn about novel methods to aid in the treatment of periodontal and peri-implant diseases. Various benefits such as pocket depth reduction, gain of clinical attachment, and improved wound healing are reported in the scientific studies. However, the use of the laser for these therapies generates controversial discussion in the literature. Nonetheless, adjunctive or alternative use of dental lasers, both direct minimally invasive surgical or non-surgical procedures as well as in photochemical activation, are becoming part of the practitioner's armamentarium.

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Laser-Assisted Multi-tissue Management During Aesthetic or Restorative Procedures

Donald J. Coluzzi

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Core Message

Whether treating new carious lesions or planning extensive prosthodontics, the dental clinician must consider how the restoration will harmonize with the periodontium so that the result will be both healthy and maintainable. Likewise, recontouring the gingiva and the underlying supporting bone for improved aesthetics must entail the same deliberation. Dental lasers can be used for modification of soft or hard supporting tissue. The appropriate wavelength and operating parameters must be chosen for the specific tissue, but the result can be very predictable and biologically compatible with the restoration.

15.1 Introduction

This chapter will describe the use of multiple laser wavelengths to alter and improve hard and soft dental tissues for improved aesthetics and successful restoration placement. While this chapter's intention is to not exhaustively review all aspects of periodontal surgery, fundamental concepts of soft tissue anatomy such as biotype and biologic width will be discussed. The basic principle is that, after any alteration to soft or hard tissue, good physiologic contour must be restored. Predictable tissue management primarily relies on the clinician's choice of the proper wavelength to interact with the target tissue, while using appropriate parameters and techniques to maximize the efficiency of tissue removal, establish proper contour, and minimize any collateral damage. ► Chaps. 3 and 4 discuss these concepts in great detail.

15.2 Review of Laser Wavelengths and Tissue Interaction

15.2.1 Diode and Nd:YAG Lasers

These near-infrared wavelengths produce photonic energy that is generally scattered in soft tissue and is transmissive through water but will be absorbed by pigmented and/or inflamed areas. These lasers are for soft tissue only; they have virtually no interaction with healthy tooth structure and should not be used on bone. They work well in well-vascularized tissue and provide excellent hemostasis. As noted previously, Nd:YAG instruments operate in a free-running pulsed mode, producing very high peak powers; some diode lasers also can operate with relatively short pulse durations and moderate peak power output. This pulsing modality can help to control collateral thermal damage.

15.2.2 Erbium Lasers

The two wavelengths of these mid-infrared instruments have the highest absorption by water compared to any other available lasers, with a smaller secondary interaction with the mineral components of hard tissue. These lasers employ a free-running pulsed emission, and their high peak power is primarily and rapidly absorbed into water. In soft tissue, this produces a shallow area of ablation. In hard tissue, there is superheating of the water content of the tooth or bone, resulting in an explosive expansion. This disrupts and ejects whole fragments of the calcified structure, resulting in a «cavity.» The mineral remains unchanged. The term «all-tissue laser» implies that an erbium instrument can perform soft tissue excisions, tooth preparation, and osseous procedures.

15.2.3 Carbon Dioxide Lasers

There are also two far-infrared wavelengths in this category. Both are highly absorbed by hard tissue and secondarily by water. Current developments in technology allow the 9300 nm machine to remove carious lesions and prepare teeth, contour bone, and perform soft tissue surgery. The 10,600 nm device can only be used for soft tissue procedures in its present form.

15.2.4 For Soft Tissue Surgery Procedures, the Following Points Should be Considered

- **Very fibrous gingival tissue surrounding chronic inflammation due to a margin discrepancy of a crown will be much more difficult to incise with the near-infrared wavelengths because of their photonic energy's preference for melanin or hemoglobin in the tissue. Moreover, these wavelengths can cause some conductive heat buildup in tissue distant to the surgical area with possible peripheral edema. Lasers with longer wavelengths, such as carbon dioxide, would be much better instruments for that type of tissue.**
- **Alternatively, acutely inflamed gingiva with its well-vascularized structure would be easily ablated by the same near-infrared lasers.**
- **A water spray can be used to control the tissue temperature during ablation. This irrigation can either be emitted from the laser (erbium and 9300 nm carbon dioxide instruments) or from other sources such as the operatory triplex syringe. The near-infrared wavelengths are generally transmitted through water, but the mid- and far-infrared photonic energy is highly interactive. While the water will cool the tissue, it would reduce the average power at the target tissue when using erbium or carbon dioxide wavelengths, since some of the laser energy will be actively absorbed.**
- **When using all-tissue lasers, care must be exercised while removing soft tissue to avoid unintentional removal of tooth structure. The laser beam must be aimed as precisely as possible and a suitable physical barrier (such as a matrix band or plastic instrument)**

could greatly aid in only ablating the target tissue. This precaution is especially important with some noncontact laser delivery systems.

- **While performing a gingivectomy, the clinician must strive to match the healthy physiologic contour of the adjacent gingiva. The desired goal is that the healed site will not only be harmonious with the patient's periodontium, but will retain its shape with a healthy attachment. One benefit of using a laser for the procedure is that small areas of tissue can be treated in steps until the desired contour is achieved. This precision is easier to accomplish compared to tissue removed with a surgical blade.**

15.2.5 For Procedures Involving Alveolar Bone, the Important Points to Remember Are

- **During osseous surgery, care must be taken to avoid overheating the bone and compromising its vascularity. The appropriate lasers for this procedure use a water spray, and the clinician should ensure that the irrigation is properly directed toward the target tissue.**
- **When performing osseous crown lengthening, an open flap or closed flap technique may be used. With the absence of visualization during a closed flap procedure, the clinician must use maximum tactile sense while excising and contouring the bone, while simultaneously avoiding alterations to the healthy root surface.**
- **Whether an open or closed flap is chosen, it is recommended that the soft tissue modification proceed first. It is much more difficult to excise and reshape the gingival tissue after the new bone form is established.**
- **Similar to soft tissue surgery, the laser beam's placement should be as precise as possible. The bony tissue must be properly contoured so that there are no remaining defects, troughs, or unusual anatomy. The underlying bone will determine the ultimate contour of the soft tissue covering it.**

15.3 Gingival Biotype

Gingival anatomy has been generally described and categorized as either thin or thick [1, 2]. Variations of those terms sometimes appear in print as «thin-scalloped» or «thick-flat,» and current terminology is phrased thick or thin biotype. Although somewhat difficult to determine visually, the disappearance of the tip of the periodontal probe into the sulcus usually indicates a thick tissue biotype. Other characteristics can aid in the classification:

- The *thin biotype* is generally less than 1.5 mm in thickness with a width of 3.5–5 mm and is characterized by a narrow zone of keratinized tissue with thin marginal bone surrounding teeth with triangular anatomic crowns. An example is shown in Fig. 15.1a.
- The *thick biotype* is at least 2 mm in thickness with a width of 5–6 mm and features a large amount of keratinized tissue, thick marginal bone, and bony plates surrounding square anatomic crowns. An example is shown in Fig. 15.1b.

The alveolar crest position and labial cortical plate thickness has a significant correlation with the gingival biotype [3]. It has been shown that patients with thin biotype tissue had a great prevalence of gingival recession [4], whereas patients with thick biotype are less likely to experience those changes after surgical or restorative therapy [5]. Thus the laser clinician should identify the gingival biotype before treatment and take special care with cases of thin anatomy.

15.4 Biologic Width and the Dentogingival Complex

This term is defined as the dimensions of the soft tissue attachments of the soft tissue to the portion of the tooth coronal to the crestal alveolar bone. Based on measurements first published by Gargiulo [6], biologic width is generally stated as approximately 2 mm—the sum of the width of the epithelial and the connective tissue attachments. There are some variations in different studies of that 2 mm value, and clinicians also find the same variety. This can be due to many factors such as the position of the tooth in the alveolus, the anatomy of the roots, and especially the health of the

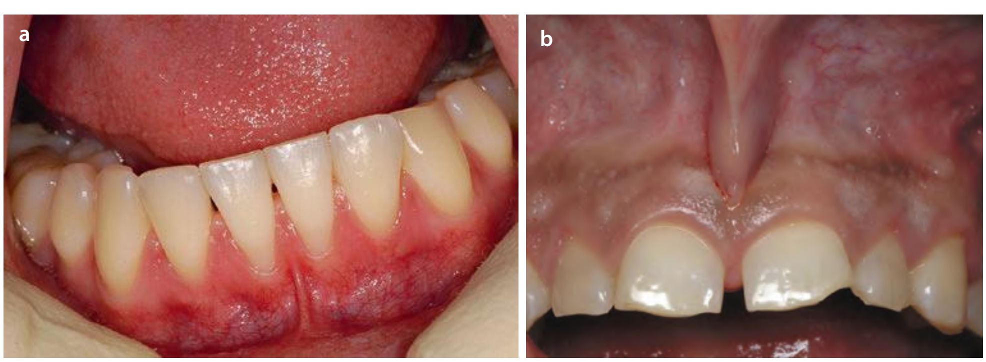


Fig. 15.1 **a** An example of thin biotype tissue in the mandibular incisor area. Note the narrow zone of keratinized tissue. **b** An example of thick biotype tissue with a large area of attached gingiva

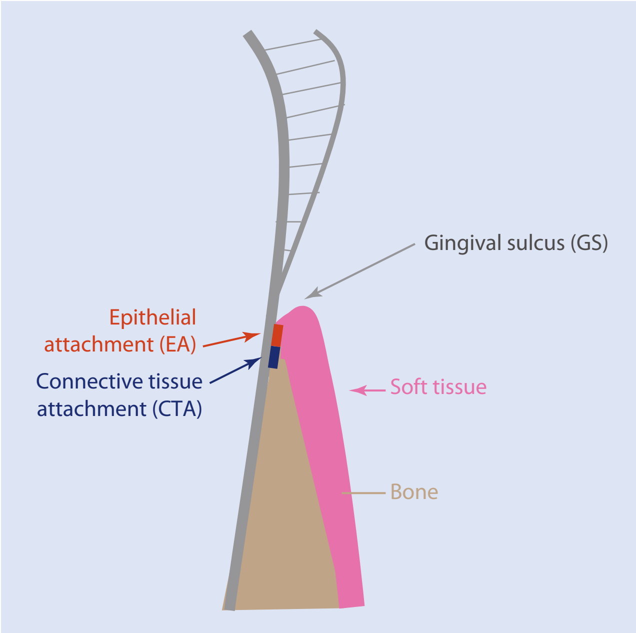


Fig. 15.2 A graphic depiction of the dentogingival complex (DGC) and the biologic width W). BW is composed of the epithelial attachment (*EA*) and the connective tissue attachment (*CTA*) and usually measured as a total of 2.0 mm. The DGC includes the gingival sulcus (*GS*) with a minimum depth of 1.0 mm

periodontium [7]. Most practitioners generally use the term dentogingival complex which includes the gingival sulcular depth when discussing biologic width for ease of measurement. The literature states that 3.0 mm is the ideal distance from the free gingival margin to the alveolar crest on the facial aspect of anterior teeth and from 3.0 to 5.0 mm measured interproximally [8, 9]. Thus the apical aspect or bottom of the sulcus can be viewed as the top of the attachment. Therefore the clinician can account for any variation in the attachment position by ensuring proper measurements. Figure 15.2 illustrates the ideal dentogingival complex and measurements.

As the clinician designs the restoration, this concept will guide the placement of the margin relative to the attachment and bone to ensure optimal periodontal health [10]. This can be a critical decision in the aesthetic zone, where one of the treatment objectives is to mask the junction of the margin with the tooth. Other situations such as creating adequate resistance and retention form or to make significant alterations to the shape of the restoration will dictate the apical extension of the preparation. However, placement of the apical margin of the restoration within the biologic width can produce inflammatory periodontal disease [10]. This subgingival margin location can create the greatest biologic risk, and the best practice is to place that margin a maximum of 0.5 mm into the sulcus. This distance will minimize any chronic inflammation by not impinging on the biologic width. From another perspective, this would mean that the margin should be a minimum of 2 mm away from the alveolar crest.

For aesthetic procedures where only the periodontium is altered without placing any restorations, the new soft tissue must still retain an optimum biologic width so that there will be long-term stability.

Thus any restorative or aesthetic procedure that alters hard or soft tissue must establish a new healthy biologic width and dentogingival complex.

15.5 Emergence Profile

The emergence profile is that portion of the clinical crown's contour extending from the base of the gingival sulcus to the proximal contacts and to the height of contour on the facial and lingual surfaces [11]. This circumferential shape of the tooth or restoration in relation to the surrounding soft tissue is crucial for both periodontal health and aesthetics. The emergence profile must be scrutinized on each axial surface depending on various clinical situations ranging from a diastema closure and height of contours of partial denture abutments to placement of interproximal contact areas and all subgingival margins. In all situations, the final restoration on an implant abutment or a pontic in a fixed bridge must harmonize with the rest of the patient's dentition.

The reestablishment of a normal embrasure with a restoration is particularly challenging when there is no papilla, as in pontic or implant spaces and some diastema areas [12]. Adding width to close a space generally necessitates a deeper subgingival margin of the restoration [13]. Of course, the final result must achieve periodontal health. Various techniques are necessary such as troughing the gingiva to add additional restorative material, contouring the edentulous ridge, and troughing around the implant fixture. All of these are ideal procedures that can be performed with a laser.

Fig. 15.3 **a** Preoperative view of a crown restoration with a recurrent carious lesion at the gingival margin. **b** A 2-week postoperative view showing the healed tissue after crown lengthening and troughing with an Nd:YAG laser using a 320 micron fiber and an average power of 2.0 W (100 mJ at 20 Hz). **c** Four-week postoperative view showing the crown delivery. Note the emergence profile. **d** Preoperative view of a bonded pontic replacing the maxillary lateral incisor. **e** An Er:YAG laser used with a 400 micron tip and an average power of 2.0 W (40 mJ per pulse at 50 Hz) without water spray to produce an ovate pontic concavity on the soft tissue. **f** Four-week postoperative view with new restoration in place. Note the much improved gingival embrasures and papillae due to the improved emergence profile. **g** A 810 nm diode laser used with a 400 micron tip at 1.0 W continuous wave begins to uncover an implant fixture. **h** A 2-week postoperative view of the healed gingival contour. **i** A 6-week postoperative view of the restored implant. Note the healthy gingival tissue (Implant case courtesy of Dr. Steven Parker)

15.5.1 Clinical Cases Illustrating Emergence Profile

Figure 15.3 shows three different clinical situations where a laser was used to create a new emergence profile. In each case the soft tissue needed careful contouring so that the final restoration could be constructed with ideal axial surfaces to restore both function and health

15.6 Crown Lengthening

This term is used to describe the intentional surgical removal of periodontal tissues for both aesthetic improvements and/or proper and predictable placement of a restoration. Many clinical conditions can be indications for crown lengthening, such as subgingival carious lesion, subgingival fracture of tooth structure, inadequate axial height of a preparation, unequal gingival levels, altered passive eruption, and short clinical crowns due to wear [14].

The primary goal is to attain a healthy biologic width around the total circumference of the tooth. There are other important objectives such as achieving the proper aesthetic tooth form or providing sufficient tooth structure for a successful restoration. For aesthetic procedures, the clinician can achieve the desired result of a more pleasing smile by applying the principles of maintaining a healthy dentogingival complex. Crown lengthening can be limited to soft tissue only, or both soft and hard tissue can be contoured.

15.7 Soft Tissue Crown Lengthening

This surgery consists of two procedures—the excision of the gingival tissue to the desired height (gingivectomy) and the recontouring of that newly established marginal tissue to match the adjacent anatomy (gingivoplasty.) The amount of gingivoplasty will depend on the tissue biotype: thin biotype will need less contouring than a thicker anatomic form. After ensuring that biologic width is adequate, it is essential to restore the physiologic contours after soft tissue crown lengthening. This combination of removal and sculpting should produce a harmonious gingival outline segment and will also minimize any «rebound» or undesired tissue regrowth. ◘ Figure 15.4 demonstrates how a laser is used for both procedures.

Any available dental laser can be used, keeping in mind how it interacts with the target tissue and adjusting the parameters for optimum ablation. When using erbium or carbon dioxide wavelengths, caution should be taken to avoid any tooth interaction until needed. In ◘ Fig. 15.2a, the diode laser can be aimed directly at the enamel, since that wavelength has minimal interaction with healthy tooth structure. However, the beam of erbium and carbon dioxide wavelengths should be placed parallel to the enamel to avoid unintended removal of the enamel, as shown in ◘ Fig. 15.2b. As noted, biologic width must be considered both when planning this surgery and after it is completed. After soft tissue crown lengthening, the clinician should determine if adequate biologic width remains; if not, then osseous crown lengthening must be performed.

15.7.1 Soft Tissue Crown Lengthening for Aesthetics

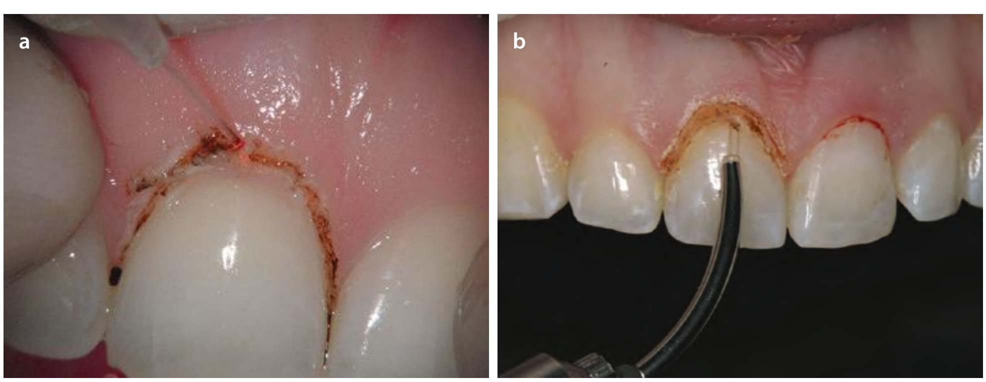
Before any gingival surgery, proper treatment planning is essential. Aesthetic gingival procedures should consider the overall design of the smile that exists and how the practitioner can change that form. Clearly, there are personal interpretations of aesthetics, and those can have a wide variance among patients both individually and culturally. Moreover, the clinician may have specific opinions. In the end, the treatment objectives are to produce a pleasing and healthy result for the patient.

The starting point for any smile design is the clinical crown profile of the maxillary central incisors and the corresponding gingival shape surrounding them [15]. If the patient desires some alteration, for example, for a «gummy smile,» then the biologic width must be located. After that, the surgical plan would be to create good symmetry on both sides of the midline. The zenith or apical most point of the gingival outline should ideally be the same height on the central and cuspid, while the lateral incisor's height can be 1–2 mm shorter [16].

The ideal gingival contour has a scalloped shape, and all of the interdental papillae fully occupy the interproximal embrasures. During gingival surgery, care should be taken to not produce a less scalloped, flatter gingival margin, since that could result in shorter interdental papilla and the opening of the embrasure spaces. The latter condition is sometimes referred to as «black triangles,» and that would be a compromised aesthetic outcome. The most predictable gingival response will occur when the new postoperative outline follows the smile design principles as well as providing optimum periodontal health.

15.7.2 Soft Tissue Crown Lengthening for Restorative Dentistry

The traditional restorative requirements of adequate and sound tooth structure can be problematic when a carious lesion extends subgingivally. The clinician must be able to visualize and remove the diseased tooth structure, while analyzing the periodontal condition. In addition, an acceptable emergence profile must be produced.



◘ **Fig. 15.4** **a** The diode laser is used for a gingivectomy and subsequent gingivoplasty on a maxillary central incisor. Note that the beam can be directed toward the tooth with minimum interaction or damage potential. **b** An Er:YAG laser is performing the gingivoplasty on the maxillary right central incisor. The gingivectomy was already performed on both central incisors. Since this wavelength can also be used for tooth preparation, the tip should not be aimed directly at the tooth surface during the soft tissue crown lengthening

Retraction or removal of gingiva impinging on a lesion is essential for thorough caries removal. If biologic width is adequate after the preparation is complete, then the clinician must decide if the margin placement will aid or hinder the patient's ability to maintain oral hygiene to try to prevent another lesion [17]. In both cases, a laser can be used.

15.7.3 Clinical Cases of Soft Tissue Crown Lengthening

Figure 15.5 shows the use of an erbium laser to improve gingival aesthetics. Excessive gingiva results in the appearance of short clinical crowns. After biologic width is measured, it was determined that soft tissue crown lengthening could proceed. A tissue marker provided a «layout» to guide the clinician for the procedure. Note that the laser is used parallel to the labial surface to avoid any interaction with the enamel. The immediate postoperative view shows good tissue contour (Clinical case courtesy of Dr. David Hornbrook).

Figure 15.6 illustrates a case of porcelain veneers placed to improve aesthetics and to close the diastema of the maxillary incisors. The patient opted out of orthodontic treatment as a first step. A harmonious gingival architecture to produce a pleasing smile along with a good emergence profile for the restorations was meticulously planned. A diode laser was used.

Figure 15.7 illustrates another case of aesthetic crown lengthening utilizing an Nd:YAG laser. Adequate biologic width was measured, and the laser performed a gingivectomy and gingivoplasty. The Nd:YAG wavelength produces a similar tissue interaction result to a diode laser, although the free-running pulse emission mode produces very short duration pulses with a low emission cycle. The relatively long intervals of non-emission are periods of thermal relaxation for the tissue during the surgery, which is an advantage for thinner tissue biotype.

Figure 15.8 shows the use of a diode laser to remove gingiva at an abfraction lesion in order to finish the apical extent of the preparation. The laser can easily recontour the tissue and maintain a dry field for placement of the restoration. As noted above, the diode wavelength has no interaction with the tooth structure. In addition, the new gingival level will facilitate the patient's oral hygiene in that area.

Figure 15.9 depicts a recurrent carious lesion around an existing restoration on bicuspid. The inflamed marginal gingiva prevents total access to the lesion. A carbon dioxide laser was used to remove the tissue, repositioning it more apically so that a new composite could be placed. The 9300 nm instrument also removed the carious lesion, and that discussion can be found in ► Chap. 8 (Clinical case courtesy of Dr. Josh Weintraub).

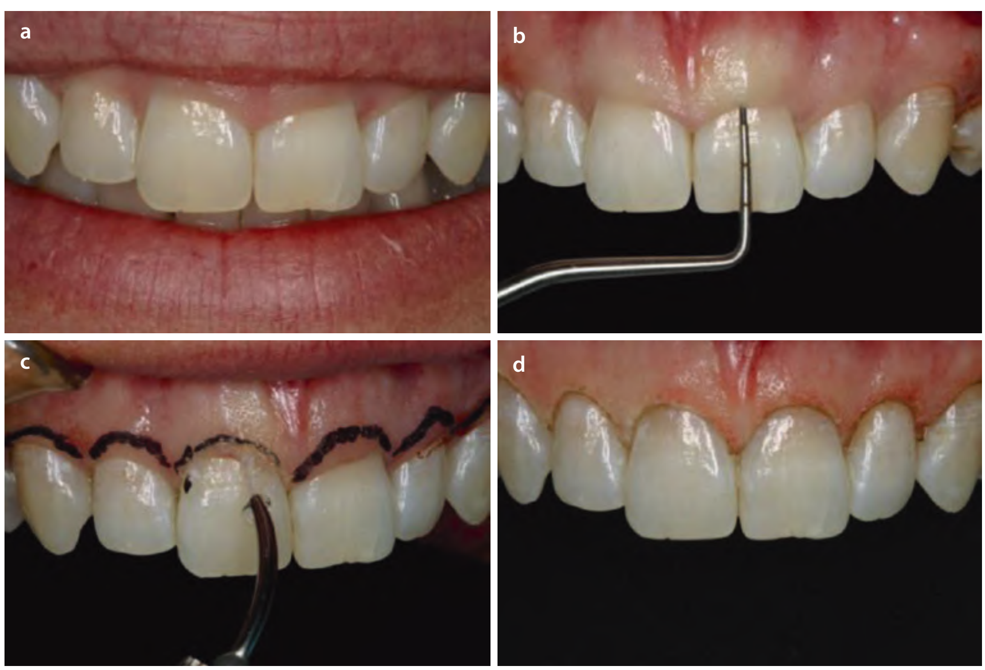


Fig. 15.5 **a** Preoperative view showing uneven gingival contour, with pronounced differences in the zeniths of the maxillary central incisors. **b** A periodontal probe is used for the determination of biologic width and the overall dimensions of the dentogingival complex. **c** After tissue is marked, an Er:YAG laser with a 600 micron tip is used with an average power of 2.0 W (40 mJ per pulse at 50 Hz) without a water spray to perform the gingivectomy and gingivoplasty on all six maxillary anterior teeth. **d** Immediate postoperative view showing excellent hemostasis and tissue contour (Clinical case courtesy of Dr. David Hornbrook)

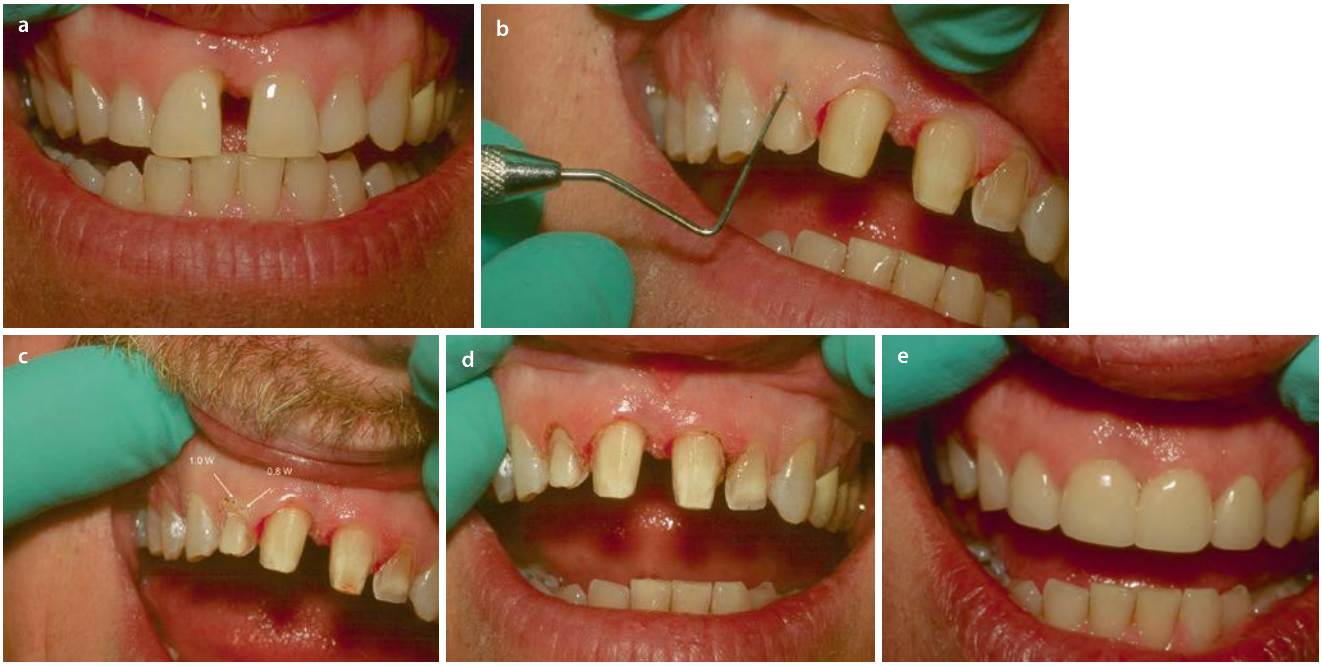


Fig. 15.6 **a** Preoperative view of the maxillary anterior segment with a large diastema between the central incisors and uneven gingival height of all incisors. **b** Biologic width determination and analysis of the dentogingival complex is performed with a periodontal probe. **c** After verifying the periodontal condition, soft tissue crown lengthening was performed with an 810 nm diode laser using a 400 micron bare fiber. In order to lay out the intended new gingival form, a 400 micron diameter «dot» was placed at the new gingival zenith using a power of 1.0 W continuous wave. Careful inspection of that small area of ablation revealed slight carbonization, which indicates the tissue temperature was excessive. The laser parameter was adjusted to 0.8 W continuous wave and other dot was placed. That area showed normal ablation and that parameter was chosen to utilize for the surgery. **d** The immediate postoperative view shows the completed crown lengthening and finished preparations. Note that the central incisors were reduced on their mesial aspect and a subgingival trough was placed. Both of those procedures will enable new porcelain contours so that the diastema can be closed. **e** Six-month postoperative view demonstrates how the laser adjunctively fulfilled the principles smile design and emergence profile while creating a healthy periodontal condition

Fig. 15.7 **a** Preoperative view of the anterior maxillary sextant with asymmetrical gingival scalloping. Biologic width measurements revealed adequate tissue available for soft tissue crown lengthening. Note the thinner biotype on the later incisors compared to the central incisors. An Nd:YAG laser was used with a 320 micron fiber at an average power of 1.8 W (60 mJ per pulse at 30 Hz). **b** Immediate postoperative view. The laser's free-running pulse mode emission allows for thermal relaxation of the tissue, particularly on the lateral incisors' thinner biotype. Note the areas of gingivoplasty for new tissue form and outline. **c** Three-week postoperative view showing improved aesthetics with a more harmonious gingival scallop and embrasures

Fig. 15.8 **a** Preoperative view showing abfraction lesion on a maxillary molar. The gingival tissue has proliferated over the apical aspect of the lesion. **b** An 810 nm diode laser with a 400 micron bare fiber is used with an average power of 1.0 W to remove the gingival tissue and reestablish proper contour. The lesion can then be prepared and restored. **c** Immediate postoperative view of the final restoration. The laser created a dry field with lack of any bleeding from the tissue to aid in the placement of the restorative material. The final margin placement should allow easy patient access for maintenance

Fig. 15.9 **a** Preoperative view showing a recurrent carious lesion with inflamed gingival tissue. The carious lesion extends subgingivally. **b** The gingiva was recontoured with a 9300 nm carbon dioxide laser using 0.25 mm spot size, a 65 µs pulse duration, and a cutting speed between 10% and 30% with minimal water spray. **c** The immediate postoperative view showing the new tissue contour with the margin of the new composite restoration placed at the free gingival margin. Note how the laser achieved good control of tissue fluids to aid in the composite placement

15.8 Osseous Crown Lengthening

If the intended crown lengthening will compromise the biologic width, an osseous procedure will be required. The desired goal is to shape the osseous crest to match the gingival scallop outline form, and both should parallel the restorative margin [18]. As implied above, in general, soft tissue crown lengthening is performed first before the osseous procedure. The clinician must consider whether to proceed by raising a flap in an «open flap» surgical approach or operate without elevating any soft tissue—the so-called closed flap or flapless technique. A contact laser tip can transmit tactile information to guide the clinician in the procedure; however, laser energy does not easily distinguish between bone and root surface cementum and/or dentin. Conventional flap reflection may be necessary to both visualize and properly contour bone, especially in large areas of missing tooth structure or in multiple adjacent sites. In a localized area, for example, with a subgingivally fractured cusp, a closed flap osteotomy and osteoplasty can be performed. In either case, the bone must be contoured as close to an ideal physiologic form as possible—without ledges, craters, or other deviations. Meticulous attention to creating proper anatomical form is much more challenging without flap access [19]. The overlying principle of biologic width dictates the amount of hard tissue removal along with the maintenance of adequate periodontal support.

The typical surgery begins with designing the new gingival outline and determining the initial biologic width. In this case, it is assumed that both soft and osseous crown lengthening will be performed. Next, the gingival tissue is excised and contoured to achieve that new sculpture. That may result in destruction of all or part of the soft tissue attachments. If possible, the existing osseous crest should be sounded. Then the clinician makes the decision about raising a flap. Removal of 2–3 mm of osseous resection is generally required to reestablish new biologic width [20]. Similar to soft tissue crown lengthening, an osteotomy and osteoplasty should be performed, resulting in a stable anatomic scaffold for the overlying gingiva. If an open flap procedure was used, the soft tissue flap is usually apically repositioned and sutured. In a flapless technique, the clinician should ensure that the soft tissue is well approximated on the tooth surface [21].

15.8.1 Lasers for Osseous Crown Lengthening

As mentioned above, only the erbium family and the 9300 nm carbon dioxide lasers are currently indicated for bone procedures. The Er,Cr:YSGG (2780 nm) and the Er:YAG (2940 nm) instruments primarily target the water component in osseous tissue, whereas the 9300 nm carbon dioxide energy interacts the hydroxyapatite. All three wavelengths utilize free-running pulse emission with very short pulse durations. Each features a water spray to help minimize any overheated areas of ablation. To guide the beam, some instruments have contact tips and others have small cylindrical guides used out of contact.

15.8.2 Osseous Crown Lengthening for Aesthetics

All of the concepts of smile design must be considered before any surgery begins. If any restorations will be placed, their gingival margin position should also be planned. Typically multiple teeth are involved in aesthetic dentistry, and harmony among them must be achieved. A diagnostic wax up can certainly aid in visualization of the desired treatment outcome. In addition, approximate areas of laser excision and contouring can be simulated.

15.8.3 Osseous Crown Lengthening for Restorative Dentistry

As a tooth preparation extends deeply into the gingival sulcus, the clinician must evaluate how and where the bone will be repositioned. The restoration's margin and the surrounding periodontium will correspond to each other; therefore the immediate postoperative tissue position, form, and contour will dictate the ultimate result.

15.8.4 Clinical Cases of Osseous Crown Lengthening

Figure 15.10 depicts a typical clinical dilemma where an existing crown restoration has fractured off with an inadequate amount of clinical crown remaining. Osseous crown lengthening was performed in an open flap procedure using an Er:YAG laser. The successful procedure resulted in sufficient tooth structure for a new crown to be constructed.

Figure 15.11 demonstrates an open flap osseous crown lengthening procedure so that the two posterior teeth can be restored. The 9300 nm carbon dioxide laser was used, and a 5-month postoperative photo shows good healing with the reestablishment of biologic width (Clinical case courtesy of Dr. Josh Weintraub).

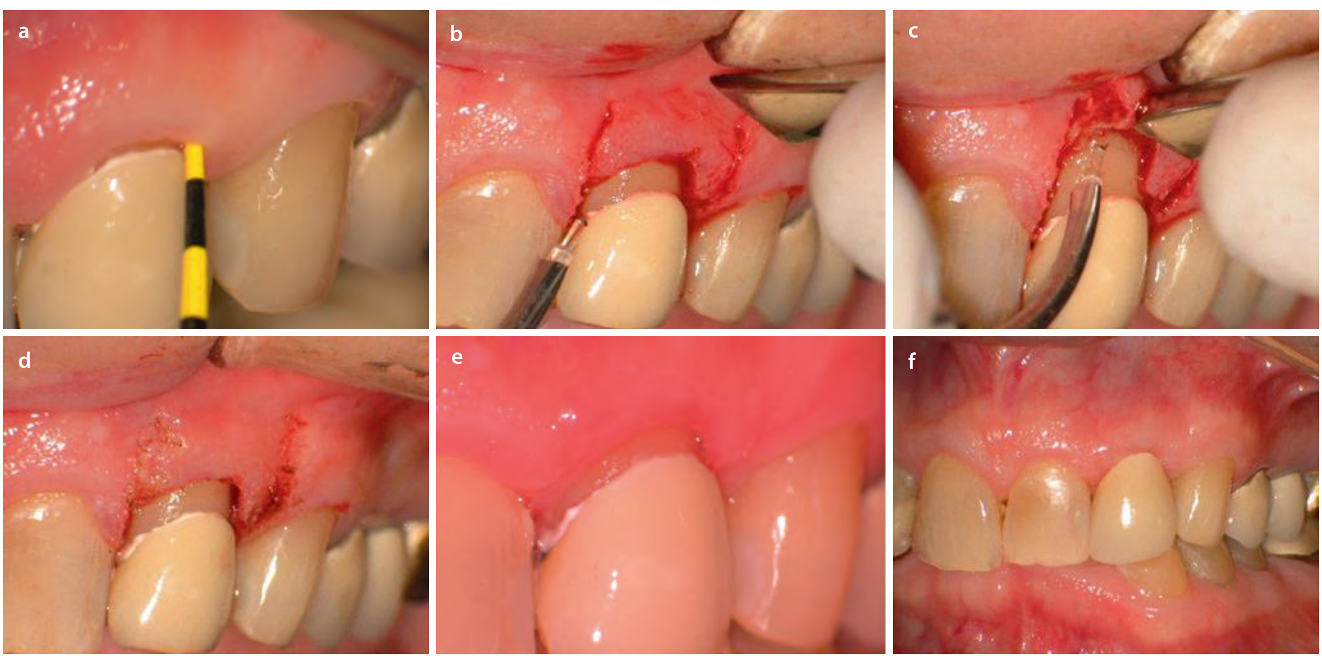


Fig. 15.10 **a** Preoperative view. The patient presented with a porcelain fused to metal crown that had become dislodged. The incisal one-third of the preparation had also fractured. The crown was recemented, and it was determined that osseous crown lengthening would be necessary because of the inadequate biologic width. **b** An Er:YAG laser was used with a 400 micron tip with an average power of 2.4 w (80 mJ at 30 Hz) with a copious water spray to apically reposition the gingival margin, achieving the soft tissue portion of the crown lengthening. **c** After raising a flap with conventional instruments, the same laser parameters were used to remove and reposition the osseous crest. Note that the tip is aimed at the bone, avoiding contact with the root. **d** The immediate postoperative view of the flap repositioned with new tooth form revealed. **e** One-month postoperative view shows the healed attachment and new gingival height. A new crown preparation can proceed with adequate ferule for good retention form. **f** Two weeks later, the crown is delivered, and the tissue should continue to heal for a successful restorative result

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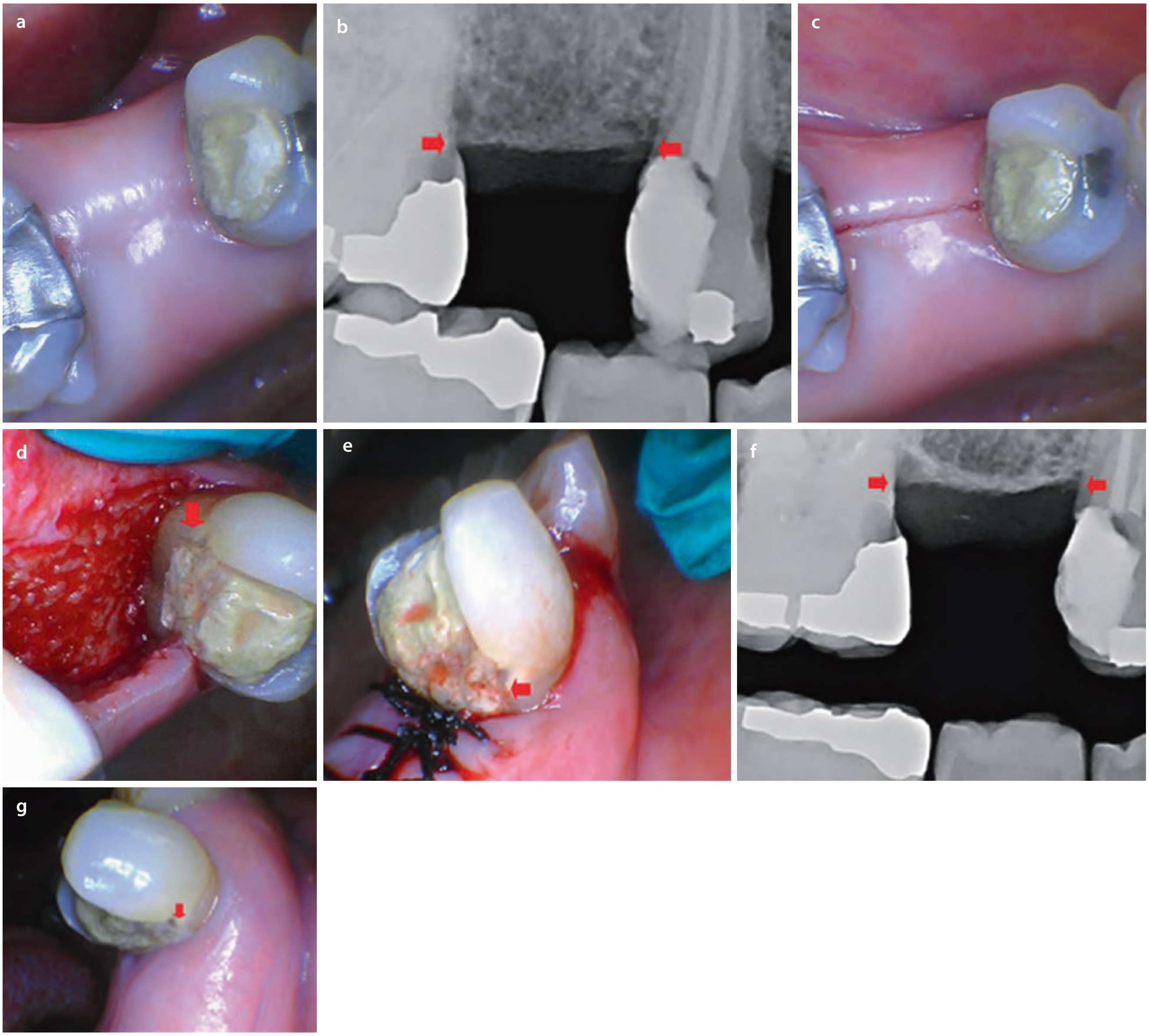

Fig. 15.11 **a** Preoperative view of a maxillary posterior segment of edentulous ridge between a bicuspid and molar that will be restored because of recurrent carious lesions. The patient was considering treatment options for replacing the missing tooth. **b** The preoperative radiograph shows that the carious lesions are violating the biologic width zone and indicated by the red arrows. Thus osseous crown lengthening is indicated. **c** The 9300 nm carbon dioxide laser was used in its noncontact mode with a 0.25 mm spot size, a 65 µs pulse duration, 50–100% speed, and minimal water spray to perform the soft tissue incision. The flap extended to the proximal surfaces of both teeth. Note the minimal bleeding and the clean, linear cut. **d** After the flap was raised with traditional periodontal instruments, a 1.0 mm spot size, 75 µs pulse duration, and 50–100% speed, with full water spray for the initial alveolar bone ablation. The spot size was reduced to 0.25 mm for the final contour of the osseous tissue adjacent to the tooth. The red arrow indicates the previous tissue level, and sufficient bone has been removed to reestablish biologic width. The alveolar ridge adjacent to the molar received the same treatment. Note the good vascularity of the ablated osseous structure. **e** Immediate postoperative view with the gingival tissue sutured in place. The red arrow shows the preoperative gingival level. **f** Immediate postoperative radiograph showing a smooth osseous contour and a clear gain in clinical crown length, indicated by the red arrows. **g** A 5-month postoperative view showing complete tissue healing after osseous crown lengthening. A new restoration can now be constructed without a biologic width violation (Clinical case courtesy of Dr. Josh Weintraub)

Figure 15.12 shows a case of varied gingival heights and contour of some maxillary teeth. Closed flap gingival and osseous crown lengthening were accomplished with an Er:YAG laser, and then porcelain veneers were placed. The clinical photos show a portion of that procedure on the cuspid. A 4-year postoperative view shows healthy periodontium and excellent aesthetics (Clinical case courtesy of Dr. David Hornbrook).

Figure 15.13 depicts a case of severely worn maxillary and mandibular anterior teeth. Closed flap gingival and osseous crown lengthening were performed with an Er,Cr:YSGG laser followed by porcelain restorations. At the 6-month postoperative review appointment, a biologic width violation was discovered around the maxillary right central incisor. The laser was used again to correct the discrepancy in the tissues and the problem was resolved (Clinical case courtesy of Dr. Mark Cronshaw).

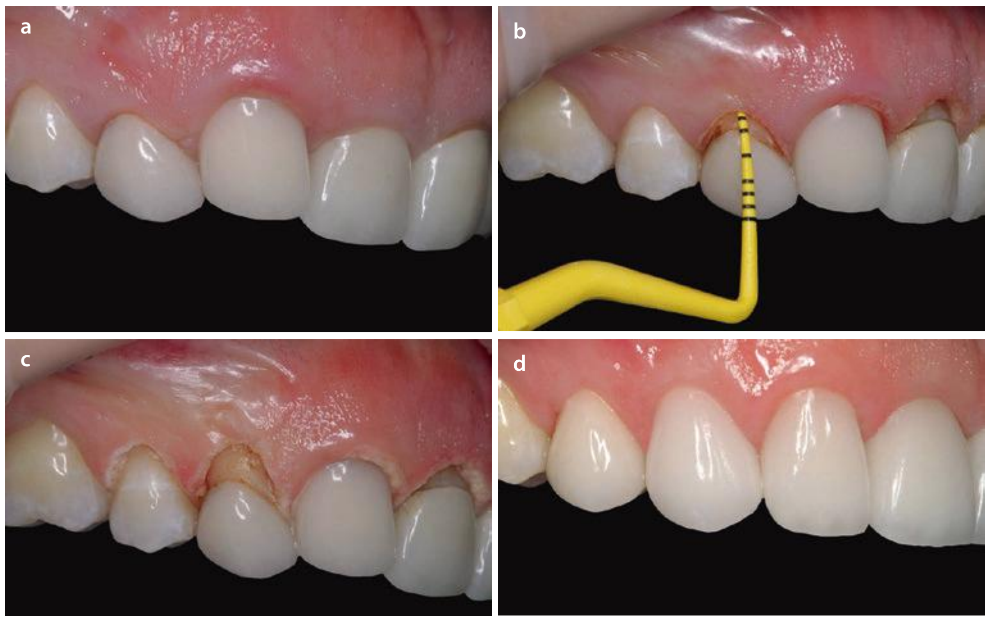

Fig. 15.12 **a** Preoperative view of varied gingival architecture around existing porcelain crowns. **b** An Er:YAG laser was used with a 400 micron tip with an average power of 2.0 W (40 mj at 50 Hz) without water spray and was used for the soft tissue removal. This photo shows that procedure in progress on the cuspid, and perio-probing on that tooth shows that there will be a violation of biologic width in order to establish the intended new gingival outline and to place the margin of the restoration. Osseous crown lengthening is necessary on the labial surface, and a close flap technique was used. The Er:YAG was used with the same parameters—2.0 W (40 mj 50 Hz) but with a water spray. **c** The crown lengthening is completed on all of the teeth. **d** Four-year postoperative view shows excellent periodontal health along with good smile design (Clinical case courtesy of Dr. David Hornbrook)

Fig. 15.13 **a** Preoperative view of severely worn anterior dentition. The treatment plan consisted of porcelain restorations for those teeth after the appropriate crown lengthening. **b** After the initial preparation of teeth, the desired new gingival outline is placed. The Er,Cr:YSGG laser was used for the gingivectomy with a 600 micron diameter zirconia tip at an average power of 2 W (80 mJ, 25 pps, 20% air, 40% water, 60 µs pulse duration). **c** Probing the existing osseous crest shows that osseous crown lengthening must be performed to establish a healthy dentogingival complex and biologic width. **d** Closed flap osseous contouring was then accomplished. The photo shows the carful placement of the 600 micron zirconia tip aiming toward the osseous crest. The laser parameters were 3 W of average power (100 mJ, 30 pps, 60% air, 60% water, 60 µs pulse duration.) A Wedelstaedt bone chisel and a piezo device subsequently smoothed the bone contour. **e** Probing confirms reestablishment of biologic width. **f** Six-month postoperative close-up view shows residual inflammation around the right central restoration. The perio-probe indicates a biologic width violation remains. The Er,Cr:YSGG laser was used with the previous parameters **b, d** to refine the gingival and osseous tissue. **g** Two weeks later, the tissues have healed. **h** Six-month postoperative view of completed mandibular restorations. **i** Six-month postoperative view of reestablished smile line and vertical dimension of occlusion (Clinical case courtesy of Dr. Mark Cronshaw)

15.9 Soft Tissue Management for Placement of Direct or Indirect Restorations

Manipulation of soft tissue with various wavelengths and subgingival margin placement has been discussed earlier in this chapter. The restorative dentist must consider and apply all of those principles while preparing the tooth. Modern dental direct restorative materials generally require meticulous control of moisture and bleeding to ensure a good bonding environment. Successful fabrication of indirect restorations involves many factors. One important one is to duplicate the finished preparation with as much accuracy as possible. Whether for direct fillings, impressions, or optical scanning, any available dental laser can accomplish soft tissue management, moisture control, debridement, and hemostasis.

Figure 15.14 depicts a molar carious lesion with distal tissue overgrowth. A carbon dioxide laser was used to remove the tissue so that a core buildup material could be placed. The laser beam was aimed directly at the gingiva. The 9300 nm instrument also removed the carious lesion, and that discussion can be found in ► Chap. 8 (Clinical case courtesy of Dr. Josh Weintraub).

Figure 15.15 shows how an Nd:YAG laser is used for troughing around two preparations during the construction of new crowns. The laser is gently placed in the sulcus and aimed toward the gingival soft tissue. It offers excellent tissue management which facilitates any impression technique.

Figure 15.16 depicts an Er,Cr:YSGG laser used for troughing around a molar. The rigid tip was aimed at the soft tissue in the sulcus, being careful to avoid contact with the preparation margins. The impression precisely captured all the marginal detail (Clinical case courtesy of Dr. Glenn van As).

Figure 15.17 shows a comparison between diode laser tissue retraction and conventional cord technique during full crown preparations on adjacent maxillary premolars. Using careful technique and proper parameters, the laser easily reveals the subgingival margins with excellent bleeding control (Clinical case courtesy of Dr. Glenn van As).

Figure 15.18 shows how a carbon dioxide laser is used to retract the tissue around a central incisor. The 10,600 nm wavelength is very effective in soft tissue removal while achieving excellent hemostasis (Clinical case courtesy of Dr. Steven Parker).

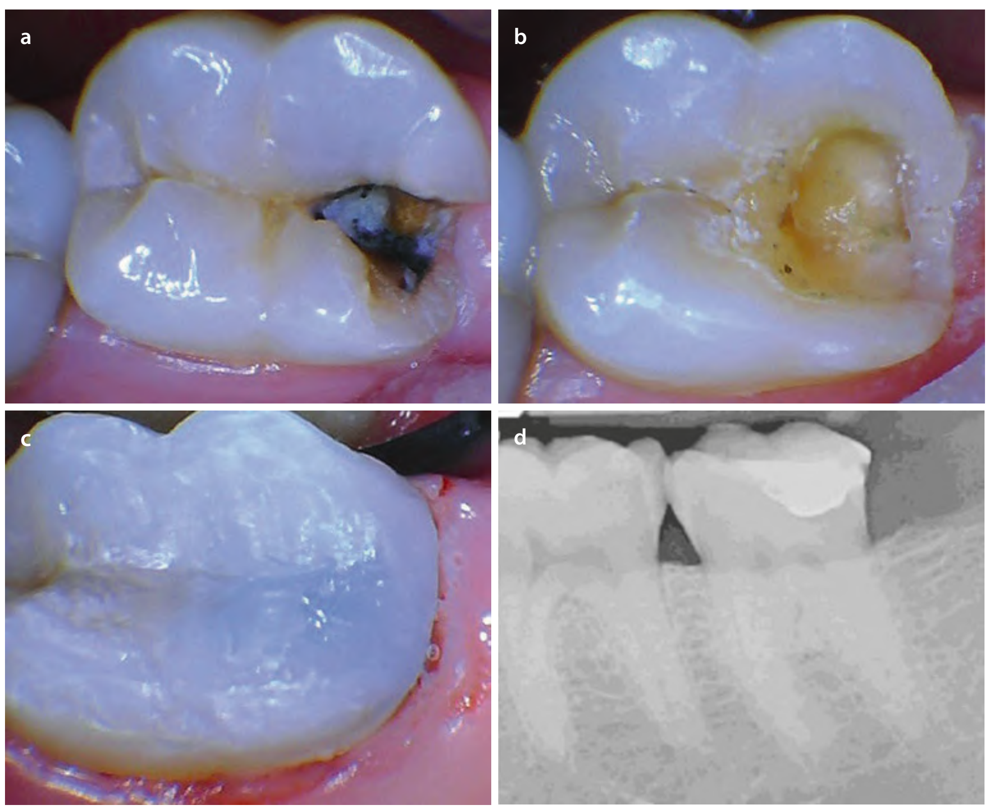

Fig. 15.14 **a** Preoperative view showing a large carious lesion with gingival overgrowth. **b** The gingiva was recontoured with a 9300 nm carbon dioxide laser using 0.5 mm spot size and a 45 pulse setting with minimal water spray. **c** The immediate postoperative view showing good tissue contour around the core buildup material. Note good moisture control to aid in the composite placement. **d** A postoperative radiograph showing no biologic width violations. The crown preparation margins should be easily placed while maintaining gingival health (Clinical case courtesy of Dr. Josh Weintraub)

Fig. 15.15 **a** Preoperative view of the maxillary left central and lateral incisors which will be prepared for porcelain crowns. **b** Immediate postoperative view of the laser troughing. An Nd:YAG laser was used with a 320 micron bare fiber at an average power of 1.2 W (40 mJ at 30 Hz) in the sulcus, aimed at the soft tissue side of the pocket with gentle pressure. The fiber is used in short arcs of a circle, interacting with small segments of the tissue at a time. The goal was to gently retract and debride the tissue space along with controlling bleeding so that the impression material can accurately capture the subgingival margins. The interdental papilla was also slightly contoured. This average power is less than the parameters generally used for incisions since there is no need for any tissue removal. **c** The resulting impression shows accurate marginal detail. **d** Three-week postoperative and 1-week post-delivery view of the completed restorations showing an excellent tissue response

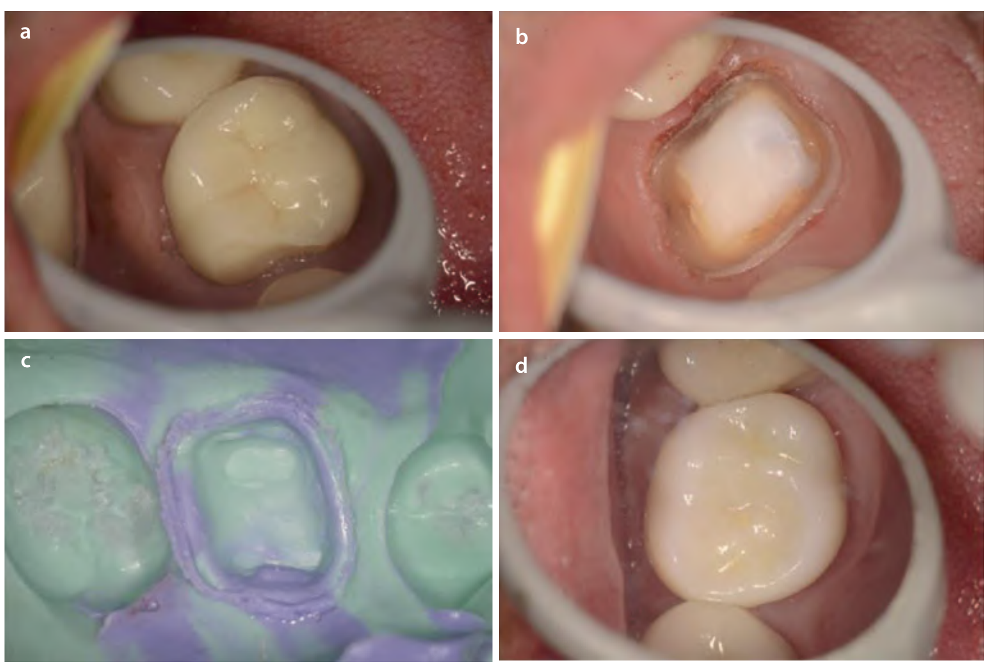

Fig. 15.16 **a** Preoperative mirror view of a maxillary molar defective crown restoration. A new crown will be constructed. **b** Immediate postoperative mirror view of the laser troughing. After the tooth was prepared, an Er,Cr:YSGG laser was used with an MZ 5 tip at an average power of 2.25 W (75 mJ per pulse at 30 Hz) in the sulcus with minimal water spray. The tip was moved around the tooth in short arcs of a circle to debride and widen the sulcular tissue so that the subgingival margins were revealed. **c** A photo of the final impression. Note the clear margin definition. **d** The final crown was delivered with excellent results including gingival health (Clinical case courtesy of Dr. Glenn van As)

Fig. 15.17 **a** The mirror view of two maxillary premolar teeth that will receive full porcelain crown restorations. **b** A diode laser with a 400 micron bare fiber and an average power of 0.8 W is used parallel to the long axis of the preparation of the first premolar to expose the margins and debride the sulcus. The fiber is used in short arcs of a circle. **c** Retraction cord is placed in the sulcus of the second premolar. **d** The preparations are ready for the impression. Note the excellent control of bleeding and tissue retraction on the first premolar's gingiva after the laser use. **e** View of the final impression showing excellent capture of both preparations. **f** Two-week postoperative view of the preparations, after the provisional restorations are removed, showing adequate gingival health. **g** Three-week postoperative view of the final restorations showing an excellent result (Clinical case courtesy of Dr. Glenn van As)

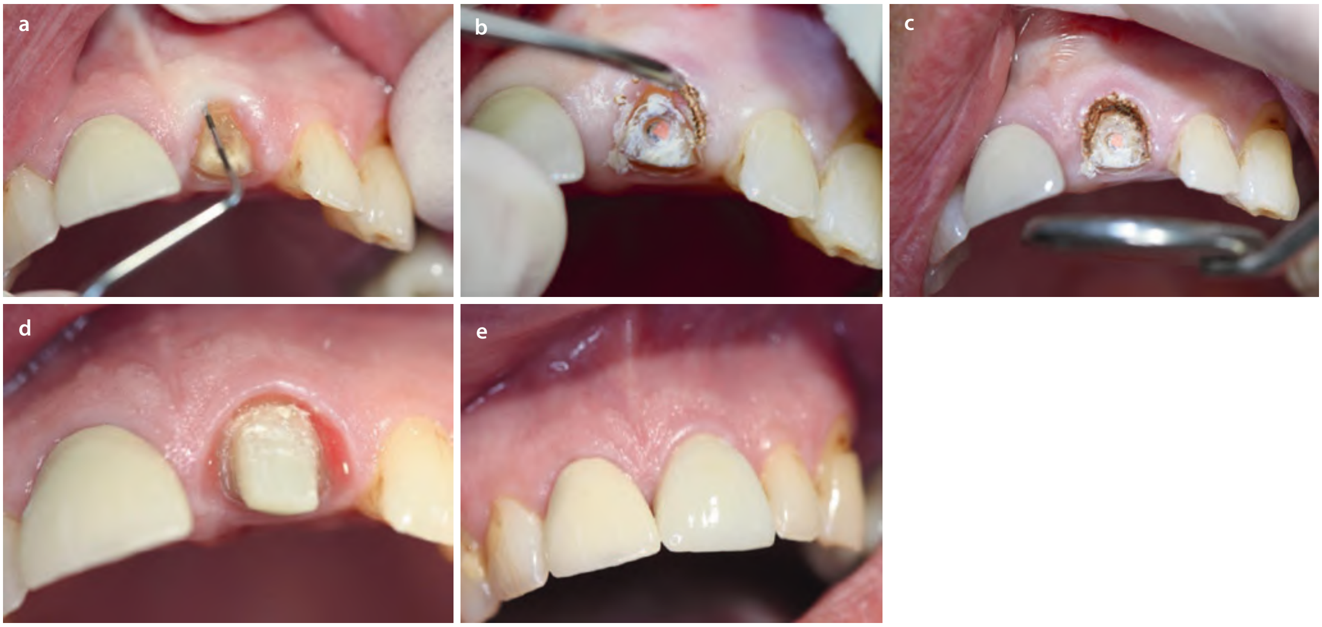

Fig. 15.18 **a** Preoperative view of a crown preparation in progress while determining the dentogingival complex measurement. **b** A 10600 nm carbon dioxide laser used with a 600 micron beam diameter in noncontact at a power of 1.0 W continuous wave. The beam was aimed precisely at the soft tissue while avoiding interaction with any tooth structure. **c** Immediate postoperative view. The small area of tissue removal that appears carbonized will be rinsed away; however, the hemostasis is excellent. **d** Two-week postoperative view shows the healed tissue contour which will facilitate the good emergence profile of the restoration. **e** View with crown delivered (Clinical Case courtesy of Dr. Steven Parker)

15.10 Tissue Preparation for a Fixed Prosthodontic Pontic Restoration

As discussed, the emergence profile ultimately determines the periodontal and aesthetic success of the dentition. Toward that end, the periodontal tissues can be manipulated with dental lasers to provide a stable and healthy foundation to guide the axial contours of the restoration or natural tooth. Crown lengthening can be used to perform these alterations. In the case of a fixed bridge pontic, the edentulous ridge can be prepared with a concave area so that the apical portion of the pontic can be made into a convex surface. This avoids a «ridge-lap» design which usually prevents the patient from adequate oral hygiene in the area. Instead a more natural appearing prosthodontic restoration can be fabricated.

Figure 15.19 shows the development of an ovate pontic area prior to replacing a fixed bridge. The tissue surface of the previous pontic was poorly contoured which resulted in chronically inflamed tissue. A diode laser was used to remove and reshape the soft tissue. The long-term (15-year) picture demonstrates how this procedure allowed the patient to maintain periodontal health (Case courtesy of Dr. David Hornbrook).

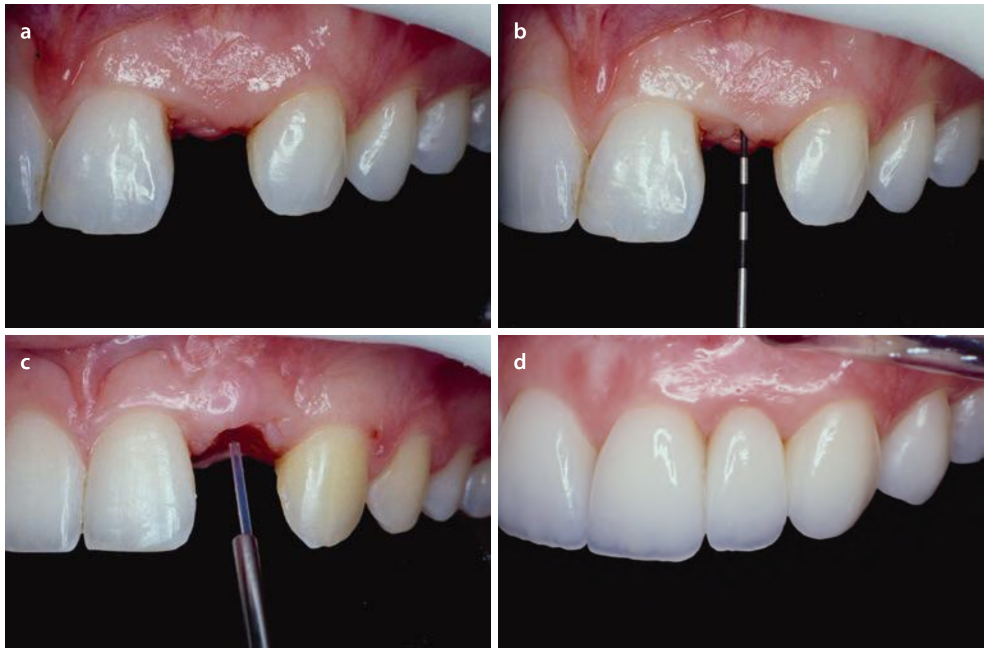

Fig. 15.19 **a** Preoperative view of edentulous ridge after removal of a bonded bridge. Note the chronic inflammation of the tissue due to the ridge-lap design of the previous pontic, which prevented the patient from adequately cleaning the area. **b** A periodontal probe is used to measure the tissue thickness. There is sufficient tissue to allow removal for an ovate pontic design. **c** A diode laser is used with a bare 400 micron fiber at 1.0 W continuous wave emission to sculpt the concavity where the convex pontic will be positioned. The laser shaping can proceed with small amounts of tissue removal, but the clinician must be careful to leave at least 1.0 mm of tissue covering the bone. **d** A 15-year postoperative view showing excellent periodontal health with the new bridge restoration with its ovate pontic. The patient can easily maintain the pontic space and adjacent tissue (Clinical case courtesy of Dr. David Hornbrook)

Conclusion

The purpose of this chapter is to demonstrate that utilization of the variety of dental wavelengths allows the clinician to precisely and predictably manage the soft and hard tissue surrounding the teeth. Any available dental surgical laser will incise and ablate soft tissue, although the interaction can vary among the emission wavelengths. For removal and contour of osseous tissue, the available choice of instruments is more limited to the erbium family and the 9300 nm carbon dioxide ones. These latter «all-tissue» lasers can facilitate treatment by allowing incremental removal of the tissues so that the target treatment section can harmonize with the adjacent areas. However, careful placement of the laser beam is essential to avoid unintended removal of one tissue while treating the other.

As always, thorough diagnosis and detailed treatment planning of a well-chosen case are highly important. It is equally important that the clinician be familiar with current periodontal surgical therapies and protocol, which can be found in any textbook [22]. The treatment phase must pay attention to several biologic principles so that the dentogingival complex and the tooth and/or restoration are harmonious and allow the patient to maintain good oral hygiene. Elective aesthetic procedures require the same principles along with elements of smile design and other dentofacial aesthetic details. In order to provide sufficient tooth structure for a successful restoration, the biologic width must be respected.

Thus for successful placement of restorations and pleasing aesthetic procedures, a dental laser is a beneficial and significant addition to the clinician's armamentarium.

15

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Impact of Laser Dentistry in Management of Color in Aesthetic Zone

Kenneth Luk and Eugenia Anagnostaki

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Core Message

A pleasingly attractive smile is composed of a harmonious balance of a well-aligned set of teeth with healthy anatomic contour of the gingiva and lips. Patients' demand for aesthetic dentistry can be met with the practitioner's choice of procedures and materials. Dental lasers can certainly be integrated into the treatment plan, and this chapter will provide details about modifying the color of the dental soft and hard tissues to help attain the desired outcome. The first section will describe on treatment for pigmentation of nonneoplastic origin. The second section will provide details about whitening.

16.1 Gingival and Lip Pigmentation Management

Kenneth Luk

16.1.1 Introduction

A well-aligned set of teeth not only improves function and oral hygiene maintenance but most importantly produces a confident and attractive smile. Gingival contour, emergence profile, and teeth proportion all contribute to the smile profile [1]. However, dark pigmentation (Table 16.1) of the gingiva and lip may deflect the attention of a perfect smile. Melanin pigmentation of the gingiva and lip is most commonly noticed in ethnic groups [2–4]; smokers [3, 5, 6]; patients under medication such as antimalarial agents, tricyclic antidepressant, and minocycline [7, 8], and those with hormonal disorder [9, 10]. Recent studies have also reported the correlation between passive smoking in women and children with hyperpigmentation [10–12]. Amalgam tattoo is a condition that is commonly observed in the gingiva [13].

Table 16.1 Colours in oral pigmentation

Color	Endogenous	Exogenous
Blue, red, purple	*Hemoglobin* – varix, hemangioma	–
Brown	*Hemosiderin* – nevus, drug-induced pigmentation	–
Brown, black, gray	Melanin	*Chromogenic bacteria* – superficial colonization
Gray, black	–	*Silver amalgam, graphite* Amalgam tattoo, nevus, trauma
Gray	–	*Lead, mercury, bismuth* Ingestion of paint or medicinals

Adapted from Eversole [95]

Postinflammatory hyperpigmentation (PIH) is a sequelae of cutaneous disorder described in dermatology. PIH on the lip is a common cause by trauma (e.g., burns, lip biting, and trauma by pen and pencil).

Various Treatments for Depigmentation

The use of chemical peel and cryosurgery has been used for melanin depigmentation. Treatment with scalpel and diamond bur [14] has also been used and compared with lasers [15–19]. In a split-mouth clinical trial, the use of lasers has been shown with less relapse 3 months post-op when compared with electrosurgery [20].

16.1.2 Laser Ablation

For over 10 years, CO_2, Er:YAG, Er,Cr:YSGG (Fig. 16.1), Nd:YAG, and diode lasers (Fig. 16.2) have been reported with good results in melanin depigmentation [21–26]. The procedure requires ablation (vaporization) of the surface gingiva or mucosa to the basal layer where the melanocytes are located.

Erbium and CO_2 wavelengths (Fig. 16.1) are well absorbed in water and thus will remove shallow layers of soft tissue and eventually reach the layer of melanin. Sapphire tips or focusing window is used in noncontact mode. The use of erbium lasers has the advantage of using water spray not only to keep the ablation front from dehydration but also to irrigate the debris to give a clear view during the procedure. Although this reduces the hemostatic effect, bleeding would be a good warning signal that the depth of ablation is beyond the basal layer. Water spray is not used with 10,600 nm CO_2 irradiation, but the 9.3um CO_2 laser delivers very short pulse duration (down to 2usec) with the water spray. Near-infrared diode and Nd:YAG (810–1064 nm) wavelengths are poorly absorbed in water but well absorbed in pigment. Initiated 320 um fibers and similar sized quartz tips are commonly used to ablate the layers in contact mode. Apart from direct surface absorption, the laser photons can also penetrate to the basal layer and capillaries to be absorbed (Fig. 16.2). The tissue tag on the treatment site should be removed regularly to view the color improvement. For diode lasers, it has been demonstrated that water irrigation during ablation can be used to reduce the collateral thermal damage [27, 28].

Clinical Cases of Ablative Depigmentation

Figure 16.3 shows a case of split-mouth depigmentation using Er:YAG (2940 nm) and Nd:YAG (1064 nm) lasers. The upper right hand quadrant was ablated using Er:YAG laser. This free-running pulse laser is well absorbed by water. Ablation of the soft tissue is very effective as the soft tissue contains high percentage of water by volume. Water spray was used not only to keep the surface cool but more importantly to prevent dehydration of the surface layer and to sustain the efficacy of ablation. The upper left quadrant was ablated by Nd:YAG laser which is effective in ablating the melanocytes. The free-running pulse emission can help control the tissue temperature and avoid thermal damage to the underlying periodontium (Clinical case courtesy of Dr. Ryan Seto).

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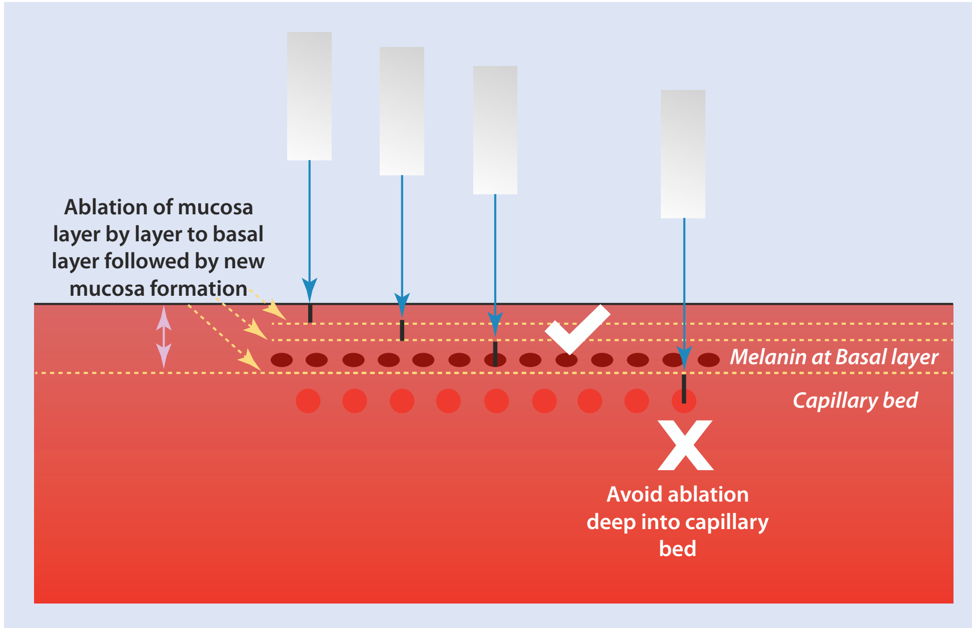

Fig. 16.1 Er:YAG, Er, Cr:YSGG and CO_2 laser depigmentation by ablation in non contact mode

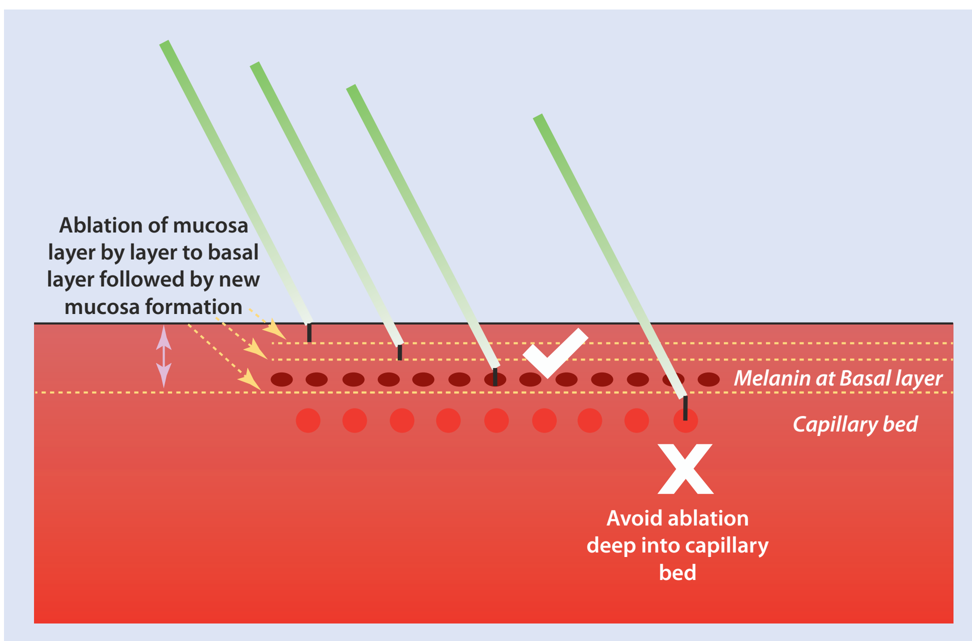

Fig. 16.2 Diode and Nd:YAG laser depigmentation by ablation in contact mode

Figure 16.4 shows depigmentation with 980 nm diode laser. Under local anesthesia, an initiated 320 µm fiber was used to ablate the pigmented area with a sweeping motion. 1.9 W average power with 1000 Hz and a 30% emission cycle was set and a peak power of 6.3 W was calculated. The treatment time took 12 min to complete the upper and lower anterior segments (Clinical case courtesy of Dr. Mudasser Iqbal).

16.1.3 Non-ablative Laser Procedures

The word non-ablative is frequently used in dermatology on skin resurfacing techniques. Unlike an ablative laser procedure which vaporizes the skin surface, a non-ablative procedure penetrates the surface and coagulates the subsurface layer of the skin while keeping the surface layer in place. In depigmentation, the author uses the description of

Fig. 16.3 **a** Preoperative view of melanin pigmentation. **b** On the right quadrant, the Er:YAG laser was used with 800 μm sapphire tip at an average power of 1.8 W (120 mJ, 15 Hz) and a 1000 μs pulse duration. The Nd:YAG laser was used with a 320 μm bare fiber and an average power of 4 W (MSP mode and 20 Hz) on the left quadrant. Treatment time for each side was 10 min. **c** Six-month postoperative view shows stable tissue color and good tissue tone performed by both lasers (Clinical case courtesy of Dr. Ryan SK Seto)

Fig. 16.4 **a** Preoperative view of melanin pigmentation. **b** Immediate postoperative view of upper and lower anterior segments. **c** One-week postoperative view showed mucosa with good maturation. Although some areas still showed pigmentation [11, 12], the overall aesthetic appearance was very pleasing (Clinical case courtesy of Dr. Mudasser Iqbal)

"non-ablative" to describe this effect using near-infrared and visible light diode lasers. The surface mucosa will peel off at day 1 or 2 after treatment.

The Fundamental Interaction Is Photocoagulation

Photocoagulation, in this case laser coagulation, describes a laser-tissue interaction where the target tissue component is well absorbed by the laser wavelength, and there is a coagulation effect when the temperature reaches 60 °C. Hemoglobin is very well absorbed in Nd:YAG, visible light, and near-infrared diode lasers. Thus, photocoagulation is most commonly applied for hemostasis of a surgical wound such as extraction socket or a periodontal pocket. Treatment of vascular lesions such as varix and hemangioma can also benefit by photocoagulation.

Near-Infrared Diode

A non-ablative technique using high-power 810 nm diode laser (30 W, 20 kHz, 16 μs pulse duration) was reported by the author [29, 30]. Since the 810 nm wavelength is well absorbed by melanin and hemoglobin, the use of a high-power laser can concentrate the thermal energy on the surface with the very short pulse (Fig. 16.5). A continuous sweeping motion should be used and re-irradiation of the already coagulated area should be avoided. This technique resulted in a treatment time of 2 min for single arch between first premolars. Using a low-power diode laser with long pulse to continuous wave usually allows thermal conduction deeper into the tissue [27, 28]. A similar principle called laser-patterned microcoagulation using 20 W 980 nm diode laser was reported on depigmentation of one papilla [31].

16.1.4 Clinical Cases of Non-ablative Technique with an Infrared Diode

Figure 16.6 shows a case of melanin depigmentation using a 810 nm very short-pulsed high peak power diode laser.

Figure 16.7 shows a case of lip depigmentation using an 810 nm very short-pulsed high peak power diode laser. The patient, a young lady, had tried to mask the pigment with dark-colored lipstick but was unable.

Figure 16.8 shows a case of photocoagulation of a lip hemangioma using an 810 nm diode. Three laser treatments

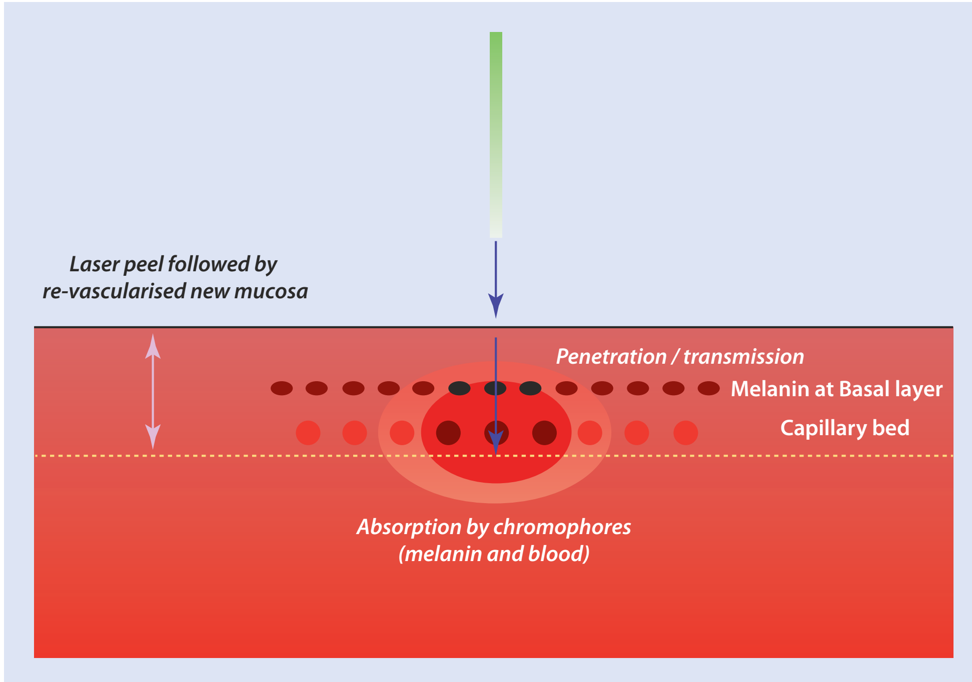

Fig. 16.5 Diode and Nd: YAG 445nm, 810nm and 980nm laser depigmentation by non ablative technique

Fig. 16.6 **a** Preoperative photo of gingival melanin pigmentation. An 810 nm diode laser was used with a 600 microns bare fiber with 30 W of peak power, a 16 µs pulse duration at 20 kHz. Under local anesthesia, the treatment time was 80 s on the maxillary arch only. **b** Immediate post-op showing non-ablative mucosa. **c** The 6-week post-operative photo is shown and the pigment is not present

were performed at a monthly interval. The patient wanted the lesion removed for her wedding photos.

Figure 16.9 shows a case of photocoagulation of a varix (dilated venule) using an 810 nm diode. The patient was a sales representative whose clients mistook the lesion for retained food, which embarrassed the patient.

16.1.5 Visible Light Diode

A new instrument has become available with a wavelength of 445 nm. This visible blue diode laser has the highest absorption by melanin and hemoglobin compared with other dental laser wavelengths. The author showed 1 W continuous wave being comparable in achieving the same result and speed as 30 W 810 nm diode laser [32]. This much lower-power density produces the same effect and can minimize any unwanted thermal damage to the tissue. Table 16.2 shows some further details in comparing the two wavelengths.

16.1.6 Clinical Case of Visible Light Diode for Non-ablative Depigmentation

Figure 16.10 shows a preoperative view of mandibular gingival pigmentation. A visible blue light laser (445 nm) was used for the depigmentation procedure.

16.1.7 Pigmentation of Exogenous Origin

Metal tattoo such as amalgam is not uncommon in pigmentation of the gingiva. Pigmentation lip is regularly caused by pencil (lead) and pen.

Fig. 16.7 **a** The preoperative view of a pigmented area on the lower lip. **b** The immediate postoperative view. Under local anesthesia, a 810 nm diode laser was used with a 600 µm fiber with 30 W of peak power, 16 µs pulse duration, at 20,000 Hz for an exposure time of 8 s with non-ablative technique. **c** Two-day postoperative view. **d** 5.5-year postoperative view showing no relapse of pigmentation

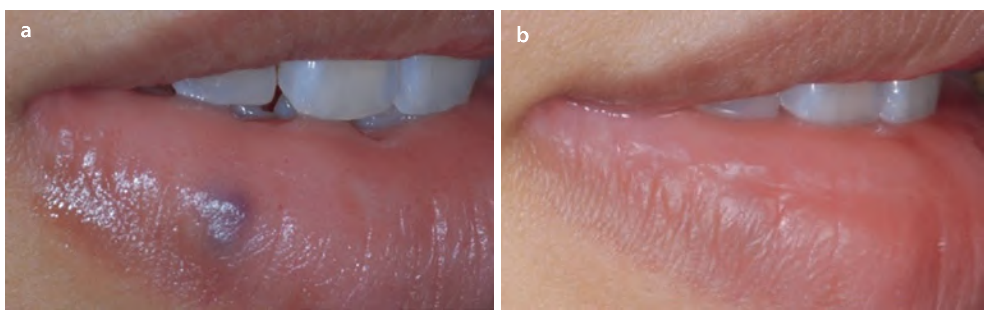

Fig. 16.8 **a** The preoperative view of a hemangioma on the lower right lip. An 810 nm diode laser was used for photocoagulation with 30 W, 20,000 Hz, 16 µs pulse duration (3 s in the first visit, 3 s in second visit and 10 s in third visit) without anesthesia. **b** Three-month postoperative view showing normal lip tissue

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Fig. 16.9 **a** Preoperative view of a varix (venous blood vessel) on the interproximal papilla of the maxillary central incisors. An 810 nm diode laser was used for photocoagulation with 30 W, 20,000 Hz, and 16 µs pulse duration for two visits (2 s on labial in the first visit and 2 s labial and 2 s palatal in the second visit). **b** 8-month postoperative view

Metal Tattoo

Figure 16.11 showed a patient presented with amalgam tattoo at the gingival margin and papilla on the upper central incisors [33]. Under microscope and local anesthesia, the Er:YAG laser (40 mJ at 30 Hz) with water spray was used. The metal debris embedded in the connective tissue were effectively removed, without producing major thermal damage such as carbonization and coagulation. (Photographs a, b, and d from Ishikawa et al. [33]; with permission. *Journal of Periodontal Research* ©Copyright (2004) Blackwell Munksgaard, Inc. Pictures are courtesy of associate professor Akira Aoki)

Table 16.2 A comparison of 445 and 810 nm

Wavelength	Parameters used	Power density	Treatment time	Comments
445 nm	1 W, continuous wave, Average power = 1.0 W	88 W/cm^2 2 mm defocused from tissue	40 s in one case report	Absorption in melanin ten times higher than 810 nm Absorption in hemoglobin 100 times higher than 810 nm Novel wavelength with no complications yet reported; however, the absorption and significantly lower-power density should produce fewer complications
810 nm	30 W peak power pulse duration 16 μs, 20,000 pulses per second Average power 9.9 W	1697 W/cm^2 2 mm defocused from tissue	40 s–3 min for a comparable area	Complications can be gingival recession and bone necrosis

Fig. 16.10 **a** The preoperative view of the lower anterior gingiva with melanin pigmentation. **b** The 445 nm diode laser with a 320 microns bare fiber, defocused 2 mm from the tissue, was used at 1 W CW for 40 s under local anesthesia. Immediate post-op with non-ablative technique. Gingiva bewteen the lower left central incisor and the lower left lateral incisor showed an ablated site indicating over-irradiation beyond coagulation temperature. **c** The 5-month postoperative view shows normal tissue color and contour

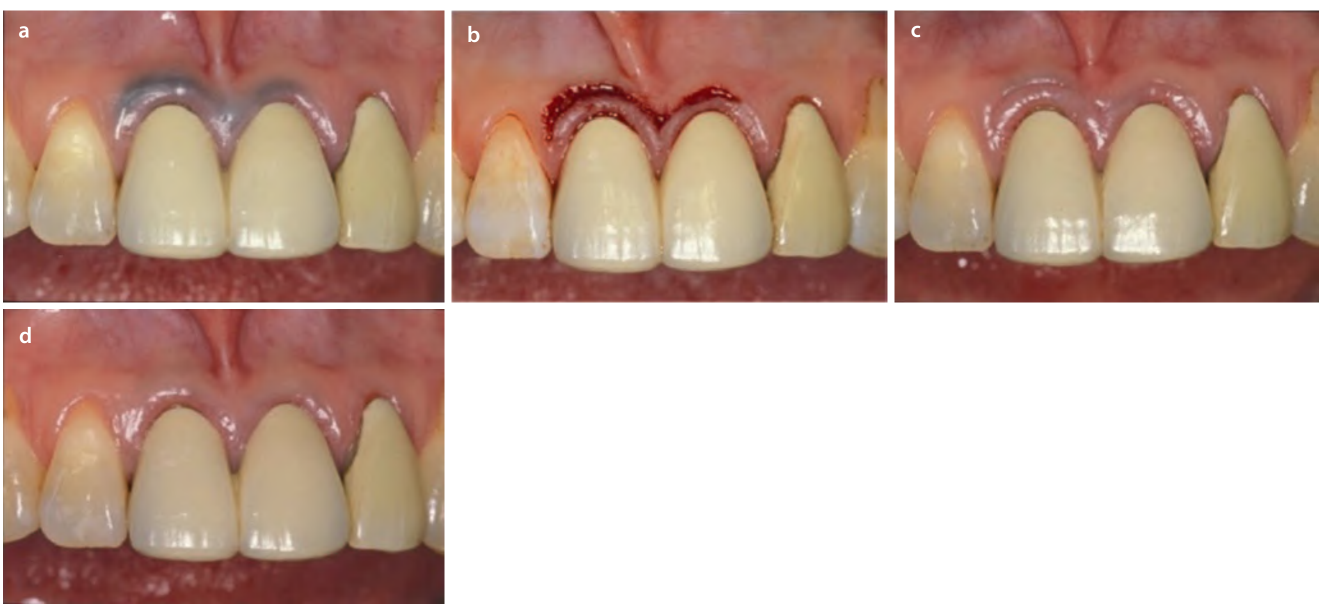

Fig. 16.11 **a** Metal tattoos at marginal area of central incisors before the treatment. **b** Immediate postoperative view. Under microscope and local anesthesia, the Er:YAG laser was used with an average power of 1.2 W (40 mJ, 30 Hz) with water spray. The metal debris embedded in the connective tissue were effectively removed, without producing major thermal damage such as carbonization and coagulation. **c** One-week postoperative view. **d** After 1 year of posttreatment, favorable wound healing was achieved without any gingival tissue defects or recession. The gingival color recovered a natural aesthetic appearance. (Clinical photos courtesy of associate professor Akira Aoki)?

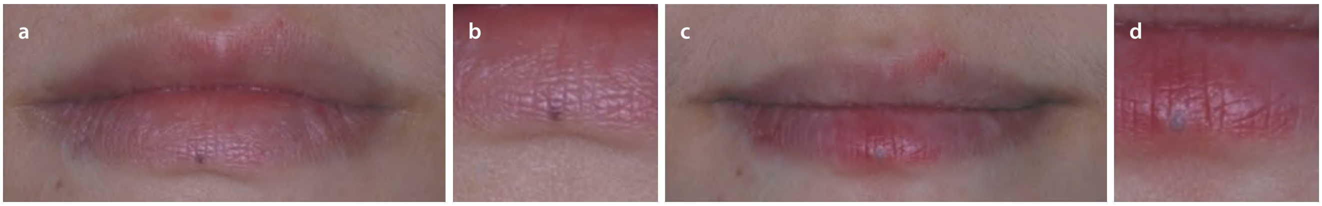

Fig. 16.12 **a, b** Preoperative photo. **c** Immediate postoperative view where the 810 nm diode laser set at 30 W, 16 µs, and 20,000 Hz was used in noncontact mode. The pigment was ablated in less than 1 s without local anesthesia. **d** Five-year postoperative photo shows no recurrence

Fig. 16.13 **a** Preoperative view. **b** Immediate postoperative view after laser exposure of 1 s with 30 W, 20,000 Hz, and 16 µs pulse duration using a non-ablative technique with anesthesia. **c** One-year postoperative view

Metal Tattoo on the Lower Lip

Figure 16.12 showed a 25-year-old female reported pigmentation on the lower lip traumatized by pencil at childhood. Such pigment is more likely to be a result of PIH (postinflammatory hyperpigmentation).

Pigmentation Caused by Lip Biting

Figure 16.13 showed a 40-year-old male complaining of pigmentation on the lower lip. It was revealed that he had a habit of biting the lower lip at his younger age showing the result of PIH.

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16.1.8 Postoperative Care

The patient should be advised to avoid smoking, alcohol, and acidic and spicy food. Sashimi is best avoided for the first few days. Gentle tooth brushing around the gingival margin and warm salt mouth rinse is recommended. In general, no analgesic is required. However, there has been report from mild discomfort to pain with hot food 1 day after treatment [34, 35].

16.1.9 Recurrence of Melanin Pigmentation

Although depigmentation with laser is an effective procedure, recurrence of pigment should be considered. The causes of pigmentation have been described in ▶ Sect. 16.1. The mixed reports of recurrence are listed on Table 16.3 [22, 23, 26, 35–41]. Depigmentation of gingiva was performed on the anterior segments of maxilla and mandible. Ablative technique was used in all articles. Two of the four reports cited reported recurrence after 1 year [35] and at 2 years [37] after treatment. Patients should be aware of the recurrence of pigmentation, but this can be retreated readily. Cessation of medication and giving up on smoking habit reduce the likelihood of relapse.

16.1.10 Treatment Duration

El Shenawy [42] reported 15 cases of depigmentation on the maxilla and mandible using 3 W continuous wave 980 nm diode laser. The cases were completed in contact mode within 20–25 min. Berk [36] reported two cases using Er,Cr:YSGG laser completing the procedure on upper and lower anterior segments in 30 min. In contrast, when using the non-ablative procedure, the author reported a treatment time of 1–2 min to complete one dental arch [29, 30].

16.1.11 Ablative Versus Non-ablative Technique

The ablative technique can be performed by all class IV surgical lasers and is most commonly used. The operator is able the observe color change layer by layer during ablation. Carbonization during treatment should be avoided, and any tissue tags should be removed during the procedure to have a clear view of the ablation front.

The non-ablative technique relies on the optical properties, biophysical properties (laser-tissue interaction), and laser parameters described above. Therefore, not all class IV lasers can use this technique. Although the non-ablative

Table 16.3 Details of published articles about recurrence of pigmentation

Recurrence of pigmentation					
Author	**Wavelength**	**Reevaluation period (months)**	**No. of cases**	**Location**	**No. of recurrence**
Atsawasuwan, *J Periodontal*, 2000	Nd:YAG	11–13	4	Max	0
Tal H, *J Periodontal*, 2003	Er:YAG	6	10	Max	0
Rosa DS, *J Periodontal*, 2007	Er:YAG	3	5	Max	1
Berk G, *J Oral Laser Appl*, 2005	Er,Cr:YSGG	6	2	Max and Man	0
Ozbayrak, *Oral Surg Oral Med Oral Path*, 2000	CO_2	18	8	Max	0
Nakamura, *Lasers Surg Med*, 1999	Super pulsed CO_2	12–24	7	Max	0/4
E.Esen, *Oral Surg Oral Med,Oral Path,Oral Rad,Endod*, 2004	980 nm	12–24	10	Max	2
Gupta, *J Cutan Aesthet Surg*, 2011	980 nm	15	1	Max and Man	0
Doshi Y, *Int J Laser Dent*, 2012	940 nm	12	1	Max	1
Hedge R, *J Periodontol*, 2013	Er:YAG/CO2	6	35 on 140 sites	Split mouth	More with Er:YAG than CO_2

technique can be completed much faster, the operator should have a clear understanding of the principles before performing this technique.

There have not been reports of any major clinical complications; however, there is a possibility of gingival recession and bone necrosis which is caused by excessive ablation, over-irradiation, and deep tissue heat conduction. The clinician should carry out the procedure with good understanding of the optical property of the laser he/she is using and the laser-tissue interaction involved. On the other hand, a clinician is accustomed to completing many procedures in one appointment. The thought of «touching up» a pigmented area should not be construed as poor operative technique; rather, it should be viewed as an opportunity to further improve the aesthetic result.

Summary

In the author's experience, many patients are troubled by the pigmentation, even one spot of pigment on the lip, for example, but not aware of possible treatment. Pigment on the lip is more of concern than gingiva. Furthermore, ethnic communities in the Middle Eastern countries are more concerned with gingival pigmentation.

For those who are made aware of their pigmentation, acceptance of treatment is high. They are usually more appreciative of our examination skills and will have confidence in our techniques. In addition, treatment acceptance is good for both men and women at any age group.

When discussing the procedure, the patients must be made aware of possibilities of relapse, depending on the cause of pigmentation. One example is shown in Fig. 16.4c, and the patient should be informed that a second procedure will be necessary. As an aside, this is an opportune time to discuss smoking cessation. After the laser treatment of the pigmentation, the shade of the teeth may look darker as their gingiva returns to a pinker color, since there will be less contrast between the enamel and the soft tissue.

16.2 Laser-Assisted Dental Bleaching

Eugenia Anagnostaki

16.2.1 Introduction

A smile creates an immediate visual first impression. A bright tooth shade is the most important factor for making a smile attractive, according to Dunn [43].

During recent years, aesthetic dentistry has become a very important field of dentistry. But it is also among the achievements of preventive dentistry that people are taking more care of their teeth in recent times. The most popular and the least invasive procedure within aesthetic dentistry is dental bleaching.

Dental bleaching was known and performed from ancient years, but in the scientific literature, bleaching as a procedure was first described in 1951 by Pearson [44], night-guard vital bleaching in 1989 by Haywood and Heymann [45], and laser-assisted tooth bleaching in 1998 by Reyto [46].

It is important to clarify the often interchangeable terms «bleaching» and «whitening»: According to the FDA, the difference between bleaching and whitening is that the term «bleaching» should only be used when the teeth can be whitened beyond their natural color and when the products used contain bleach. «Whitening» refers to restoring a tooth's surface color by removing superficial staining and debris.

In order to keep bleaching noninvasive, we have to ensure that the materials used, and the methods performed, are not going to harm the enamel, the dentin, the pulp of the teeth, and the surrounding tissues.

16.2.2 Tooth Structure

Enamel

Enamel is the outer layer of the tooth and the hardest tissue in the body.

Mature dental enamel has a complex organized structure, mainly containing inorganic minerals (96%), a small amount of organic material and water (4%), but no cells or collagen [47]. The basic inorganic structural blocks are hydroxyapatite crystals. Ionic exchange can occur, resulting in ionic substitutions, which have key effects on the hydroxyapatite physical and chemical properties. As an example, the fluoride incorporation in enamel was shown to increase its resistance to demineralization [48]. Mineral gain and loss is a dynamic physicochemical process on the tooth surface. Light scattering by the mineral crystals plays a considerable role in light scattering processes.

The organic component contains non-collagenous proteins (60%) and lipids (40%) and can act as a semipermeable membrane, allowing small molecules to penetrate through [49]. According to a study of Eimar et al. [50], this is a possible explanation for the mechanism of bleaching.

Dentin

Dentin contains about 48% of mineral, 28% of organic material, and 24% of water. Dentinal tubules extend from the dentin-enamel junction up to the edge of the pulp. The tubules are where the majority of scattering occurs, whereas collagen fibrils play a minor role; scattering by the mineral crystals in dentin is negligible [51].

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16.2.3 Natural Tooth Color

The main determinant for the tooth shade is dentine with its yellow to brown shades, but enamel properties like thickness, chemical and physical composition, as well as the hydroxyapatite crystal size affect the scattering of the light. Smaller crystals scatter more light and the tooth appears brighter [51]. The enamel can have blue, green, and pink tints.

The color perception is depending on the observer, the object, and the light source. It is a complex procedure resulting from reflection, absorption, and scattering of the light to the object and coming back to the eye of the observer [52].

As visual examination is a subjective method, there are instruments available in dentistry – colorimeters and spectrophotometers – which give unbiased information on the tooth color.

16.2.4 Discoloration

Extrinsic Staining

The exposed surface of the teeth is covered by a protein-polysaccharide coating, the pellicle. The pellicle is easily stained by exogenous colorants from food, drinks, mouth rinses, or oral medications and also from chromogenic bacteria, dental materials, or industrial exposure to metal dust. The chromogen either binds and directly stains the tooth or binds and then stains and darkens with time, or a pre-chromogen binds and then undergoes a chemical reaction to cause staining [53].

The extrinsic staining can either stain the pellicle, which can easily be removed by means of a thorough cleaning, or be retained on the tooth surface forming a stain-enamel complex through ion interaction. Accumulation of extrinsic stains is affected by the oral hygiene habits, saliva composition and flow, and enamel surface roughness.

Intrinsic Staining

This staining is distributed throughout the internal structure of the teeth and can either develop preeruptive during odontogenesis or appear at any time after eruption. The staining can be localized to few teeth or be present on all of them depending on the period of development when it took effect. It can be caused by changes in the structure of the hard tissue itself or by incorporation of chromogenic molecules inside the hard tissue [54].

Conditions such as alkaptonuria, congenital erythropoietic porphyria, congenital hyperbilirubinemia, amelogenesis imperfecta, dentinogenesis imperfecta, tetracycline intake, fluorosis, and enamel hypoplasia can contribute to preeruptive intrinsic staining.

Hemorrhagic products in the pulp, root resorption, and aging can cause post-eruptive staining.

16.2.5 Chemistry of Bleaching Materials

The bleaching gel used for home bleaching can contain carbamide peroxide as an active substance, in concentrations from 5% up to 20% or hydrogen peroxide in concentrations of maximal 10%. Some countries have specific regulations for contents. As an example, there is the 2011/84/EU European Directive [55].

Chemically, a carbamide peroxide concentration of 16% is equivalent to 5.76% of hydrogen peroxide, because carbamide peroxide is being reduced to approximately two parts of ammonia and carbon dioxide and one part of hydrogen peroxide.

For in-office use, available bleaching gels contain from 25% up to 40% hydrogen peroxide. The action of the gel can be accelerated chemically or by means of a light source such as plasma, LED, halogen lamps, or lasers.

The chemical reaction is a reduction of hydrogen peroxide into oxygen and water and preferably into perhydroxyl

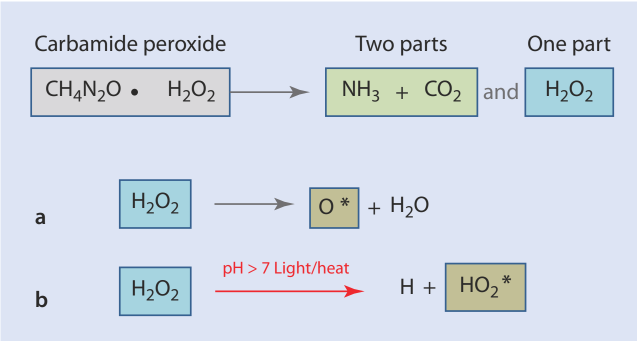

Fig. 16.14 Chemical reaction mechanisms of carbamide peroxide and hydrogen peroxide. The first phase is the reduction of carbamide peroxide into two parts of ammonia and carbon dioxide and one part hydrogen peroxide. Hydrogen peroxide can be further reduced **a** into an oxygen radical and water or **b** under certain conditions into a perhydroxyl radical and a hydrogen ion

and hydrogen. The perhydroxyl (HO_2•) free radical belongs to the most reactive species in tooth bleaching, the formation of which is favored by high (alkaline) pH, but this is rarely the situation as the product shelf life is adversely affected under these conditions [56]. Figure 16.14 shows a graphic representation of the reduction and subsequent reaction of carbamide peroxide and hydrogen peroxide during activation.

16.2.6 Bleaching Methods

There are two main approaches to vital tooth bleaching: home bleaching (night-guard bleaching) and in-office bleaching. The two techniques can be combined to enhance the result. According to Auschill [57], 7 days of home bleaching result to a similar effect of one session of office bleaching.

Night-/Day-Guard Vital Bleaching or Home Bleaching

As first described by Haywood and Heymann [45], this is the most popular bleaching method. Customized trays, sometimes referred to as «night-guards,» have to be used for several hours a day, or overnight, depending on the concentration of the material used.

The material mainly used is carbamide peroxide in concentrations up to 20%. Several companies also offer prefabricated-preloaded trays for home bleaching.

Indications for Home Bleaching (According to So-Ran Kwon [58])

- Generalized yellow, orange, or light brown discoloration
- Age-related yellow discoloration
- Mild tetracycline staining
- Superficial brown fluorosis stains
- Discoloration due to smoking or chromogenic foods or drinks
- Genetically yellow or gray teeth
- Patient wanting shade improvement with minimally invasive treatment
- Yellow discoloration of single vital teeth

Contraindications for Home Bleaching (According to So-Ran Kwon [58]):

- Amelogenesis or dentinogenesis imperfecta
- Severe tetracycline staining
- Discoloration due to restorative materials
- Pregnancy/lactation
- Severe surface damage due to attrition, abrasion, and erosion
- Untreated dentinal hypersensitivity
- Lack of compliance

In the case of home bleaching, the outcome depends on a good supervision and motivation by the dentist, which will lead to a good compliance from the side of the patient.

In-Office Bleaching or Power Bleaching

The procedure is performed chairside, and highly concentrated bleaching gels are used. The appointment time can be lengthy, but the result is visible immediately and is even enhanced in the next 1–2 days. There are disadvantages: the costs for such treatment are higher, the post-op sensitivity might be more intense, and there can be some reversible but moderately painful damage to the soft tissue surrounding the teeth.

After a thorough cleaning with oil- and glycerine-free pumice, hydrogen peroxide gels in concentrations between 25% and 40% are applied on the teeth to be whitened. The soft tissue has to be protected from the caustic action of the bleaching gel. Depending on the material used, activation is achieved chemically by thorough mixing of the gel components usually contained in syringes or by noncoherent light, heat, or laser. The different light sources are used to enhance the chemical decomposition of hydrogen peroxide and with this to enhance the whitening efficacy. When heat is used, a temperature elevation in the gel of 10 °C is reported to double the speed of hydrogen peroxide decomposition [59]. For laser-activated use, the gel should contain a proper photocatalyst, which is an absorber that matches the spectrum of the light used to activate or accelerate the gel. In addition, special filtering substances are used in order to keep the energy inside the gel and not allow a temperature rise inside the pulp [60].

Studies have shown that the hydrogen peroxide penetrates deeper if activated by laser or other light sources [56, 61]. Furthermore, So-Ran Kwon [62] found that light-activated bleaching is not more dangerous to the pulp by the stronger oxidizing action.

Laser-Assisted In-Office Bleaching

During an in-office bleaching procedure, it is possible to activate the bleaching material by a laser. ◘ Figure 16.15 shows the laser wavelengths and their basic mechanism of action, which is photothermal catalysis in the case of diodes and Nd:YAG and photochemical in the case of Argon and KTP, in order to have the highest possible outcome of powerful perhydroxyl radicals from the bleaching gel and provide the most effective bleaching.

The use of KTP, Argon, and diode lasers is widely supported by the literature [60, 62, 63]. Nd:YAG lasers possibly cause overheating due to their high peak power and are under investigation for their safety in bleaching [61, 64, 65] Recently, diode lasers in the wavelength of 445 nm have been introduced and approved for dental use; their safety in dental bleaching is still to be investigated.

CO_2 lasers have been the first lasers approved for use during bleaching procedures, but their use is not supported, since Luk et al. [66] showed overheating on tooth surface and pulp. Additionally, there have not been any controlled clinical studies for that wavelength.

Erbium lasers (Er:YAG and Er,Cr:YSGG) have not been enough investigated yet, and controlled clinical studies are missing for this group of lasers as well. In a recent study, Nguyen et al. [67] show that laser-assisted bleaching (KTP and Er:YAG) gives similar results in a shorter time compared to non-activated bleaching, but they conclude that data on mechanisms of action of the Er:YAG laser on bleaching gel and dental tissues are still limited and additional studies are needed to assess the contribution of the Er:YAG laser in tooth bleaching.

Erbium and CO_2 Lasers are absorbed in the water contained in the bleaching gel and have a photothermal action. Caution must be given due to the absorption of these lasers in hydroxyapatite and due to the high peak power of erbium lasers. It is essential to stay far below the ablation threshold for enamel and always keep the teeth covered by bleaching gel.

The difference between activation by ordinary light or by laser is that ordinary light sources emit a broad spectrum of photonic energy with increased possibility of thermal damage [68]. Using an appropriate laser, it is possible to shorten the interaction time of the material on the tooth surface, thus avoiding possible superficial damages.

The risks of damaging the underlying tissue are depending on the wavelength of the laser to be used: erbium family and CO_2 lasers are well absorbed in water and will be absorbed in the tooth surface, but shorter wavelengths in the red to near-infrared, as well as in the visible spectrum, are more likely to penetrate into the pulp.

Therefore, it is essential to always use the appropriate bleaching gel with a particular laser wavelength, in order to have a high absorption of the energy inside the gel and to minimize any increase of the temperature in the pulpal tissues. To achieve this high absorption, bleaching gels for the blue and green wavelengths contain orange-red dyes like rhodamine, and bleaching gels for red to infrared wavelengths contain bluish-purple dyes. Titanium dioxide particles also act as a broadband absorber in a gel offered by many laser manufacturers.

The action of the Argon and KTP wavelength is not only photothermal and photochemical but photolytic as well. This relies upon specific absorption of a narrow spectral range of green light (510–540 nm) not only in rhodamine but also into chelate compounds formed between apatite, porphyrin, and tetracycline. Through this, Argon and KTP lasers are capable to achieve a good bleaching result even in teeth not responding to other techniques (tetracycline-stained teeth) [69].

In addition, the KTP laser induces a photochemical reaction in the special formulated bleaching gel, providing a higher free radical outcome than during a photothermal action [67]. Through buffering to an alkaline pH of 9 and high energy, the produced free radicals were shown to be more reactive [70].

Blue diode laser	445 nm	Photochemical action
Argon laser	488–515 nm	
Frequency doubled Nd:YAG laser (KTP) or semiconductor	532 nm	
Diode lasers	810–1064 nm	Photothermal action
Nd:YAG laser	1064 nm	
Er,Cr:YSGG laser	2780 nm	
Er:YAG laser	2940 nm	
CO_2 laser	9300-10,600 nm	

◘ **Fig. 16.15** A listing of the active medium of dental lasers with their corresponding wavelengths and the two mechanisms of action in laser-assisted bleaching

16.2.7 Mechanisms of Bleaching

The mechanism of the action of either carbamide peroxide or hydrogen peroxide is not completely investigated. Until now, studies have shown that the unstable oxygen or perhydroxyl radicals are diffusing through the organic matrix of the enamel and dentine and are causing a breakdown of ring structures of stain molecules followed by a breakdown of long molecular chains in the organic tooth matrix into shorter ones, which absorb less, and therefore reflect more light. It is important to know that there is a saturation point during the bleaching process, where there are only hydrophilic pigment-free structures and the lightening of the teeth stops dramatically. At this point, bleaching should be stopped immediately, or the next step would be a rapid loss of enamel [58].

However, this «breakdown of stain molecules» hypothesis might be weak since (i) the organic chromophore's concentration, if they exist, in tooth enamel is extremely low (below the detection limit of many spectroscopy techniques) and (ii) several studies have shown that following tooth bleaching, the translucency of tooth enamel decreased significantly, making it more opaque.

Studies have shown that the tooth enamel organic matrix is mainly composed of amide groups that represent enamel proteins. Eimar et al. [50] found that hydrogen peroxide does neither modify the organic nor inorganic relative contents of dental enamel but oxidizes their enamel organic matrix. The conclusion states that oxidation of enamel protein and the increase in enamel opacity following peroxide treatment seem to indicate that the peroxide whitens teeth by oxidizing its transparent organic matrix into an opaque whiter material. This is a more comprehensive theory of the mechanism by which peroxide might whiten teeth.

16.2.8 In-Office Bleaching Contraindications

According to *L. Walsh* [70], bleaching is contraindicated in case of:

- Severe untreated tooth sensitivity due to exposed cervical dentine from dental erosion, gingival recession, or gingival pathology. In this case, the sensitivity problem has to be resolved first.
- Unrealistic expectations of the treatment result.
- Inability of the patient to sit still in the dental chair during the procedure and tolerate the required soft tissue isolation devices.
- Inability of the patient to follow (at least for a while) changes needed to prevent reformation of extrinsic stains (smokers).
- Inability to have the restorations in the teeth to be bleached changed, after a necessary delay of 2 weeks after the whitening treatment.

16.2.9 Safety Concerns

Studies show varying results concerning the safety of the bleaching methods. One main point is the toxicity of hydrogen peroxide as a strong oxidative, and another is the possible corrosiveness of the gels used.

1. The exposure of the organism to the hydrogen peroxide, according to Li and Greenwall [71], is minimal when used properly, either in office or at home. Enzymes in the saliva are capable to neutralize up to eight times the amount of hydrogen peroxide used in a home bleaching session. During in-office bleaching, with a good isolation of the soft tissue, the level of chemical is not detected systemically.
2. Local soft tissue effects usually manifest as chemical burns. These can be due to either poor isolation or extended contact time with the material and poor-fitting trays, in the case of home bleaching. Vitamin E used locally on the defects is supported by the literature [72].
3. Tooth sensitivity is another side effect and might be an indication of a pulp response to the oxygen and perhydroxyl free radicals [73] (produced from the breakdown of hydrogen peroxide, see ◻ Fig.16.1). It usually appears for the first 24 h–3 days, and this has to be differentiated from the post-bleaching sensitivity which appears like a sudden shooting stimulus and is possibly related with a direct activation of neuronal receptors by the hydrogen peroxide and its products [74]. In a study by Schulte [75], the sensitivity was severe enough to cause 14% of the patients to discontinue the bleaching treatment.

   For sensitivity treatment, potassium nitrate gels or casein phosphopeptide-amorphous calcium phosphate (CPP-ACP) pastes are used immediately after the bleaching session with an effective reduction of sensitivity. Agents such as potassium salts, which do depress nerve excitability, are claimed to be more effective than tubule-occluding agents in reducing sensitivity according to Markowitz [74], but according to a newer randomized controlled clinical trial, there is no significant difference between gel and paste [76].

   In a recent study by Moosavi et al. [77], low-level laser therapy with an infrared diode laser could be recommended as a suitable strategy to reduce the intensity of tooth sensitivity after in-office bleaching. The parameters used with an 810 nm diode laser were 3 J of energy, energy density of 12 J/cm^2, and power density of 800 mW/cm^2 on the cervical area of the tooth.
4. Penetration of the bleaching material into the pulp has been shown in several in vitro studies to take place. However, the pulp tissue can protect itself from damage by hydrogen peroxide through the enzymatic breakdown of the molecule by peroxidase and catalase [78]. These cellular enzymatic systems eliminate the excess oxygen, but still it is not known how much hydrogen peroxide can be tolerated by the pulp tissue [79]. Additionally, an in vivo study demonstrated that bleaching with or without light activation did not cause damage on pulp tissue of young sound premolar teeth [80].
5. Overheating of the pulp in the case of in-office bleaching has to be avoided, through the choice of a material which needs only a short time activation and contains the proper filtering absorber to block the heat inside the gel. According to Zach and Cohen [58], the pulp can only tolerate a temperature rise up to 5.5 °C. Eriksson and Albrektsson [81] found that 42 °C might be a critical temperature to the pulp when sustained for 1 min. On the other hand, Baldissara et al. [82] reported that an intrapulpal temperature rise of 8.9–14.7 °C in humans does not induce pulpal pathology. The values of temperature rise obtained in this study were not critical for pulp health; however, this was a preliminary study.
6. Enamel surface morphology. The effect of bleaching materials (either home or in- office) on the enamel surface is controversially documented in the literature.

The studies that have been performed on the adverse effects of bleaching on chemical and physical characteristics of the enamel use several different methods: SEM (direct or indirect), profilometry, microhardness, calcium loss, and infrared spectroscopy. Out of these, the microhardness seems to be the preferred choice of the researchers [83]. However, those methods are destructive, which means that it is impossible to follow up the same samples during a period of time. But the processes in the mouth are dynamic, so there is the need of examining what is happening in vivo, over time. Out of the numerous studies investigating the impact of bleaching procedures on enamel, only a few are performed in vivo conditions.

Clinical studies found no statistically significant loss of surface enamel hardness or loss of calcium and phosphorus as minerals out of the enamel [84]. In contrary, many in vitro studies show microhardness reduction after bleaching. Attin et al. [85] reviewed the published literature on the effect of bleaching on enamel microhardness. They conclude that if in the different (in vitro) studies, the intraoral conditions are simulated as close as possible (e.g., with use of artificial or human saliva as a storage medium, or re-fluoridation after bleaching), then the study outcome shows a lower risk of enamel microhardness reduction due to the bleaching treatment, compared to the remaining studies.

The most severe alterations in enamel in vitro have been described when acidic bleaching gels were used [86]. The hydrogen peroxide per se is acidic, and the gels are usually kept in acidic pH in order to increase shelf life. Only the gels produced for use with the KTP laser contain a special buffering system and set the pH to around 9.5 [60].

16.2.10 Long-Term Effectiveness and Stability of Tooth Whitening

A number of authors have investigated the effectiveness of tooth whitening by comparing different techniques and different peroxide concentrations. The evidence on effectiveness suggests that all of them are effective and reach similar results when their respective protocols are followed.

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The stability of outcome of various whitening products has been widely evaluated, and significant shade improvement can be predicted when products such as carbamide peroxide gel, or hydrogen peroxide, with or without light activation are used according to a study of Sulieman [87].

Unfortunately, only short-term results on bleaching efficacy have been reported by most studies [62], while only a few of them report results over the long term (Auschill et al. [57], Grobler et al. [88]). It has been shown that although higher peroxide concentrations produce a quicker shift than lower concentrations, the result on whitening is the same for all concentrations at the end of the whitening process. However, the differences in effectiveness of tooth whitening appear to be significant when results are evaluated over a longer period.

In a retrospective case series study, Leonard [89] had shown that long-term shade retention was reported by 82% of the participants 4 years post-bleaching. Later the group of Boushell and Leonard [90] showed that satisfactory retention of the shade change without re-treatment can be expected in at least 43% at 10-year posttreatment.

Two long-term studies done by Grobler et al. [88] assessing the effectiveness of 10% carbamide peroxide showed that the majority of patients maintained whitening improvement for up to 6 months. From an initial shade change of five, there was between 18% and 26% relapse. However, significant relapse was noticed when the patients were evaluated 14 months after tooth whitening, mostly for the whiteness/ brightness parameter. It is suggested that re-whitening should be done at about 14 months post-whitening in the case of home bleaching.

Clinical studies evaluating the outcome of laser-assisted bleaching are controversial: Strobl et al. [64] concluded after a split-mouth study in 20 patients that the Nd:YAG laser did not enhance the bleaching success; furthermore, the laser-activated sites have been more sensitive after treatment than the non-activated sites. Gurgan et al. [63] could show that the use of a diode laser results in spectrophotometric-measured better outcome, with less gingival and tooth sensitivity, and it might be preferred among in-office bleaching systems. Concerning tetracycline-discolored teeth, Kuzekanani and Walsh [91] found in vivo, through a quantitative analysis of digital pre- and post-bleaching digital images, that KTP laser photodynamic bleaching provides a clinically useful improvement in tooth shade.

Regarding the relapse in the color after tooth whitening, it is known that the oxygen within the tooth from the oxidative process initially alters the optical properties of the tooth. Then oxygen dissipates over the following week(s), and the tooth takes on the actual lightened shade [92].

Is it the protein molecules re-bonding the double bonds, is it aging or the oxidized organic matrix which is turning less opaque and more transparent again with time, or finally is it the enamel changes caused by the bleaching materials, guiding the teeth to a new discoloration by leakage from extrinsic stains? Investigations will continue, especially in comparing color relapse after laser-activated bleaching, with the traditional methods.

Unfortunately, the available studies concerning laser-assisted bleaching do not provide clear conclusions. The details of the protocols, laser wavelengths, and gels used are often not fully described. Long-term outcome studies are absolutely necessary in order to evaluate the advantages of this method.

16.2.11 Patient Inclusion/Exclusion Criteria

Before starting a bleaching procedure, there are several items to be considered as *inclusion criteria:*

- Informed consent has to be obtained from the patients.
- An initial detailed examination is performed, including medical and dental history, occlusion and TMJ exam, radiographic, soft and hard tissue status with tooth vitality, percussion and mobility testing.
- After this, a professional cleaning and polishing of all teeth has to be done, and hygiene instructions are given to the patient.
- In case of combined in-office/home bleaching, alginate impressions of both upper and lower arch have to be taken, in order to fabricate on stone die casts so that customized bleaching trays with reservoirs on the teeth to be bleached can be constructed.

The *exclusion criteria* are poor general or dental health, untreated periodontal disease, pregnancy/lactation, inability to quit smoking during the bleaching and post-bleaching examinations period, and carious or fractured teeth to be bleached.

16.2.12 Shade Evaluation

In order to prove that the bleaching procedure is successful, a shade evaluation has to be periodically performed. The initial shade inspection, as well as every shade evaluation, e.g., immediately after the procedure, 1 week later, and additionally every 6 months after the usual dental hygiene appointments, is advised to be performed with a spectrophotometer, as it has been found to give the most repeatable results [93]. ◘ Figure 16.3 shows a result of one such analysis (◘ Fig. 16.16).

The color detected by the spectrophotometer can be confirmed visually by a value- oriented scale or shade guide. The color is expressed in «shade guide units» according to Paravina [94], and the difference in shade guide units shows the color improvement. A photographic documentation with a digital camera is mandatory. It is advantageous to obtain pictures with the corresponding shade tab placed on the tooth. ◘ Figure 16.17 shows a typical shade guide. An additional «bleach guide» might be useful for colors lighter than B1.

◘ **Fig. 16.16** Screen shot of handheld spectrophotometer with tooth color map. Spectroshade MHT (MHT Optic Research AG, Niederhasli, Switzerland)

16.2.13 Laser Parameter Calculation and Reporting

A complete parameter report is essential to ensure that a bleaching procedure produces consistent results.

- Intrinsic parameters: device manufacturer, model and type, wavelength delivery system, emission mode, and energy distribution.
- Adjustable parameters: pulse width, repetition rate or frequency, the tip diameter, tip-to-tissue distance, beam divergence, tissue cooling, and length of treatment.
- Calculated parameters: average power, peak power, tip area, spot diameter and spot area at the tissue, power density, pulse energy density, total energy, and fluence are indispensable details for every case, in order to have the option of a repeatability of the procedures.

An additional advantage would be the use of a power meter to verify the accuracy of the laser's display panel. Often the power indicated on that panel does not correspond to the power at the exit of the handpiece/fiber.

Ideally the energy distribution out of the handpiece used for bleaching should be «flat-top» If not, care must be taken for not creating «hotspots» on the teeth which result from a Gaussian distribution of the beam. One option is to keep the handpiece/fiber continuously moving in the defined distance from the target.

16.2.14 Clinical Examples of Laser Bleaching Materials and Methods of Use

LaserWhite20 (◘ Fig. 16.18)

LaserWhite20 (Biolase Inc., Irvine, CA USA) was developed for the company's 810 or 940 nm lasers. The gel is produced by mixing the base and activator gel contained in two syringes, and the resulting hydrogen peroxide concentration is 38%.

The clinical protocol is as follows. The initial color is documented. The teeth to be whitened are cleaned with a glycerine- and oil-free pumice, dried with air, and a gingival barrier

◘ **Fig. 16.17** Value-oriented shade scale (Vita, Zahnfabrick, Germany.) The *black* numbers superimposed on the scale show the ascending order of darkness of the shade, with number 1 being the higher (brighter) value

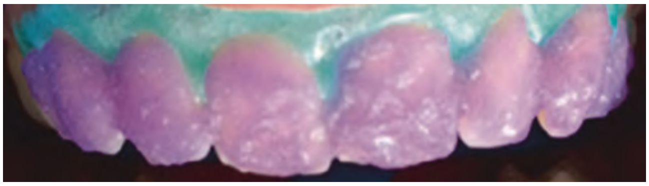

Fig. 16.18 LaserWhite20 applied with gingival barrier in place

is applied to protect the gingiva. Soft tissue is protected with cheek retractors and cotton rolls. The gel is applied on each tooth in a uniform layer, approximately 0.5–1 mm thick, directly from the syringe using a brush tip applicator. Figure 16.5 shows the gingival barrier in place and the gel applied to the teeth.

The patient, staff, and operator will wear the appropriate protective eyewear, and all other laser safety measures have to be followed.

The laser (Lasersmile, Biolase Inc., Irvine CA, USA), with an emission wavelength of 810 nm, is used with a power of 10 W continuous wave, delivered into a quadrant whitening handpiece. The same protocol can be applied for the 940 nm diode laser when using a similar quadrant handpiece. The application time is 15 s application per quadrant with the handpiece approximately 3 mm away from the gel. After the 15 s exposure, the handpiece is moved to the next quadrant, and the photonic energy is reapplied for 15 s. After all quadrants are exposed in that manner, the laser is deactivated for 1 min. This protocol is being performed three more times for the first gel application. Thus, the total laser activation time per quadrant is 60 s with a total waiting time between laser activations of 4 min.

The bleaching gel is removed with the high-volume suction and rinsed off carefully, to avoid damage of the gingival and soft tissue barriers. Then a new layer of gel is applied on the teeth, and the above technique is repeated on all quadrants.

After completing the procedure, the protective barriers are removed. The final color is documented.

If any bleaching gel leakage affected the soft tissue, vitamin E oil should be applied to the area.

In case of hypersensitivity or pain, a nonstaining desensitizing gel can be applied.

Total contact time of the bleaching gel with the teeth is 16 min, with 2 min of laser exposure. As an aside, the entire chairside appointment time needed is not included in the calculation. The barrier application time will vary, and the application time for all bleaching gels is approximately 2 min. Table 16.4 is the laser parameter report.

Heydent JW Power Bleaching Gel (Fig. 16.19)

JW Power Bleaching Gel (Heydent, Kaufering-Germany) can be activated with any wavelength from 532 to 1064 since it contains a multi-wavelength absorber. A gel is produced by mixing the kit contents of liquid hydrogen peroxide fluid with the powder, which contains titanium dioxide. The resulting hydrogen peroxide concentration is 35%.

The clinical protocol is as follows: The initial color is documented. The teeth to be whitened are cleaned with a glycerine-free pumice, dried with air, and a gingival barrier is

Table 16.4 Laser parameter report using the 810 nm wavelength diode laser and LaserWhite20 gel following Dr. Wayne Selting's template

Intrinsic properties		Adjustable parameters		Calculated parameters Calculation are per quadrant, per cycle (four cycles are performed twice)	
Laser manufacturer	Biolase	Power	10 watt	Average power	10 Watts
Model	LaserSmile	Tip width	35 mm	% on time	100 %
Type	Diode	Tip height	8 mm	Energy per pulse	150 Joules
Wavelength nm	810	Tip-to-tissue	3 mm	Peak power	10 Watts
Delivery system	Optical fiber	Beam divergence	8 Degrees	Tip area	2.80 cm^2
Emission mode	Continuous	Length of treatment	15 s	Spot area at tissue	3.2594 cm^2
Energy distribution	Quasi-flattop			Peak power density	3.07 w/cm^2
Energy delivery	Non-initiated			Average power density	3.07 w/cm^2
Handpiece used	Quadrant bleaching handpiece			Total energy	150 Joules
				Energy density	46.02 j/cm^2

Note: This table's calculations are per activation cycle and per quadrant, using the bleaching handpiece mentioned

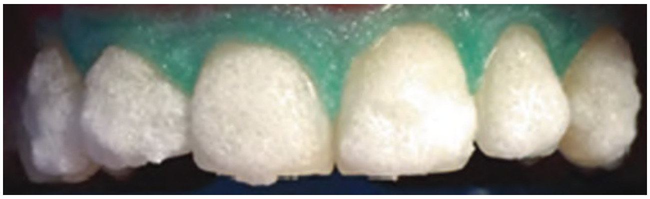

Fig. 16.19 JW Power Bleaching Gel applied with the gingival barrier in place

applied in order to protect the gingiva. Soft tissue is protected with cheek retractors and cotton rolls if necessary. The gel is applied in a layer of approximately 2 mm on each tooth, using a plastic spatula. Figure 16.6 shows the gingival barrier in place and the gel applied to the teeth.

The patient, staff, and operator must wear the appropriate protective eyewear, and all other laser safety measures have to be followed.

The laser (Fox 1064, ARC Lasers Nürnberg Germany) with an emission wavelength of 1064 nm is used at 1.6 W continuous wave and delivered into a collimated handpiece of 6 mm diameter that is placed a distance of 10 mm from the gel. Each tooth is exposed for 30 s.

After having activated the bleaching gel on all teeth to be bleached, the gel is removed with high-volume suction and is rinsed off carefully to prevent damage of the gingival and soft tissue barriers, tooth by tooth every 30 s, starting with the tooth which was activated first. In this way, the resting and contact time of the gel on each tooth is approximately the same.

Then a new layer of gel is applied on the teeth and the procedure is repeated twice.

After completing the procedure, the protective barriers are removed. The final color is documented.

If any bleaching gel leakage affected the soft tissue, vitamin E oil should be applied to the area.

In case of hypersensitivity or pain, a nonstaining desensitizing gel can be applied.

Total contact time of the bleaching gel with the teeth is approximately 30 min, and each tooth was exposed to the laser photonic energy for 90 s. Table 16.5 is the laser parameter report.

Smartbleach Gel 36% (Fig. 16.20)

Smartbleach KTP Gel (SBI Dental-Herzele, Belgium) is activated by the 532 nm wavelength. The gel is produced by mixing the kit's contents of hydrogen peroxide and bleaching powder. The resulting hydrogen peroxide concentration is 36%.

The clinical protocol is as follows: The initial color is documented. The teeth to be whitened are cleaned with a glycerine-free pumice, dried with air, and a gingival barrier is applied in order to protect the gingiva. Soft tissue is protected with cheek retractors and cotton rolls if necessary. The gel is applied in a layer of approximately 1 mm on each tooth, using a plastic spatula and a micro-brush. Figure 16.7 shows the gingival barrier in place, the gel applied, and the laser handpiece focused on a tooth.

The patient, staff, and operator must wear the appropriate protective eyewear, and all other laser safety measures have to be followed.

Table 16.5 Laser parameter report using the 1064 nm wavelength diode laser and JW Power Bleaching Gel following Dr. Wayne Selting's template

Intrinsic properties		Adjustable parameters		Calculated parameters Calculations are per tooth, per cycle	
Laser manufacturer	ARC	Power	1.60 Watt	Average power	1.60 Watts
Model	FOX	Tip diameter	8000 µm	% on time	100 %
Type	InGaAsP diode	Tip-to-tissue distance	10 mm	Peak power	1.60 Watts
Wavelength nm	1064	Beam divergence	6 Degrees	Tip area	0.5027 cm^2
Delivery system	Optical fiber	Length of treatment	30 s	Spot diameter at tissue	1.0102 cm
Emission mode	Continuous			Spot area at tissue	0.8015 cm^2
Energy distribution	Flattop			Peak power density	2.00 w/cm^2
Energy delivery	Non-initiated			Average power density	2.00 w/cm^2
Handpiece used	Single tooth bleaching handpiece			Total energy	48 Joules
				Energy density (fluence)	59.88 j/cm^2

Note: This calculation is per activation cycle per tooth. Usually three activations in total per tooth have to be performed

Fig. 16.20 Gingival barrier in place and the Smartbleach gel applied to the teeth

The laser (DEKA Smartlite, DEKA M.E.L.A. Srl. -Firenze, Italy) with an emission wavelength of 532 nm is used at 1 W, continuous wave, and delivered into a handpiece that is placed a distance of approximately 40 mm to the gel. Each tooth is exposed to the laser energy for 30 s, and then the activated gel is allowed to interact with the tooth for a total of 10 min.

After this, the gel is removed with the high-speed suction, tooth by tooth every 30 s, starting with the tooth which was activated first, second, third, etc., and rinsed off carefully in order to not damage the gingival and soft tissue barriers. In this way, the resting and contact time of the gel on each tooth is approximately the same.

Then a new layer of gel is applied on the teeth, and the procedure outlined above is repeated twice. After the third cycle, the bleaching gel is removed tooth by tooth again, with the high-speed suction and rinsed off, and then the protective barriers are removed. The final color is documented.

If any bleaching gel leakage affected the soft tissue, vitamin E oil should be applied to the area.

In case of hypersensitivity or pain, a nonstaining desensitizing gel can be applied.

The total contact time of the gel on the teeth is therefore approximately 30 min, and the laser exposure time is 90 s per tooth. Table 16.6 is the laser parameter report.

16.2.15 Laser-Assisted Bleaching Protocol

A flow diagram of a typical appointment for laser-assisted bleaching includes the following step:

1. Obtain the patient's informed consent.
2. Obtain the initial shade using shade tabs and/or spectrophotometer and document it with a clinical photograph.
3. Apply cheek retractors
4. Polish the teeth with pumice or glycerine-/oil-free paste and avoid any contact with saliva.
5. Remove bleaching gel from refrigerated storage and mix, following manufacturer's instructions.
6. Air dry teeth to be bleached and apply gingival protection barrier.
7. Apply bleaching gel in an appropriate thickness.
8. Irradiate tooth by tooth or per quadrant following appropriate laser protocols, using Tables 16.4 and 16.6 as examples. Adhere to laser safety principles.
9. After recommended interaction time, remove gel and rinse teeth with water.
10. Air dry teeth, check gingival barriers, reapply gel if required, and repeat steps 8 and 9.

Table 16.6 Laser parameter report using the 532 nm KTP laser with Smartbleach gel following Dr. Wayne Selting's template

Intrinsic properties		Adjustable parameters		Calculated parameters	
				Calculations are per tooth, per cycle	
Laser manufacturer	DEKA	Power	1.00 Watt	Average power	1.00 Watts
Model	SmartLite	Tip diameter	6000 µm	% on time	100 %
Type	KTP	Tip-to-tissue distance	40 mm	Peak power	1.00 Watts
Wavelength nm	532	Beam divergence	3 Degrees	Tip area	0.2827 cm^2
Delivery system	Optical fiber	Length of treatment	30 sec	Spot diameter at tissue	1.0193 cm
Emission mode	Continuous			Spot area at tissue	0.8189 cm^2
Energy distribution	Flattop			Peak power density	1.23 w/cm^2
Energy delivery	Non-initiated			Average power density	1.23 w/cm^2
Handpiece used	Single tooth bleaching handpiece			Total energy	30 Joules
				Energy density (fluence)	36.77 j/cm^2

Note: This calculation is per activation cycle per tooth. Three activations in total per tooth have been performed

11. If necessary, apply desensitizing gel or other similar material.
12. Give post-bleaching instructions—for example, avoid dark-colored food and liquids, and continue good oral hygiene.
13. Evaluate shade change.

16.2.16 Clinical Cases

Two clinical cases of laser-assisted bleaching are shown. Case 1 was performed with the 532 nm KTP laser and Smartbleach, and case 2 was performed with a 1064 nm diode laser using JW Power Bleaching Gel.

Figure 16.21 demonstrates bleaching with KTP 532 nm and Smartbleach. The 6 months post-bleaching photo shows good color stability.

Figure 16.22 depicts bleaching using a 1064 nm diode with JW Power Bleaching Gel.

16.2.17 Summary

In summary, the use of lasers is a safe and effective way to enhance in-office bleaching procedures.

Thorough knowledge of laser-tissue interaction and laser safety is indispensable. Through this, a well-trained clinician is able to perform a laser-assisted bleaching with no side effects. Precise evidence-based clinical protocols need to be established and followed, in order to standardize the procedures and guide to predictable outcomes.

Conclusion

The clinician's first goal for a dental patient is usually to help maintain a healthy dentition. Many patients also desire a smile that fits their own aesthetic criteria. Of course, the interpretation of those concepts will vary widely based on an individual's culture, philosophy, and personality, to name just a few. Thus, practitioners should be aware of techniques to help fulfill the patient's aesthetic demands. This chapter has demonstrated how dental lasers are one instrument that can be used for hard and soft tissue enhancement.

Fig. 16.21 **a** Pre-bleaching shade selection—A 2. **b** Retractors and gingival protection in place. **c** Bleaching gel applied. **d** Activation with the KTP (532 nm) laser. **e** Immediately after bleaching. Note some blanching on papilla between the central incisors due to leakage of the gel. **f** Five days after bleaching. Papilla has normal appearance. Shade B1 has been achieved. **g** Six months after bleaching. **h** 2 Years after bleaching

Fig. 16.22 **a** Pre-bleaching view. **b** Pre-bleaching shade match of the canines is A 3.5. **c** Pre-bleaching shade match of the central incisors is C-1. **d** After retractors and tissue protection are in place, the bleaching gel is placed on the teeth. The laser is placed approximately 2 cm from the teeth and the gel is activated. **e** Immediately after the first bleaching session, the canines are matched to A-3 and the centrals are A-1. **f** Immediately after the second session, the canines are now A-2 and the centrals are B-1. **g** One month after bleaching, treatment the color is stable. **h** Six years after treatment, the color is very stable and remains bright

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The Way Forward?

Contents

Current Research and Future Dreams: The Second Generation of Hard Tissue Lasers

Peter Rechmann

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Core Message

While all commercially available dental lasers can be clinically used for soft tissue procedures, the quest continues for the ideal instrument to safely and efficiently interact with dental hard tissue. This chapter will describe several years of research that has resulted in the second generation of hard tissue lasers. The interaction of carbon dioxide laser photonic energy with tooth enamel and dentin has been studied for several decades, with first publications in the 1960s. Carbon dioxide lasers at 9.3 μm and 9.6 μm wavelength show the highest absorption of all dental lasers in dental hard tissues. Laboratory studies have shown that these short-pulsed CO_2 lasers can efficiently be used to render enamel caries resistant by transforming the originally carbonated apatite into the much acid less soluble hydroxyapatite. Adding fluoride after the laser treatment additionally reduces the acid solubility of enamel and creates the desired least acid-soluble fluorapatite. Irradiation with the 9.3 μm laser wavelength can reduce mineral loss by 55% over untreated enamel. Safety studies have shown that without harmful effects to the pulpal tissue these lasers can efficiently and safely be used on vital teeth. The first in vivo clinical study engaging an orthodontic bracket model showed over 4 weeks a 46% and over 12 weeks a 87% reduction in mineral loss. The first in vivo occlusal caries prevention by pulsed CO_2 laser and additional fluoride varnish application demonstrated that a microsecond-pulsed 9.6 μm CO_2 laser with additional fluoride varnish applications significantly inhibited the formation of carious lesions in fissures of molars in vivo in comparison to a non-irradiated control tooth in the same arch over a 1-year observation interval. Using ICDAS and the SOPROLIFE daylight and fluorescence assessment tools proved the reduction in caries. Moreover, the 9.3 and 9.6 μm CO_2 μs short-pulsed lasers are very efficient in cutting dental hard and soft tissue. Results of shear-bond strength testing with multiple bonding agents to such laser cuts are promising.

17.1 Rendering Enamel Caries Resistant: Laboratory Work

During the creation of tooth mineral, a pure hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] is actually not formed. In fact, the mineral portion of the enamel and dentin is best called a highly substituted carbonated apatite [1]. The mineral is closely related to hydroxyapatite, but in acid it is much more soluble. Carbonated apatite is deficient in calcium (sodium, magnesium, zinc, etc. replaces the calcium) and contains between 3% and 6% carbonate by weight. In the crystal lattice, carbonate mostly replaces phosphate ions [2–4]. The mineral of enamel and dentin can be described by the formula of carbonated hydroxyapatite [$Ca_{10-x}(Na)_x(PO_4)_{6-y}(CO_3)_z(OH)_{2-u}(F)_u$].

Numerous laboratory studies in the past have shown that increasing resistance to enamel demineralization may be achieved by microsecond-pulsed CO_2 laser irradiation [5, 6]. The most strongly absorbed wavelengths in dental enamel are the 9.3 and 9.6 μm CO_2 laser wavelengths [7, 8] (Fig. 17.1).

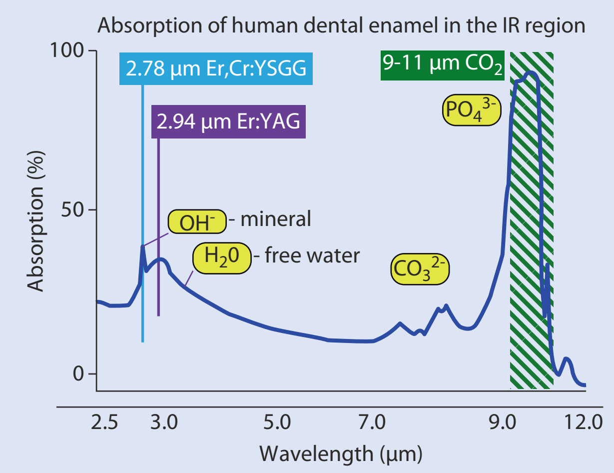

Fig. 17.1 Absorption of human dental enamel in the infrared (IR) spectral region showing the position of the primary absorbers, namely, phosphate (PO_4^{3-}), carbonate (CO_3^{2-}), hydroxyl (OH−), and water (H_2O), overlapped by the positions of the Er, Cr:YSGG, Er:YAG, and carbon dioxide (9.3, 9.6, 10.3, and 10.6 μm) emission wavelengths (the curve is a simplified transformation from an infrared transmission spectrum of dental enamel; significantly modified from Refs. [5, 8, 9])

Table 17.1 Selected optical properties of enamel and dentin, tabulated from references mentioned as sources, from Ref. [9]

Absorption coefficients (μ_a) of light in dental enamel			
Wavelength		**μ_a cm^{-1}**	**Source**
Visible			
450–700 nm		3–4	Fried et al./Ten Bosch
Near IR			
Nd:YAG	1.06 μm	<1	Fried et al.
Mid IR			
Ho:YAG	2.10 μm	<20	estimate
Er:YSGG	2.79 μm	450	Zuerlein et al.
Er:YAG	2.94 μm	770	Zuerlein et al.
CO_2	9.3 μm	5500	Zuerlein et al.
	9.6 μm	8000	
	10.3 μm	1125	
	10.6 μm	825	

At 9.3 and 9.6 μm wavelengths, the enamel absorption coefficient is ten times higher compared to the 10.6 μm CO_2 laser wavelength [7, 8]. This is demonstrated in Table 17.1.

Due to the irradiation heat, the carbonate phase loss from the enamel crystals is responsible for the reduced dissolution of enamel in acid [10] due to transforming the carbonated

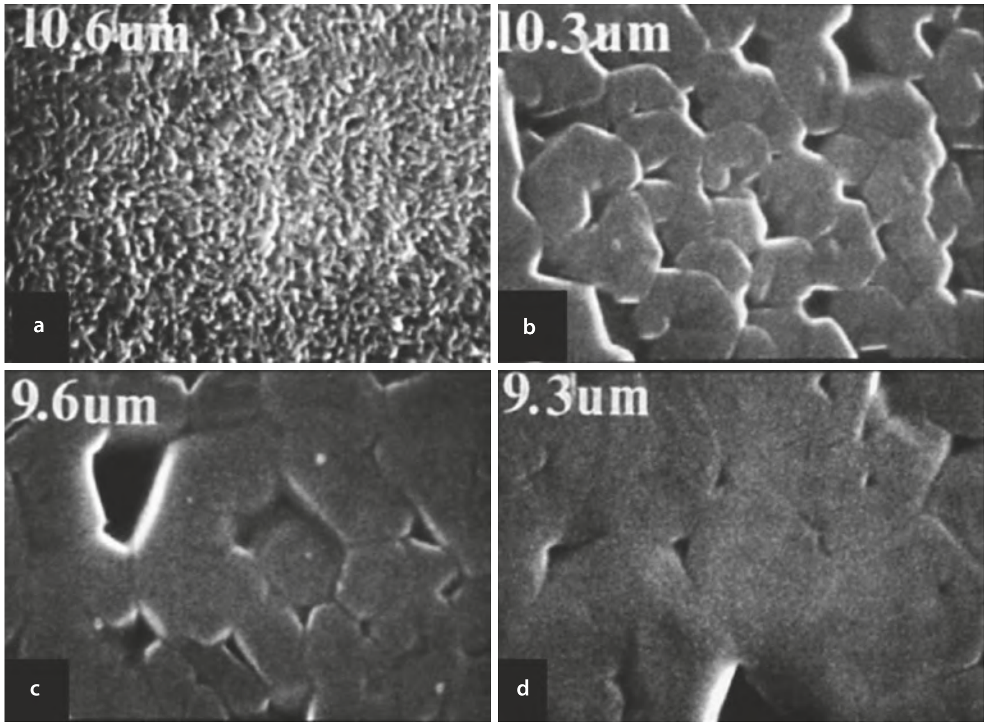

Fig. 17.2 SEM pictures of unpolished enamel after irradiation with CO_2 laser wavelength **a** 10.6 µm, **b** 10.3 µm, **c** 9.6 µm, and **d** 9.3 µm, all 50 µs pulse duration; melting of the enamel prisms occurs at 10.3, 9.6, and 9.3 µm but not at 10.6 µm (Photos from Ref. [16]. Used with permission from the Journal of Dental Research)

hydroxyapatite into the more acid-resistant hydroxyapatite. If at this point in time fluoride is added, fluorapatite is created, which is even less acid soluble than hydroxyapatite [11].

Fluoride works predominantly via topical mechanisms, including [1] demineralization inhibition at the crystal surfaces inside the enamel, [2] remineralization enhancement at the surfaces of the crystal (the newly created remineralized layer is very resistant to acid attack), and [3] finally inhibition of bacterial enzymes [12].

Topical fluoride in solution in the oral cavity boosts remineralization by accelerating the growth of a new surface on top of the partially demineralized subsurface crystals in the carious tooth structure. The newly formed veneer-like surface layer on top of the crystal is like fluorapatite, exhibiting much lower acid solubility than the original carbonated apatite mineral [13, 14].

Initial investigations postulated that melting of enamel was required to accomplish caries resistance. Surface enamel melts at about 1100 °C and fuses at or above the hydroxyapatite melting point of about 1280 °C [15]. The goal in basic research was to determine parameters that will selectively melt and/or chemically alter crystals near the surface to a depth that will provide the greatest efficacy for caries prevention [16]. Consequently, McCormack et al. in 1995 irradiated bovine and human enamel by a tunable, pulsed CO_2 laser (Fig. 17.2) [16]. This specific laser prototype could be tuned to the wavelengths 9.3, 9.6, 10.3, and 10.6 µm. To irradiate the samples, 5, 25, or 100 pulses were used, at fluences of 2, 5, 10, or 20 J/cm^2 with pulse widths of 50, 100, 200, and 500 µs, respectively. The authors observed crystal fusion at fluences of 5 J/cm^2 with the 9.3, 9.6, and 10.3 µm wavelength but never with the 10.6 µm wavelength [16].

Fried et al. in 1996 showed when using a 9.6 µm CO_2 laser at 100 µs pulsed duration and a fluence of 4 J/cm^2 that they achieved a 800 °C enamel surface temperature, which was just not melting enamel. Surface temperatures of 800 °C and up to 1200 °C, achieved at 6 and 8 J/cm^2, respectively, caused the mineral to melt [17]. Applying 10 J/cm^2 resulted in vaporization of the enamel (Fig. 17.3).

As consequence of irradiation with a 9.6 µm carbon dioxide laser with 100 µs pulse duration, Featherstone et al. in 1997 showed using fluences of 0–3 J/cm^2 did not or only slightly reduced the carbonate content of enamel. In contrast, irradiation with fluences of 4, 5, or 6 J/cm^2 eliminated the carbonate from enamel surfaces. Measurements were done by Fourier Transform Infrared Reflectance (FTIR) spectroscopy (Fig. 17.4) [9, 18].

Lately a short-pulsed carbon dioxide laser emitting at a wavelength of 9.3 µm became available on the US market for use in dental offices (Solea, Convergent Dental, Inc., Natick, MA). The CO_2 gas of the laser medium is «radio-frequency excited,» and thus the direct-pulsed laser can emit extremely short laser pulse durations as short as a 3 µs minimum pulse duration.

In order to test the caries preventive potential of the 9.3 µm short-pulsed CO_2 laser, five different pulse durations between 3 and 7 µs were used irradiating enamel samples in a laboratory study. The consequently delivered pulse energies ranged from 1.49 mJ/pulse up to 2.9 mJ/pulse, resulting in fluences between 3.0 and 5.9 J/cm^2. Non-irradiated samples served as control in this study. In addition a series of samples received additional fluoride treatment. After a 9-day pH cycling period, when using cross-sectional microhardness testing, this study showed by laser treatment without

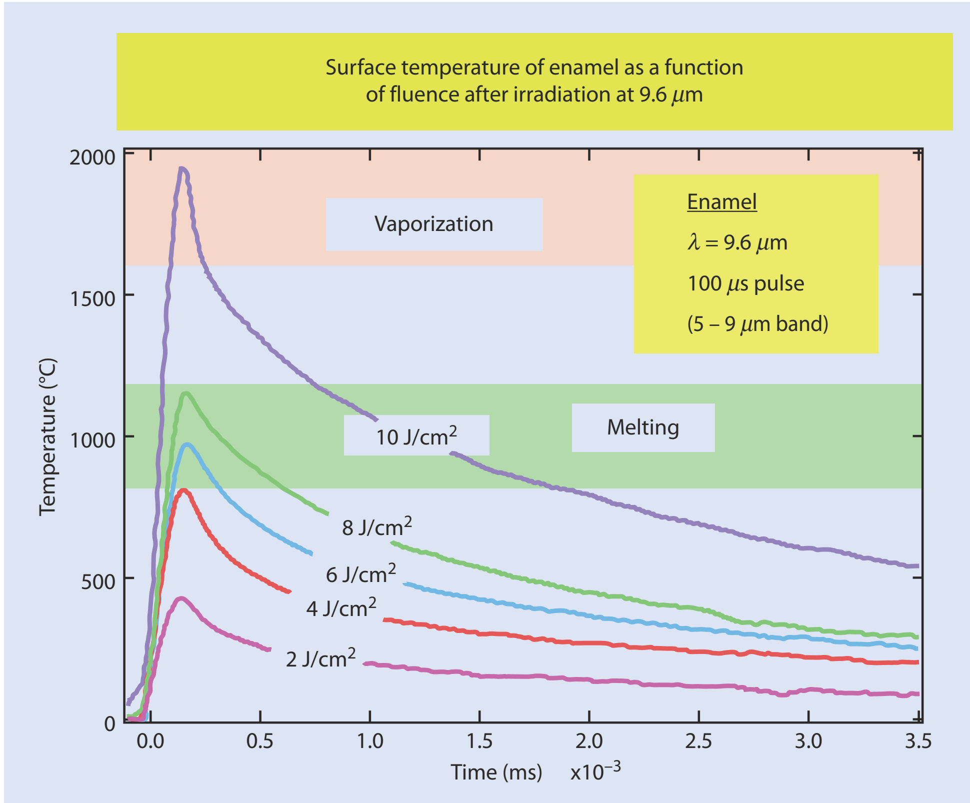

Fig. 17.3 Plot of temperature at the surface of dental enamel versus time following irradiation by a carbon dioxide laser at 9.6 µm, over a range of fluences, and with a pulse duration of 100 µs (Adapted from Ref. [17])

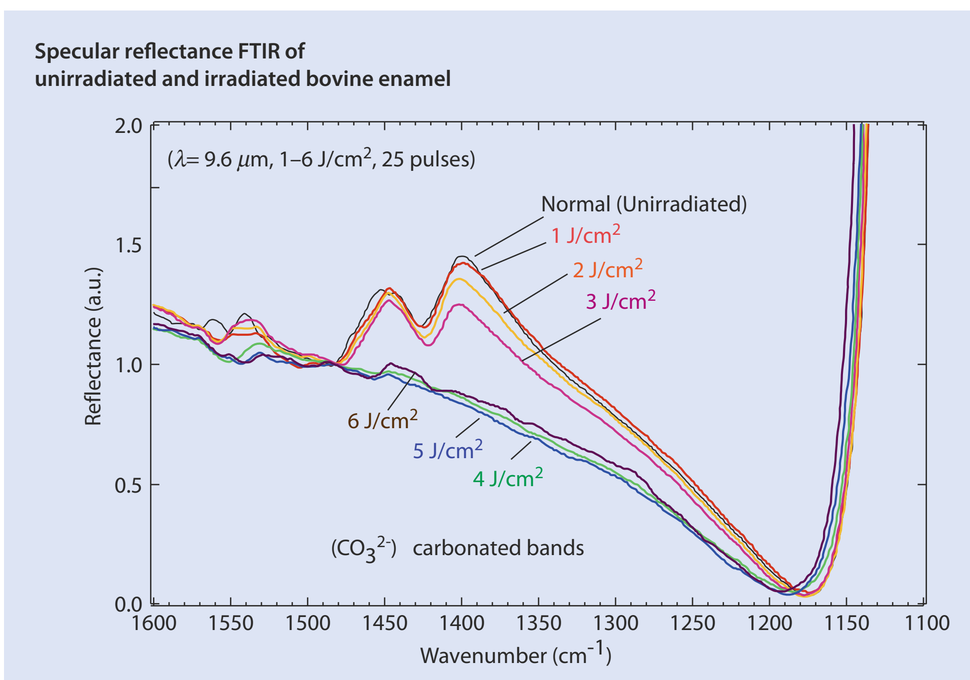

Fig. 17.4 Fourier Transform Infrared Reflectance (FTIR) spectrum showing the carbonate bands following surface treatment of dental enamel after applying a range of fluences with a 9.6 µm CO_2 laser (Adapted from Ref. [18]. Used with permission: SPIE, Bellingham, WA)

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additional fluoride the average mineral loss of the test samples was already significantly reduced by 53 % ± 11% (Fig. 17.5a). When additional fluoride applications were used without any laser treatment, the mineral loss of these controls was already reduced in average by more than 50 %. Adding laser irradiation, the average mineral loss was significantly reduced by 55 % ± 9% (Fig. 17.5b) [19] on top of the already gained resistance when using fluoride alone.

As mentioned above, it had been reported that enamel surface temperatures of 800 °C and above caused the mineral

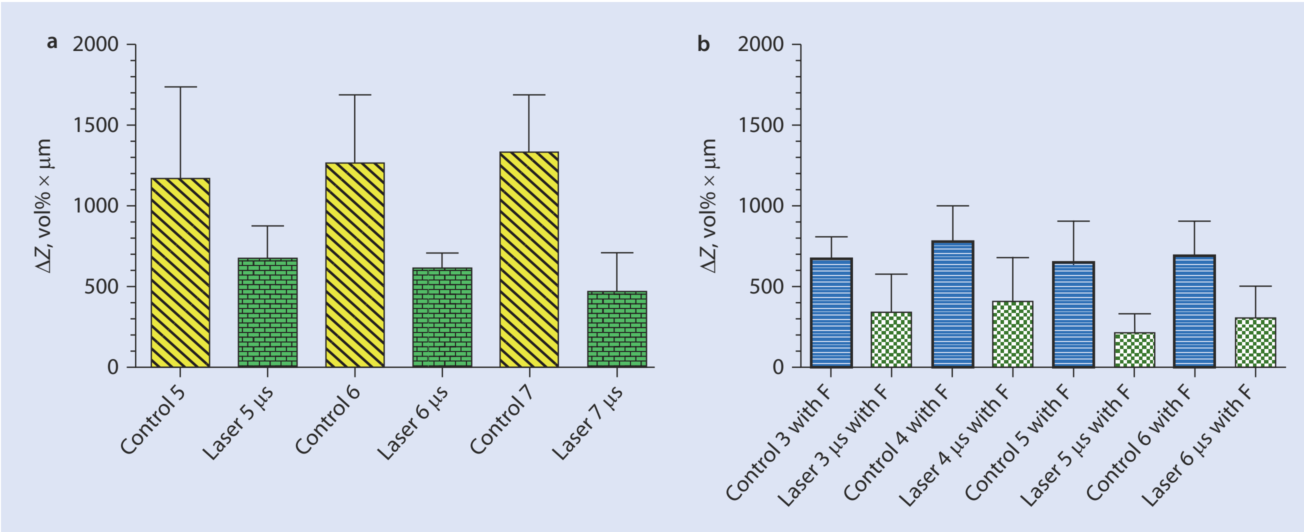

Fig. 17.5 **a** Mean relative mineral loss DZ for the laser-treated enamel and for the control groups, three different laser energies, after 9 days of pH cycling with no additional fluoride use resulting on average in 53% reduction in mineral loss for the laser-treated teeth (statistically significant reduced mineral loss with $P < 0.0001$; error bars represent standard deviations. **b** Mean relative mineral loss DZ for the laser-treated and for the control groups, four different laser energies, after 9 days of pH cycling with additional fluoride, showing on average 55% reduced mineral loss for the laser-treated teeth (statistically significant reduced mineral loss with $P < 0.0001$; error bars represent standard deviations) (Adapted from Ref. [19])

melting and the mineral transformation into less acid-soluble mineral after cooling [15, 20, 21]. Other work has established that temperatures of 400 °C and above are necessary to decompose the carbonate inclusions in the enamel and transform the carbonated hydroxyapatite to the much less acid-soluble hydroxyapatite [21, 22]. As seen below, the scanning electron microscope of the Rechmann et al. study in 2016 revealed that the lowest applied energies (pulse durations) did not produce very noticeable surface modifications, besides some minor areas with insignificant melting (Fig. 17.6). Nevertheless, the cross-sectional microhardness testing after simulating caries demineralization and

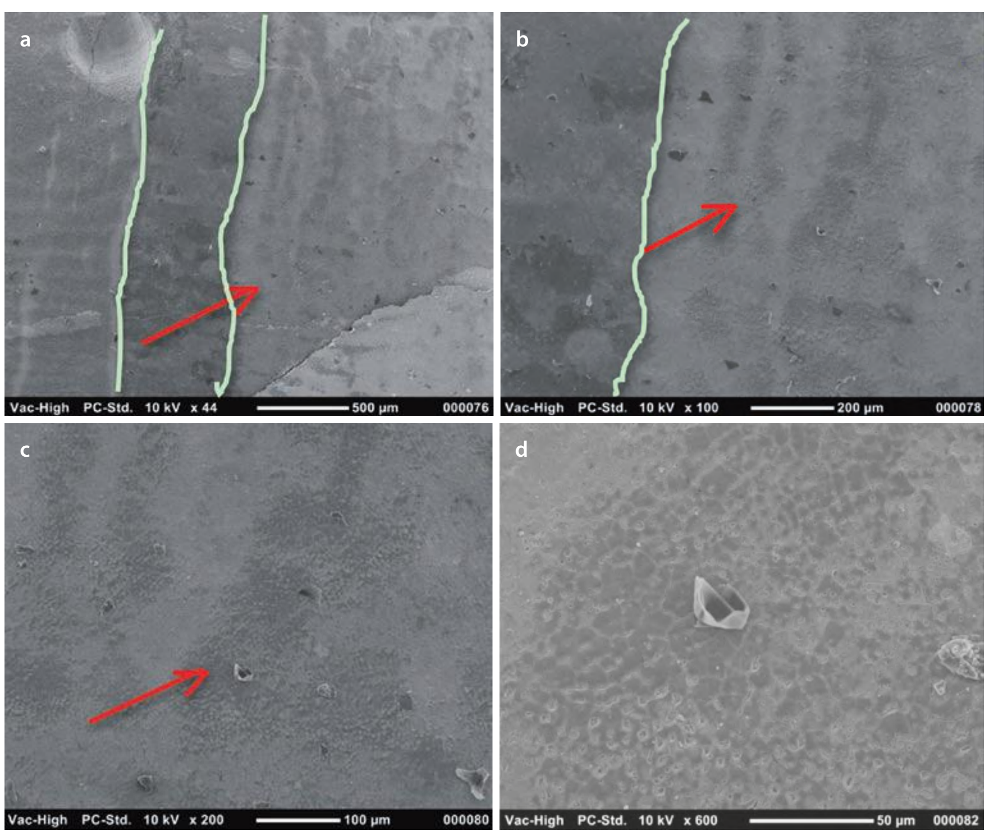

Fig. 17.6 SEM pictures of enamel after 3 µs pulse duration irradiation; only minor or no changes are visible with a few molten areas at the highest magnification (*lines* are drawn between irradiated and non-irradiated surfaces; *arrows* indicate area showed at the next higher magnification) (Adapted from Ref. [19])

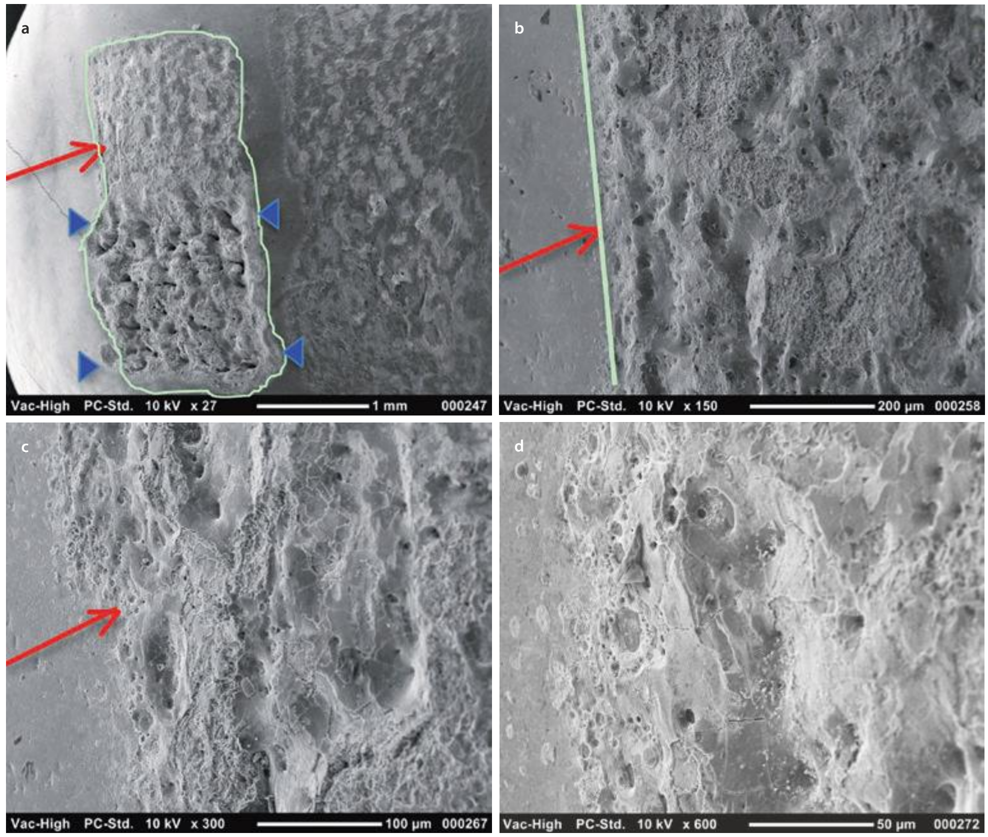

Fig. 17.7 SEM pictures of enamel after 6 and 7 µs pulse duration irradiation; rough surface morphology with slight ablation of the enamel occurs at 6 µs pulses; 7 µs pulses (in *1*, between *triangles*) result in noticeable ablation of the enamel (*lines* are drawn between irradiated and non-irradiated surfaces; *arrows* indicate area showed at the next higher magnification) (Adapted from Refs. [19, 22])

remineralization in the pH cycling model revealed significantly reduced mineral loss in the laser treatment group; thus, one could conclude that enamel melting is not necessary in driving out carbonate as reported above and achievement of enhanced caries resistance [19].

It had been established that ablation of enamel occurs at temperatures above 1200 °C [17]. In the laboratory study presented here [19], when 9.3 µm CO_2 laser short-pulsed laser energies were applied, causing ablation of enamel for cutting teeth (Fig. 17.7), caries resistance of the remaining enamel was also enhanced. A 65% reduction in mineral loss in comparison to the non-irradiated surfaces was shown (Fig. 17.5a, b). This effect is an advantage when cavities are drilled with a 9.3 µm CO_2 short-pulsed laser, and a restoration then is placed. The restoration margins will be better protected against recurrent caries. A failure of the restoration will be more unlikely.

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17.2 Pulpal Safety Study

Before proving that both short-pulsed CO_2 9.6 and 9.3 µm laser irradiation clinically render enamel more caries resistant, a pulpal safety study had to be performed. The intention of such a study was to show that the laser treatment would not harm the dental pulp. A clinical study using third molars was completed performing pulp histology after laser treatment and sham dental procedures, respectively. The conclusion was that the 9.6 µm CO_2 laser, pulsed with 5–8 µs pulse width, can be safely used to alter enamel surfaces to render them more resistant to caries without permanently damaging the dental pulp. Histological examination of all teeth disclosed no indication of an inflammatory response in the pulp tissue at any time point. All histological sections appeared normal with no changes seen in the normal pulpal morphology. Permanently or serious damaging of the dental pulp was not observed [23]. Lately a second pulpal safety study performed with a 9.3 µm, 15 µs pulsed CO_2 laser confirmed that this laser can ablate enamel safely without harming the pulp [24].

17.3 Inhibition of Caries in Vital Teeth by CO_2 Laser Treatment: First In Vivo Study Using the Orthodontic Bracket Model

To test the caries preventive, specific CO_2 laser irradiation for the first time in vivo, an orthodontic model was used [25]. Typically, orthodontic treatment is associated with rapidly enhanced demineralization of the enamel due to the increased plaque accumulation around the brackets [26]. This also includes a change to a more cariogenic bacterial milieu [27, 28]. After bracket bonding in orthodontic patients, demineralization takes place at the gingival and middle thirds of the facial surfaces [29]. Demineralization switches from typically the interproximal areas to the facial as well as from posterior to anterior areas of the mouth [30, 31]. This well-established caries pattern was used as a model system [25, 32] to determine whether the laser treatment prevents demineralization and/or even enhances remineralization in vital human teeth at those more caries prone regions.

Twenty-four orthodontic patients with need for extraction of bicuspids within the planed orthodontic treatment gave their consent and were enrolled into the study. Brackets were bonded with a conventional light-cured composite resin (Transbond XT, 3M ESPE, St. Paul, MN) [25] onto the buccal surface of the bicuspid scheduled for extraction. An enamel area directly next to the bracket at the cervical area of the tooth (Fig. 17.8) was treated according to the laser treatment protocol. The two pictures in Fig. 17.9 demonstrate the clinical aspect of the laser-treated surfaces; due to the biofilm removal, the irradiated enamel is very shiny. Nevertheless, after 1 week of homecare typically the shiny aspect faded off.

The laser employed was a CO_2 laser, Pulse Systems, Inc. (PSI) (Model #LPS-500, Los Alamos, NM), which had been designed for dermatology indications (9.6 μm wavelength, 20 μs pulse duration, 20 Hz pulse repetition rate, 1100 μm beam diameter). To achieve caries preventive changes, each irradiated spot had to receive 20 laser pulses; the laser fluence per pulse averaged is 4.1 ± 0.3 J/cm^2 (for more details, see [33]). An area cervical to the bracket (Fig. 17.8) on one side of the bracket was irradiated, while the opposite site on the same tooth served as the control side later on.

The patients were instructed to brush for 1 timed minute twice daily with a provided over-the-counter (OTC) toothpaste (1100 ppm fluoride as NaF).

The study teeth were extracted 4 or 12 weeks after irradiation, respectively. In the laboratory they were cut into halves through the bracket so that the laser-treated area was on one half and the non-laser control area on the other half. Afterward they were embedded in acrylic and prepared for the cross-sectional microhardness testing. Figure 17.10 shows a microscopic picture of a typical cross section with enamel, dentin, and the orthodontic bracket with the composite and the micro-indents. During the cross-sectional microhardness testing procedure, a pyramid-shaped diamond tip is pushed into the enamel with a defined weight. The softer the enamel (due to the occurred demineralization), the wider the indent will be. The width of the indent is measured and the actual mineral loss can be calculated.

In Fig. 17.11 the mineral loss of enamel (volume percentage) is plotted versus the depth into the tooth presenting a mineral loss profile for the 4-week study arm teeth. The green line with the triangle symbols represents the average mean volume % mineral at each depth for the laser-treated teeth and

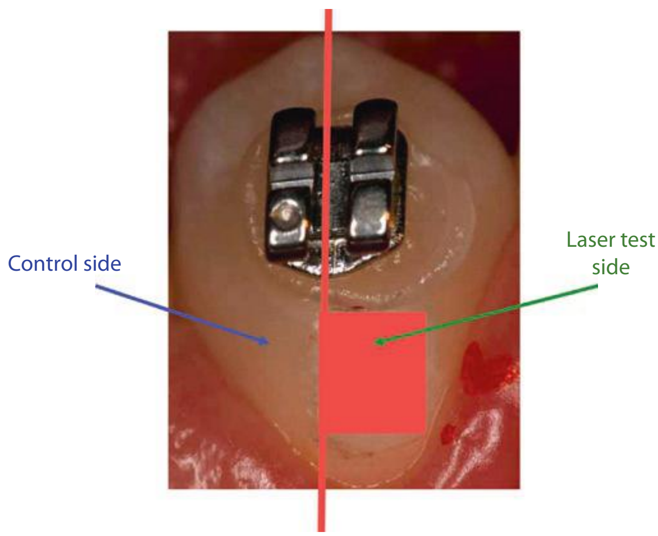


Fig. 17.8 Orthodontic bracket placed on a study bicuspid using an abundant amount of composite to create a microbial plaque trap; the irradiated area cervical to the bracket is marked *red* in this picture; the other side served as control

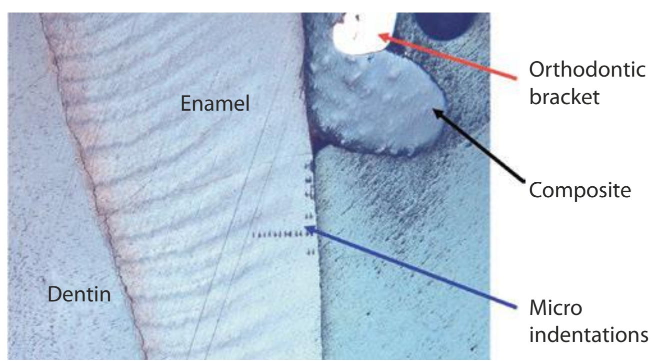


Fig. 17.10 Microscopical picture demonstrating the cross-sectional microhardness testing; the bicuspid histological cross section shows the dentin, enamel, and the composite, used to bond the orthodontic bracket onto the enamel; the micro-indentations were placed right below the enamel surface following an elaborated distribution pattern; the indents are located right below the area where the orthodontic bracket was bonded to the enamel; this area represents the microbial plaque challenge and consequently demineralization occurs here (Adapted from Ref. [33])

Fig. 17.9 Orthodontic bracket placed on the lower right (*left picture*) and on the upper left (*right picture*) study bicuspid showing an irradiated area beyond the bracket. Obviously the biofilm is removed by the laser irradiation, and the area appears white and shiny, but after a period of a week of homecare, the colors matched again

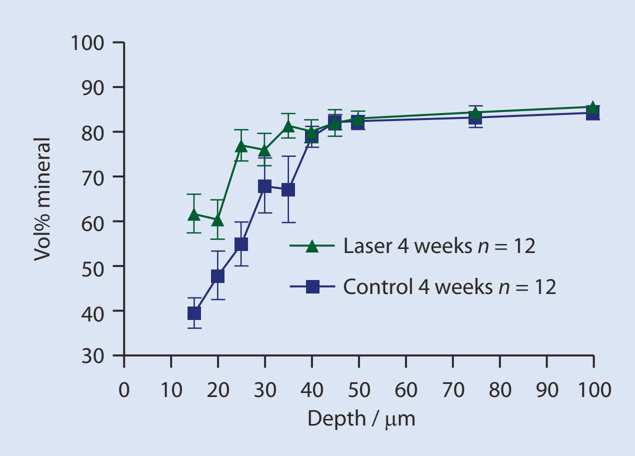


Fig. 17.11 A depth profile of volume % mineral loss for the laser-irradiated areas (*green line* with *triangle* symbols) and for the controls (*blue line* with *square* symbols) for the bicuspids at 4 weeks' time point (mean ± standard error) (Adapted from Ref. [33])

the blue line with the square symbols for the non-laser-treated controls. At 15 µm depth the control teeth (square symbols) show a very high loss of mineral with a remaining only 40% average volume % mineral, increasing to an average of 82% at a depth of 45 µm. In contrast, the CO_2 9.6 µm laser-irradiated enamel (triangle symbols) shows 62% volume % mineral at the 15 µm depth. Further into the tooth, the volume % mineral increases at 45 µm depth to 85%, which represents the typical volume % mineral content of sound enamel.

To compare the «mineral loss» between groups, the mean relative mineral loss, ΔZ (vol% × µm) can be calculated. After the 4-week observation, the mean relative mineral loss ΔZ for the laser-treated enamel was 402 ± 85 (mean ± standard error [SE]), while the controls showed an almost doubled mineral loss ΔZ of 737 ± 131. The laser treatment resulted in a significant 46% reduction of demineralization around the orthodontic brackets in comparison to the controls (Fig. 17.12) (significance level $P = 0.04$).

The reduction in mineral loss was even more impressive after 12 weeks (Fig. 17.12). The control areas showed a fairly high relative mineral loss ΔZ of 1067 ± 254. In contrast, for the CO_2 laser-treated area, the mean relative mineral loss was much lower (ΔZ 135 ± 98) and even lower than for the 4-week mineral loss. The difference in mineral loss between laser and control for the 12-week observation was significant (significance level $P = 0.002$). For the 12-week group, the laser treatment produced a noticeable 87% inhibition of enamel demineralization.

Previous studies had demonstrated that the orthodontic bracket model employed in this study here presents a high caries demineralization challenge to the enamel. In addition, this demineralization challenge cannot simply be overcome by using an OTC 1100 ppm fluoride toothpaste [25]. Gorton et al. in 2003 reported using the orthodontic bracket model that the mean mineral loss value ΔZ in their control group was 805 ± 78 (Mean ± SE) vol% × µm. This establishes a considerable, measurable, demineralization in only 1 month even when fluoride toothpaste is used. In this CO_2 laser orthodontic bracket model study, the participants in the control regions around the brackets had a high mineral loss of ΔZ of 737 ± 131 vol% × µm at the 4-week and even higher one of 1067 ± 254 vol% × µm at the 12-week arm, similar to the mineral loss Gorton et al. stated [25].

However, the application of the CO_2 9.6 µm short-pulsed laser irradiation significantly reduced the mineral loss in the 4-week and in the 12-week arm of the study by 46% and 87%, respectively. While the mineral loss for the 12-week group controls was higher than for the 4-week group controls, the additional reduced mineral loss for the treatment group after 12 weeks in comparison to the 4 weeks might be explained by enhanced remineralization over a this longer observation time period.

This study showed that caries inhibition demonstrated in numerous models and experiments in the laboratory [34–37]

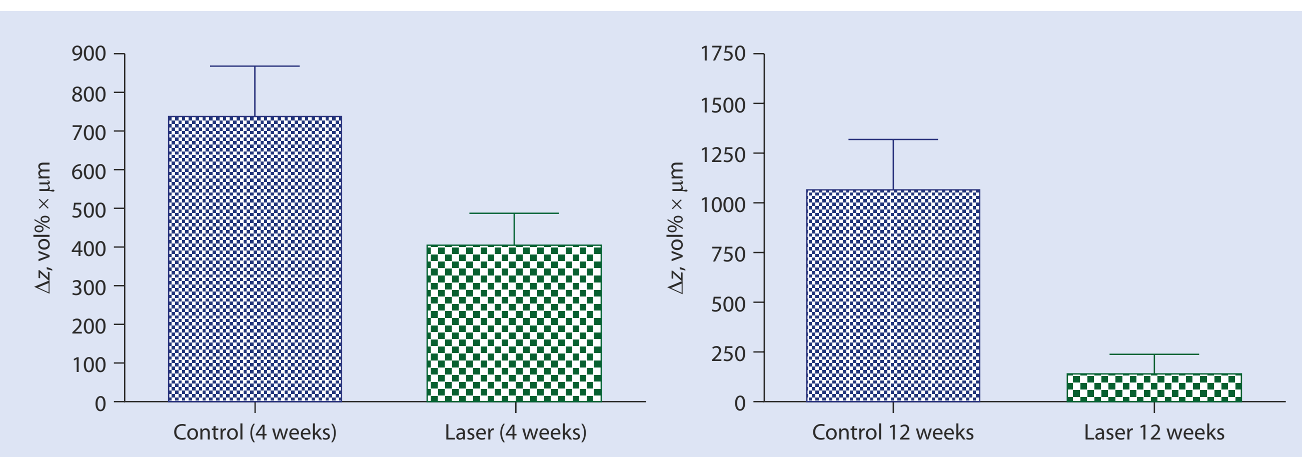


Fig. 17.12 Relative mineral loss ΔZ (vol% × µm) for the laser-treated enamel and for the non-laser-treated controls (*n* = 12 for both groups, mean ± SE) 4 weeks (*left* and 12 weeks *right* graphs) after treatment. The differences in relative mineral loss between laser-treated and control groups are statistically significant with a significance level of $P = 0.04$ for the 4-week and $P = 0.002$ for the 12-week observations (Adapted from Ref. [33])

can also be achieved in humans in vital teeth using short-pulsed 9.6 μm CO_2 laser irradiation [33]. Moreover this study showed that the orthodontic bracket model could be considered to explore any caries inhibition agents or tools in living teeth in humans.

17.4 In Vivo Occlusal Caries Prevention by Pulsed CO_2 Laser and Fluoride Varnish Treatment

While in the orthodontic bracket model study, the test teeth were extracted to perform the cross-sectional microhardness testing, a subsequent, in vivo study was designed with a goal to determine the caries prevention effects of a short-pulsed CO_2 laser without the need to extract the study teeth for analytical assessments [38].

In this study for the first time, in vivo occlusal pits and fissures of second molars in the oral cavity were irradiated; and the change in demineralization and remineralization was assessed by three visual methods: (1) the International Caries Detection and Assessment System (ICDAS), (2) SOPROLIFE in daylight and in blue fluorescence mode, and (3) the DIAGNOdent fluorescence tool. The study's intention was to show caries inhibition in fissures of molars [38]. The significant challenge was to reach normal as well as deep pits and fissures with the laser irradiation. In order to facilitate adequate laser interaction with the walls of deep fissures, we designed and used a custom contra-angle laser handpiece made for this study.

Twenty subjects were recruited and consented for the study. Their age ranged between 10 and 15 years; they were at high caries risk according to CAMBRA rules [39–41] and presented at least two fully erupted second molars in the same arch (contralateral) with untreated, non-carious (non-cavitated) occlusal surfaces. One molar was randomly selected for the laser irradiation; the tooth on the opposite site in the same jaw functioned as control.

At baseline, right after laser treatment and at the 6- and 12-month recall visit, the occlusal surfaces of the study molars were visually judged for decalcification applying the ICDAS II criteria (International Caries Detection and Assessment System) and the SOPROLIFE light-induced fluorescence evaluator system (SOPRO, ACTEON Group, La Ciotat, France).

17.4.1 Caries Assessment Methods Applied in In Vivo Occlusal Caries Prevention by Pulsed CO_2 Laser Study

The *International Caries Detection and Assessment System* provides a standardized method of lesion detection and assessment, leading to a caries diagnosis [42, 43]. ICDAS scores range from code 0 to 6, with code 0 as no mineral loss, code 1 and 2 as precavitated lesions, and code 3 and above showing the first physical enamel break down to more than 50% of the tooth surface is cavitated. ICDAS criteria are built on the visual enamel properties of translucency and microporosity. After increasing number of demineralization attacks, the microporosity of the subsurface of enamel intensifies. Consequently a change in translucency and light refraction of the enamel surface represents the first sign of a carious alteration. If the demineralization process continues, the enamel microporosity increases, which results in an even further decrease in the refractive index of enamel [44].

Ekstrand et al. [45–47] validated ICDAS by demonstrating an association between the lesions' histological depth and the severity of caries lesions (as described by ICDAS codes). Other authors confirmed this close relationship between ICDAS scoring and the histological depth of the caries lesion, especially in precavitated (ICDAS codes 1 and 2) but also in slightly cavitated stages (ICDAS code 3 and above [48, 49]).

Fluorescence is a property of specific materials to absorb energy at shorter wavelengths and emit light at longer wavelengths. Several caries detection methods use fluorescence. The *SOPROLIFE system* basically combines the benefits of a visual inspection method (high specificity) by employing a high-magnification oral camera with a laser fluorescence instrument (high reproducibility and discrimination [50]). The system uses four white LEDs in the daylight mode and four blue LEDs in the blue fluorescence mode. Bacteria and their by-products trigger the fluorescence signal and expression. The blue light transmits through healthy enamel and evokes a green fluorescence of the dentin core. The green fluorescence light coming back from the dentin core then leads to a red fluorescence from bacteria and bacterial by-products like porphyrins [50–52]. ◘ Figure 17.13 shows a graphic representation of the SOPROLIFE system, and ◘ Fig. 17.14 depicts both the visible light and SOPROLIFE images of an ICDAS code 3 occlusal lesion.

The laser was the same instrument that was used in the inhibition of caries in vital teeth by CO_2 laser treatment orthodontic bracket model study (CO_2 laser, Pulse Systems, Inc. (PSI) Los Alamos, NM), with a 9.6 μm wavelength, 20 μs

◘ **Fig. 17.13** The SOPROLIFE light-induced fluorescence evaluator system uses in the blue fluorescence mode four blue LEDs emitting light at 450 nm. The light is transmitted through the enamel and then induces *green* fluorescence from the dentin body. If *green light* on the way back hits porphyrins in caries, the emitted fluorescence is *red*

Fig. 17.14 The left picture of the occlusal surface of a molar is taken with SOPROLIFE in daylight mode (white LEDs illumination) and the right taken in blue fluorescence mode (blue LEDs illumination). The tooth shows an ICDAS 3 code, already exhibiting physical enamel breakdown in the central grove. The enamel breakdown became clearly visible

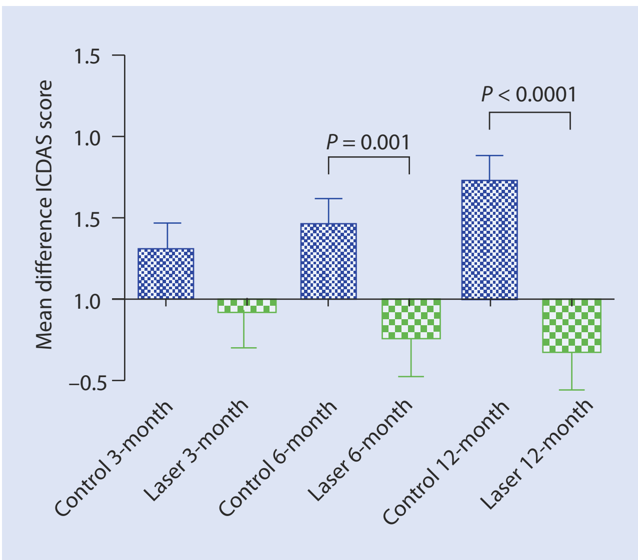


Fig. 17.15 Average change of ICDAS scores between baseline and 3-month, baseline and 6-month, and baseline and 12-month recall (mean ± SE) for laser-treated and control teeth; statistically significant differences between laser and control at 6- and 12-month recalls ($P = 0.001$ and $P < 0.0001$, respectively)

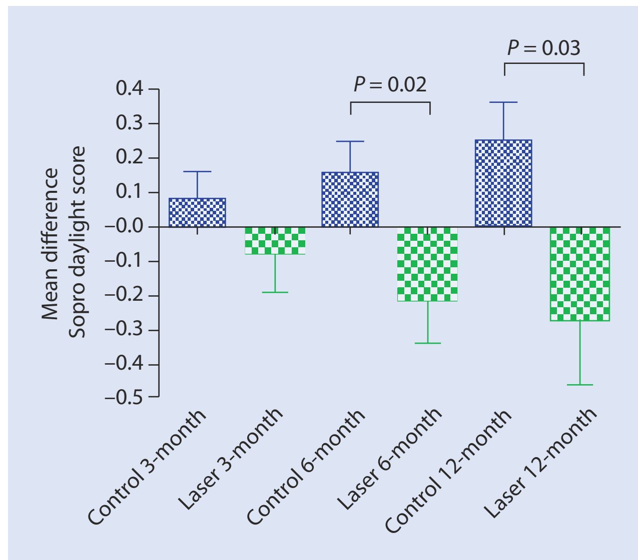


Fig. 17.16 Average changes of SOPROLIFE daylight scores for laser-treated and control teeth between baseline and the 3-, 6-, and 12-month recall (mean ± SE) showing statistically significant differences at the 6- and 12-month interval (significance level $P = 0.02$ and $P = 0.03$, respectively) (Graph adapted from Ref. [38])

pulse duration, 20 Hz pulse repetition rate, and 800 μm beam diameter delivered through a custom-made contra-angle handpiece. Each irradiated spot received 20 laser pulses; the laser fluence per pulse averaged 4.5 ± 0.5 J/cm^2.

All subjects received fluoride varnish applications to all teeth (Omni varnish fluoride varnish, Omni Preventive Care, West Palm Beach, FL) at baseline and 6-month recall (for more details, see [38]).

The ICDAS scores ranged at baseline from code 0 to code 2. Figure 17.15 shows the average change of ICDAS scores between baseline and 3-month, baseline and 6-month, and baseline and 12-month recall (mean ± SE) for laser-treated and control teeth. While for the controls the average ICDAS increased over time, a decrease in ICDAS could be observed for the laser-treated fissures. The differences in average change in ICDAS scores over time were statistically significant between laser and control at 6-month and again between laser and control at the 12-month recalls (significance level $P = 0.001$ and $P < 0.0001$, respectively).

In addition to the ICDAS scoring, the study teeth were also evaluated with the SOPROLIFE system. They were scored with a recently presented scoring system, which was developed for the SOPROLIFE light-induced fluorescence evaluator for daylight and for the blue fluorescence mode [51, 52]. For the control as well as the laser-treated teeth, the SOPROLIFE scores ranged between 0 and 3 at baseline with no statistically significant differences between study and control group.

Calculating the changes in SOPROLIFE daylight scores between baseline and each recall time point (Fig. 17.16) revealed an increasing daylight score for the controls and a decreasing score for the laser-treated fissures similar to the ICDAS scoring. The differences between the average changes were again like the ICDAS scores statistically significant between baseline and 6-month and baseline and 12-month recall.

Figures 17.17 and 17.18 show the occlusal surface of a control and a laser-treated tooth, respectively, with the pictures taken with the SOPROLIFE camera in daylight mode

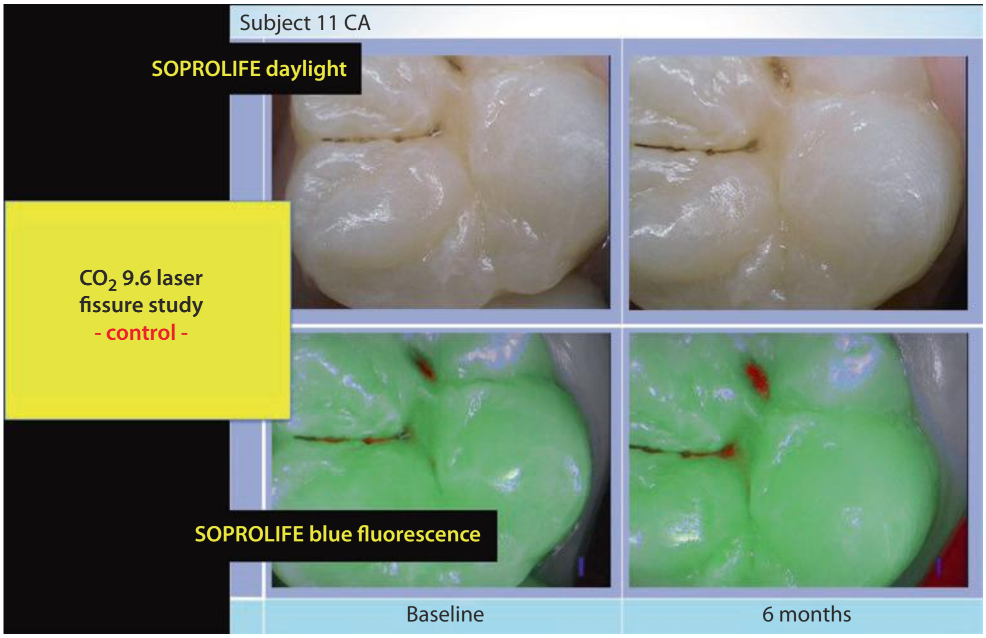


Fig. 17.17 Control tooth of a subject at baseline and at the 6-month recall, pictures taken in daylight and fluorescence mode, respectively. The area of demineralization appears wider in daylight mode and in fluorescence mode after 6 months (*upper row* daylight, *lower row* blue fluorescence mode; baseline left, 6-month recall right) (Photos from Ref. [38])

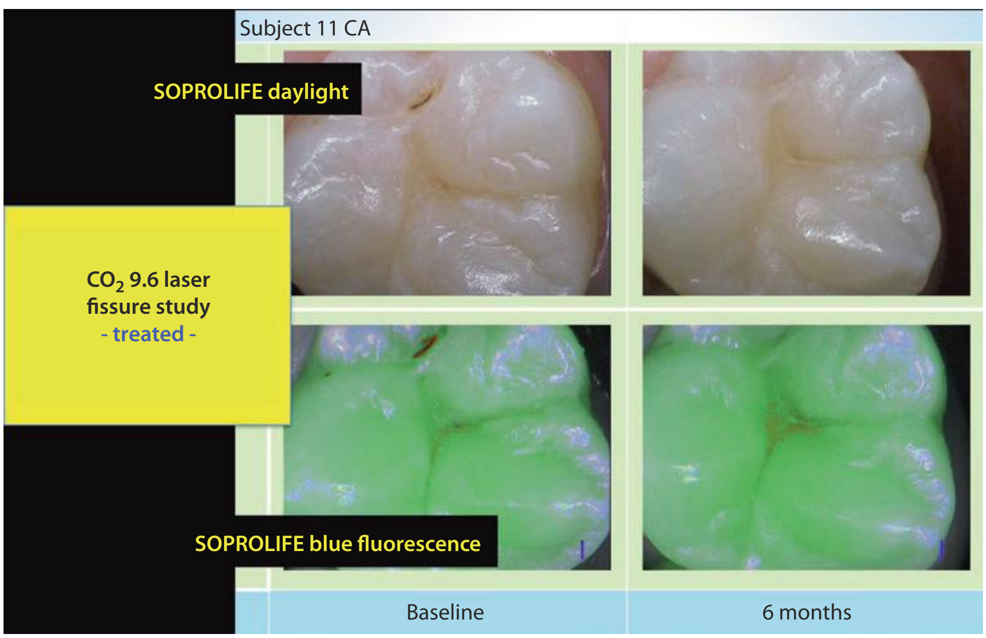


Fig. 17.18 Laser-irradiated tooth of a subject at baseline and at the 6-month recall, pictures taken in daylight and fluorescence mode, respectively. The area of demineralization in the distal fossa of the laser-treated tooth in daylight mode and fluorescence mode, respectively, is not visible anymore (*upper row* daylight, *lower row* blue fluorescence mode; baseline left, 6-month recall right) (Photos from Ref. [38])

and in the blue fluorescence mode. The pictures demonstrate the obvious differences over time between the baseline and the 6-month recall. Both molars show noticeable changes in the fissure system, being very distinct in the distal groove. While the area of demineralization in the control tooth appears to become more extended in both daylight mode and fluorescence mode, after 6 months the demineralization zone and the red fluorescence width and intensity, respectively, disappeared on the laser-irradiated tooth.

Similar to the SOPROLIFE daylight scores, the SOPROLIFE blue fluorescence average scores for baseline and the 3-, 6-, and 12-month recall demonstrated increased scores for the controls, and decreased scores for the laser-treated fissure were observed (except for the 12-month recall for the laser group, which did not change). Figure 17.19 demonstrates the average changes for SOPROLIFE blue fluorescence scores between baseline and 3-month, baseline and 6-month, and baseline and 12-month recall for the laser-treated and control teeth, respectively. The differences are statistically significant between the laser and the control group at 6- and 12-month recalls.

In summary, this single-blind, controlled, randomized clinical pilot trial showed that using a microsecond-pulsed 9.6 μm CO_2 laser with additional fluoride varnish

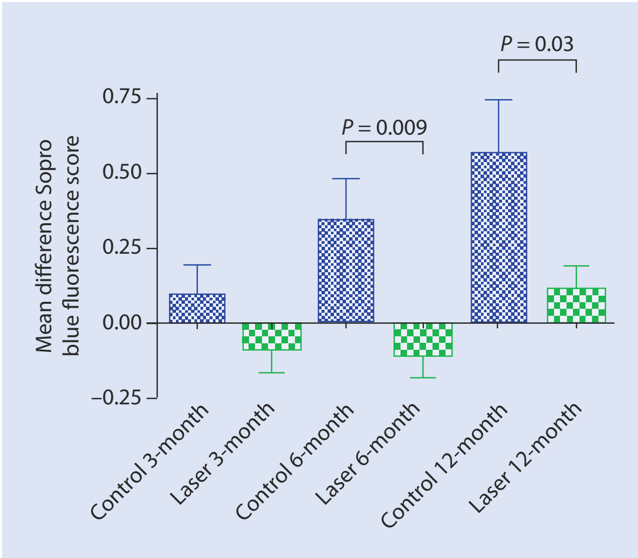


Fig. 17.19 Average change of SOPROLIFE blue fluorescence scores between baseline and 3-month, baseline and 6-month, and baseline and 12-month recall (mean ± SE) for laser-treated and control teeth; statistically significant differences between laser and control at 6- and 12-month recalls ($P = 0.009$ and $P = 0.03$, respectively) (Adapted from Ref. [38])

applications significantly inhibits the formation of carious lesions in fissures of molars in vivo in comparison to a non-irradiated control tooth in the same arch over a 1-year observation interval. With regard to the ICDAS score change over time, the control teeth scores constantly increased describing more severe mineral loss, while the control teeth showed constantly decreasing ICDAS scores, demonstrating a certain mineral gain.

From both the occlusal caries prevention study and the orthodontic bracket study, it can be reasonably concluded that the CO_2 short-pulsed laser irradiation drives out the carbonated phase from the enamel crystal and decreases the demineralization of the modified hydroxyapatite in an acid environment. Specifically when fluoride is present, the transformed hydroxyapatite appears to be prone to higher remineralization. The phenomenon of increased remineralization proven by ICDAS and SOPROLIFE daylight and fluorescence assessments was observed in this study over a period of 12 months.

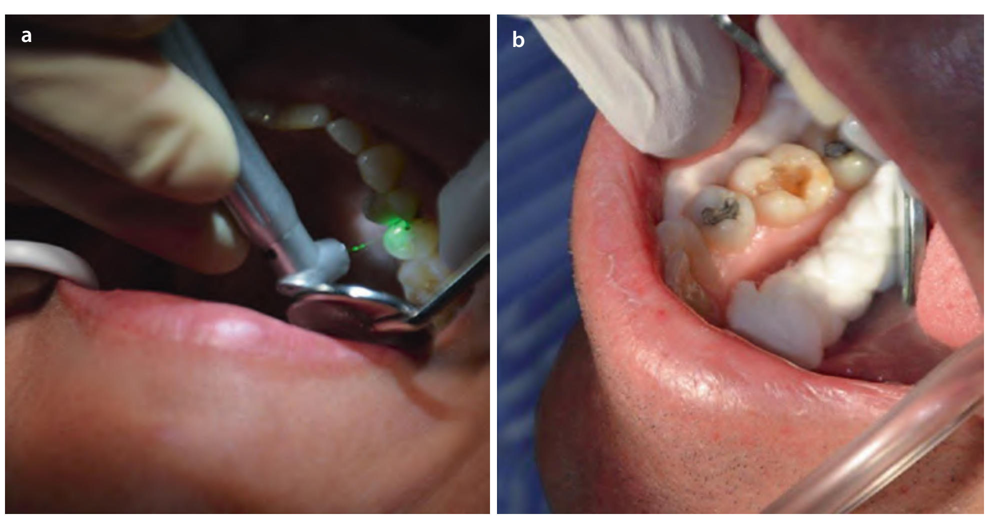
17.5 Cavity Preparation and Soft Tissue Cutting with the CO_2 9.3 µm Short-Pulsed Laser

The previously mentioned 9.3 µm wavelength short-pulsed carbon dioxide laser (Solea, Convergent Dental, Inc., Natick, MA) has been available on the US market for soft and hard tissue procedures. The instrument offers a wide range of beam diameters; the basic beam diameter is actually 0.25 mm, but by using computer-controlled galvo mirrors, the beam can cover up to a diameter of 1.25 mm by using a spiral movement of the focus point. The focus distance is relatively long and is set between 10 and 19 mm. The emitted laser energy is controlled by the pulse width, varying between 10 and 130 µs, controlled by the foot pedal.

In addition to preventive procedures, this laser can perform carious lesion removal, tooth preparation, and osseous surgery. Figure 17.20 shows the first patient receiving a Solea laser cavity preparation in 2013. The green pilot laser helps in guiding the laser beam; the computerized laser control facilitates easy cavity preparation. Clinical case examples will be found in Chap. 8.

Figure 17.21 shows that, for the first time, true minimal invasive treatment becomes a reality. This fissure on a molar is prepared with a 0.25 mm laser beam. The preparation borders are completely smooth. The scanning electron microscopic picture (Fig. 17.22) shows a similar smooth cut with a diameter of roughly 0.75 mm, done by the author, in 1997 with an experimental carbon dioxide laser used to produce a carbon-13 (^{13}C) isotope. Thus 20 years ago, the search for a second-generation hard tissue cutting laser had begun.

Fig. 17.20 First Solea cavity preparations: **a** upper left jaw with the *green* pilot laser visible; **b** lower right jaw after the clean laser preparation was finished (Clinical photos courtesy of Dr. Mark Mizner)



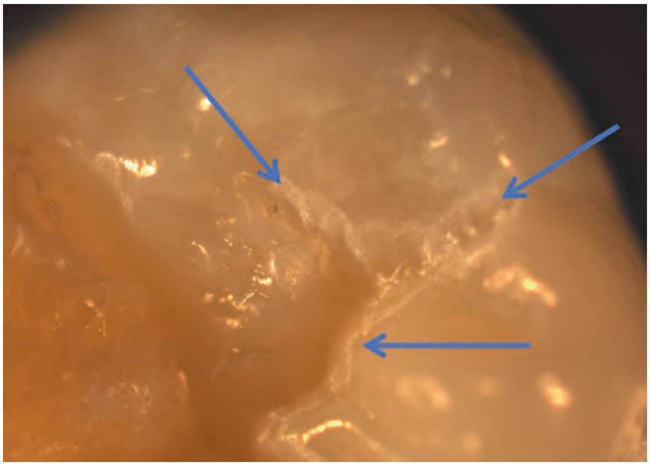


Fig. 17.21 The Solea was used for a minimal invasive preparation of an occlusal fissure. Note the very smooth preparation in enamel

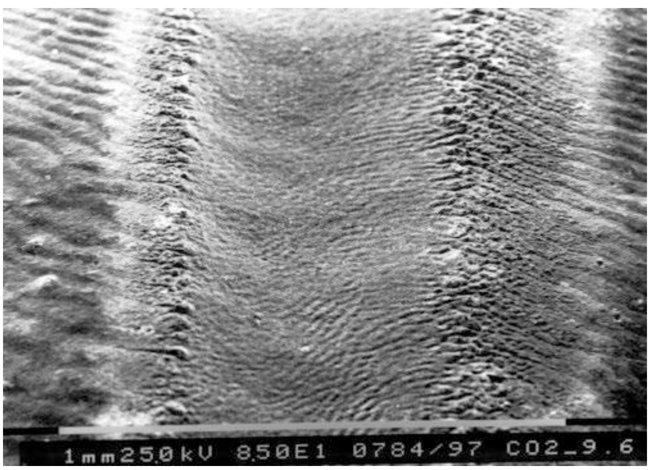


Fig. 17.22 Scanning electron microscope picture showing a similar smooth surface cut in enamel as in Fig. 17.21. Here an experimental 9.6 µm short-pulsed CO_2 laser (described above) was used

Figure 17.23 depicts a distal occlusal cavity preparation with the Solea laser. In addition, the overgrown gingival tissue was quickly removed with the laser without any bleeding (Clinical case courtesy of Dr. Joshua Weintraub).

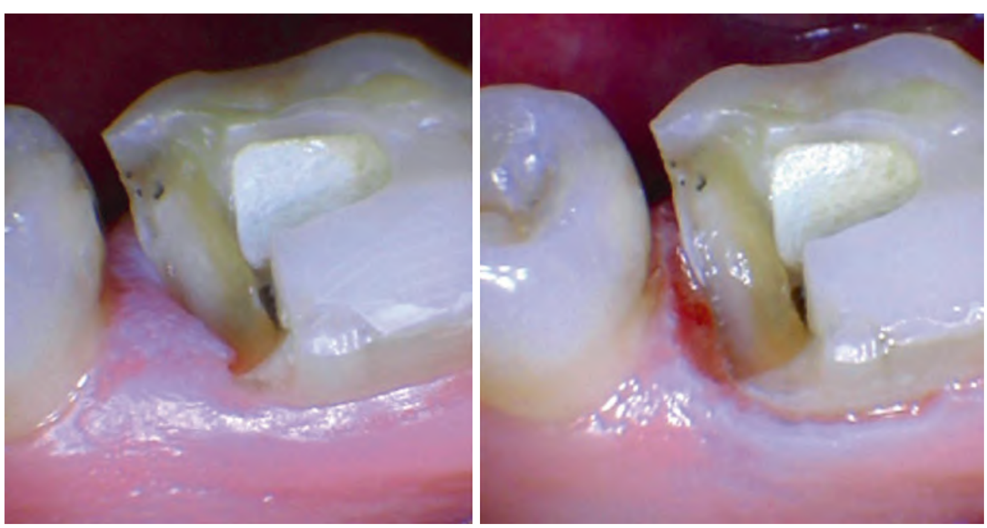
The CO_2 9.3 µm short-pulsed laser offers when it is already too late for caries prevention a wide potential for cutting hard tissues as well as soft tissue.

17.6 Shear-Bond Strength Testing to Human Enamel

A series of bond strength testing was conducted to answer the question whether enamel, already rendered caries resistant with the CO_2 9.3 µm short-pulsed laser, would still allow sufficient bonding of composites. The additional question how bond strength to dentin might be influenced by the laser irradiation was also of interest. Consequently, enamel and dentin samples were irradiated with a wide range of laser parameters. Different total-etch and self-etch bonding systems of the fourth- and fifth-generation bonding materials were tested using Clearfil AP-X, a micro-hybrid composite (Kuraray America, New York, NY) as testing composite. The adhesive bonding strength was determined by performing a single-plane shear-bond test with the UltraTester testing device (Ultradent Products, Inc., South Jordan, UT).

Figure 17.24 shows as an example the shear-bond strength values using a self-etch bonding system Clearfil SE bond (Kuraray America, New York, NY) after the enamel was irradiated with laser parameters known to render enamel more caries resistant. Irradiation with the two different 3 µs caries preventive patterns (3 µs pulse width engaging the straight 0.25 mm beam and the 1 mm spiral patterns) resulted in higher bond strength values compared to the non-laser-treated controls. The 16.9% increase in bond strength observed for the 3 µs pulse duration with the 1 mm spiral irradiation pattern was even statistically significant (* $P \leq 0.05$).

Fig. 17.23 Solea cavity preparation – *left* picture after laser preparation with overgrown gingiva; *right* picture after gingivectomy was performed without anesthesia; no bleeding occurs due to the high hemostatic effect when cutting soft tissue with a CO_2 laser (Clinical photos courtesy of Dr. Joshua Weintraub)



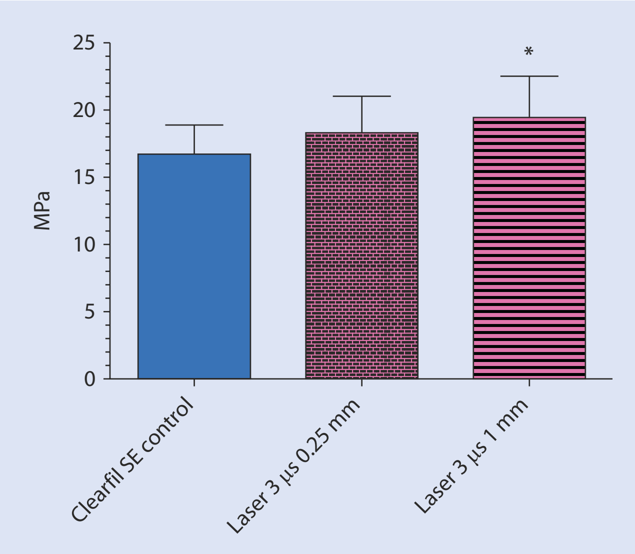


Fig. 17.24 Human enamel, uncut – Clearfil SE bond self-etch shear-bond strength values (mean ± SD), caries preventive laser irradiation increased the bond strength to enamel; the 1 mm spiral pattern showed even statistically significant differences to the control marked with *, significance level $P \leq 0.05$

The results for all laser settings tested for shear-bond strength in enamel and dentin as well as for the different self- and total-etch bonding systems were promising and will soon be reported.

17.7 Future Dreams

Research continues to both improve existing instruments and to discover new technologies, wavelengths, and clinical applications. The possibilities are certainly numerous within any area of study.

As mentioned in Chap. 3, production of very high-power densities coupled with extremely short-pulsed durations can result in photoablation, plasma-induced ablation, and molecular photodisruption. Indeed, over 30 years ago, investigators were experimenting with pulse durations of 30 picoseconds (10^{-12} s) for removing initial carious lesions in tooth enamel [53]. A recently published study described using a 400 femtosecond (10^{-15} s) pulse duration and its effects on ablation efficiency of dentin and enamel [54]. It would seem that a trend is emerging toward ultrashort-pulsed irradiance, which could provide a new horizon in plasma physics and target molecular cleavage. Chapter 7 discusses using completely opposite parameters: very low power density and very long and/or continuous pulse emissions to achieve photochemical cellular responses. All of these tissue interactions will be novel concepts compared with our current photonic energy effects on dental tissue.

The use of a laser in hard and soft tissue for diagnostics, described in Chap. 6, will certainly be enhanced by developments of scanning and reflective photonic energy. Many chapters describe current delivery systems for the laser beam, and their further refinement will allow access to the complex anatomy of dental structures. The ability to select several wavelengths from a tunable instrument could aid in the quest for having the ideal wavelength available for any procedure. As a natural result of research, well-designed clinical trials are essential. Ultimately, the goal of all the studies is to provide credible evidence for improved patient care.

Conclusion

9.3 and 9.6 µm CO_2 µs short-pulsed lasers are the most highly absorbed laser in dental hard tissues. They can safely and efficiently be used to render enamel caries resistant by transforming carbonated apatite into the much less soluble hydroxyapatite. Adding fluoride after the laser treatment additionally reduces the acid solubility of enamel and creates the desired least acid-soluble fluorapatite. These 9.3 and 9.6 µm CO_2 µs-short-pulsed lasers are very efficient in cutting dental hard and soft tissue. Results of shear-bond strength testing with multiple bonding agents to such laser cuts are promising.

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Lasers in General Dental Practice: Is There a Place for Laser Science in Everyday Dental Practice – Evidence-Based Laser Use, Laser Education (Medico-Legal Aspects of Laser Use)

Steven P.A. Parker

D.J. Coluzzi, S. Parker (eds.), *Lasers in Dentistry—Current Concepts*, Textbooks in Contemporary Dentistry,
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Core Message

«Science is the pursuit and application of knowledge and understanding (*of the natural and social world*) following a systematic methodology based on evidence» – *source:* ► www.sciencecouncil.org. Within such a generalized statement, there is much to commend on the acquisition of knowledge and understanding when using a dental laser of any description and preferably *before* using a dental laser. The author is acknowledged with the statement «*to know is to use; to understand is to empower*», in connection with laser use. The key to understanding and the correct application of laser photonic energy must be awareness of the basics of light physics, laser-tissue interaction and dosimetry of the laser being chosen for a given procedure. Evidence-based research and peer-reviewed clinical investigations provide the bedrock of a growing interdependent structure to enable the dental professional to use laser technology expressly to the benefit of the patient and within a safe environment, free of risk.

18.1 Introduction

> Over the years, the clarity of the positive results of laser use in dentistry has been clouded by gizmo idolatry, occasional sales hype and clinical anecdote. Whatever the reasons, we must continue to educate ourselves, our colleagues and our patients about the science, the risks, the benefits … as well as the limitations of phototherapy. Taken from: Raymond J. Lanzafame, Editor-In-Chief, Photomedicine and Laser Surgery Volume 26, Number 4, 2008

There are two protagonists in the debate as to who benefits from laser use in dentistry. Primarily, it would seem that the patient, anxious to receive cavity preparation without the noise, vibration and pain of the «drill», should demand of their dental clinician that they should embrace this technology and therapy, but a deeper conviction is that it should always be the clinician who not only should decide what is an appropriate therapy but should also assume responsibility for employing techniques that are evidence-based and deliver maximal benefit with minimal risk.

To those of us old enough to have witnessed at first-hand the progress of dental care during the past 30 years, two areas of primary dental care appear to have evolved outside the undergraduate teaching structure – dental implants and laser dentistry. Both modalities derived their theoretical and primary application outside dentistry, and in the case of implantology, it has led to a wide and far-reaching expansion of techniques and application that benefits clinician and patient alike. By way of specific example, the consideration of dental implants within a postextraction treatment plan is now considered mandatory by many dental licensing authorities. With the review of an ever-expanding time base over nearly 40 years, the initial near certainty of success with implants has now been supplanted by a realization that a new «disease» has emerged, with ever-increasing prevalence among those ageing patients with long-term implant-supported prostheses. In 1989, Dr Carl Misch is recorded as saying «Peri-implantitis – if you haven't had a case of PI, you're either lying or you haven't done enough cases» (*International Congress of Oral Implantologists London Congress. 1989*).

In response to this emerging picture of possible permanent damage and deterioration, the whole emphasis of investigation into implant design, placement techniques, restoration and long-term survivability of implants has concentrated on a recognized science base, built upon and sustained through peer-reviewed rigorous studies.

Another significant area of concern to dental professionals lies within the near epidemic of «cracked tooth syndrome» among the baby-boomers and younger generation. At the time of a strong belief in the principles of restorative dentistry that had spanned nearly 100 years, undergraduate teaching of cavity design and the use of amalgam formed a benchmark of understanding, sustained by near dogma postulated through G. V. Black.

With the emergence of failing dentition through fractures within the clinical crown, an understanding of the causative factors emerged through scientific investigation. «Micro-fractures adjacent to cavity margins, damage to teeth adjacent to inter-proximal cavity design, thermal injury to the pulp caused by rotary instrumentation» [1, 2] and «Restorative procedures …( ) ..can all induce stresses onto the residual tooth structure culminating in a possible fracture» [3]. Even the underlying philosophy of university education became open to examination through publication, «the placement of poor quality dental amalgam alloys, the contamination of freshly placed dental amalgam by moisture and excessive condensation pressures when placing amalgam may also induce fractures» [4].

The purpose of this discussion, in what purports to be a textbook of laser use in dentistry, serves to highlight the precarious nature of our profession; the employment of ever-increasing sophisticated therapies applied to address dental and oral disease, for which the patient undertakes to pay and through which a legal contract of service and responsibility, exists.

Laser dentistry? Isn't that some fringe activity that «amuses» a few dentists who believe in its poorly defined application in dentistry and convinces patients that it's a «magical» and painless alternative to the drill? How common is such a statement, and over the years this has been the response of the cynics who question the application of lasers within the many disciplines of clinical dental practice.

Having written a great deal on the integration of laser use into dentistry, the author is at once compelled to defend its use as being as important to modern dentistry as implantology and restorative therapy, but to concede that he once coined the phrase «lasers are just looking for a home in dentistry». During personal association with lasers spanning 27 years of their existence in dentistry and a growing passion over the expanding opportunity for integration, there was disappointment with the early machines, to the extent that belief that laser use in dentistry was simply because they enjoyed success in other areas of medicine, so why not dentistry?

If there is a place for lasers in general within dentistry, there must be a place for laser science and much more.

There is also an emerging shift in treatment patterns that every dentist will recognize. Emphasis on prevention, early interceptive treatment of caries and preservation of healthy tooth structure, maintenance of sound periodontal support for natural teeth and an overriding patient-driven quest for an aesthetically pleasing smile have all contributed to modern dentistry. The demands of the once-sound biologic and mechanical principles of Black's cavity design – outline form, retention form, extension for prevention – have been transformed by the near-ubiquitous use of micro-retentive direct composite resin restoratives. It is through this revolution that has growing acceptance through evidence-based protocols that dentists can offer supportive oral treatment that at least has a potential of being acceptable to the patient.

Within this framework, laser dentistry – to the cynic to be «just looking for a home in dentistry» – might establish itself as an ideal philosophy and treatment tool, and this might be best seen in the following clinical scenario:

A 9-year-old patient attends as a new patient with her mother. Both are anxious through past experience of dental treatment. The patient has several deciduous cavities, evidence of malocclusion, an upper permanent central incisor has failed to erupt and remains sub-gingival, and there is a high insertion of a fibrous maxillary midline frenum that may prevent approximation of the permanent central incisors. Few of us have the blessed sanctity of the pediatric dentist, and the hope of a successful long-term happy relationship is slowly ebbing with the realization of what treatment is required. Equipped with a suitable laser, there is a possibility of enjoyment for patient, mother and dentist. Pain control in such situations can often be achieved through the use of topical anesthetics and the removal of caries and cavity preparation easily performed with an Erbium YAG or Erbium, Chromium YSGG laser. During cavity preparation, it is discovered that there is a vital pulp exposure and gingival ingrowth interproximally; here, the soft tissue correction and effective pulpotomy can be achieved without bleeding, using either Erbium lasers or possibly a near-infrared diode or Nd:YAG or far-infrared CO_2 laser. In addressing any possible bacterial contamination, it is possible to use a low-level laser to activate a photochemical liquid placed in the cavity, prior to placement of the restoration. The exposure of the un-erupted incisor using a suitable surgical laser can follow, and labial frenectomy achieved almost imperceptibly without bleeding or the need for sutures or dressings.

Our challenge is not to dwell on the near certainty of laser-assisted therapy, as considered above, but to establish the science base that defines the use of laser technology as the prime consideration of instrumentation in delivering such treatment.

18.2 Wisdom and Knowledge: Are They Mutually Exclusive and Beneficial?

> Wisdom is the reward for surviving our own stupidity.
> (Brian Rathbone, author)

The author first «knew» of lasers in 1989 when encouraged to purchase a newly arriving model in the United Kingdom of the first dental laser – the American Dental Laser. It was considered a positive vehicle in the provision of dental care under private contract, and the encouragement received from the seller was that such a machine would lead to greater patient uptake. As the promotional material relating to this laser proclaimed:

> …. Imagine a beam of light so powerful it vaporizes tooth decay, cuts dentin and cementum, etches enamel, desensitizes teeth, incises soft tissue …. A beam of light so intense that it kills bacteria.
>
> So quick that pain is virtually eliminated … what you have imagined is a dental laser …..

The personal understanding of lasers at that moment was zero, and initial personal instruction in its use amounted to a 1-h demonstration, once the laser was purchased and delivered. Frustration at the total lack of understanding as to what was exactly happening (the laser operating beam was invisible, adding to the «magical» effects on tissue) was compounded by the fact that this first laser – a near-infrared Nd:YAG – was ideally suited, indeed originally developed, for soft tissue ablation; indeed, any possible use on tooth tissue was limited to a slow and erratic ablation of accessible pigmented caries. It is hardly an instrument that would deliver pain-free cavity preparation – a purpose for which the purchase was intended.

Fig. 18.1 The use of the Nd:YAG 1064 nm laser in a case of lower labial frenectomy (**a**). (**b**) Initial laser surgery at excessive power and lack of consideration of anatomical structures, leading to deeper tissue damage. (**c**) Appearance at 4 weeks and (**d**) 8 months, necessitating onward specialist referral. Laser operating parameters: 320 µm fiber in contact mode. 250 mj/pulse/15 Hz. Average power 3.74 W. Fluence 1162 J/cm^2. Time taken 30 s. Total energy delivered 113 J. Pulse width 100 µsec. Peak power density 3,108,495 W/cm^2

Undeterred and within a belief that the interaction of this laser wavelength with soft tissue would deliver predictable outcomes, it rapidly emerged that something was drastically wrong, and mostly it was the lack of operator understanding (Fig. 18.1). In this clinical case, the fibrous nature of the frenum was recognized, and high-output laser power was chosen to ablate this tissue. Unfortunately, the power levels, with the benefit of hindsight, far too high for such delicate tissue, together with an incorrect angle of approach with the delivery fiber, led to thermal damage to the soft tissue, the underlying periosteum and necrosis of the underlying bone. As a result, the early postoperative period was very painful with a delayed period of sloughing of tissue and a resulting gingival fenestration. The patient was later referred to a periodontist for corrective gingival surgery.

There was no pride associated with such failure, and the combination of personal shame and litigation fuelled an anger to overcome the lack of knowledge as to what was exactly happening and how the effects of laser use on oral tissue might be better controlled. Much of the early personal learning about laser use was through overcoming mishaps in wavelength choice and dosage. During the following 4 years, a great deal of work was made available with several laser manufacturers together with extensive travel; in addition, other laser wavelengths such as the carbon dioxide and some early «diode» wavelengths were experienced through company affiliation. A fundamental example of lack of understanding of a new laser wavelength – the carbon dioxide 10,600 nm – was highlighted through the belief that the examples of relationship between laser wavelength and target tissue chromophores (essentially, tissue pigments, proteins, water and hard tissue mineral) provided a safe guide as to the choice of laser (Fig. 18.2).

The oral cavity is a complex mixture of tissue elements, and each element – protein, water, hemoglobin and carbonated hydroxyapatite – exhibits differing levels of absorption with laser wavelength. Essentially, shorter laser wavelengths, those within the visible and near-infrared portions of the electromagnetic spectrum, are absorbed by pigmented protein and hemoglobin. Longer wavelengths (mid to far

Fig. 18.2 The use of the CO_2 10,600 nm laser in an attempted Class V cavity preparation, having provided assurance to the patient that no rotary instruments would be used (**a**). Relatively low average power delivered (1.0 W) was not the prime issue in the complications incurred ((**b**) carbon deposits after initial laser irradiance), but the emission mode (CW) and lack of water, leading to overheating of the tissue. (**c**) Following attempts to remove the carbonized dentine and residual caries, the restoration was completed (**d**). Fortunately, no pulpal damage followed. Average power 1.0 W. Continuous wave emission. Noncontact delivery/beam size 600 µm. Fluence 111 J/cm^2. Time taken 5 s. Power density 164 W/cm^2

infrared) are absorbed by water and hard tissue mineral. The phenomenon of absorption leads to a conversion of incident photonic energy into thermal energy within the target tissue element, and this can be predictably configured to deliver a desired change in the tissue. With high-powered surgical lasers, the rise in temperature will lead to structural change, which will cause ablation.

The supposed high absorption in hydroxyapatite led to the belief that here was an answer to the quest to own a laser suitable for tooth cavity preparation. As shown in Fig. 18.2, the result of using incorrect and inappropriate laser operating parameters continued to expose a personal lack of understanding of the relevant fundamentals of laser science and biophysics. Once again, a lack of control of rapid overheating led to damaging effects, and furthermore, as in Fig. 18.3, this led to painful after-effects and delayed healing.

If there is a consequence to this self-imposed and dangerous learning curve that formed the early part of the author's association with dental lasers, it was that clinical experience should be complemented by a grounding in relevant science, applied clinical training and development of prescriptive analytical skill in case selection and laser choice.

The rapid expansion in recent years in laser wavelengths available to the dental clinician, together with a rationalization towards machine size, sophistication and, in many instances, cost, has allowed a full range of clinical treatment areas to be further explored and managed with the help of laser photonic energy. Figure 18.4 provides a (nonexhaustive) list of those clinical procedures or areas of treatment that can be carried out with the help of lasers – either those delivering tissue ablation or those associated with nonablative photobiomodulation.

■ **Fig. 18.3** The use of the 810 nm diode laser to treat pericoronitis at lower left wisdom tooth. **a** Shows inflamed operculum associated with functional wisdom tooth. **b** Immediately post-laser resection of soft tissue. Care must always be given to the equal irradiation of keratinized and nonkeratinized epithelium, and in the case of excessive power, the possibility exists for deeper edema to spread within «loose» retromolar anatomical structures and spaces. **c** 16-day postoperative presentation. The patient had experienced severe pain, discharge, halitosis and trismus. Healing eventually achieved. Laser operating parameters: Average power 2.0 W. Continuous wave emission. Contact delivery/beam size 320 µm. Fluence 310 J/cm^2. Time taken 25 s. Total energy 50 J

What is of fundamental importance is that no matter what the level of adjunctive use a given laser may bring, the clinician is first and foremost a dentist, and it remains a duty to the patient that treatment offered should be based on evidence and within the capability or regulation of the dentist to provide it. Evidence demands science and furthermore enforces the belief that like all other aspects of clinical procedures and techniques, the presence of a laser must be justified and all parameters of its use for a given procedure defined through evidence base.

This philosophy and approach can be simply demonstrated through the adoption of the «MIMO» concept – minimum input maximum outcome.

18.3 "MIMO"

The predominance among laser manufacturers to safeguard against untutored and inexperienced use of a laser may be seen through the availability of treatment «menus» – dial-up options with associated preset laser operating parameters. These are far from a «safety net» and in many cases provide the only means of selecting operating values for a chosen clinical procedure. In ■ Fig. 18.5 a simple algorithm provides contrast to reliance on manufacturer's setting, as opposed to individual assessment of patient needs, condition and laser settings.

In all cases, for a proposed treatment, the exact nature of a chosen target tissue is unique; the physical structure and optical parameters relative to incident laser irradiation will define the extent to which the electromagnetic energy is absorbed or scattered/transmitted and thus allow conversion to thermal energy with attendant effect. An example may be seen in a procedure such as gingivectomy, where the rate of target ablation may differ significantly between a north European and an Afro-Caribbean patient through the degree of melanin pigmentation present.

Total reliance on manufacturer's settings may lead the unwary or untrained to encounter unforeseen outcomes, whereas a fully developed and qualified experience and training pathway will allow the clinician to anticipate the demands of the case and adjust operating parameters accordingly to protect the patient. Minimal «input» amounts to operating parameters (power density variants) sufficiently low to produce a desired outcome and avoid unwanted tissue damage.

Clinical Applications for Lasers-Assisted Treatment	
Surgery	*Periodontology*
Gingivectomy, gingivoplasty	Periodontitis/treatment of periodontal pockets
Crown lengthening	Curettage
Frenectomy	Gingival grafting
Tumor removal (fibroma, epulis)	
Operculectomy	*Implantology*
Drainage and incision of abscess	Uncovering of implants
	Sterilization and decontamination of implants
Endodontology	Peri-implantitis
Decontamination of the root canal	
Granuloma	*Prosthetics/ Prosthodontics*
Pulpectomy	Ovate pontic development
Pulpotomy	
	Aesthetics
Therapy	Laser bleaching/ activation of bleaching materials for teeth whitening
Aphthae, herpes, angular cheilitis	
Bio-stimulation – TMJ disorders, post-surgery healing, neuropathic pain etc	
Leukoplakia, lichen planus	

Fig. 18.4 Specific areas of therapy and clinical procedures where laser-assisted treatment may be carried out. Each procedure has received peer-reviewed publication as listed in PubMed (▶ www.ncbi.nlm.nih.gov/pubmed)

18.4 Evidence-Based Pathways in Laser Use in Dentistry

A suitable explanation of the meaning and extent of evidence base may be seen as the following:

> The conscientious, explicit and judicious use of current best evidence in making decisions about the care of the individual patient. It means integrating individual clinical expertise with the best available external clinical evidence from systematic research. [5]

Within the field of laser dentistry, at the time of the launch of the first Nd:YAG laser in 1989, the extent of dedicated research as applied to dentistry was virtually nonexistent. Unfortunately, the early investigations to establish scientific rigor to claims of clinical benefits with this laser were to some extent open to criticism and claims of bias and limited direct significance to possible use within clinical dental practice.

A pathway to research might explore available science and define a hypothesis as to examination of variables within a system. Accuracy in so-called materials and method must be ideally underpinned by degrees of bias limitation or «blinding». In essence, this would be when one investigator defines the subject matter and sample size(s), followed by another investigator carrying out the experiment but not aware of the sampling process or identity of subjects. Results might be collected by another «blinded» worker, adding further to the objectivity of the investigation, the strength of the outcome and true value to the progress expected from the outcome.

The method of propagation of such investigations is through published media. Within this wide area of communication, the gold standard remains high-value peer review. Quality journals involved in the publishing of dental laser research include titles such as *Lasers in Medical Science* and *Journal of Photomedicine and Laser Surgery*, together with frequent publication of laser-related studies and articles in journals of periodontology, endodontics, implantology and restorative dentistry. Key to the value of such publications must always surround a declaration of strict peer review, where each article submission is subject to review by more than one referee who is considered expert in the given subject matter. Additional guidance as to sustainability of rigor is the impact factor, a computation for an individual journal as a measure of the frequency with which the «average article» in a journal has been cited in a particular year or period. The impact factor is useful in clarifying the significance of absolute (or total) citation frequencies. It eliminates some of the bias of such counts which favor large journals over small ones or frequently issued journals over less frequently issued ones and of older journals over newer ones. Particularly in the latter case, such journals have a larger citable body of literature than smaller or younger journals. All things being equal, the larger the number of previously published articles, the more often a journal will be cited.

18.5 "Apple Pie" Philosophy and Sustainability of Scientific Investigation

Imagine if you will, the following relating to a published case of laser-assisted frenectomy:

> Diode laser used. Power 1.5 Watts. Frenectomy completed ….

May be simplistic but examples abound of similar accounts of laser use. Even the laser wavelength is not recorded and operating technique absent.

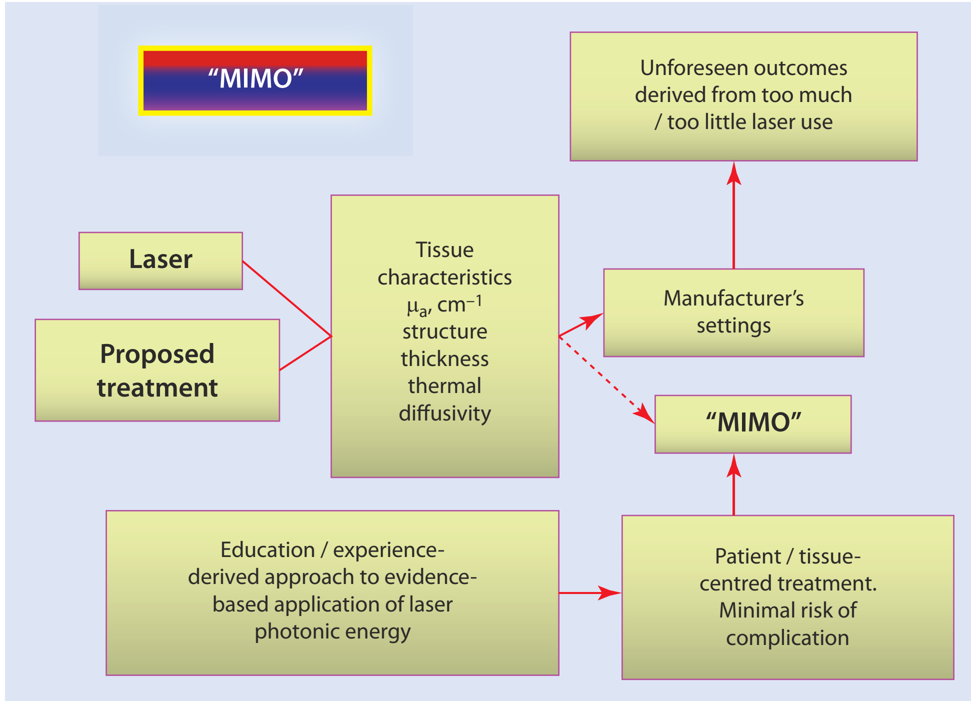

Fig. 18.5 «MIMO» algorithm. Minimum input maximum outcome. The use of a minimal level of total laser photonic energy, relative to irradiated tissue volume, in order to deliver a desired outcome and avoid collateral damage events

Of course, of more concern might be the materials and methods report of a clinical investigation:

> Patient group C treated with the laser. Laser used: Nd:YAG. Average power 1.5 Watts. Pocket debridement carried out …..

If there is a basic, profound flaw in each of these examples, it is the abject lack of subsequent opportunity to reproduce the laser action and outcome by others. The former case presentation might give rise to risk as similar to that outlined in Fig. 18.1; the latter, if part of a study into the use of the Nd:YAG laser in the treatment of periodontal disease, provides grave danger of compounding the risk to an indeterminate number of patients and was such a study to be cited or implemented in further clinical investigation.

In ▶ Chap. 4 it was shown that important parameters relating to the laser and the output represent a bare minimum.

18

In cooking an apple pie, it would be necessary to consult and follow a recipe. To add to the attraction of what awaits, a tempting image of the finished pie would add to the excitement. But what if some stages of the recipe were missing; or maybe instead of «two eggs» or «100 g sugar», the recipe merely stated «eggs» and «sugar». How confident would we be of success – and first time success! In the same way, a published article or investigative study highlighting laser use should detail exactly the laser, it's emission wavelength and mode, beam/spot size and average power. From there, computed values such as fluence, irradiance and possible peak power can be recorded, together with coaxial water/air if use and total time are taken. When such more extensive parameters are applied to our two «basic recipe» examples above, a much greater degree of certainty emerges – reproducibility that enables successive use of each laser in similar clinical scenario to meet the basic «apple pie» rule!

The situation is changing; for so long the level of reproducibility among published material was low, often with merely laser control panel readings of laser output. Recognition of possible power losses – vis a vis between control panel data and hand-piece emission – along a delivery system can affect the actual fluence by as much as 20%.

Through precise and comprehensive recording of all standing and computed laser parameters, the rigour of science and research can be sufficiently strong to allow truly representative progress in the broadening application of laser technology to develop.

The risk of «bias» is considered greater if the article is company sponsored, either through direct support or through investigators with declared interest. The type and extent of criteria under investigation – so-called «inclusion» and «exclusion» criteria – may have a profound effect on the predictability of outcome and/or the statistical significance of the results.

Figure 18.6 provides an overview of the relationship of published work, the type of investigation, the type or format of published media and associated distorting factors that might affect any of the preceding factors. Each of these will have relevance to the «objectivity» of the paper or article, the scientific rigour and the reproducibility («apple pie» factor)

Distorting factors and influence of bias through predetermination of material or funding support, together with «manipulation» of data or materials and method, have been discussed above.

Within the Science Publication Sequence, there is a hierarchical relationship between type of medium and lack of subjectivity. Apart from occasional national blanket controls

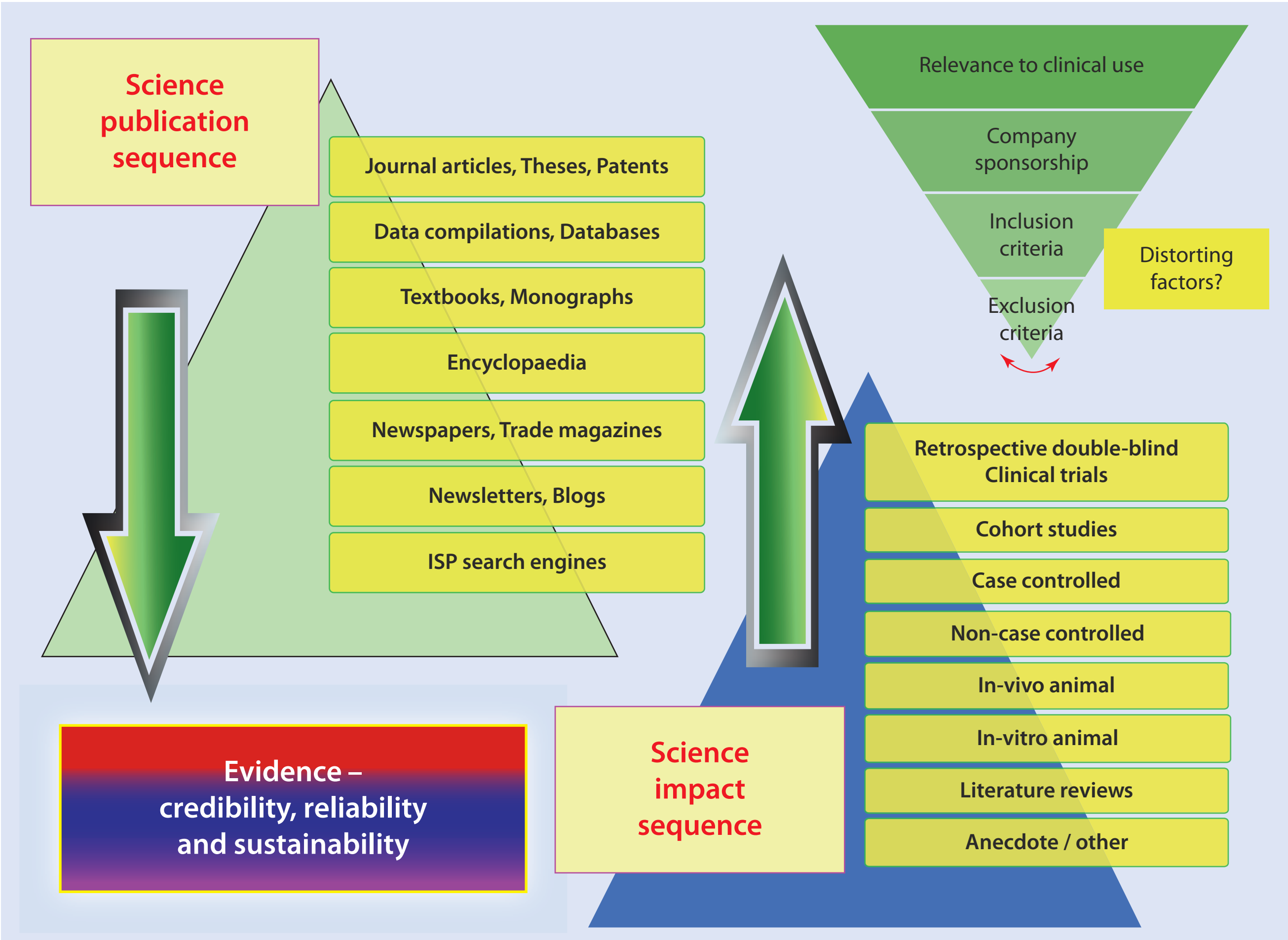

Fig. 18.6 Hierarchical relationships of publication media, study design and distorting factors as they relate to the sustainability of science and evidence in laser dentistry

on public dissemination of sensitive data, the Internet is limitless in terms of breadth of knowledge but also position within a spectrum of truth. Anyone can upload anything and claim intellectual property rights; whether a statement is true or not or even if the material is original or not, it is possible to both host a dubious source of knowledge and manipulate its truthfulness. Of course, such a viewpoint is offensive to those who post honest and scientifically strong material (clinical and nonclinical) relating to laser action within dentistry. Nonetheless, the Internet as a generic source may be seen as least robust or dependable.

From there, online newsletters and blogs together with corporation-led «advertorial» and «infomercial» (yes – there is a difference!) publicity of a clinical team, company, technique or laser instrument while striving to uphold the corporate or personal ethics of those involved may be seen as being open to claims of subjectivity and massaging of truth to some extent.

So-called «reference» texts, of which this book is an example, are often seen as totally credible but lacking in peer review; hence there is only the reputation of individual authors and overall publisher's approach to scrutiny that provides reinforcement of truth and ethics. Within the hierarchy of publication, only high-impact-factor-independent journals may get close to a perfect source of objective knowledge, science, and applied clinical laser therapy. Public university degree theses will enjoy a degree of peer review, and instrument or technique patents (but not exclusively, registered trademarks) must prove originality and pass the severe scrutiny of approval boards.

Having explored the medium of knowledge dissemination, the other hierarchy relates to the type of article, study or investigation in our quest for originality and objectivity within laser dentistry.

Certainly, in the early days of laser use in dentistry, the common currency of technique and application of lasers in dentistry was the anecdote. Individual presentation of results through case presentation led the way and provided pathways of clinical therapy. Of course, the great drawback was whether results – so proudly demonstrated – represented definitive protocols of technique, laser wavelength and operating parameters, or maybe just luck! If laser dentistry was to receive acceptance among professional colleagues, groups or those entrusted with teaching, the reliance on anecdote represented too fragile a base in sustainability and (possibly) truth.

From Fig. 18.6, it is possible to view the ascending levels of study types, in terms of objectivity, scientific rigour, reproducibility and, ultimately, clinical relevance. Literature reviews are sometimes suspect – what control exists to mandate the selection of published material? The risk would lie with individual reviews that declare their own chosen agenda. Certainly, «super-objective» filters such as the Cochrane Database of Systematic Reviews represent the leading resource for systematic reviews in health care. The following is taken from their website (▶ www.cochrane.org):

> The Cochrane editorial process follows a consistent and structured path. It is unique in two ways: (1) to monitor the process of review development throughout the editorial life cycle, beginning with registration of a title, through preparation and publication of the protocol and completed review; (2) Cochrane Reviews are updated to take account of emerging evidence, to provide the best and most current evidence to guide decision-making.

However, sometimes the restrictive nature of literature review might result in (for instance) several 100 published papers being considered, but with application of inclusion criteria only a handful are further examined. Certainly, the reader is encouraged to look at the exact nature of review, and if this is a personal enquiry into a given laser technique or study, care and caution should be exercised in total reliance on article abstract material, as often a brief overview of a paper belies the complete impact of the publication.

Further upwards and to the peak of *excellence*, the «double-blind» study has been described earlier, and the component compartmentalization of study design (inclusion and exclusion criteria), materials and method, data collection and interpretation, statistical analysis and audit through successive studies not only confers a gold standard in all aspects of dentistry research but must provide the way forward in defining the extent and strict methodology of laser application in clinical dentistry.

Such studies are complex and expensive; often they are collaborative efforts within a group, university, or professional clinician cohort. An example of audit (among others) of prevalence of such refined studies within laser dentistry was published by Cobb (2006) [6]. This «snapshot» of the types of papers relating to specific application of laser therapy within periodontology involved a review of 278 articles. Applying consideration that has been explored above, only 12.6% of papers were classified as «objective, controlled», amounting to 35 papers. If this points to a possible 87% being «subjective» and possibly unreliable, it would provide ample ammunition to those non-laser users (possibly hypocritically immersed in their own nonobjective field of dentistry) to brand lasers as if no sustainable benefit to dentistry.

The author prefers to draw upon my own experience during the past 10 years, not only as a clinician but within university teaching and research, journal editorial duties and personal publication, to bear witness that the general standard of objective research and clinical application of laser use in dentistry has progressed enormously and with it the quality and sustainability of objective publication.

18.6 Education and Qualification Pathways in Laser Dentistry

So why is laser use in dentistry so sporadic? There may be several reasons: financial, lack of awareness among dentists or knowledge of what lasers can perform, but perhaps the greater one is the lack of grounding and integrated teaching of laser therapy at undergraduate level. If a student is introduced to tooth cavity preparation using a rotary drill, such treatment modality forms the basis of the concept of restorative dentistry; equally, a soft tissue incision performed with a scalpel defines an approach to surgery that will be carried into one's professional career. The early learning in undergraduate life forms a bedrock foundation to clinical opinion and techniques, and this, together with the bonds established between student and professor, is part of the excellence and integrity of clinical dentistry seen all over the world.

Early adopters of laser dentistry were not able to access structured educational pathways; rather, those who wished to consider laser use would attend an introductory course, often provided by the company selling the machine. Such courses would prove invaluable in providing the novice with basics. Many such courses had a drawback in that they would often limit presentation material to the extent of the particular laser and what could be achieved with it. Notwithstanding, introductory experiences continue to provide initiation into the world of lasers.

Awareness of different laser wavelengths and clinical opportunities will drive the clinician to explore wider education avenues. Courses at varying levels of intensity, subject matter and complexity are now frequently promoted – often as breakout sessions at a laser scientific conference.

With both these types of courses, verifiable continuing education credits underline the significance of learning and awareness to benefit clinician, patient and professional licensing body. As such they will be quantifiable in terms of course content and expectation. Many of such courses draw upon accepted core curriculum structures, an example of which is set out in a paper by White J. et al. on curriculum guidelines for dental laser education [7].

Often, however the value of such courses is thwarted through the nonlinear pathway that such attendance implies. Course X given by organization Y may have integrity and convey accurate contemporary opinion, presented by an accredited experienced practitioner. Taking such credit to a higher level, such as postgraduate degree application, may suffer from noncompliance with the entry criteria of that university. In consequence, so much of education in laser use in dentistry has suffered because of lack of structure and progressive pathway.

This is not a new phenomenon; in 2005 when installed as president of one laser organization, the author was invited to join the editorial board of another laser organization, located in a different continent. Despite best efforts to effect change, neither organization would forego their own exclusivity and allow reciprocation of (otherwise complementary) education achievement levels in laser use. What frustration! Those having progressed through one organization and wishing to join another would need to begin once more at the bottom. Examples of such perceived selfishness and blinkered ambition continue to the present time in dissuading dental professionals from joining and benefitting from the forum of like-minded colleagues in laser use.

In many regions of the world, public university-based education has supplanted some historically popular laser organization-centered course pathways with their own. Accredited diploma and postgraduate MSc and PhD degree opportunities are now common – certainly in Europe – with the benefit to the busy clinician that many are part-time and distance-learning modular courses. Of particular benefit is the international recognition of such education and graduates of such courses are becoming the opinion makers within an emerging generation of specialists and experts. In turn, those universities that have developed degree opportunities have themselves witnessed expansion in accredited personnel, over and complementary to existing faculty staff – ambassadors who in turn develop the outreach of evidence-based education. The appeal of these courses is high, and in the author's experience as a university faculty member, students have travelled thousands of miles across continents to take advantage of accredited learning pathways.

At the beginning of this chapter, I wrote «to know is to use; to understand is to empower». The fundamental elements to support such a statement must be the acknowledgement of a scientific base to all laser-tissue interaction, together with an accredited grasp of biophysical principles that govern the degree of laser-tissue interaction, by laser type, laser wavelength and target tissue composition.

18.7 Regulation and Medico-Legal Aspect of Laser Use

It is beyond the scope of this chapter to provide definitive regulatory requirements as they might apply in every country. However, there is scope for discussion of core principles in both regulation and medico-legal aspects that might impact on the use of lasers.

18.7.1 Regulation as It might Impact on Laser Use in Dentistry

? A common and logical question that might be asked by those wishing to use a laser in clinical practice is «why?» Is there regulation governing the use of a high-speed air rotor or a scalpel? Surely, as a dentist or hygienist, the issue or reissue of a licence or practising certificate defines capability in using any instrument of choice in the delivery of primary dental care.

Of course, as dental professionals, there is obligation to provide specific treatment only inasmuch as defined within the scope of practice. There are different regulations of practice in many areas of the world. For example, it is outside the remit of hygienists in the United Kingdom to provide treatment that «consists of or is implicit in making an incision in the periodontal tissues» (▶ www.gdc-uk.org). Equally, US dentists may be prohibited from providing treatment that is perioral and outside the vermillion border. To some, such regulation may appear illogical relative to their own geographical location and licensing authority. In general, however, the basic duty of care of the clinical dentist or allied professional is only to provide treatment for which they are licensed, only to provide treatment that the dentist feels able or experienced in providing and to only provide treatment that the patient understands and is willing to undergo.

Added to such basic general licensing regulation, there is the impact of owning a device emitting electromagnetic radiation. All dental professionals must be aware of and abide by Ionizing Radiation Regulations as they impact on the use of X-ray equipment and use. At present, the spectral range of current commercial lasers in dentistry is from the visible to far-infrared nonionizing band of the electromagnetic spectrum. No inherent risk posed by photonic energy within this range to cause ionization of DNA, but sufficient risk by virtue of exposure of the unprotected eye exists, aspects of which have been covered extensively in ▶ Chap. 5.

There is therefore considerable legislation surrounding the safety aspects of laser use in general, and many of these statutes have been adapted or simply adopted to the use of lasers in dentistry. The International Electrotechnical Commission provides exacting standards for the construction and use of lasers in clinical practice, and these are implemented as a whole or through national or federal agencies in individual countries. Crossover legislation governing safety at work and statutory instrument specification (e.g., OSHA and ANSI within the USA and CE accreditation within the EU) will have implication for the clinician in housing and using equipment, provision of laser therapy and safety protocols. Objective resources exist to provide the dentist or hygienist with reference material as to how laser use impacts their duty of care as a provider of dental care, and the reader is recommended to investigate their position within this framework and how that is implemented through their individual country or licensing authority.

It is acknowledged that laser dentistry, like dental implants as modalities, has supplanted long-standing therapies within the armamentarium of the practising dental clinician. As a result, some «quirky» legislative outcomes have provided confusion and possible incredulity! Within the United Kingdom, a growing use of early lasers in dermatology during the late 1970s and early 1980s – use that outside the licence to practice of the doctors concerned – was completely unregulated. At that time a popular national television consumer program championed the claims of patients who were disfigured through supposed malpractice using these lasers. So strong was the level of concern that the UK government sought to legislate clinical laser use and thought it expedient to «piggy back» onto a developing Act of Parliament – the 1985 Nursing Homes Act. As such, overnight the duty of medical practitioners (and some years later the first dentists to use lasers) was to register their premises as a nursing home and to abide by all aspects of the act in treating patients. As a laser dentist in 1989, the author was required to register with the local health authority, seek the services and report of a laser physicist appointed as a laser protection advisor, as well as complete a yearly audit on quite unrelated aspects as care of the dying, number of beds, registration and training of nursing staff, etc.

That early legislation was supplanted by the Care Standards Act in 2000 and later versions, with added obligation to undergo fitness to practice medical examination, financial liquidity disclosure and even criminal records check for the dentist and all staff.

Hopefully, the reader may be excused such levels of suffocation in examining their obligation in using Class III and IV lasers!

18.7.2 Medico-Legal Aspects of Laser Use

Those lasers powerful enough to ablate tissue carry additional risk of damage through breach of duty of care and causation. Simple reference to the case in ◘ Fig. 18.1 provides an example of breach of duty of care in that inappropriate levels of power were used without thought to underlying tissue and collateral gingival damage. It may be proposed that *beyond reasonable doubt*, a breach of duty on the part of the dentist occurred. Furthermore, the outcome of such breach – termed causation – would suggest that *on the balance of probability* either the need for reparative treatment or permanent damage was linked directly to the excessive laser power or inadequate technique.

Very few patients attend for dental treatment; most patients are required or even compelled to attend by virtue of the need for treatment of a dental condition, and it is the duty of the clinician to diagnose, treat and maintain the function and health of the oral cavity. Aristotle, perhaps himself not a dental patient is attributed with the phrase «the object of the wise is not to secure pleasure, but to avoid pain». This is surely the mantra of the dental patient and the objective of the successful dentist. The growth in consumerism in general and the liberalization of choice has rendered the provision of dental treatment to that of a «customer-centered service experience». Most of the therapeutic instrumentation that formed the basis of our undergraduate training is quite abhorrent to the anxious patient; the noise, vibration and perception of pain associated with the high-speed drill and the bleeding, postoperative swelling inflammation and associated sutures and dressings that accompany intraoral soft tissue surgical procedures serve to interfere with all aspects of oral function for the patient during what may be a long period of healing. This doesn't suggest that dental treatment is intrinsically wrong or justifiably avoided by the patient, but the opportunity to address these disadvantages that are subjective to the patient experience and also to deliver high-quality dental treatment must surely represent a gold standard. It also represents an extremely potent marketing tool that compliments that essential business base of every private dental clinic.

However, the choice of a laser to deliver prescribed treatment or therapy should be made by the dental professional. Lack of proper training and development of core knowledge and education (both quantitative and qualitative) may be viewed as serious examples of negligent action.

It should be acknowledged that few cases of litigation have reached a level of seriousness or constituted sufficient breach of licensing protocols, to be the subject of dental registering and governing bodies. However, were such events to occur, it is highly likely that the relative lack of precedence (case history) within dentistry would result in such breach being examined against the wider health and safety legislation in the workplace, together with IEC standards on laser use.

Summary

Of course, the myths persist that laser dentistry is somehow «magical», delivering «painless dentistry» and that the laser dentist never uses a drill or scalpel. Such perceptions are not just in the domain of the patient as he or she seeks therapeutic absolution of their dental sins. The author is guilty of seeking a marketing advantage over local colleagues in 1989 when purchasing his first laser. As explained above, it was quickly learned that it was not possible to deliver what patients demanded as treatment, with that laser. Internal marketing, the quiet dissemination of evidence-based techniques that are targeted at the needs of individual dental patients, provides a base for practice growth that, although less spectacular than the glittering advertising campaign, promotes a value-added loyal patient list. Laser dentistry is not painless: it is certainly *less* painful, when compared to cavity preparation with an air rotor, as it is possible to target caries selectively using a nontactile interaction of light energy with target structural elements. As such, the determination of patient acceptance itself often shrouded in a personal history of a painful experience is much more a process of comparative evaluation and gradual co-operation, and it is my opinion that it is negligent to promote laser dentistry as a panacea that will transform the patient experience as if by «magic». Equally, no laser will cut metal restorations or prepare self-retentive crown abutments. Early investigations into the suitability of laser energy applied to oral and dental tissue suffered from allegations of subjective supportive inclusion criteria, company sponsorship or anecdotal experience or, at best, the application of incorrect laser wavelengths to subject tissue. With the tremendous growth in wavelengths and machines that are dentistry specific, the objectivity of investigation through peer-reviewed retrospective crossover studies has led to an acceptance not only of the suitability of lasers in dentistry but also the evidence-based protocols for their supportive role in treatment.

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Supplementary Information

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Glossary

Ablation Removal of a segment of tissue or (dental restorative) material using photo-thermal energy. When applied to laser-tissue interaction, it describes the irreversible disruption of the physical structure of the target. It is sometimes termed vaporization, although that is not technically correct.

Absorption The transfer of electromagnetic radiation into the target tissue resulting in a change in that tissue. For available dental lasers, that transfer is primarily light into heat. The true opposite of absorption is transmission.

Absorption coefficient The change in energy as the wave passes through a layer is a constant of the material for a given wavelength and is called its absorption coefficient.

Active medium The material within the optical cavity that, when stimulated and amplified into a population inversion, will emit laser energy. This medium may be an ion, molecule, crystal, semiconductor wafer, or combination of gases. A synonymous term is lasant.

Amplification A process that occurs within the optical resonator of the laser whereby stimulated emission produces a population inversion. The amount of amplification is known as gain.

Articulated arm One type of laser delivery system that uses segments of a hollow tube that are coupled with right angle mirrors that allows propagation of the laser beam along its length. Commonly found as part of the delivery system in mid- and far-infrared wavelength dental lasers.

Attenuation The observed decline in energy as a beam passes through an absorbing or scattering medium.

Average Power An expression of the amount of laser photonic energy delivered over a unit of time. In continuous wave emission, it is the total power delivered; with free-running or gated pulse emission, it is an expression of the product of the peak power multiplied by the emission cycle.

Beam A directional stream of photons; any collection of radiant electromagnetic rays that may be divergent, convergent, or collimated.

Carbon dioxide laser A laser whose active medium is composed primarily of helium, with carbon dioxide, nitrogen, and small amounts of hydrogen and helium. The laser is pumped with an electrical discharge and the emission is due to the population inversion of the carbon dioxide molecules. Current available wavelengths range from 9,300 to 10,600 nm and are in the far-infrared thermal portion of the electromagnetic spectrum.

Chopped pulse See gated pulse mode.

Chromium A transition metal element used as a dopant for laser-active medium crystals, such as yttrium scandium, gallium, garnet (see YSGG).

Chromophore A compound or molecule normally occurring in tissues that is an absorber of specific wavelengths of laser energy.

Cladding A thin coating that surrounds the core of glass in a fiber-optic delivery system. The cladding maintains the propagation of the laser beam along the glass. The cladding is surrounded by a thicker jacket to aid in flexibility.

Coagulation For thermal tissue interaction, an observed denaturation of soft tissue proteins that occurs at approximately 60°C. The term is usually applied to blood when it changes from a fluid to semisolid congealed mass.

Coherency A term that describes radiant waves travelling in phase both temporally and spatially.

Collimation The state in which all electromagnetic rays are parallel with virtually no divergence.

Contact mode The direct touching of the laser delivery system to the target tissue.

Continuous wave mode A manner of applying laser energy in which beam power density remains constant over time, also abbreviated as CW. This mode is commonly used clinically.

Delivery system The manner in which laser energy is transferred to the target tissue. For dental lasers, there are fiber-optic, hollow waveguide, and articulated arm systems. The distal end can employ additional tips, and the beam may be used in a contact or noncontact mode.

Diffraction The bending of a light ray as the light passes through a medium; also known as refraction.

Divergence An observed amount of the spread of the laser beam as it increases its distance from the emission aperture or focal point; the opposite of collimation. It is measured in degrees of an angle.

Diode laser A laser whose active medium consists of an array of semiconductor wafers in a double-heterostructure arrangement. These lasers are pumped with electrical current, and the resulting light is collected and focused into a beam. Various elements, such as aluminum, arsenide, gallium, indium, nitrogen, and phosphorous, are part of the composition of the wafer. The emission wavelengths can range from the visible to the near-infrared thermal portion of the electromagnetic spectrum.

Doping The addition of an element to the laser-active medium crystal, resulting in a specific emission of energy. Those elements are known as dopants and in most cases they are either rare earth ions or transition metal ions. An example is doping an yttrium aluminum garnet crystal with the element of erbium.

Electromagnetic radiation Flow of energy consisting of oscillating electric and magnetic fields lying transverse to the direction of the wave's propagation.

Electromagnetic spectrum The entire range of all forms of radiant energy from gamma rays to radio waves and is usually depicted with increasing wavelength and/or decreasing frequency.

Emission cycle A ratio of the emission on time to the on plus off time, expressed as a percentage. An alternative term is duty cycle, although that term usually refers to the limit of operation of a machine.

Energy The ability to perform work, measured in a unit known as a joule, abbreviated J. For dental lasers, a common value is a millijoule (mJ) which is one-one thousandth of a joule.

Energy density The measurement of energy per unit area, usually expressed as joules/square centimeter, also known as fluence.

Erbium A rare earth element that is used to dope a crystal of yttrium aluminum garnet or yttrium scandium gallium garnet (see YAG or YSGG).

Excited state An atom or molecule with electron orbit(s) in an energized or higher level than the resting state.

Extinction length The distance into a material where the power density has dropped to 37% of its original value. A synonymous term is attenuation length.

Fiber optic A laser delivery system composed of a glass fiber, which can contain multiple strands, and is used to propagate the laser beam along its length. The glass is surrounded by cladding and a jacket or layers of jackets. The bare fiber can be used for laser procedures or additional quartz or sapphire tips can be added to the distal end of the fiber optic.

Fluence See energy density.

Focal length The distance between the focusing lens and the focal point, which is the place where the laser beam's power and energy are delivered at maximum density. It is usually measured in millimeters. In bare fiber-optically delivered lasers, there is no focusing lens so focal length does not exist. The greatest emission is at the end of the fiber. In other delivery systems, such as an articulated arm, the focal point is usually several millimeters from the end of the delivery system.

Free-running pulse mode A primary (inherent) laser operating mode where the emission is truly pulsed and not gated. The pumping process only sustains lasing conditions for a very short time. Flashlamps, radio frequency electron signals, and diode lasers are examples of the pumping mechanism used. The resulting laser emission consists of very short pulse durations in the microsecond range, and peak powers of thousands of watts are possible. A laser operating in this mode cannot be operated in continuous wave. This mode is commonly used clinically for dental hard tissue procedures.

Frequency The number of oscillations or cycles of a wave of electromagnetic radiation per second, usually expressed as hertz and abbreviated Hz. Frequency is the inverse of wavelength.

Gated pulse mode A laser operating mode where the emission is a repetitive on and off cycle. The laser beam is actually emitted continuously, but a mechanical shutter or electronic controls «chop» the laser beam into pulses. This term is synonymous with chopped pulse mode, and this mode is commonly used clinically. When the «on time» and the «off time» can be controlled separately, it is termed variable gated continuous wave mode.

Gaussian curve A graphic depiction of normal distribution of an entity. For lasers, it illustrates the cross section of the power density during a certain time period, usually a pulse.

Handpiece An instrument attached to the distal portion of the delivery system that contains the focusing lens system. In some cases, an additional tip is attached to the handpiece to complete the assembly.

Hertz A term of frequency of an electromagnetic wave. The term is sometimes used for the number of pulses per second or repetition rate of a pulsed dental laser, with some confusion.

Hollow wave guide A laser delivery system that uses a flexible hollow tube with a mirrored inner surface to propagate the laser beam along its length.

Infrared spectrum That portion of the invisible, nonionizing electromagnetic spectrum radiation whose wavelengths range from the red border of the visible spectrum at 700 nm up to 10,000 nm (.07–1.0 µ). Commonly understood, but not universally agreed to, subdivisions are (1) near-infrared wavelengths from 700 to 1,400 nm, (2) mid-infrared 1400–3000 nm, and (3) 3000–10,000 nm.

Intensity See power density.

Irradiance See power density.

Joule A unit of expression of energy.

Lasant See active medium.

Laser An acronym of light amplification by stimulated emission of radiation. The basic components of the device are the active medium, external energy source or pumping mechanism, optical resonator, and the focusing and delivery systems.

Meter A unit of measurement and, for electromagnetic waves, used to describe the wavelength. For dental lasers, it is divided by a million and termed a micron symbolized by µm or divided by a billion and termed a nanometer, abbreviated nm.

Mode-locked laser This laser uses a group of techniques of modulation or absorption in the resonator to produce ultrashort pulses in the pico- or femtosecond range. These lasers are currently used experimentally.

Monochromatic The characteristic of a laser beam where only one wavelength is present.

Neodymium A rare earth element used to dope an active medium laser crystal, such as yttrium aluminum garnet (see YAG).

Noncontact mode The delivery system is used without touching the target tissue.

Optical resonator (optical cavity) The component of a laser containing the active medium in which the population inversion occurs. At each end of the resonator, there are reflective surfaces or mirrors which produce amplification and coherency. The distal mirror is partially transmissive; when there is sufficient energy, the beam can exit through that mirror.

Peak power The measurement of the maximum power in each pulse. It is the result of dividing the energy per pulse by the pulse duration.

Photon A unit or quantum of radiant energy.

Plume Essentially the smoke produced from aerosolization of by-products due to the laser-tissue interaction. It is composed of particulate matter, cellular debris, carbonaceous and inorganic materials, and potentially biohazardous products.

Population inversion A state within the laser cavity in which the quantity of excited species of the active medium exceeds that of the unexcited species (those at the resting, stable state.)

Power The amount of work performed per unit time, expressed in watts (W) or thousandth of a watt (mW.) A watt is 1 J/s.

Power density The measurement of power per unit area, usually expressed as watts/square centimeter, also known as intensity, irradiance, and radiance.

Pulse duration A measurement of the total amount of time that the pulse is emitted; also known as pulse width.

Pulse rate The number of pulses per second produced by the laser. Sometimes known as «hertz,» although that is technically incorrect.

Pulse width See pulse duration.

Pumping The process of energy transfer from an external energy source into the gain medium of the laser. This pumping provides for the excitation and stimulation of the active medium. Some examples of pumping mechanisms are electricity, electrical fields, radio frequency signals, or a flashlamp.

Q-switched laser This laser using Q (quality) switching to produce pulse durations in the nanosecond range. The Q (quality) factor of resonator losses is modulated and the result is that the power can build up quickly. These lasers are currently used in the laboratory.

Radiant energy Energy transferred by an electromagnetic wave; also called radiation.

Reflection The returning of electromagnetic radiation by surfaces upon which it is incident. The two general types are specular, which is created from a smooth polished surface, and diffuse, which emanates from a rough surface.

Refraction See diffraction.

Repetition rate See hertz.

Selective photothermolysis A precise laser-tissue interaction in which the radiation is well absorbed and the pulse duration is shorter than the thermal relaxation time which minimizes tissue damage.

Spontaneous emission The release of energy (a photon) as the previously excited particle level returns to its resting, stable state.

Stimulated emission The release of energy (a photon) from an already excited particle by interaction with a particle of identical energy, producing two coherent particles. This process was theorized by Albert Einstein in 1916 and is the basis for laser operation.

Superpulse A variation of gated pulsed mode in which the pulse durations are very short, often producing high peak power; also termed very short pulse.

Thermal effect For lasers, the absorption of the radiant energy by tissue producing an increase in temperature.

Thermal relaxation time The amount of time required for temperature of the tissue that was raised by absorbed laser radiation to cool down to 37% of that value immediately after the laser pulse.

Transmission The passage of electromagnetic radiation through any medium. The opposite of absorption.

Vaporization The physical process of converting a solid or liquid into a gas; for dental procedures, it describes conversion of liquid water in the target into steam.

Watt A unit of power.

Wavelength The distance between any two similar points on a wave; for example, from peak to peak, measured in meters.

YAG An acronym describing a solid crystal of yttrium, aluminum, and garnet that can be doped with various rare earth elements and is used as an active medium for some lasers.

YAP An acronym describing a solid crystal of yttrium, aluminum, and perovskite (a calcium titanium oxide mineral) that can be doped with various rare earth elements and is used as an active medium for some lasers.

YSGG An acronym describing a sold crystal of yttrium, scandium, gallium, and garnet that can be doped with various rare earth elements and is used as an active medium for some lasers.

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