Lasers in Restorative Dentistry

A Practical Guide

Giovanni Olivi
Matteo Olivi
Editors

Springer

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This book is dedicated to all patients, collaborators, and assistants who with their patience and cooperation contributed to the success of my clinical work. A special thanks to my lovely wife Maria Daniela for her continuous support and for tolerating my absence from our family life during the long period of time for the production of this book.

Giovanni Olivi

Special thanks to all my family for supporting my personal growth.

Matteo Olivi

Foreword

We have known Dr. Giovanni Olivi for more than 15 years. During this time we have had the pleasure to concurrently speak at different international congress venues about the use of lasers in dentistry. In all of them Dr. Olivi's conferences have been exceptional, presenting clinical cases and well-documented research. We believe that this book will be of great help for those who want to know more about the applications of lasers in dentistry, and we hope it will be a reference book in this field.

Antonio España
Josep Arnabat

Barcelona, Spain

Preface

This unique book presents the author's experience and knowledge in restorative and laser dentistry making this book a complete up-to-date review of the international literature on laser application in restorative dentistry, while connecting the research with daily clinical work.

The goal of this textbook is to share with the reader the current "state of the art" of laser applications for cavity preparation and adhesive dentistry, in the attempt to offer help for dentists who are looking for new and innovative techniques that improve the quality of their work. This textbook offers a comprehensive look at all indications for the use of lasers in restorative dentistry, including diagnosis, pits and fissures sealing, carious removal, cavity preparation and decontamination, and pulp capping, and introduces operative modalities that lead to predictable outcomes. Detailed instructions with an overview on the use of different laser wavelengths are provided with over 600 clinical photographs, charts, and tables. Laser in restorative dentistry is a practical guide for general dentists who use laser in their daily practice and want advice on the "know-how" on laser dentistry. If you are a new, experienced, or even advanced laser user, this book represents a valuable guide and source. This book will also be helpful to students graduating in dentistry, as a source of references to specific clinical uses in the laser treatment of dental caries. Enjoy delving into the wonderful world of laser dentistry!

Giovanni Olivi
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Acknowledgments

The editors graciously acknowledge the contributions of the following esteemed colleagues and friends.

Special thanks to Vasilios Kaitsas, for the valuable contribution to Chap. 1 and for his help in producing SEM images and in researching laser dentistry; Roeland DeMoor, esteemed researcher in the field of adhesion and endodontics, and his team for establishing a milestone in the field of laser adhesive dentistry that he shared in Chap. 5; Maria Daniela Genovese, for her hidden help in day by day work, who with her intuition contributed and simplified many chapters; and Stefano Benedicenti, for his contribution to advance laser technology in cosmetic dentistry in Chap. 9.

Their clinical work, research, and knowledge have made this book as comprehensive as possible.

Contents

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Part I

Restorative Dentistry Background

Knowledge

Beware of false knowledge; it is more dangerous than ignorance.

–George Bernard Shaw

Structure and Ultrastructure of the Hard Tissue of the Human Teeth

1

Vasilios Kaitsas and Giovanni Olivi

Abstract

The macroscopic anatomy of the tooth is well known to the dentists. However, the histology and ultrastructural aspects of the tooth are not visible during the clinical procedures, but at the same time, they are subject to modification during the cavity preparation and filling. Conventional instrumentation, laser irradiation, and adhesive procedures involve the knowledge of the tooth ultrastructure, and the success of the therapy is closely related on these topics. The interaction of lasers is different on different tissues and selective for some particular component, water, organic substances, and pulp. Accordingly a review of the ultrastructure of the tooth may help the understanding of clinical procedures of laser preparation and adhesive restoration.

1.1 Basic Anatomy

A well-formed human primary tooth and a permanent tooth are formed by a crown and one or more roots. The coronal dentin is covered by enamel, while the radicular dentin by cementum. The dentin surrounds and delimits the pulp tissue, the vascularized part of the tooth, rich of innervation and vascularization and essential for the integrity of the tooth.

The hard tissues of the tooth have similar chemical composition but different proportions of minerals, inorganic and organic components.

1.2 Enamel

1.2.1 Chemical Properties of Enamel

When the human enamel is normally and completely formed, it is a highly mineralized, very hard, and radiopaque tissue. The enamel is made up of inorganic and organic components and water.

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The inorganic components consist of minerals, mainly a calcium phosphate, specifically a hydroxyapatite (93–96 % in weight and 85 % in volume), with the crystal hexagonal shape containing P and Mg ions and carbonate compounds. Other minerals are Na, Cl, K, and F; Zn, Fe, Sr, Ra, and Cu are found in trace amounts. The Ca and P ions ratio ranges from 1.92 to 2.17 by weight [1]. The apatite crystals, in various forms, are sticking to each other with a very limited organic matrix (1 % by weight and of 3 % by volume) [2]. The water (3–5 % in weight and 12 % in volume) is linked to the organic matrix and also placed around the apatite crystals, thus facilitating ion exchange and molecular transport.

Some authors reported little different value for the hydroxyapatite (96–98 % by weight or 89–91 % by volume) and the remaining proportion of tissue volume being occupied by the organic matrix and water [3].

Variation in the water and mineral content of the enamel also explains the different power necessary to laser irradiation to vaporize the healthy or decayed enamel of different people (see Chaps. 4 and 7).

The enamel is also formed from carbohydrates, lipids, citrates, and other organic substances which are mixed with proteins in various compounds such as proteoglycans. Some of them are more water soluble and this explains the different enamel resistance in oral fluids from person to person.

1.2.2 Physical Properties of Enamel

1.2.2.1 Hardness

Enamel is the hardest tissue in the human body. In the Mohs scale where diamond has the maximum value (10), the human enamel is between 5 and 8 (between quartz and apatite) [1]. The enamel is nonelastic tissue with almost double values than the dentin. It is intimately locked onto the surface of the dentin and cannot function without this support.

1.2.2.2 Solubility

The ion exchange between the fluids and the oral surface of the enamel takes place in a nonuniform manner due to the different density and different orientation of the crystals and also because of the different amount and quality of the various ions. The superficial external layer is more resistant to acids than those with organic content richer in carbonates which are more permeable.

In nature, the apatite is very unstable and easily yields ions from the periphery of its crystals to the environment and absorbs others. The activity of ionic motion and consequent dissolution and destruction of apatite crystals are one of the aspects of the formation of the carious lesion. The absorption of fluoride ions can substitute the OH radicals, forming the fluoride–apatite, a more stable and resistant to acid attack crystal, and this is why the applications of fluorides can help in a more stable mineralization of the enamel and dental caries prevention (see Chaps. 2 and 6).

1.2.2.3 Permeability

The permeability of the enamel is very low. Water is present, in the spaces between the crystals, where also molecules of organic dyes or radioactive tracers can penetrate.

1.2.2.4 Color

The enamel is translucent and its color depends on its thickness and on the color of the underlying dentin. The enamel of human permanent teeth may be up to 2–3 mm in thickness over the tips of cusps and about 1–1.3 mm thick over the lateral surfaces. It is 1 mm or less in the deciduous teeth [3] (Fig. 1.1).

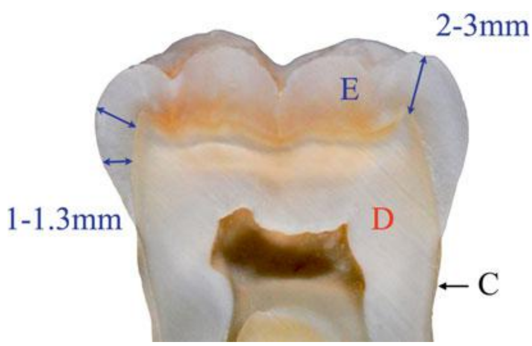

Fig. 1.1 Human permanent molar crown section: the enamel is thick up to 2–3 mm over the tips of cusps and about 1–1.3 mm thick over the lateral surfaces (*E* enamel, *D* dentin, *C* cementum)

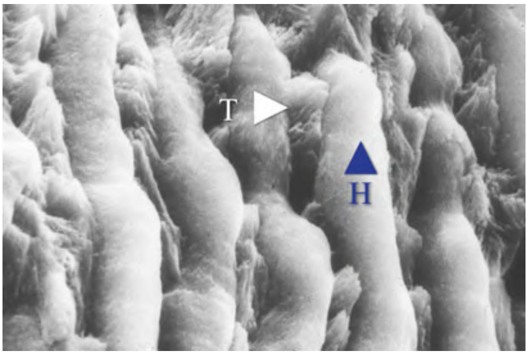

Fig. 1.2 SEM higher magnification image shows group of prism units in intimate contact one to one another. Underlying conglomerates of prisms (corresponding in section to the tail of prism, *T*) are emerging through the prisms (corresponding in section to the head of prism, *H*)

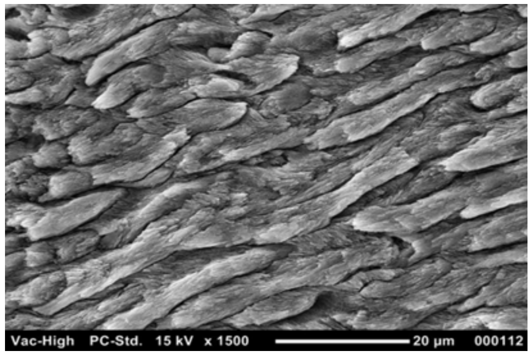

Fig. 1.4 SEM image at 1500× magnification shows the typical aspect of non-etched lateral surface enamel

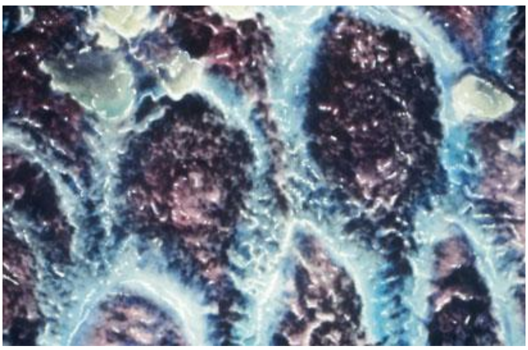

Fig. 1.3 SEM hand-painted image (5200×) of cross section of enamel prisms shows the typical key-hole aspect or so-called head and tail of the prism. The head of each prism is located between two tails of the neighbor prisms and leaves a very small empty space that is filled by organic substances (interprismatic space). Colored in blue is the sheath of the prism (Reprinted with permission from Fonzi et al. [4])

In young people the enamel is whiter and more yellowish in the elderly. In absence of the underlying dentin, as the incisal margin of anterior teeth, the color is more bluish. In cases of teeth with mineralization defects, the enamel color looks white-yellow, opaque, and brown-yellow and porous (see Chap. 6).

Enamel surface with time undergoes discoloration due to the greater presence of dyes and trace of minerals in the dentin and also due to the gradual increase of fluorapatite presence. Sometimes when the pulp has died, the dentin becomes discolored and darker. It may also become gray and brown in individuals who have assumed tetracycline antibiotics during dentin formative stages (development stages); consequently also the enamel appears to acquire the same coloration.

1.2.3 Ultrastructure of the Enamel

The ultrastructure of the enamel is formed of conglomerate of many units of enamel prisms (from 4 to 13 million depending on the volume of the tooth).

A prism has a cylindrical shape and it is in intimate contact one to another; they are arranged in overlapping wavy rows starting from the enamel–cement junction up to the cusps (Fig. 1.2). In cross section the prism has a typical key-hole aspect, the so-called head and tail; the disposition of the head of the prism between the two tails of the neighbor prisms leaves a very small empty space that is filled by organic substances. Each prism is covered by crystals and interprismatic substance with longitudinal arrangement called the *sheath* of the prism (Figs. 1.3 and 1.4).

Etching with common acids in adhesive procedures modify the enamel surface, resulting in the dissolution of the prism's structure; depending on the part of surface etched, occlusal cusps or lateral (buccal and lingual), the central part of the crystal or its periphery is demineralized and so highlights the prism's structure in a different

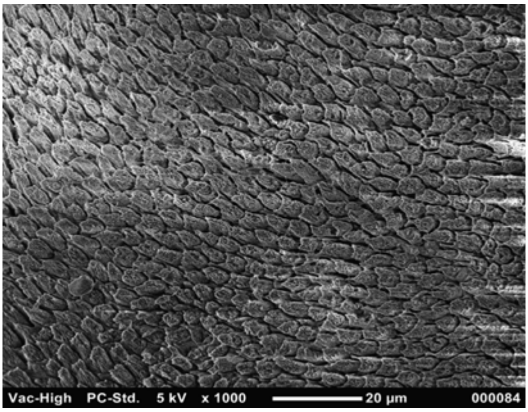

Fig. 1.5 SEM image at 1000× magnification shows buccal and lingual enamel surface etched with 37 % orthophosphoric acid: Silverstone type II pattern

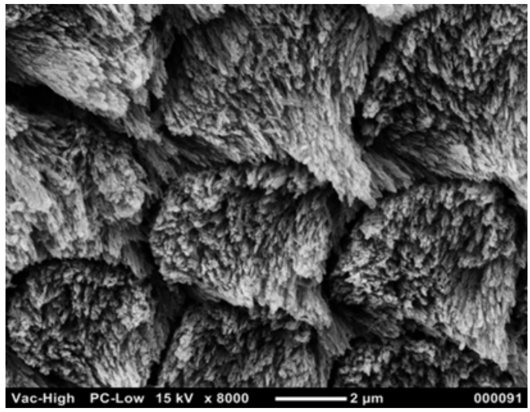

Fig. 1.7 SEM image at higher magnification (8000×) shows buccal and lingual enamel surface etched with 37 % orthophosphoric acid: Silverstone type II pattern. The etching works more on the periphery of the prism than on the core

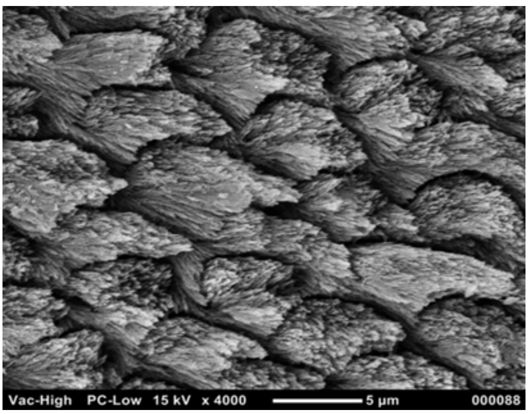

Fig. 1.6 SEM image at 4000× magnification shows buccal and lingual enamel surface etched with 37 % orthophosphoric acid: Silverstone type II pattern

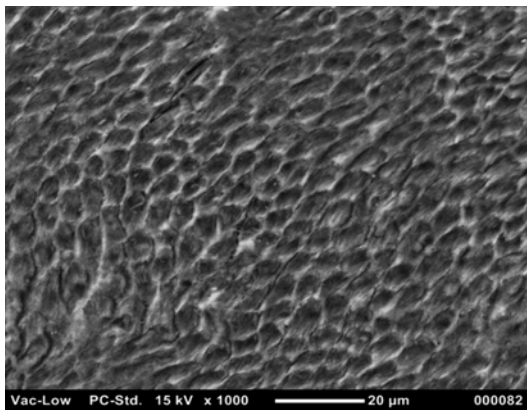

Fig. 1.8 SEM image (1000×) of cross section of enamel prisms etched with 37 % orthophosphoric acid: Silverstone type I etching pattern. The acid works more on the core of the prism, typically on the occlusal enamel surface

way (Silverstone type I and II patterns) (Figs. 1.5, 1.6, 1.7, 1.8, and 1.9).

The enamel of marginal ridges of young permanent teeth and of the surface of primary teeth presents an irregular arrangement of the crystals, parallel to each other and perpendicular to the surface (aprismatic enamel), that confers a higher resistance to acid dissolution to the enamel (Fig. 1.10).

The enamel–dentin junction is the border area between the enamel and the dentin. At microscopic observation it shows a wavy line with a more or less pronounced concavity facing the enamel. This arrangement favors the most intimate union of the dentin and the enamel. In correspondence of the cusps, the junction is crossed by numerous terminal branches of the dental tubules [1] (Figs. 1.11 and 1.12).

Enamel modification are observable on the surface of the enamel; the so-called perichimita or incremental lines are layers of prisms spaced every 20–80 µm overlapping from the enamel–cement junction to the internal layers of the enamel that are formed by the eruption onwards [1] (Fig. 1.13).

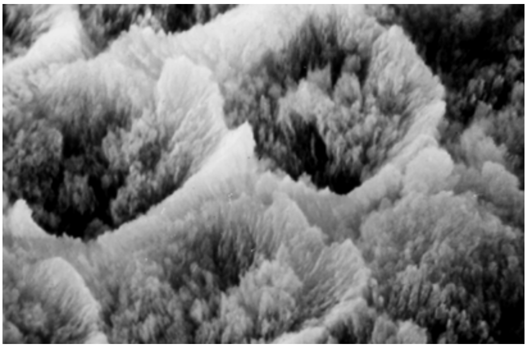

Fig. 1.9 SEM image of cross section of enamel prisms etched with 37 % orthophosphoric acid: Silverstone type I etching pattern. The acid works more on the core of the prism, typically on the occlusal enamel surface

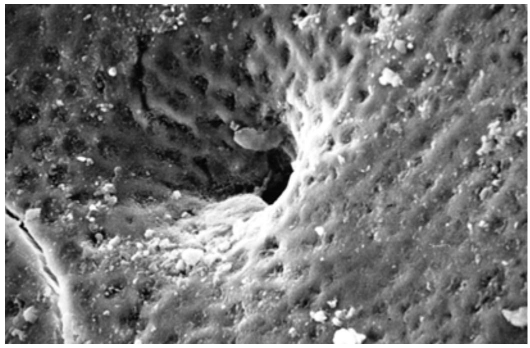

Fig. 1.10 SEM image (1000×) of aprismatic enamel also showing a development defect (lacuna)

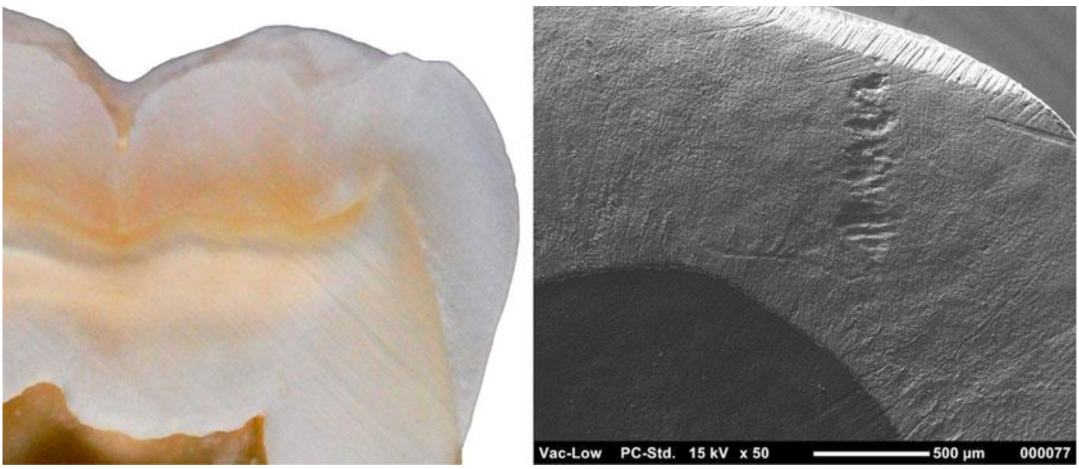

Fig. 1.11 Microphotography and SEM image (50×) of enamel–dentin junction

Sometimes a young enamel surface shows development anomalies (qualitative and quantitative) in the form of holes or gaps or hypomineralization that facilitate the start of the carious process.

1.3 Pulp–Dentin Complex

Pulp–dentin complex is a specialized connective tissue of the tooth. Both the pulp and dentin originate from the mesodermal tissue derived from the dental papilla. The dentin is a highly mineralized and avascular tissue; on the opposite, dental pulp is a highly vascularized tissue, with rich innervation. The dentin forms the largest part of the tooth, being the bearing structure of almost the entire length of the tooth [1]. The dentin surrounds the pulp tissue, from the pulp chamber up to the radicular canal. Externally it is covered by enamel on the crown and by cementum on the root/s of the tooth. The initial stages of odontogenesis begin in the external area of the dentin and continue with a centripetal direction; effectively, the odontoblasts move towards the inside of the tooth, leaving during their path their cytoplasmatic extension, called the odontoblast process, included within the secreted organic matrix of the primary dentin. The dentin consists mostly of an

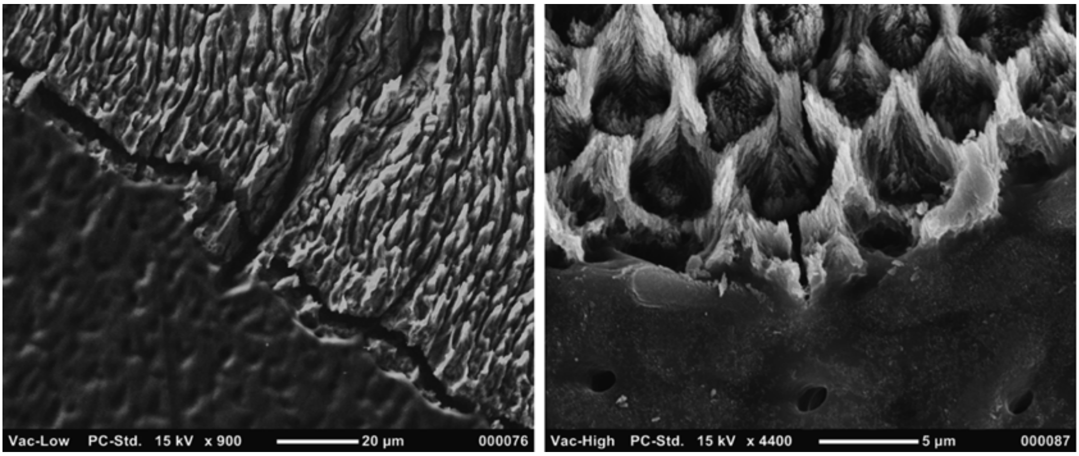

Fig. 1.12 SEM observation off enamel–dentin junction: left lower magnification (900×) shows a wavy lines with a concavity facing the enamel that favors a most intimate union of tissues; right higher magnification (4400×) shows dentin tubules and enamel prisms just on the border

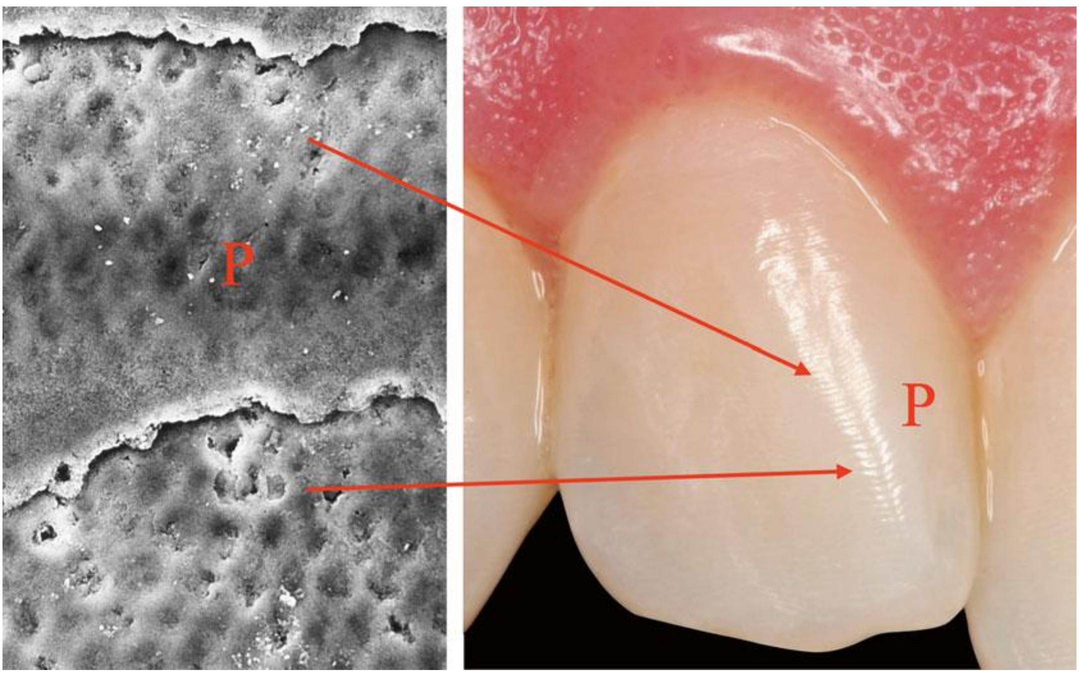

Fig. 1.13 Microphotography and SEM image of perichimita (*P*) or incremental lines. The layers of prisms are spaced 20–80 µm

irregular weave of collagen fibrils intimately interwoven with hydroxyapatite crystals. The dentin progressively mineralized due to the deposition of hydroxyapatite crystals to form the dentin tubules that represent the basic architecture of the dentin. Each odontoblastic process is located in one dentinal tubule and its cellular body do not remain included in the produced tissue, but in the outer layer of the pulp, and this is why these two tissues are closely related to one another and are so named pulp–dentin complex [1] (Fig. 1.14). The inner layer of the dentin, the predentin, is not

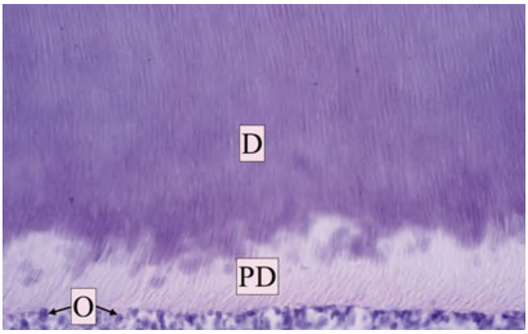

Fig. 1.14 Dentin pulp complex at optical microscopy (OM). Dentin (*D*) and predentin (*PD*) with dentin tubules; the odontoblasts (*O*) are aligned on the external layer of the pulp (Reprinted with permission from Fonzi et al. [5])

mineralized. The odontoblasts make the formation of the new dentin layer, just above the pulp, possible; in fact the dentin undergoes several changes in its volume during the life, due to its continuous formation from the periphery of the underlying pulp tissue (secondary dentin) or to formation of a barrier as a reaction from irritating external stimuli (tertiary dentin: reactive and sclerotic), with subsequent reduction of the pulp chamber volume [1].

1.4 Dentin

1.4.1 Chemical Properties of Dentin

The dentin is composed of 70 % inorganic material, 18 % organic matrix, and 12 % water in weight.

The inorganic material consists mostly of hydroxyapatite crystals, whose size is 50–60 nm in length and 20–30 nm in width; carbonate and traces of other elements (F, Na, Mg, C, Ba, Al, Z, K, Fe) are also present [3]. The fluoride concentration in the inorganic phases seems to be influenced by the content of fluorine ions in the diet and by the amount of time of tooth exposure to the same fluorides.

The organic matrix consists essentially of type I collagen and non-collagen proteins that also work as regulator of the mineralization of dentin (proteoglycans, phosphoproteins, glycoproteins, gamma-carboxyglutamic acid, etc.); there is lack of type III collagen fibers.

The type I collagen represents 80–90 % of the organic matrix. Proteoglycans (protein–glycosaminoglycan complexes) act as regulators of the fibrillogenesis during the dentinogenesis and, therefore, for the organization of the predentin matrix, with a specific role for the inhibition of the formation of the mineral phase.

Phosphoproteins (PP-H) play a role in the front of mineralization of the dentin, facilitating the formation of hydroxyapatite crystals for their ability to bind Ca and P; the gamma-carboxyglutamic acid has the same role to bind proteins (Gla protein).

Other organic components are lipids (cholesterol and phospholipids), citric acid, and lactates. According to their specific metabolic role, these different organic components are mainly present in the different areas of dentin.

1.4.2 Physical Properties of Dentin

The dentin is less mineralized and more elastic than enamel (Ca/P ratio lower: 1.96 ± 0.062), but it is stiffer and more mineralized than the cement and the bone. Dentin has a pale yellow color, thus affecting the color of the crown. It is very permeable for the presence of the tubular system that crosses it for the whole thickness, from the pulp to the enamel-dentin and dentin–cement junction. The presence of dentin tubules also affects conductivity and thermal diffusivity of the dentin; however, because of its compact shape, the presence of dentin tubules does not allow the passage of liquids and microorganisms. The tubular structure and organic collagen matrix give the dentin a high degree of elasticity.

1.4.3 Ultrastucture of the Dentin

A chronological and functional subdivision of the dentin considers primary, secondary, and tertiary dentin. The dentin can be divided, from the border with the pulp to the junction with the enamel, into three regions, each one with specific

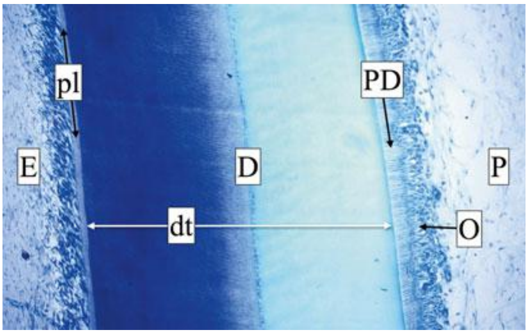

Fig. 1.15 Cross section of a tooth crown at optical microscopy (OM). From left to right are the visible enamel (*E*); the proteic layer (*pl*); the dentin (*D*), crossed by dentin tubules (*dt*); the non-mineralized predentin (*PD*); and the odontoblast (*O*) on the external part of pulp tissue (*P*)

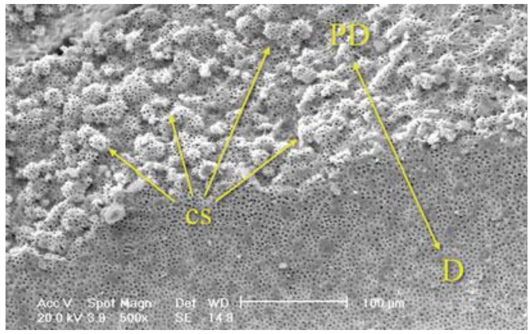

Fig. 1.16 Border between predentin and circumpulpal dentin presents globular structures called calcospherites and represents the mineralization front of the dentin

characteristics: the predentin, the circumpulpal dentin, and the mantle dentin (Fig. 1.15).

1.4.3.1 Predentin

The predentin is a non-mineralized layer (15–40 µm thick) of the dentin, placed just above the pulp and below the circumpulpal dentin. The predentin is continuously formed and persists throughout the life of the tooth; its formation is followed by the simultaneous mineralization of the dentin at the same speed with which it is formed, so that the thickness of the predentin remains constant. The type I collagen fibrils are arranged parallel to the boundary line between the pulp and dentin, to form an overlapping network intertwined in a messy way. During the early stages of dentin mineralization, at the border with circumpulpal dentin, crystals of hydroxyapatite are deposited inside and around the collagen fibers of the predentin, in the form of spherical clusters growing in centrifugal direction. These structures are called calcospherites and represent the mineralization front of the dentin (Fig. 1.16). Getting closer to the front of mineralization of the predentin, the collagen network becomes more and more compact, as the result of a process of maturation of interfibrillary bonds. Therefore, predentin can be considered as an area of maturation of collagen fibers and of inhibition of mineralization.

1.4.3.2 Circumpulpal Dentin

It is the main and more calcified mass of dentin, located between the predentin and the mantle dentin. The type I collagen fibrils are arranged perpendicularly to the dentinal tubules; they increase in number and diameter towards the junction with the enamel, becoming more compact. Some thin areas of circumpulpal dentin present hypomineralized and not mineralized matrix; these areas are formed as the result of the lacking coalescence of the calcospherites and appear as irregular or roughly spherical and apparently empty spaces, called interglobular dentin.

1.4.3.3 Mantle Dentin

It is the thin peripheral layer of dentin (thickness of about 15–20 µm) placed just below the enamel-dentin junction and above the circumpulpal dentin. It is the first dentin to be formed and differs from the circumpulpal dentin for a different arrangement and a greater diameter of the collagen fibrils (0.1–0.2 µm). The collagen fibrils are perpendicularly aligned to the enamel-dentin junction and are covered by glycosaminoglycans. Aperiodic fibrils (type III collagen) are present among the collagen fibrils. The mantle dentin is less mineralized of the circumpulpal dentin.

1.4.3.4 Dentinal Tubules

Dentinal tubules present different size and distribution in different areas of the tooth. Their diameter is about 2–3 μm in proximity of the pulp, and it is reduced to 0.5–0.9 μm in proximity to the junction with the enamel (Fig. 1.17). Also their number varies from about 45,000 per mm² in the proximity of the pulp to 29,000–35,000 per mm² in the intermediate part, up to about 20,000 per mm² close to the enamel. The reduction in diameter is due to an increase of the peritubular dentin, while the decrease in the number of tubules is only apparent, because of a gradual increase of the surface area of the tooth towards the enamel–dentin junction. In fact, also considering the decrease in tubular diameter, the distance between two adjacent tubules is 15 μm in the outer periphery of the dentin and only 6 μm in proximity of the pulp (Fig. 1.18). The number and the diameter of the tubules affect the reaction of the pulp and many properties of dentin, such as the sensitivity and permeability. Dentin permeability is proportional to the product of the number of tubules for their diameter and increases towards the pulp exponentially, since the dentinal tubules progressively increase precisely in number and diameter towards the pulp. The tubules have a curvilinear S-like path, with

Fig. 1.17 SEM image showing lateral cross section of peripheral dentin (preparation per fracture)

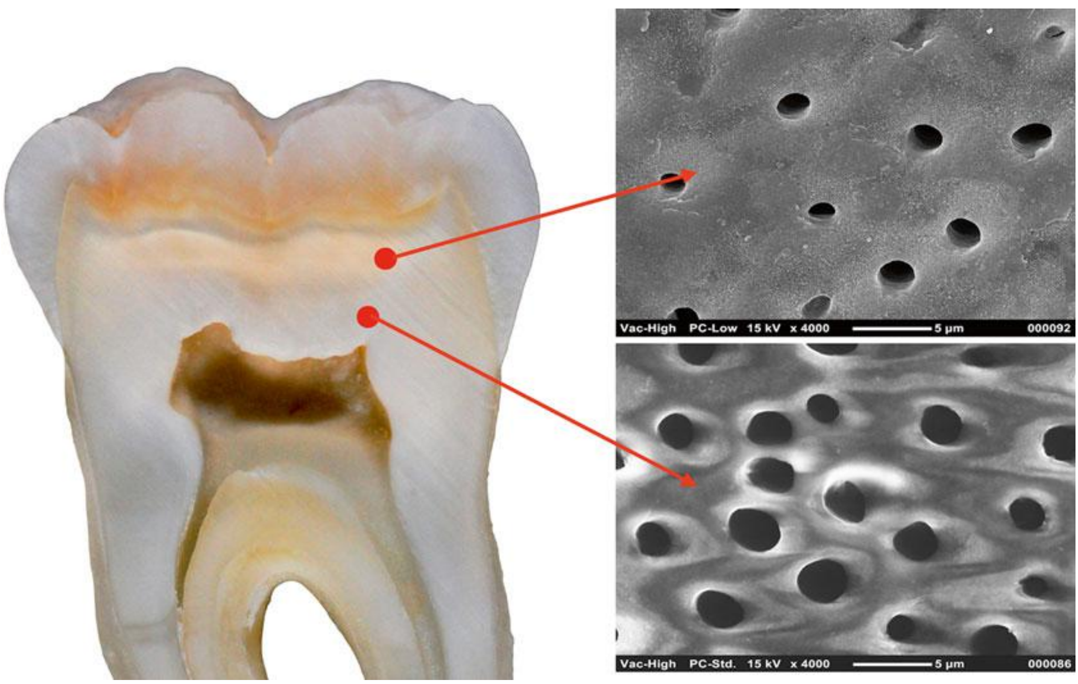

Fig. 1.18 The number of dentin tubules varies from about 45,000 per mm² in the proximity of the pulp to 29,000–35,000 per mm² in the intermediate part and up to about 20,000 per mm² close to the enamel. Also the tubular diameter decreases, while the distance between two adjacent tubules changes from 15 μm in the outer periphery of the dentin up to only 6 μm in proximity of the pulp

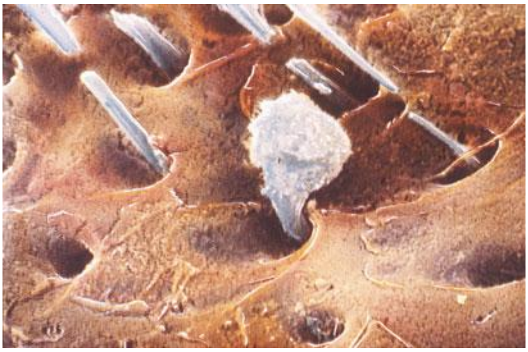

Fig. 1.19 Hand-painted SEM image (3500×): view from pulp side of predentin showing one odontoblastic cell body and other odontoblastic processes (Reprinted with permission from Fonzi et al. [5])

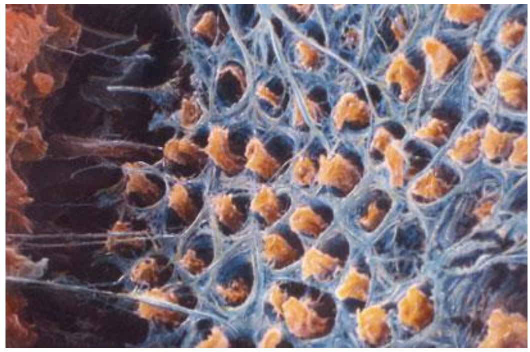

Fig. 1.20 Hand-painted SEM images of circumpulpal dentin: dentin tubules are crossed by the odontoblastic processes

the first external convexity facing in the occlusal direction but substantially perpendicular to the outer surface of the tooth. This is particularly important for laser irradiation practice. In correspondence of the apical one-third of the root and above the horns pulp and below the respective cusps, the curvatures are almost absent. The tubules are connected by small lateral canals that diverge along their path, reaching the junction with the cement and the enamel, where they bifurcate.

1.4.3.5 Contents of the Dentinal Tubules: Odontoblast Process

Each tubule is crossed by the cytoplasmic extension of the odontoblast, the odontoblast process. In contrast to the cell body, the odontoblast process contains few organelles and a fairly developed cytoskeleton, characterized by microtubules (27 nm in diameter) and actin microfilaments (5–8 nm in diameter). Some immunofluorescence investigations report that the odontoblastic process extends for the whole length of the tubule, but more recent data, on the contrary, seems to confirm that the odontoblastic process occupies and only extends in the inner one-third of the dentin tubule [2] (Figs. 1.19 and 1.20).

1.4.3.6 Periodontoblastic Space

The periodontoblastic space is a space included between the wall of the dentinal tubule and the odontoblastic process. The space is very small in the vicinity of the pulp because the odontoblastic process occupies the whole dentinal tubule and its thickness increases moving away from predentin. This space contains the dentinal fluid that may be considered a transudate or filtrate of the capillaries of the pulp (see Fig. 1.21). The periodontoblastic space and the dentinal fluid are a way through which various substances can reach the enamel-dentin junction [2].

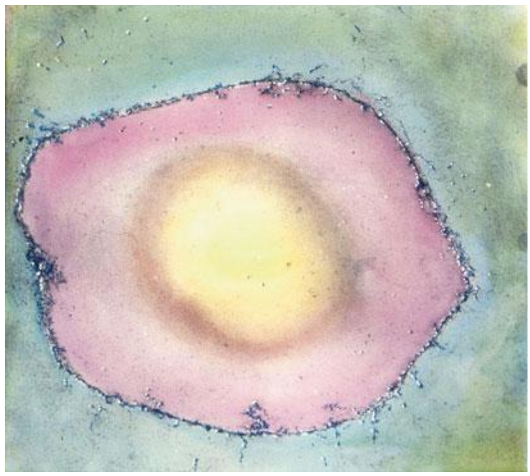

Fig. 1.21 Hand-painted SEM image shows dentin tubule section. Hypomineralized inner layer or sheath (often referred to as lamina limitans) is colored pink; the calcified peritubular dentin appears light blue. The odontoblastic process is inside the tubule (colored in *yellow*) (Reprinted with permission from Fonzi et al. [5])

The presence of dentinal fluid is the base of the hydrodynamic theory of the dentinal hypersensitivity.

Fig. 1.22 Hand-painted SEM image of a dentin tubule section: the dentin fluid is colored pink and the odontoblastic process is yellow; the wall of the dentinal tubules is covered by a hypomineralized sheath (colored in *light blue*) (Reprinted with permission from Fonzi et al. [5])

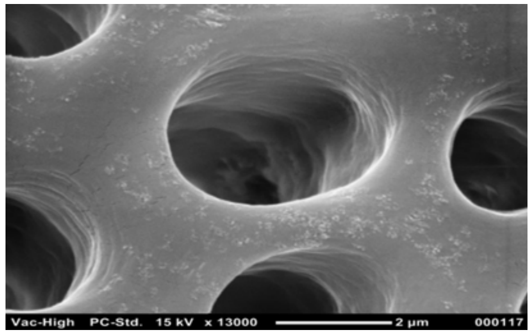

Fig. 1.23 SEM image at high magnification (13,000×) shows the hyper-mineralized layer of peritubular dentin as high electron-reflecting area. The intertubular dentin is a dentin present between the dentinal tubules

1.4.3.7 Hypomineralized Sheath (Lamina Limitans)

The wall of the dentinal tubules is covered, from the border with predentin up to the junction with the enamel, by the hypomineralized sheath (often referred to as the lamina limitans or hypomineralized inner layer) [2].

The hypomineralized sheath has a high content of glycosaminoglycans and high resistance to the demineralization processes of the tooth and to the treatment of the dentin with collagenase but not to that with hyaluronidase.

SEM observation shows the peritubular hypomineralized sheath as a continuous coating or in the form of thin fibrils. Using an MET the hypomineralized sheath is always visible as a line of demarcation between the electron-dense dentin and the periodontoblastic space (Figs. 1.21 and 1.22). For its high content in glycosaminoglycans, the sheath could act as an inhibitor of the mineralization; the glycosaminoglycans prevent the precipitation of the Ca ions present in dentinal fluid and, therefore, the processes of dentin sclerosis.

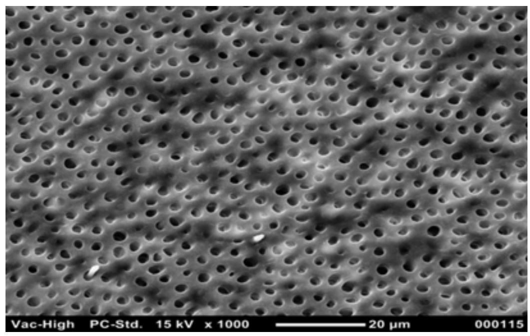

Fig. 1.24 SEM image at 1000× magnification showing non-prepared occlusal dentin surface after tooth section per fracture

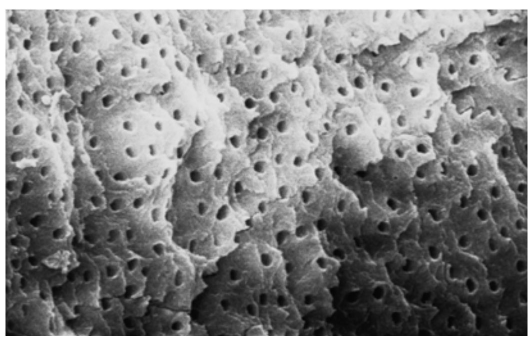

Fig. 1.25 SEM image at same magnification of laser-prepared dentin shows the typical aspect of laser ablation prevalent on intertubular dentin

1.4.3.8 Peritubular Dentin and Intertubular Dentin

The peritubular dentin is a hyper-mineralized layer of the dentin that lines the inner wall of the dentinal tubules. The intertubular dentin is the dentin present between the dentinal tubules (Fig. 1.23). The intertubular dentin is less mineralized than the peritubular and this is why it is easier to be ablated by erbium lasers, producing at SEM observation, the typical aspect of lased dentin surface (Figs. 1.24 and 1.25). The peritubular dentin, being an intratubular dentin, is deposited continuously throughout the life of the tooth. It is not present in the predentin and in the interglobular dentin. Into dentinal tubules of the circumpulpar dentin the thickness of peritubular dentin gradually increases, from the border with predentin towards the enamel-dentin junction. With age, there is a progressive reduction of the diameter of the dentinal tubule, in the peripheral dentin close to the enamel junction, until its complete obliteration; this physiological sclerosis process is likely a defensive attempt of the pulp, through the reduction of the tubular diameter, to reduce the dentinal permeability. The physiological sclerosis of the tubules is also completed, more and more quickly in areas corresponding to dentin surfaces subjected to particular stress or affected by initial carious lesions.

The collagen fibrils are poorest than in intertubular dentin, while greater is the content in glycosaminoglycans and glycoproteins.

The peritubular dentin has higher concentration of mineral ions (Mg, Ca, and P), whose average content per unit volume appears to be 40 % higher than in the intertubular dentin. The crystals mainly consist of hydroxyapatite and whitlockite (beta-tricalcium phosphate).

Intertubular dentin has the fibrils of type I collagen (from 0.5 to 0.3 μm diameter) of the intertubular dentin, so arranged perpendicular to the axis of the dentinal tubules; the crystals of hydroxyapatite, 10–90 nm long and 4–17 nm thick, are arranged with their axis parallel to the axis of the fibrils themselves. The proteoglycans constitute part of the fundamental substance.

1.4.4 Dentin Development

Depending on its development stage, the dentin is divided into primary, secondary, and tertiary dentin.

1.4.4.1 Primary Dentin

The primary dentin is produced during the odontogenesis until the eruption of the tooth into the oral cavity. The process of dentinogenesis begins from the predentin, the inner noncalcified organic matrix of the dentin positioned on the surface of the pulp tissue and containing the odontoblasts.

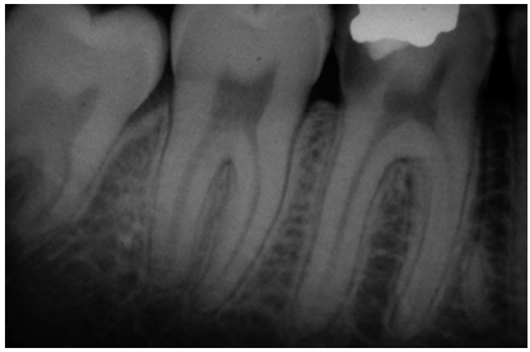

Fig. 1.26 X-ray shows a reactive response of dentin of first lower molar to a carious process

1.4.4.2 Secondary Dentin

After the eruption in the oral cavity, the formation of the dentin continues, albeit slowly throughout life, as the secondary dentin, gradually reducing the extension of the pulp chamber. In the posterior teeth its deposition is not uniform but occurs in prevalence in correspondence of the floor and of the roof of the pulp chamber, especially in correspondence of pulp horns; therefore, the pulp volume tends to decrease with age.

1.4.4.3 Tertiary Dentin

The tertiary dentin is a reactive response of the dentin to external stimuli. Irritative, moderate-acute and/or repeated stimuli of any nature, including incorrect tooth brushing, attrition, erosion, carious process, trauma, or deep conservative restorations, can induce the odontoblasts from the affected area to produce the reactive dentin, just called tertiary (Fig. 1.26). The amount of tertiary dentin produced seems proportional to the amount of primary dentin affected or removed, and its structure may vary in relation to the intensity and duration of the irritative stimulus (acute or moderate or mild) and finally to the damage suffered by odontoblasts.

The tertiary dentin can be tubular (in the cases of medium irritative stimuli without damage to the odontoblasts) or atubular (in the cases of acute irritative stimuli) for the incapacity of the cells, fibroblasts and mesenchymal cells to become odontoblasts and to produce the typical dentin. In this case, the irregularity of the tertiary dentine seems to relate to the state of differentiation of the replacement cells. The dentinal tubules

Fig. 1.27 X-ray shows a physiological modification called dentin sclerosis, due in this case to aging

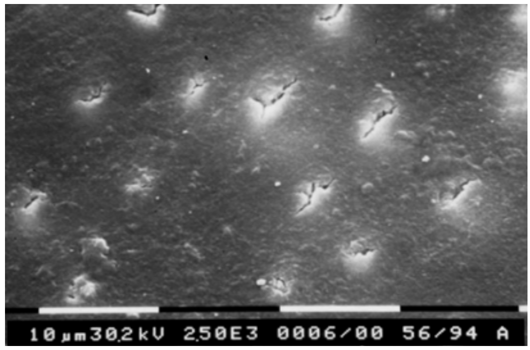

Fig. 1.28 SEM image (2500×) of sclerotic dentin shows the deposition of calcified material that progressively occludes the dentinal tubules. The more calcified tubular areas reflect more the electrons during the scansion (whiter areas)

can be quite irregular or sometimes show a partial or total atypical sclerosis.

1.4.4.4 Sclerotic Dentin

Due to aging, the dentin can undergo physiological modification called physiological dentin sclerosis. These modifications may also happen as a reaction to mild irritative stimuli (such as a light continuing abrasion or slowly, advancing chronic decay), and in this case the dentin is named reactive sclerotic dentin. The sclerosis process is consequent to the slow production and deposition of a calcified material that progressively occludes the dentinal tubules (Fig. 1.27). The calcified crystals appear to be made up mostly of whitlockite (or crystals of caries) (beta-tricalcium phosphate), with the characteristic form of large cuboidal or rhomboid crystals (200–600 nm). The calcified area is harder, less sensitive, and more protective against irritative stimuli. Observing with the optical microscope tooth sections presenting sclerotic dentin, these areas appear translucent due to obliteration of the dentinal tubules with a calcified material, which has the same index of refraction of the surrounding dentin (Fig. 1.28).

1.4.4.5 Eburnated Dentin

It is a reactive sclerotic dentin that is exposed to the external environment for progressive loss of external covering dental tissues, for chronic caries, or for other mechanical stimuli (erosion and abrasion). Eburnated dentin is a very hard and dark but also smooth and cleansable surface.

1.4.4.6 Dead Parts

Consequently to moderate and/or repeated irritative stimuli, the odontoblastic process may suffer, shrinking and degenerating, as a consequence of deposition of tertiary reactive dentin or dislocation of the odontoblast body.

1.4.4.7 Incremental Lines

The incremental lines are spaced about 4–6 μm and correspond to the rhythmic succession of activity and quiescence phases of dentin deposition and represent the daily increase of tissue. Observation at optical microscope of tooth sections can show dark lines with an approximately perpendicular path to the dentinal tubules. Sections of the teeth of persons that received tetracycline antibiotics during the period of odontogenesis show, at fluorescence microscope observation, yellow fluorescent incremental lines. These areas correspond to the anatomical sites of dentin undergoing mineralization at the time of taking the tetracycline. The rhythmicity of dentinogenesis and persistence in the teeth of the fluorescence area allow going back with a good approximation to the period when the antibiotic was taken.

1.4.5 Dentin and Cavity Preparation

During carious removal of a decayed tooth, the deeper the cavity, the greater are the diameter and the number of dentinal tubules exposed and, therefore, the greater the permeability of the dentine. As a consequence, the deeper the cavity, the more

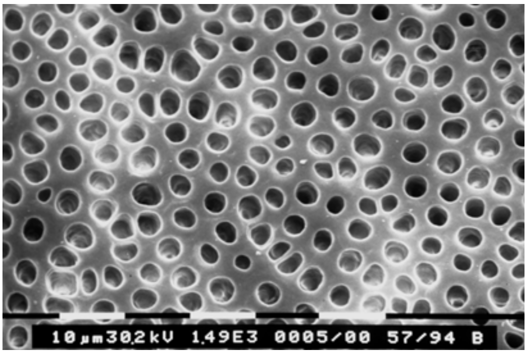

Fig. 1.29 SEM image (1400×) of occlusal cross section of dentin surface of class 1 cavity

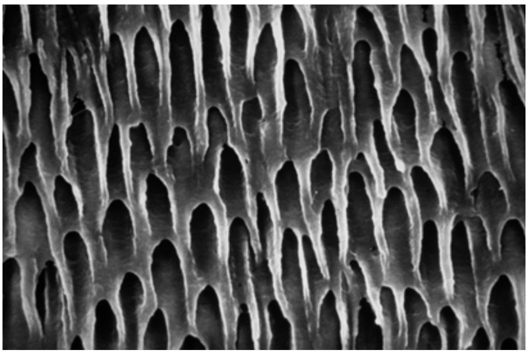

Fig. 1.30 SEM image showing the oblique inclination of dentin tubules of the axial walls of class 2 and 3 cavities

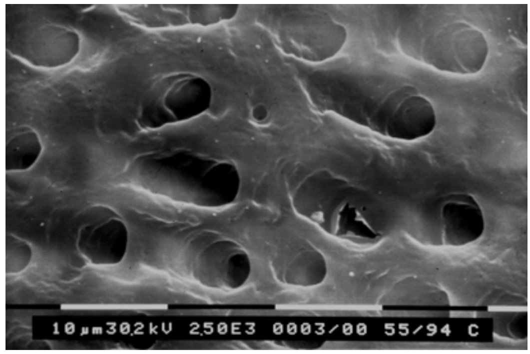

Fig. 1.31 SEM image showing the oblique inclination of dentin tubules of the axial wall of class 5 cavities

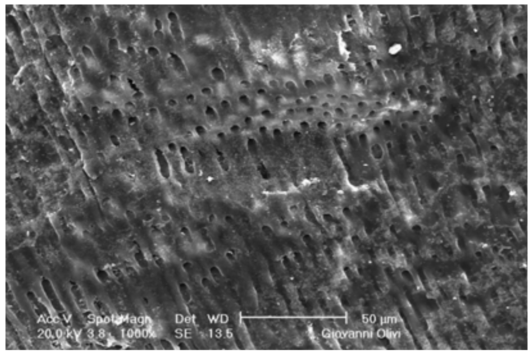

Fig. 1.32 SEM image shows the oblique aspect of deep dentin after class 5 laser cavity preparation (Er:YAG 160 mJ, 10 Hz, 50 μs pulse duration, 600 μm tip); the dentin tubule opening is insufficient and acid etching is required to improve the adhesion

the possibility of a dentin postoperatory sensitivity and of an inflammatory reaction in the pulp. The bottom of occlusal cavity (class 1 cavity) represents the roof of the pulp chamber and it is the part that presents more changes in the number and size of the dentin tubules, proportionally to the dentin distance from the pulp. The orientation of dentin tubules is perpendicular to the bottom of the surface in class 1 cavities. The orientation of dentin tubules is oblique to the axial wall in class 2 and class 3 cavities, while in the cervical wall of class 5 cavity, the transversal aspect of tubules appear ovoidal (Figs. 1.29, 1.30, and 1.31).

Operative Considerations When a cavity is very deep close to pulp tissue, the very thin remaining layer of dentin has a very different composition, varying from deep circumpulpal dentin and predentin. Depending on the type of decay, a fast and aggressive caries or a slowly chronic one, the presence of very mineralized tissue (reactive or sclerotic tissue) or fibril organic matrix tissue (predentin) conditions the procedure approach (see Chaps. 4, 7, and 8) and the choice of adhesive system to be used (see Chap. 5). Also, the type of cavity involves considerations on the number of tubules exposed and their orientation and also in this case conditions the clinical approach of laser irradiation and the type of bonding procedure to be applied (Fig. 1.32).

1.5 Dental Pulp

Dental pulp is a connective tissue, highly vascularized and richly innervated, contained into the pulp chamber of the crown and root canals. As other connective tissues, the pulp is composed of a population of different cells immersed in intercellular organic matrix characterized by fundamental substance and fibers. The organic matrix amounts to 25 %, while the remaining 75 % is represented by water. *This variety of components is an important factor to consider for understanding the laser–tissue interaction among the different wavelengths available and the pulp tissue, during the pulp vital procedures (pulp capping and pulpotomy).* The main proteic components are the type I and III collagen fibers.

Pulp tissue is contained in a rigid cavity (dentin walls) with high tissue pressure (interstitial pressure) of 20–25 mm/Hg [2]. The presence of vital pulp is essential for the integrity of the tooth. Through the orifice of dentin tubules and small accessory lateral canals of the root, the pulp communicates with the periodontal ligament. Under the metabolic profile, the pulp shows a reduced consumption of oxygen compared to other connective tissues and is able, using anaerobic glycolysis, to withstand mild ischemic phenomena. Through the apical foramen the pulp tissue receives its vascularization from two terminal arterioles and innervation from terminal myelinated sensory fibers of the trigeminal nerve.

Dental pulp is organized in three well-defined areas. From predentin towards the center of the pulp chamber, successive layers include the odontoblast layer, the subodontoblastic layer (including an acellular area and an area rich in cells), and the main mass of the pulp.

1.5.1 Layer of Odontoblasts

The pulp is characterized by the presence along its border of the bodies of odontoblasts, the cells responsible for dentinogenesis during both odontogenesis and throughout the life of the tooth. The odontoblasts are postmitotic cells composed by a body and by a cytoplasmic process which engages in the respective dentinal tubule. The layer of the odontoblasts is constituted by a single row of odontoblast bodies arranged below the predentin. The body is cylindrical and of about 30–50 µm per about 5–8 µm. In an already erupted tooth, the odontoblasts ensure not only the constant formation of secondary dentin but also the formation of tertiary dentin. Different phases of intense metabolic activity are alternated with periods of quiescence (Figs. 1.33 and 1.34).

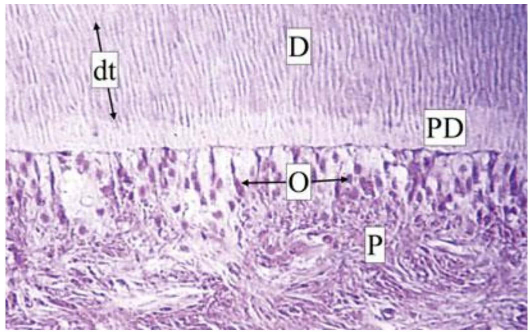

Fig. 1.33 Dentin pulp complex at optical microscopy (*OM*). On the top are the dentin (*D*) and predentin (*PD*) with dentin tubules; the odontoblasts (*O*) are aligned on the external layer of the pulp (*P*)

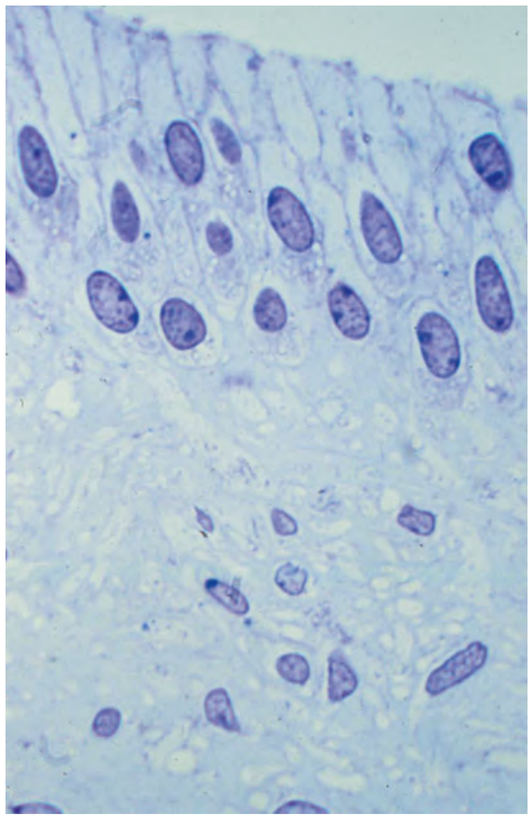

Fig. 1.34 Odontoblast bodies aligned on the border of the pulp, just close to the predentin (image at OM) (Reprinted with permission from Fonzi et al. [5])

1.5.2 Subodontoblastic Area

This area is most developed in the coronal pulp and young people and consists of two different areas, one poor of cells immediately below the layer of odontoblasts and another rich in cells; however, this partition in two zones may miss. The poor of cells area (about 40 μm) is rich in capillaries and amyelinic nerve fibers that, under the layer of odontoblasts, constitute the subodontoblastic neural plexus (of Raschkow). From this plexus, amielinic axons rise, wrapping around the body of the odontoblasts, penetrating into the dentinal tubule on the odontoblastic process for a short distance. The area rich of cells is characterized by the presence of a thick layer of fibroblasts and indifferentiated mesenchymal cells that, in case of pulp reactivity, may differentiate into odontoblasts and participate in the formation of tertiary and sclerotic dentin. Lymphocytes are also present in this area.

Fig. 1.35 SEM image of predentin surface: in cases of inflammation macrophage are present on the periphery of the pulp

1.5.3 Main Mass of the Pulp

The main mass of the pulp is formed by fibroblasts, lymphocytes, macrophages, undifferentiated mesenchymal cells, rare mast cells, and intercellular matrix.

1.5.3.1 Cells

The fibroblasts are the most numerous cells, especially in the old pulp of the teeth. The undifferentiated mesenchymal cells retain the ability to evolve into well-defined cellular types and this is a factor of considerable importance in the economy of biological tissue. Also "helper" and "suppressor" T cells, dendritic cells, and immune cells are present and essential for the initiation of immune response. The polymorph cells and macrophages are also found in cases of pulp inflammation or in case of enamel dysplasia (Fig. 1.35).

1.5.3.2 Intercellular Matrix

The fundamental substance of the pulp is formed by different proteoglycans. The fibers mainly consist of type I collagen and type III and constitute 34 % of the total protein. In the young pulp the fibrils, with a diameter of 10–20 nm, have an irregular arrangement and are diffusely present. As age progresses, in line with the reduction of cellular component, the collagen fibrils (40–70 nm) are united in compact bundles of fibers present in the central region of the pulp and in the apical third of the root. The apical part of the pulp becomes more fibrotic than in the coronal part.

1.5.3.3 Vascularization

Vascularization of the pulp is made by one or two terminal arterioles which penetrated in the pulp space through the foramen of the root apex. From the arterioles (the most voluminous vessels 100–150 μm in diameter), branch along the course in the central part of the root and coronal pulp, metarteriole, and capillaries. These form a rich plexus, in the poor layer of cells, that especially in young pulp come in contact with the odontoblasts. Subodontoblastic capillaries are made up of 4–5 % of capillary with a fenestrated endothelium with pores having a diameter of 60–80 nm. Venules, which are formed by the confluence of thin venous capillaries from the subodontoblastic network, follow the course of the arterioles. The pulp is rich in arteriovenous anastomoses to which it attaches particular importance in the regulation of pulpar microcirculation, especially in cases of hemorrhage or tissue

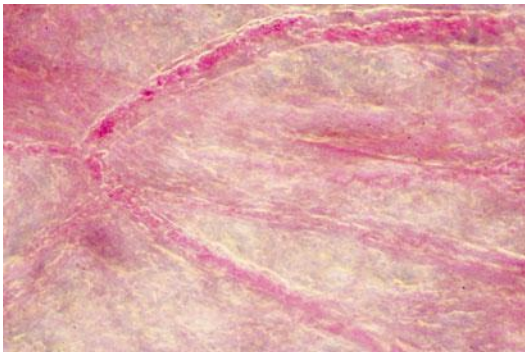

Fig. 1.36 OM (optical microscope) image shows pulp tissue suffering from pulpitis: diffuse vasodilation of capillaries within pulp tissue (Reprinted with permission from Kaitsas [6])

damage. The arteriolar wall is innervated by simphatic vasoconstrictor amyelinated fibers. In the pulp there are also lymphatic vessels (Fig. 1.36).

1.5.3.4 Innervation

The innervation of the pulp is very rich and includes both myelinated and amyelinated fibers. The myelinated are sensitive fibers of alpha–delta group belonging to the trigeminal nerve. Following the course of the vessels, the nerve fibers originate from the subodontoblastic nerve plexus; they pass between the odontoblast layer and reach the predentin, where they run for a short distance before engaging as naked axons in the dentinal tubules for about 100–150 nm, closely packed to the odontoblastic process by which they are separated by a gap of 20–40 nm.

1.6 Pulp–Dentinal Sensitivity

The stimulation of the pulp and dentin, either chemical or electrical or resulting from temperature changes or operator actions, evokes an exclusive nociceptive response and therefore a pain sensation.

The stimulation of the dentin produces a momentary acute pain, unlike the continuous acute pain that characterized pulpitis. The type of pain is very different if the stimulation is on the crown or on the exposed root and, thus, can be a diffused pain, and it is difficult to localize. Dentin shows different sensitivity according to the different areas: very sensitive in correspondence of the junction with the enamel and much more in the proximity of the pulp. Even today, there are many uncertainties and disagreements on the extent of the odontoblastic processes and of nerve fibers within the dentin tubules, while there seems to be a general agreement on the absence of nerve fibers on the outer periphery of the dentin. The issue on the pulp–dentin sensitivity is the subject of study and controversy and two theories are currently debated: the hydrodynamic theory and the theory of odontoblastic process like receptor.

1.6.1 The Hydrodynamic Theory

This theory assumes the sudden movement of dentin fluid within the tubules, caused by various stimuli (chemical, thermal, tactile, or osmotic) [7–10]. The movement of the fluid and the consequent periodontoblastic intratubular pressure variations would be able to cause an excitation of the nerve terminals (either directly or through the simultaneous displacement of the odontoblastic process): an increase of the nerve cell permeability to Na and consequently a depolarization of the membrane occurs, leading to an action potential.

The hydrodynamic theory satisfies some otherwise inexplicable occurrences:

(a) The immediate response to a stimulus of a warm or cold tooth knowing the low thermal diffusibility of the dentin
(b) The pain induced by the application on the dentin of hypertonic solutions (sugar, NaCl, or CaC_{12}) of material for temporary fillings or following a jet of air
(c) The persistence of sensitivity after applying local anesthetics on the exposed dentin
(d) The absence of pain after application of dentin algogenic substances to the skin

The cold, compressed air, mechanical stimuli, and hypertonic solutions cause an outward displacement of dentinal fluid; differently the heat causes an inward movement of fluid.

Section 8.1 debates some treatment possibility including laser therapy.

1.6.2 Theory of the Process as an Odontoblast Receptor

This theory is based on the assumption that the process of odontoblast cell has sensitive receptor capacity, acting as a primary nociceptors. The presence of synapse (gap junctions) between the odontoblastic process and terminals axons could explain the possibility of the odontoblast to transpose the stimulation of the nerve endings. On the opposite this presence is not completely confirmed and also the too low membrane potential (approximately 35 mV) detectable in the odontoblast deters to admit its function as receptor.

The origin of the odontoblast from the neural crest and the presence of AChE (acetylcholinesterase) and acetylcholine along the odontoblastic process and in the subodontoblastic layer support this theory. Also experimental results of the application of acetylcholine on dentin evoking pain that disappears after successive application of atropine support this theory.

1.7 Changes During Age

The continuous deposition of dentin restricts the pulp space and therefore reduces the total volume of the pulp.

This physiological process is sometimes enhanced by particular reactive events that can produce reactive dentin, varying the morphology of the pulp chamber from the horns of the pulp until they disappear. Also there is an accentuated narrowing or obliteration of the root canal.

In aged tooth there is a gradual reduction of the cell population and a contemporary substitution with bundles of collagen fibers (fibrosis of the pulp).

The decrease of metabolic exchanges and the hypoxia, due to the reduction of tissue, may promote the formation of extensive calcifications or denticles. *The biological reactivity of the pulp is greatly reduced and this must be considered when approaching deep decays or pulp exposures in aged tooth.*

1.8 Calcification of the Pulp

The calcification of the pulp can be classified in isolated (denticles or pulp calculus or stones) and diffuse calcifications.

The pulp calculus appears as a calcified nodule of the coronal pulp with various shape, size, and structure. Some are spherical and have a concentric lamellar structure; others, without a well-defined form, have no obvious laminations. In either case, the denticles are formed from calcified collagen fibrils; part of them may show poor, irregularly placed dentinal tubules. In this case they are also referred to as calculus, to distinguish them from atubular, false calculus. The denticles surrounded by pulp tissue are called "free" unlike those coated on the wall of the inside dentin that are referred to as "fixed." The diffused calcifications are more frequent in the radicular pulp, where they can completely occlude the canal lumen (Fig. 1.37).

Fig. 1.37 TEM (transmission electron microscope) image shows widespread calcification along the pulp capillaries (Reprinted with permission from Kaitsas [6])

1.9 Cement

The cement is a thin layer of calcified, compact connective tissue which is formed by specific cells, the cementoblasts. Cement allows the attack of the collagen fibers of the periodontal ligament on the root surface. Together with the alveolar bone, gingiva, and periodontal ligament, it is a part of the periodontal tissue called periodontium (peri = around; odons = tooth) that surrounds the tooth, contributing to its stabilization in the alveolar arch during function [2].

The cement is often described as a particular type of bone tissue, but it is significantly and substantially different because it is avascular. As a bone, the cement is a tissue with high plasticity: in fact it allows the fibers of the periodontal ligament to adapt itself to the different needs or functional moments, such as vertical migration of tooth, compensatory deposition of new tissue in case of wear of the crown, reparation of root fractures in correspondence with the resorption lacunae. Unlike the bone, just because of the lack of vascularization, the cement presents slower resorption and apposition phenomena. However, the metabolic activity of the cement is guaranteed by the vascularization of the periodontal ligament. For the purpose of this text, the cement is only briefly described.

1.9.1 Physical Properties of Cement

The cement has a pale yellow color and is less hard and mineralized than both enamel and dentin; it is very similar to the bone tissue, but less flexible.

1.9.2 Chemical Properties

The inorganic part is about 65 % in weight; the residual part is made of about 23 % organic material and 12 % water. The inorganic material is characterized by small crystals of hydroxyapatite similar to the dentin's crystals and by less chemical elements. The organic material consists essentially of collagen fibers (95 % of type I) and proteoglycans.

1.9.3 Ultrastructure of Cement

The cement is formed and deposited continuously, although very slowly, during the whole life of the tooth. Consequently, its thickness is a function of age. It is very thin (15–20 μm) at the cervical line and thicker at the apical one-third, improving thickness from about 200 μm at 20 years up to 600 μm in adulthood. A greater thickness is usually observed in the areas of bi- or trifurcation of the roots.

There are two types of tissue – the cellular cement and the acellular one. They differ not only for the presence or absence of cells but also for the localization, the extension, the thickness, the mineralization, and the relation with the periodontal ligament.

When the cement comes into direct contact with the oral environment, because of the phenomena of gingival recession, it loses its surface features and becomes sensitive to the carious attack (Fig. 1.38).

1.10 Enamel–Cement Junction

At the level of the cervical line, the border between enamel and cement is not always clear. In 30 % of cases, the cement partially covers the enamel beyond the cervical line. In 10 % of cases, the two tissues are not in contact, leaving an area of exposed dentin. In this case, a tooth with

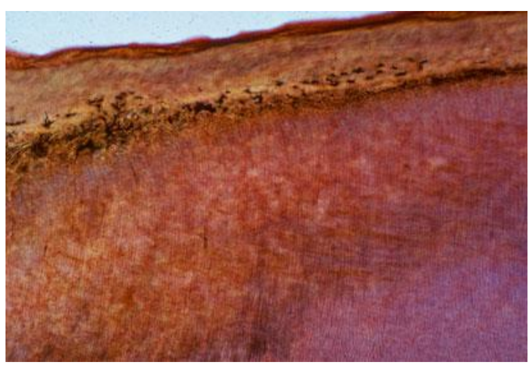

Fig. 1.38 OM (Optical Microscope) image shows the acellular external and cellular inner layers of cement in the cervical portion of the root. The cementoblasts are showed as the black bodies just close the dentin

exposed root due to gingival recession would be more sensitive to the action of cariogenic bacteria and to external stimuli.

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2 Restorative Dentistry

Giovanni Olivi and Matteo Olivi

Abstract

Restorative dentistry aims to restore the tooth anatomy, with the objective to preserve the pulp vitality and dental structure. The treatment of congenital lesions of the hard dental tissues, the prevention of dental decay, the relation with gingival marginal tissues are also included in this branch of operative dentistry. The knowledge and the adjustment of the balance between exogenous etiologic factors (cariogenic bacteria) and host factors (saliva, retention areas of plaque, tooth structure composition) of caries can allow the long-time maintenance of restoration and dental health. A treatment plan may, therefore, consider first the caries prevention, then the therapy with the more appropriate technique, and last the maintenance of the reestablished oral health with deferred follow-up sessions, according to individual caries risk factors. Different instrumentation may be used for this purpose, and the knowledge of different restorative materials as well as of the tooth anatomy (already discussed in Chap. 1) guides us to do the correct choice.

2.1 Introduction and Definition

Operative dentistry is the area of dentistry that involves the prevention and therapy of congenital or acquired lesions of the hard dental tissues. In Sturdevant's book on operative dentistry, the authors described it as the art and the science of diagnosis, treatment, and prognosis of defects of the teeth that do not require full coverage restoration for correction [1]. Accordingly to its purpose, operative dentistry also includes many other branches of dentistry: traumatology is involved when considering the preservation of the pulp vitality and the restoration of the tooth to the former shape and its function, following a tooth fracture. Periodontology is involved when the limit of a restoration is close or below the gingival tissues and bone. Considering the aim of conservation of the pulp vitality and dental structure, and the objective to restore the tooth

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anatomy, operative dentistry is also called, in some country, conservative dentistry or restorative dentistry, and these terms will be extensively used in this text.

2.2 Basic Cariology

Dental caries is a multifactorial disease. It is the result of the alteration of the balance between exogenous factors (cariogenic bacteria) and host factors (saliva, retention areas of plaque, tooth structure composition) [2]. This balance is influenced by other factors such as diet with the intake of fermentable carbohydrates and the presence or removal of bacterial plaque through the daily toothbrushing, flossing, and rinsing.

2.2.1 Bacteria and Biofilm

Today, great importance is given to the pathogenicity of the bacterial flora, but not all bacteria are able to produce acid metabolites that can lead to the production of caries. The bacterial species involved in the caries pathogenesis include *Streptococci mutans* and lactobacilli, which when increased in number alter the balance of the oral ecosystem [3, 4]. When the cariogenic bacterial species are structured and predominant in oral bacterial biofilm (plaque), there is an essential prerequisite for the establishment of dental caries [5, 6].

The composition of the bacterial biofilm varies during the life of an individual, and its disintegration and/or modification through the various measures of prophylaxis (toothbrushing, fluoride, diet) helps to modify the risk of caries [7].

The bacterial component of the plaque can be assessed through the use of selective media culture that allow a quantitative assessment, or more simply, it is advisable to use semiquantitative assessment systems performed on a saliva sample [7, 8].

These exams are just some of those needed for the evaluation of the risk of tooth decay, together with the evaluation of inappropriate diet habits, the verification of an inadequate salivary flow with low buffering capacity, an inadequate exposure to fluoride, poor oral hygiene, and the socioeconomic state, all recognized as important risk factors for caries [2, 3, 9].

2.3 Epidemiology

The epidemiological research on the prevalence of dental caries is not only based on the presence of decayed teeth but also on the missing or filled teeth. Accordingly, the term DMF index has been used for many decades and is well established as the key measure of caries prevalence in dental epidemiology.

There are two indexes: the DMFT that is related to the tooth and the DMFS related to the tooth surface (D = decayed, M = missing, F = filled, T = tooth, S = surface) [10].

In the United States, the National Health and Nutrition Examination Survey (NHANES) in 2005–2008 reported a significant decrease of dental caries in different age groups from the early 1970s [11].

More than 20 % people had untreated dental caries and 75 % had existing dental restorations. Prevalence of untreated dental caries varied significantly by poverty level for all age groups. Twenty-seven percent (27 %) of children and adolescents aged 5–19 years had at least one dental sealant. About 38 % of non-Hispanic black adults had not lost a permanent tooth compared with 51 % for non-Hispanic white and 52 % for Mexican-American persons. Almost 23 % of adults aged 65 and over were edentulous [11].

In Italy, quite recent data are available on caries experience on adults. An epidemiological survey, the National Pathfinder among Children's Oral Health in Italy, was promoted and carried out in 2004 and published in 2007 [12].

This study reported the actual oral health status of Italian 12-year-olds according to gender, residential area, and geographical distribution. Five thousand three hundred forty-two children were examined from March 2004 to April 2005, according to WHO criteria, including dental caries (decay at the dentinal lesion level) and Community Periodontal Index (CPI).

Dental caries were present in 43.1 % of the children, with a mean DMFT score of 1.09. Gingival bleeding was recorded in 23.8 % and calculus in 28.7 % of the examined children.

As result, the mean DMFT fell from over 5 to its present level, halving every decade over the past two decades; consequently, the recorded level of dental caries has become aligned with that in other Western-European countries. Nevertheless, differences in DMFT values remain between children from different socioeconomic backgrounds [12].

2.4 Objective of Restorative Dentistry

Restorative dentistry is the branch of dentistry involving people at all stages of life. When treatments are focused on children and adolescents, this branch is a part of pediatric dentistry.

The clinical expression of carious disease is the cavitation within the hard dental tissues, but the goal of restorative dentistry is not only the carious removal and successive filling but above all its prevention removing the causes and the predisposition to the pathology. Regardless of whether the patient is young or adult, the primary objective of restorative dentistry is to include in a treatment plan the measures of primary and secondary prevention besides the basic removal of cavities and their fillings.

2.4.1 Primary, Secondary, and Tertiary Prevention of Dental Caries

The assessment of risk of caries, the motivation and education to a focused program of professional oral hygiene and at-home dental care and diet, and the planning of periodic checkup and regular oral hygiene sessions are the key steps for the maintenance of oral health before and after the end of the dental treatment.

The preventive measurements for adults are limited to:

- Eliminate the causes of the dental disease and to motivate and encourage the patient for optimal control of bacterial plaque (toothbrushing and flossing) and to follow a proper diet.
- Provide control of the oral health status through periodic dental inspection and professional hygienic sessions.
- An adult with cervical exposure (gingival recession, elderly) has an increased risk of radicular decay; such patients should be motivated to correct toothbrushing. The application of fluorides in case of hypersensitivity, in addition to and maintenance of laser therapy for dental hypersensitivity, is advisable in these cases.
- An increased risk of tooth decay is also present in patients taking medications or whose salivary flow, for several reasons, is reduced.

Primary prevention program in the childhood or adolescent age includes:

- At-home twice daily brushing (with fluoridated toothpaste: 1000 ppm fluoride and pea-size dose before 6 years) [13, 14]
- Professional control of oral hygiene and diet
- Recall every 6–12 months – radiographs every 12–24 months
- Prevention of caries lesions by noninvasive but irreversible measurements (fissure sealing) [13]

Measurements of secondary prevention include:

- Interception and arrest, if possible, of the initial dental injury through noninvasive remineralization treatment
- Interception and treatment of caries, noncarious, and traumatic diseases of hard tissues

The restorative therapy also aims to the conservation of the tooth trough:

- The maintenance of pulp vitality and the prevention of future damages to dental hard tissues

- The restitution of form (shape) and function (restitutio ad integrum)
- The esthetic integration of the restoration or improvement of esthetics when it is desired, wanted, and demanded by the patient and clinically possible

These can be considered measurements of tertiary prevention.

Therefore, restorative dentistry is not uniquely focused on carious lesions, but may be associated with a precise prevention management plan, to avoid any new carious lesion or recurrence.

2.5 Diagnosis

A correct diagnosis of caries and the determination of pulp status must precede any therapeutic procedure.

The medical history of the patient, related to recent or past sensitivity or tooth pain or to past dental trauma, must be investigated. Even the type of pain, to mastication or consequent to chemical or thermal stimuli, is important for diagnosis.

The occlusal carious lesions are detectable through a direct and close inspection of the oral cavity, improved by magnification devices (loops or operating microscope); the visit must follow a professional dental hygiene session, so that when the teeth are dry and free of deposits and pigmentations, a better acquisition of visual information is possible. The caries diagnosis is based on ICDAS directions, which are simple, logical, and evidence-based systems for detection and classification of caries in clinical practice and dental research. Most of the study reported here and in Chap. 6 refers the visual inspection to this concept (Fig. 2.1).

The pit and fissure probing as well as the interdental spaces, with a well sharp-pointed probe, together with a close microscopic inspection allows a good evaluation of the type of fissure or the existence of detectable cavitation (see Chap. 6). To detect early and hidden occlusal and proximal decays in children and pregnant women, a laser fluorescent device (DIAGNOdent, KaVo, Germany) is very useful, because it allows good sensitivity and specificity diagnosis without exposing the patient to X-ray examination; in case of frequent recall sessions for high decay

ICDAS and the International Caries Classification and Management System™

ICDAS Lay Terms	Sound	Early Stage Decay		Established Decay		Severe Decay	
ICDAS Dental Terms	Sound	First visual change in enamel	Distinct visual change in enamel	Localized enamel breakdown	Underlying dentin shadow	Distinct cavity with visible dentin	Extensive cavity with visible dentin
ICDAS Detection	0	1	2	3	4	5	6
ICDAS Activity	ICDAS Activity +/–						

Fig. 2.1 A simple, logical, evidence-based system for detection and classification of caries (Based on data from ICDAS International Caries Classification and Management System™)

risk, the laser fluorescent device permits a good check and control over time, avoiding excessive X-ray dose exposure (see Chap. 6).

The pulp vitality tests should always be performed, especially in case of trauma and deep caries, and noted in the chart, to compare in subsequent tests.

Intraoral periapical and bitewing X-rays can be an important aid in the diagnosis of occlusal caries lesions underlying previous fillings and hidden proximal caries invisible to direct observation.

The examination of the superficial and deep periodontal tissues and its relationship with the restorative therapy should be performed before starting any conservative therapy (proximal and cervical tooth decay or injury, in juxta- or subgingival position) or esthetic treatment (whitening in case of presence of cervical lesions or gum recession).

The occlusal status and TMJ examination allow to evaluate the presence of functional disorders and/or anatomical factors that may affect the choice of techniques and materials to be used (filling or inlay/onlay, hardness and elasticity of the materials to be used).

An intraoral photographic series is useful for planning the work in case of complex quadrant restorations (direct and indirect multiple restorations) and completes the documentation.

The evaluation of the degree of cooperation of the patient also provides a valuable suggestion to predict its future involvement during and after treatment (oral hygiene and regular visits to the control), to direct the best treatment choice.

2.5.1 Caries Risk Assessment

The caries risk assessment (high, low, average) directs toward an operating procedure rather than another and toward choice for different types of restoration.

The presence of decayed teeth, of missing teeth, or of filled teeth and also the presence of white spot, plaque accumulation, crowding teeth, and bad oral and diet habits (dummy, nighttime use of the bottle, fermentable carbohydrates) and the socioeconomic status [15] are strong caries risk indicators and suggest for higher caries risk assessment and different preventive approaches for children and adolescents (Fig. 2.2).

Caries risk assessment

Risk factors	Low risk	Moderate risk	High risk
Patient has >1 interproximal lesions			√
Patient has active white spot lesions or enamel defects			√
Patient has defective restorations		√	
Patient has low salivary flow		√	
Patient wearing orthodontic appliance		√	
Regular toothbrush twice a day with fluoridated toothpaste	√		
Professional topical fluoride	√		
Patient with plaque accumulation		√	
Diet > 3 between meal per day sugar-containing snacks or beverages			√
Special health care needs patient		√	
Low socioeconomic status			√

Fig. 2.2 Caries risk assessment guidelines for adolescents (Based on data from AAPD clinical guidelines)

Caries management protocol					
Risk category	Diagnostics	Fluoride	Diet	Sealants	Restorative
Low risk	Recall sessions every 6 to 12 months Radiographs every 12 to 24 months	Regular toothbrush twice a day with fluoridated toothpaste	–	√	Surveillance
Moderate risk	Recall sessions every 6 months Radiographs every 12 months	Regular toothbrush twice a day with fluoridated toothpaste Professional topical treament every 6 months	Counseling	√	Active surveillance of incipient lesions
High risk	Recall sessions every 3 to 6 months Radiographs every 12 months Auxiliary diagnostics Diagnodent	toothbrush twice a day with 0.5 % fluoride Fluoride warnish Professional topical treament every 3 months	Counseling Xilitolo	√	Restore incipient, cavitated or enlariging lesions

Fig. 2.3 Different caries management protocols according to different caries risk groups (Based on data from AAPD clinical guidelines)

A caries management protocol allows to establish the need to complete the regular (standard) preventive measurements with closest measurements including fluoride supplements and professional topical treatment every 3–6 months during more frequent periodic sessions, monitoring for signs of caries progression and relapse [13] (Fig. 2.3).

2.6 Treatment Plan

A treatment plan must be explained to the patient who has to provide his informed consent to treatment. The parents or guardians of a minor patient must understand the importance of the prevention phase and provide consent, which must still be motivated and informed on the treatment plan chosen.

Dental caries can be largely prevented; prevention programs should therefore precede, accompany, and follow conservative treatment.

2.7 Methods of Caries Removal

Dentists are familiar with drills because they are the daily more frequently used instruments. These simple informations are necessary only to compare the conventional instrumentation with chemo-mechanical, air abrasion, and laser preparation.

2.7.1 High- and Low-Speed Drills

The high-speed drill or air turbine is the fastest instrument for dental structure removal (more than 200,000 rpm). The high speed and number of revolution per minute allow for minimal vibration and precise ablation of a dental cavity; it is the contact modality and the tactile feedback control that allow a precise ablation [16].

The interaction with the tooth produces abrasion of the dental structure, with formation of debris from dental ablation, and heating of the tooth structures, due to continuous friction.

Several rotating instruments are available for both high- and low-speed handpieces; diamond and multiblade carbide and the newest ceramic burrs also differ in shape, size, length, and grit.

Different shapes permit precise cutting of different forms that reproduce one of the burrs used: ball, pear, cylindric, tapered, pointed, football, or special shape. Different grits (from 100 μm up to 5–10 μm) permit different types of cut, from an unrefined dental tissue removal up to a very fine smoothening of the tooth margins and walls or a finishing of composite restoration.

Conditioning of surface and margin cavity, using 37 % orthophosphoric acid, is required after cavity preparation and margin smoothening to remove the produced debris and smear layer and to leave a surface suitable for bonding procedures; also the rise in pulp temperature may be a concern in case of deep cavities and dental trauma. Adequate water spray irrigation controls the rise in temperature and partially cleans the surface, but on the other hand contributes to the formation of mud and smear layer.

The high-speed drill can be also used to remove previously placed metal restorations (amalgam and gold).

Advantages of high-speed turbine are the fast dental procedure, the different possible shapes of preparation, the possibility to work on both the end and lateral sides of the burr and so in the undercuts of a cavity, and the tactile feedback control.

Disadvantages are related to the production of debris and smear layer during the ablation and the heating due to continuous friction. The heating is responsible for the unpleasant or painful perception. High-speed drill can create microcracks in the enamel and dentin. In deep cavity, high-speed instrumentation does not permit good control and minimal tissue removal, and also the safety is reduced when working on children and disabled patients, because of the potential of the patient's head to suddenly move during the procedure.

The low-speed drill works slowly from few revolution for minutes with a speed reducer (100–300) up to 20,000–40,000 revolution per minute, allowing better control in deep dentin carious removal, but however the tissue removal is not selective or minimally invasive.

The lower speed increases the perception of vibration but also permits less heating of the tooth and dental pulp; intermittent contact permits to control the pain perception.

However, some patients prefer the minimal vibration of the turbine, while others the lower friction of the low-speed drill; local anesthetic may be needed for comfortable preparation of the tooth or teeth.

Common disadvantages of high- and low-speed drills are the absence of caries selectivity and of antibacterial activity and the possible surrounding soft tissue damage during tooth preparation.

The introduction of adhesive restorative materials and acid-etching techniques changed the concepts of cavity preparation and led to search and development of new cavity preparation systems.

2.7.2 Chemo-Mechanical Preparation

The first chemo-mechanical system was described by Goldman et al. in 1976 [17]. This system, named Caridex, was later followed on the market by Carisolv (Rubicon Life Science, Gothenburg, Sweden) in 1997. It is a hand excavation method that uses a chemical gel (Carisolv) to soften the demineralized affected dentin tissue. The gel agent is a mixture of amino acids (leucine, lysine, glutamic acid), NaOH, NaCl, and NaOCl in purified water that produces an alkaline solution (pH11). The chemical action of these components is aimed to degrade and disrupt the affected collagen fibrils making softened dentin easy to remove; successive hand excavation steps complete the caries removal. The aim of this technique is to produce a selective and minimal tissue removal; this conservative approach may be a help in case of deep decay, reducing the risk of pulp exposure. The chemo-mechanical preparation produces dentin modifications suitable for bonding procedure. The surface does not present smear layer, dentinal tubules are open, and bonding procedure produces deeper resin tags (15 μm versus 10 μm) when compared to burr excavation, confirming the effectiveness of the chemo-mechanical preparation in achieving a selective carious removal and good adhesive surface [18, 19]. The disadvantage of this technique is the longer time needed for the treatment.

2.7.3 Air Abrasion

Air abrasion is a relatively new method for removing tooth structure and dental caries during cavity preparation and has specific characteristics

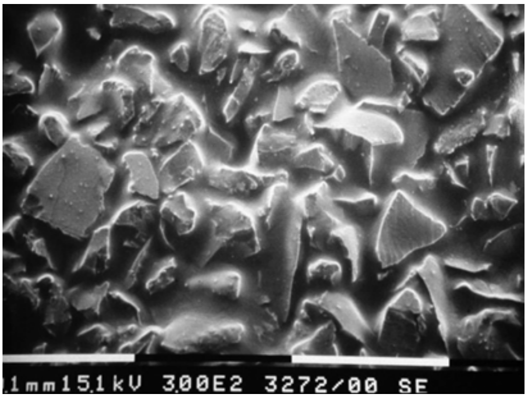

Fig. 2.4 SEM image shows the fine particles (10–50 μm) of aluminum oxide used for air abrasion system (Courtesy of Prof. Vasilios Kaitsas, Italy)

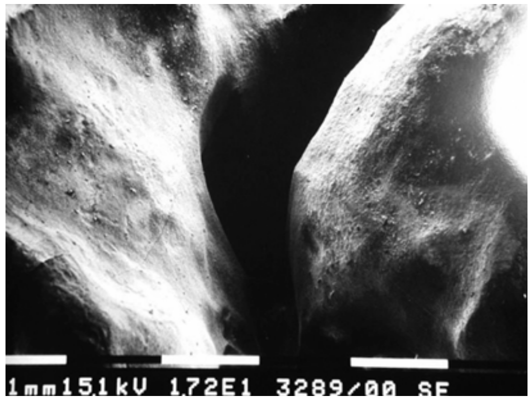

Fig. 2.5 SEM image shows a fissure preparation for sealant application using air abrasion. To note the typical round-shaped and halo contour of the interaction (Courtesy of Prof. Vasilios Kaitsas, Italy)

suitable for adhesive restorative materials. Air abrasion utilizes fine particles (10–50 μm) of aluminum oxide for the removal of superficial enamel and dentin caries allowing minimal invasive ablation of the tissue (Fig. 2.4). The dental morphologic pattern produced by air abrasion is very conservative [20, 21], with irregular surfaces due to the impact of abrasion particles [20]; the most relevant morphologic characteristic is a round-shaped and halo contour [20, 22, 23] (Fig. 2.5). This surface aspect seems to improve the adhesion, facilitating the fitting of composite materials, reducing microleakage [24–26]; also the incidence of microcracks within the tooth and fracture of composite material is reduced when comparing a cavity preparation with round contour to another with defined acute angles [25, 26] and so enhancing the longevity of tooth and of adhesive restorations [26, 27].

Air abrasion does not produce smear layer, but the main disadvantage is dust particles remaining from cavity preparation creating a film over the operatory field (teeth and rubber dam); the dust is also a potential health hazard from breathing dust particles, and emphysema of the patient's orbital area, related to the air pressure applied, has also been described in the literature (Fig. 2.6). Furthermore, as a minor side effect, the dust particles can scratch dental mirrors [28]. As for drills, air abrasion does not provide any bactericidal effect [28].

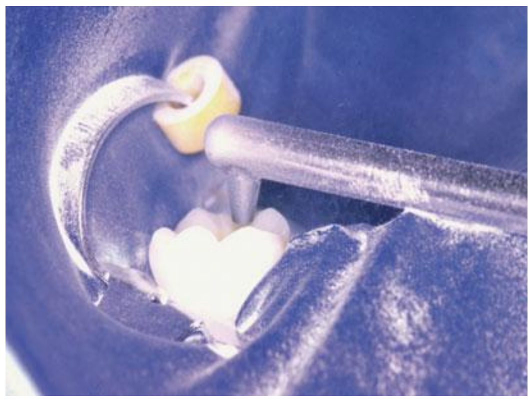

Fig. 2.6 Intraoperative image shows the dust particles remaining from cavity preparation creating a film over all the operatory field (Courtesy of Prof. Vasilios Kaitsas, Italy)

2.7.4 Erbium Family of Lasers

Among the other systems for cavity preparation, the erbium lasers are completely different because of their possibility to work on both hard and soft tissues and the ability to complete the entire conservative procedure. Erbium lasers are suitable for carious removal and are very efficient for deep dentin decontamination. They can expose subgingival cavity margins in case of class 2, class 3, and class 5 caries, easily and effectively performing a laser gingivectomy; laser can also coagulate the gingiva before cavity preparation or coagulate and decontaminate the exposed pulp during a cavity preparation. Erbium lasers can also perform a vital pulpotomy or pulpectomy, if needed, and all these abilities make the laser "unique."

Also, the morphologic pattern of lased ablated enamel and dentin is suitable for adhesive dentistry because of the absence of debris and smear layer and the increased surface for bonding; surface and margin finishing and conditioning are necessary to improve the bonding characteristics of lased surface (see Chaps. 4 and 5).

Finally, the laser has less impact on the patient because it works in noncontact mode, without vibration, and allows quite lower stimulation of the dental nerve (see Sects. 7.2, 7.3, and 7.4); the noise is also different from the shrill noise of the high-speed handpiece that often created fear in children and phobic patients; it sounds like a "popping sound" and it is better accepted by the patients. Local anesthesia is often unnecessary [29].

Tables 2.1 and 2.2 summarize the main differences between erbium lasers, high-speed drill, and air abrasion.

2.8 Methods of Tooth Restoration

The choice between direct or indirect restoration depends on many factors. Mainly are the size and complexity of the cavity as well as multiple proximal cavities in a quadrant that suggest one or another option.

Direct restorations (fillings) are more appropriate in small- or medium-sized cavities and in patients with high risk of caries that may possibly present recurrence of the pathology, needing frequent re-interventions.

In posterior teeth, composite fillings are the simpler and faster solution for class 1 and class 5 restoration, as well as for small pure class 2, class 2B, and composite class 2 restorations. On the opposite, multiple and medium- to large-sized cavities are more properly restored with indirect restorations.

Table 2.1 Comparison among erbium lasers and high-speed drill

	Erbium family laser	High-speed drill
Operative mode	No contact – no vibration	In contact, slow vibration
Noise	Popping sound	Whine, shrill sound
Control	Visual feeling	Tactile feeling
	Precision by sight	Precision by tactile feedback
Clinical applications	Soft tissue usage	No soft tissue usage > dangerous
	Slower in enamel	Faster enamel removal
	Less painful in dentin	More painful in dentin
	Cannot remove amalgam	Removes amalgam
	Not suitable for crown preparation	Suitable for crown preparation
Operative applications	End cutting only	End and side cutting
	Bactericidal effect	No bactericidal effect
	Selective for carious tissues	Nonselective for caries
	Clean surface, no smear layer	Debris and smear layer production
	No microcracks	Microcracks are possible

Table 2.2 Comparison among erbium lasers and air abrasion

Erbium family laser	Air abrasion
Less painful in the dentin	Can be painful in the dentin
Bactericidal effect	No bactericidal effect
Slower in the enamel	Faster in the enamel
Etching-like surface	Etching-like surface
Clean surface, no smear layer	Dusty surface
Selective for carious tissues	Not selective for caries
Soft tissue usage	Soft tissue damage/ abrades tissue
No contact, different focus distances	No contact, 2–3 mm away
More effective in deep dentin cavity	More effective in superficial enamel cavities

Also in anterior area, when esthetics is the main request of the patient, alterations of the shape (conoid, agenesis) and location (crowding teeth) and multiple alterations of buccal surface of the teeth (extended fillings, cervical and buccal abrasion and erosion, hypomineralization in adult) can be properly treated with indirect restoration (veneer or laminate restoration) using ceramic material. In anterior area, direct composite fillings are generally more appropriate for smaller carious lesions of class 3 and class 5 and in case of tooth fracture (class 4). This part is treated in Sects. 7.8 and 7.10.

2.9 Material for Tooth Restoration

2.9.1 Material for Direct Restoration

The silver amalgam has for years been the material of choice for posterior fillings. It is a well-adaptable material in complex cavities, and it has a sufficiently long working time to allow a proper sculpture of the dental anatomy restoration. When smoothed and polished, the amalgam has good biomechanical characteristics and resistance to marginal infiltration.

The disadvantage is the susceptibility to electric–galvanic current and chemical corrosion, when in the oral cavity, different metal restorations are present. The release of mercury from amalgam along the life is the main concern for patients, while manipulation and amalgam removal procedures are a high risk of inhaling amalgam particles and vapor for operators. Furthermore, in 1999, in Italy, the Senior Council of Health of the Ministry of Health considered it opportune to define recommendations and limitations of its use in particular situations, as patients with allergies to the amalgam, women in the state of pregnancy, children under 6 years, and patients with serious nephropathies, and a legislative decree prohibited the use, import, and marketing, on the Italian territory, of dental amalgam that is not prepared in the form of pre-dosed capsules, which include correct precautions and warnings for a safe use [30].

In addition to health concerns related to the use of amalgam, the increased esthetic demand also for posterior areas and the tendency of this material to expand, with possible phenomena of enamel–dentin microfractures, have progressively limited its use.

Adhesive dentistry has modified the approach to tooth restoration. When in the 1960s dental composites were developed and introduced in the market, they quickly replaced the acrylic resin and silicate restorative materials in anterior teeth restoration. Acrylic resin materials had a high coefficient of thermal expansion and excessive polymerization shrinkage, resulting in early recurrence of the carious process. Silicate cements presented instead a quick dissolution in the oral cavity, requiring a frequent replacement.

2.9.2 Dental Composites

Dental composites initially introduced for esthetic anterior restorations only have gradually improved their biomechanical quality and are now excellent materials also for direct fillings in posterior area. Over time, simultaneously to the improvement of adhesive systems, the tooth preparation changed, reducing accessory retention shapes and extension. Composites can be also used for indirect restoration, and specific laboratory procedures (processed at higher temperatures and polymerization under vacuum) also improve their mechanical and surface characteristics. Progress in dental technology has progressively introduced also a new material for indirect dental restoration, with biomechanical properties very similar to the original tooth structure. Resin nano-ceramic materials for CAD-CAM technology are the newest and harder materials for indirect restoration, well resisting to chipping, cracking, and wear.

Dental composite resins are formed by two phases: an organic resin matrix, soft and flexible, and a filler material of different nature, size, and composition, responsible for the strength and hardness of the material. Also a coupling agent (silane) and an initiator of the chemical reaction of polymerization are present. Colored pigments allow to create a natural chromatic scale of colors.

2.9.2.1 Resin Matrix Phase

Resin matrix of dental composites harden by a chemical reaction (polymerization) activated by chemical or by light activation. To make this reaction possible, light-curing composites (so far the most used) need a photoinitiator to be activated by a light of specific wavelength (usually from 450 to 500 nm), to initiate the polymerization reaction.

The resin matrix has similar chemical composition of specific adhesives that permits the chemical bonding between the dental tissues and composites. Resins are polymers, more frequently chain of bis-GMA oligomers (Bowen's resin) or of UDMA; also other molecules, MMA and TEGDMA, are present. The resins have bipolar characteristics allowing bonding with hydrogen ions and reactive C=C groups. A complete polymerization of composite never happens in the oral environment, because of many factors, including the depth of the filling and the superficial inhibition from the oxygen. As a result of incomplete polymerization, resin can absorb water and stain from the oral cavity, due to existing residual free radical, and consequently can easily expand and discolor. Polymerization shrinkage and water absorption and expansion are some of the critical points of composites, related to its resin phase. Resin is flexible but also weak and has few wear resistance so that manufacturers tend to minimize the matrix content of composite materials by increasing the filler content, so improving the hardness and resistance of the material [31].

2.9.2.2 Filler Phase

Filler materials of composite are of different nature (glass materials, silicon dioxide, ceramic particles, zirconium dioxide, barium), size, composition, and concentration; they are included in the resin phase, to improve the physical properties of the resin phase and the optical characteristics of composite.

(a) The size of the filler is responsible for the surface smoothness and shininess of composite restoration. The smaller the particle size, the smoother the composite surface; the larger the filler size, the rougher the surface. Also the size of filler particles influences the optical property of composite; smaller size improves the reflection and refraction of the incident light and gives more translucency to the material and the more or less natural aspect of the restoration.

    According to the particle size, composites are classified into micro-filled, macro-filled, and hybrid:

(b) An important feature that determines the physical property of composite is its filler content. Increasing the concentration of the filler, either micro, macro, or hybrid, the quantity of resin is inferior, reducing the weaker and the more critical phase. Consequently the abrasion resistance, the hardness, and the elasticity module increase, and the coefficient of thermal expansion and the polymerization shrinkage decrease. Most of the composites have a percentage in volume between 66 and 84 %.

Lower-viscosity composites, with lower content of particles, allow better wetting of the tooth and are prepared as flowable composites. They are very useful when applied on the bottom of the cavity, for filling the undercuts, for fissure sealing, and for adhesive cementation. Flowable composites confer to the obturation elasticity to absorb the shrinkage stress.

The macro-filled composites have size particle ranging from 5 to 25 μm. The filler content is approximately 70–80 % by weight. The surface became rougher because of the resin wear with exposure of the particle on the surface, losing shine and smoothness. Introduced in the 1960s, macro-filled composites are used for occlusal restoration in posterior teeth, having limited esthetic in anterior area for the excessive wear and smooth loss; today their use is limited to bonding of brackets in orthodontics.

In the late 1970s, micro-filled composites were introduced in the dental market. The filler particles have sizes between 0.01 and 0.04 μm allowing a smooth and polished surface. The filler content is less 35–60 % by weight, presenting less physical properties and limiting the use to anterior teeth.

In the 1980s a mixture of micro- and macro-filled composites was developed, just named hybrid and micro-hybrid composite; particles range from 0.2 to 1 μm size, but also lower content of bigger particles is present. The filler content is higher from 75 to 85% by weight, improving both physical properties and esthetics.

Evolution of composite uses nanotechnology to prepare particles of size inferior to the micron that fill the resin matrix and increase the property of composite. These particles, usually made of silicon dioxide (SiO_2) and zirconium dioxide (ZrO_2), are called nanomers and range from 2 to 75 nm. Further evolution of nanotechnology uses the nanoparticles of silicon dioxide and zirconium dioxide in a pre-polymerized cluster of nanomers of 1μm average size. This form warrants a higher percentage of filler, a limited wear of composite resin phase, an elevated shin, and a polished surface. Also the optical features of transparence/opalescence are well balanced using different fillers for anterior and posterior teeth where esthetic demand is higher.

The quantity of filler and its size also influence the degree of translucency/opalescence desired.

The glass ionomers are materials with insufficient biomechanical characteristics for teeth subjected to occlusal loading. Despite the release of fluoride, even the secondary caries appears to be an important cause of failure of the glass ionomer restorations, both conventional and "tunnel." They remain a good choice for lining deep cavities under composites or to cement full ceramic crowns in vital teeth.

The compomer restorations have intermediate characteristics and have indicated in the restoration of deciduous teeth [31].

Clinical Consideration

Laser preparation differs from conventional high-speed drill preparation for the irregular surface resulting from the interaction of laser with dentin and enamel surface. As for the burr preparation, a mechanical finishing, either manual or rotative or ultrasound, is mandatory to prepare surface and margins that are suitable for modern composite materials.

Due to the improved elastic module and hardness of modern composites, cavity preparation requires well-prepared margins to allow good adaptation of often enough thick composite. Micro-hybrid composites in combination with a suitable adhesive system are the material of choice in esthetic area; lower modulus of elasticity (less rigid and more elastic) is indicated in the restoration of class 5, more subjected to greater biomechanical stress. Cavity preparation of buccal margins of classes 3, 4, and 5 must be finished with a round or chamfer burr; a final smoothening improves the adaptation and esthetics. Micro-hybrid composites also in these cavities result in superior adaptability, superior elasticity, and smoother surface. Palatal and occlusal margins require a straight preparation of the margins; the choice between micro-hybrid and nano-filled composite depends on the extension of the restoration subjected to occlusal forces.

Posterior area is more subject to abrasion and wear; margins must be prepared straight to allow a great thickness of composite to support the mastication loading.

The irregular surface of the bottom of the cavity must be lined with a more elastic and wettable flowable composite that follows all the irregular craters created by laser spots. Also a base (liner) of glass ionomer cement works very well for this purpose in deep cavities. Nano-filled and hybrid composites with high elastic modulus allow better biomechanical characteristics in posterior teeth classes 1 and 2, allowing less wear during time.

2.9.3 Materials for Indirect Restoration

Materials for indirect restorations include gold, ceramics, and composites in their several variants. The preparation for indirect restoration provides a precise shape: sharp internal angles and beveled margins for gold restoration, round inner angles, and net or chamfer margins for ceramic and composite indirect restoration.

Clinical Consideration

Laser preparation in these cases is limited to caries removal only. A refined and specific preparation for the chosen material is possible only with specific burrs and rotary instrumentation (see Sect. 7.10).

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Part II

Basic Science of Laser Dentistry

Science
Science never solves a problem without creating ten more.

–George Bernard Shaw

Change
Change is the law of life. And those who look only to the past or present are certain to miss the future.

–John Fitzgerald Kennedy

3 Physics of Laser

Matteo Olivi and Giovanni Olivi

Abstract

Bohr's atomic model and Einstein's theory of stimulated emission of radiation were a prelude to the invention and realization of the first ruby laser.

Different from ordinary light, the laser light is able to aim a high amount of energy in a limited space in the form of light radiation; also laser light is collimated, coherent, and monochromatic. Most of the laser wavelength used in dentistry fall in the visible and infrared spectrum of electromagnetic waves. The medium-infrared lasers, the Er,Cr:YSGG and Er:YAG lasers, represent the all-tissue lasers, for application on both the mucosa and gingiva, tooth, and bone. The visible, near-, and far-infrared lasers are mainly used for soft-tissue applications; some of them have applications in caries detection and biostimulation (LLLT). The basic component that constitutes a dental laser unit is the optical cavity that includes the active medium; the pumping source that supplies the energy necessary for the stimulation; a controller and a cooler, necessary for controlling laser emission and cooling the laser system; a delivery system to transport the energy to the handpiece and finally to the tissue.

3.1 History of Laser

The word "laser" is an acronym of light amplification by stimulated emission of radiation.

Considering the theory of the atomic model (1913), the description of the phenomenon of stimulated emission (1916), and the formulation of the theory of stimulated emission of radiation (1917), laser technology already has a century of scientific history behind it.

Effectively, a model of the structure of the atom was proposed by Niels Bohr in 1913; it

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modified the model previously described by Rutherford, describing the position of electrons in different orbits, corresponding to different energy states. The emission of photonic energy in the form of an electromagnetic wave is the result of the shift of an electron from an orbit with higher energy state to another with lower energy state.

In 1922 Niels Bohr received the Nobel Prize for Physics for his studies and theory on spontaneous emission of radiations creating the basis of quantum theory.

In 1916 Albert Einstein described the phenomenon of stimulated emission, and in 1917 he formulated the theory of stimulated emission of radiation ("Quantentheorie der Strahlung"), a part of his studies about quantum theory of emission and absorption (Nobel Prize in 1921).

In 1958 the word "maser" was coined by Charles Townes and Arthur Schawlow as the acronym of microwave amplification by stimulated emission of radiation, a precondition for the realization of the first laser in 1960.

In 1957 Gordon Gould, a student of Charles Townes at the Columbia University, coined the word laser that he used first, but without patenting it. Later in 1960, Theodore Maiman used Gould's idea and introduced the acronym "laser," realizing the first ruby laser [1].

In 1961 Elias Snitzer developed the first neodymium:YAG laser.

In 1964 Charles Townes, Nikolay Basov, and Aleksandr Prokhorov were awarded the Nobel Prize for their research and contribution that led to the development of laser technology.

In 1965–1966 Stern and Sognanes conducted new studies on the morphological effects of laser technology on dental tissues [2, 3].

In 1965 for the first time in vivo, a laser was used (ruby laser at 694 nm) on human dental tissues by a physicist, Leon Goldman, on his brother Bernard as patient, who was a dentist; they had any success due to excessive thermal damage produced by continuous wave emission of the laser [4].

Laser was used in clinical dental practice only in the second half of 1980, thanks to the development of pulsed technology that allowed just to avoid the previous failures of continuous emission of energy of CO_2 and ruby lasers.

At the end of 1980, a quartz optical fiber was introduced as delivery system of neodymium:YAG technology by Terry Myers; the fiber allowed better access to the oral cavity and teeth for the therapies [5].

Later on, laser research was directed towards new technologies with the goal to substitute rotating instruments, and Hibst and Keller (1989) realized the first erbium:YAG laser, able to cut and ablate human hard tissues [6–8].

3.2 Electromagnetic Spectrum of Light

In nature the electromagnetic spectrum of light is represented by both visible and not visible radiations. The radioactivity produced from the cosmos generates cosmic radiations; from underground telluric radiations are also emitted.

The solar system emits a wide spectrum of radiations; part of them (approximately 40 %) are within the visible spectrum of the light, and two limited bands extend to the ultraviolet and infrared spectrum that are not visible to human sight. The optical perception of human eyes effectively does not recognize electromagnetic radiation beyond the violet zone (shorter than 400 nm) and the red zone (longer than 700 nm) of the spectrum. Various scientific sources define visible light as narrowly as 420–680 nm [9] or as broadly as 380–750 nm. Also these borders are not exactly defined depending on different individual perceptions, age and other factors.

In the ultraviolet spectrum are included wavelengths shorter than 0.4 μm (400 nm) up to 0.01 μm. Beyond this zone, with a decreasing wavelength the X-rays extend up to about 0.006 μm and farther the gamma rays.

On the opposite side, there is the infrared spectrum of radiations with wavelengths ranging from 0.7 μm up to 400 μm (700–40,000 nm). Further, longer wavelengths include the microwaves and radio waves, respectively, short (1–100 m), medium (from 200 to 600 m), and long (>600 m) (Fig. 3.1).

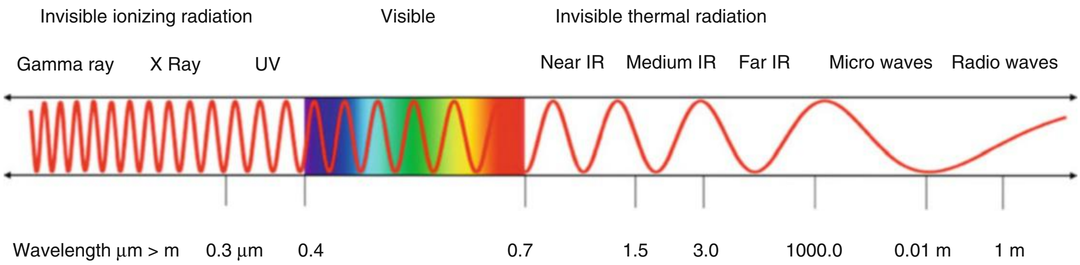

Fig. 3.1 Electromagnetic spectrum of light from gamma rays to radio wave wavelengths, *UV* ultra-violet or ultraviolet, *IR* infra-red or infrared

3.3 Characteristic of Ordinary Light and Property of Laser Light

Light is an electromagnetic radiation which besides its wave characteristic has a photonic corpuscular characteristic that transports a defined amount of energy (quantum).

The ordinary visible light, both natural (solar) and artificial, has several characteristics that must be defined to understand the laser light properties.

The ordinary light is disorderly emitted, because of the absence of coherence in the time and space of the photons; consequently the light is scattered in all the directions and diffuses homogeneously. The ordinary light is multichromatic, being composed of all the wavelengths and colors within the visible spectrum and also called white or achromatic light.

The basic colors of the visible light are violet, blue, cyan, green, yellow, orange, and red (Table 3.1).

When the sunlight diffuses through the water droplets remained in suspension after a meteorological phenomenon such as a storm or a natural phenomenon such as a waterfall, the light can scatter and refract itself within the water droplets, producing the phenomenon of rainbow, that described the colors of the visible spectrum of the light.

Table 3.1 Basic colors of the visible light

Violet 380–450 nm
Blue 450–475 nm
Cyan 476–495 nm
Green 495–570 nm
Yellow 570–590 nm
Orange 590–620 nm
Red 620–750 nm

Primary colors (or absolute colors) are the basic colors from which are obtained, combining them, all the others: they are red, blue, and yellow. The additive or subtractive combination of primary colors is used to obtain secondary colors; this concept helps to understand the use of complementary colors in photodynamic therapy and photoactivated dental bleaching (read ahead). The blue (420–470 nm) is the complementary color of yellow. The cyan (480 nm) is the complementary color of red (630–760 nm), and the magenta (that is a secondary color produced by combination of blue and red) is the complementary color of green (490–570 nm).

The laser light is different from the ordinary light, being able to aim a high amount of energy in a limited space in the form of light radiation.

Several characteristics differentiate laser light from ordinary light:

- Laser light is collimated, that is to say that the waves, thanks to the spatial coherence of emitted photons, have only one very focused direction.
- Laser light is coherent, that is to say that each wave/photon has the same phase with the other emitted waves/photons that are kept in time and space.
- It is monochromatic, that is to say that each photon has just one wavelength and just one color (if visible) (Table 3.2).

Table 3.2 Property of laser and ordinary light

Characteristics	Laser light	Ordinary light
Direction	Collimated One very focused direction	Noncollimated or multidirectional
Temporal phase	Coherent Each wave/photon has the same phase with the other emitted waves/photon that are kept in time	Noncoherent or disorganized
Color	Monochromatic One wavelength and just one color (if visible)	Multichromatic from 400 to 700 nm

3.4 Basic Component of Lasers

Several components are necessary to constitute a dental laser unit:

1. The *optical cavity* (or resonator) that includes the active medium
2. The *active medium* which characterizes different wavelengths of specific lasers
3. The *pumping source* (or energy source) to supply the energy necessary for the stimulation
4. A *controller* that is a software that controls the modality and parameter of laser emission and a *cooler*, necessary for cooling the laser system
5. The *delivery system* that transports the laser energy to a terminal *handpiece* and *tips* and finally to the tissue (Table 3.3)

3.4.1 Optical Cavity

It is a hollow cavity that contains the active medium and two mirrors located at its extremities; one is completely reflective, while the other one is partially reflective and permeable.

The excitement of the active medium by an external source of energy produces the stimulated emission of photons that, reflecting on the mirrors of the cavity and passing through the active medium many times, add their energy via an amplification phenomenon before coming out from the partially permeable mirror.

Table. 3.3 Basic components of a laser

Optical cavity
Active medium
Pumping source
Controller
Cooler
Delivery system
Handpiece and tips

3.4.2 Active Medium

It is the heart of the laser and can be a solid, a liquid, a gas, or a semiconductor in the case of diode laser. The active medium determines the specific wavelength of different lasers and its name identifies different lasers. Table 3.4 reports the active medium of lasers mostly used in dentistry.

The active medium supplies the electrons for the production of the laser photons.

3.4.3 Pumping Source (or Energy Source)

The pumping source excites the atoms of the active medium producing the inversion of the population of electrons. This source of energy is usually represented by an electric coil or a diode laser or a flash lamp. The characteristics of pumping source are important for the generation of the laser pulse, especially for short-duration pulses (high peak power).

3.4.4 Controller Subsystem and Cooler

The controller is a microprocessor that verifies the characteristics of the production of laser energy, the laser emission mode (continuous wave, mechanically interrupted or pulsed), the pulse frequency of repetition (pulses per second, pulse repetition rate or Hz), and the length of the emission of the single pulse. The cooling system is necessary to dissipate the heat produced for the pumping process.

3.4.5 Delivery System

Once generated, laser light is delivered to the target. Various delivery systems, depending on the

Table 3.4 Active media, hosting media, and doping atoms of the most used lasers in dentistry

Laser	Abbreviation	Active medium	Hosting medium	Doping atom	Wavelength (nm)
Argon	Ar	Gas	–	–	488 and 514
Carbon dioxide	CO_2	Gas	–	–	9,300, 9,600, and 10,600
Diode	–	Semiconductor	–	–	445, 635–810, 940–970, 1,064
Potassium titanyl phosphate	KTP	Solid	YAG crystal	Neodymium frequency doubled	532
Neodymium-doped yttrium-aluminum-garnet	Nd:YAG	Solid	YAG crystal	Neodymium	1,064
Neodymium-doped yttrium-aluminum-perovskite	Nd:YAP	Solid	YAP crystal	Neodymium	1,340
Erbium-doped yttrium-scandium-gallium-garnet	Er,Cr:YSGG	Solid	YSGG crystal	Erbium and chromium	2,780
Erbium-doped yttrium-aluminum-garnet	Er:YAG	Solid	YAG crystal	Erbium	2,940

wavelength carried, are optic fiber, hollow fiber, and the articulated arm (Fig. 3.2).

3.4.5.1 Optic Fiber

Lasers in the visible (445 and 532 nm) and near-infrared (from 810 to 1,064 nm) spectrum utilize optic fibers, generally made of quartz, to deliver the laser energy to the tissue, directly or via terminal handpiece, with straight and angular tips (Fig. 3.3).

Also some medium infrared lasers (2780–2940 nm) use more complex optic fibers as delivery system, of larger diameter, made of sapphire or fluorides, with a terminal handpiece holding the tips (Figs. 3.5 and 3.11). This delivery system is the easiest to use in the oral cavity, thanks to its flexibility. However, it has the disadvantage of wear over time and of reduced efficacy because of a loss of energy during transmission of the laser beam.

3.4.5.2 Hollow Fiber

Some type of laser (Er:YAG and CO_2 lasers) utilizes a hollow tube with reflective internal walls which transmit laser energy along its internal axis. These fibers are very flexible and light, but, because of their structure, the most important disadvantage is related to the loss of energy over time and also to an important and incontrollable variability of the energy delivered, caused by the internal reflection of the laser beam during the transmission to the handpiece.

Fig. 3.2 Combined laser unit (LightWalker AT, Fotona, Slovenia) present two different wavelength sources and different delivery systems: two optic fibers for the Nd:YAG laser and one articulated arm for the Er:YAG laser

Fig. 3.3 Near-infrared diode laser (Picasso, AMD, USA) has a fiber optic and a terminal handpiece with disposable tips

Fig. 3.4 No contact handpiece for Er,Cr:YSGG laser unit (handpiece turbo, Biolase)

Fig. 3.5 Er,Cr:YSGG laser handpiece with integrated air-water spray, coaxial to the laser beam (iPlus and Waterlase MD, Biolase, USA)

Fig. 3.6 Er,Cr:YSGG laser unit equipped with optic fiber (iPlus, Biolase, USA)

3.4.5.3 Articulated Arm

This delivery system uses a series of articulated mirrors (usually 7) connected one to each other, leading to transmission of energy with

Fig. 3.7 CO_2 laser unit equipped with articulated arm (Solea, Convergent Dental, USA)

Fig. 3.8 No contact handpiece for a 9,300 nm CO_2 laser unit (Solea, USA)

minimal dispersion, making it the most efficient system. It requires a precise mechanism for alignment of the mirror system. Hits and vibrations, which can happen during transportation of the laser from one operating room to another, are dangerous because they can provocate a de-calibration of the internal mirror system, and this constitutes a disadvantage (Figs. 3.7 and 3.9).

This delivery system is used by some manufacturer for some Er:YAG and CO_2 lasers.

3.4.6 Handpieces and Tips

All the delivery systems use angular or straight-ended handpieces. The ideal handpiece should be small, lightweight, and handy. Some handpieces do not have any terminal tip, but a reflecting mirror which works at a distance from the tissue (tipless or noncontact or far contact handpiece). Some other has a terminal tip which works almost in contact with the tissue (close contact handpiece). Others are hollow handpieces which permit the passage of the fiber up to the extremity.

3.4.6.1 Noncontact Handpiece

This kind of handpiece, also called tipless, uses a sapphire lens, located in the final part of the handpiece, that allows the focalization of the beam at a specific distance from the target (usually from 5 to 10 mm depending on the type). It is very efficient, and it is somewhat subject to wear, but its use requires close attention. This is because every movement made by the operator or patient moves the spot from the target and the distance amplifies errors in angulation and direction to the detriment of precision (Figs. 3.4, 3.8, and 3.10).

Fig. 3.9 Er:YAG and Nd:YAG combined laser unit (LightWalker AT, Fotona, Slovenia) equipped with a comfortable and well-balanced articulated arm (Optoflex, Fotona) and flexible optic fiber

3.4.6.2 Close Contact Handpiece

This kind of handpiece works using tips of different size, shape, length, and angle, designed for specific interaction with different kinds of tissues (Fig. 3.12). The emission of the laser beam close to or in direct contact with the target tissue improves precision of work.

Some diode lasers have handpieces with very useful disposable tips (Figs. 3.13 and 3.14).

Lasers such as Er,Cr:YSGG, Er:YAG, and CO_2 have a more complex kind of handpiece, with internal angled mirrors and terminal tips for the transfer of energy to the target tissue. Furthermore, the laser handpieces of erbium have an integrated air-water spray that is better if coaxial to the laser beam (Figs. 3.5 and 3.11). The disadvantages of this system are the fragility and wear of the tips and the loss of energy during transmission to the tissue.

3.4.6.3 Hollow Handpiece

The optic fibers of some lasers, such as KTP, some diodes, and neodymium:YAG, pass through a hollow handpiece and exit from a terminal angled tip (Figs. 3.16).

Fig. 3.10 No contact handpiece for Er:YAG laser unit (handpiece H02N, Fotona)

Fig. 3.11 Er:YAG laser handpiece (H14 N, Fotona, Slovenia)

3.5 Classification of Dental Laser Wavelengths on the Electromagnetic Spectrum

Laser can be distinguished according to their clinical use in dentistry in soft-tissue lasers and hard-tissue lasers, also called all-tissue lasers (Table 3.5).

Another classification considers the position of laser wavelength on the electromagnetic spectrum of light:

- Laser in the ultraviolet spectrum
- Laser in the visible spectrum
- Laser in the near-infrared spectrum
- Laser in the mid-infrared spectrum
- Laser in the far-infrared spectrum

In the visible and infrared spectrum of light, we find the majority of the wavelengths utilized in dentistry.

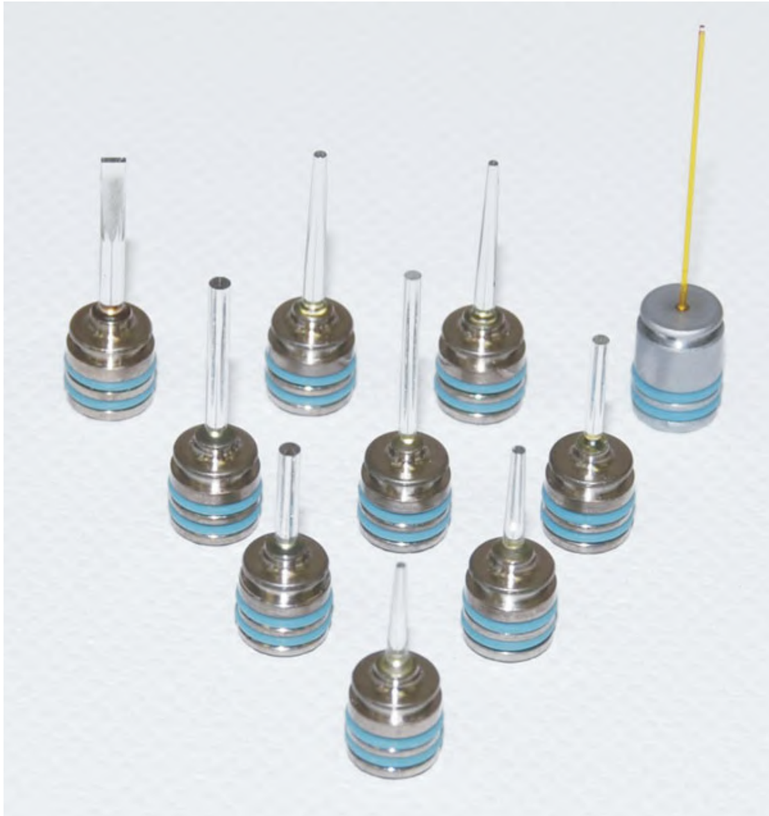

Fig. 3.12 The handpiece for Er:YAG laser works with sterilizable tips of different size, shape, length, and angle, designed for specific interaction (tips for LightWalker, Fotona, Slovenia)

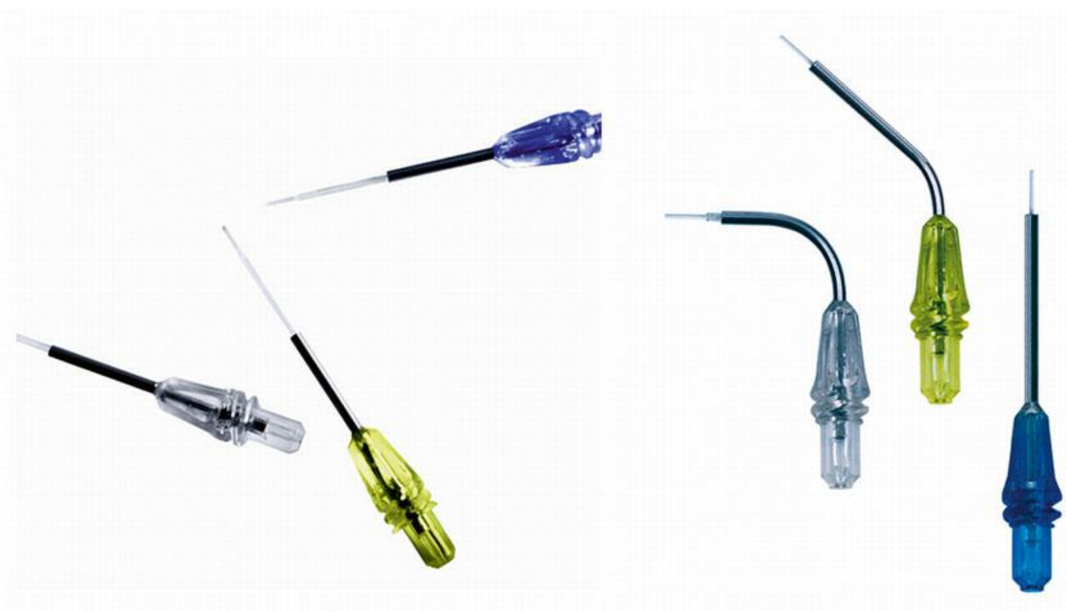

Fig. 3.13 Disposable tips (300 and 400 μm, 10 mm long) for diode laser (Epic, Biolase, USA)

Fig. 3.14 Disposable tips (300 and 400 μm, 10 mm long) for diode laser (Picasso, AMD, USA)

Fig. 3.15 Hollow handpiece for Nd:YAG laser unit that allows the passage of the fiber through the handpiece up to the terminal tip (R21-C3 Fotona, Slovenia)

3.5.1 Laser in the Ultraviolet Spectrum of Light

Between 0.3 and 0.4 μm, in the ultraviolet spectrum of light, there are the excimer family laser. Largely used in ophthalmology and experimented in the past in endodontics, the excimer laser (380 nm) is not more suitable for dentistry.

Fig. 3.16 Handpiece housing a 15 cm-long fiber to be cut after each use (SIROLaser, Sirona, Germany)

Table 3.5 Classification of laser according to clinical use in dentistry

Soft-tissue lasers	
Diode	445 nm
KTP	532 nm
Diode	810, 940, 970, 1,064 nm
Nd:YAG	1,064 nm
Nd:YAP	1,340 nm
CO_2	10,600 nm
Hard- and soft-tissue lasers	
Er,Cr:YSGG	2,780 nm
Er:YAG	2,940 nm
CO_2	9,300 nm
LLLT	
KTP	532 nm
Diode	635–675 nm
Diode	810, 940, 970, 1,064 nm
Laser for caries detection	
Diode	405 nm
Diode	655 nm

3.5.2 Laser in the Visible Spectrum of Light

In the visible spectrum of light, in the blue and green bands, respectively, at the wavelengths of 470, 488, and 514 nm, the argon gas lasers are not longer used in dentistry.

In the green spectrum at 532 nm, the KTP laser was introduced in dentistry in the 1990s for the strong affinity with hemoglobin and consequent effective coagulation. The active medium is a solid crystal of Nd:YAG, with a crystal of $KTiOPO_4$, that duplicates the vibration frequency of photons, splitting the wavelength of the Nd:YAG (1,064 nm) at 532 nm.

In the blue spectrum at 445 nm, a new diode laser was recently introduced in dentistry with similar physical characteristics to green light laser.

In the red visible spectrum, some diode lasers are built with wavelengths ranging from 635 to 675 nm and are used for low-level laser therapy (LLLT) and photodynamic therapy (PDT) in the so-called red window of the spectrum. The construction is similar to that of the near-infrared diode lasers and described ahead.

The energy of these lasers is delivered through an optic fiber of different diameters up to a terminal handpiece.

The wavelengths in the visible spectrum present an optical interaction in tissue both of absorption and diffusion (50–50 %). This explains the safe and less deep interaction in tissue. Some substance, called "photosensitizer," absorbs electively specific wavelengths in this window of the spectrum (from 630 to 675 nm) becoming a powerful germicide. In this case laser therapy is usually called antimicrobial photodynamic therapy (aPDT) or photoactivated disinfection (PAD). Other specific chromophores are included in some specific bleaching gel designed for these lasers, such as rhodamine, a red purple color complementary for green light of KTP laser at 532 nm (see Figs. 9.23 and 9.50).

3.5.3 Near-Infrared Laser

In the near-infrared spectrum (from 800 to 1,500 nm), there are the most often used lasers for endodontic and periodontal decontamination and oral surgery: diode lasers (from 810 to 1,064 nm), Nd:YAG laser (1,064 nm), and Nd:YAP laser (1,340 nm). Diode lasers were introduced at the end of the 1980s. The active media are semiconductors, which are nowadays miniaturized, made up of various layers (wafer-like construction). Gallium arsenide (GaA1As), doped with aluminum atoms, and gallium arsenide (IGaAsP), doped with indium atoms, are the widely used active media. The miniaturized and simple construction allows only a continuous emission of energy (cw); a mechanical system can interrupt the pulse emission (chopped or gated), dividing the emission in variable intervals (t_{on}/t_{off}). The pulse emission (t_{on}) has a linear evolution without variations from the beginning to the end, and its duration is variable, from a few microseconds to many milliseconds, with variable frequency up to 20,000 Hz.

The neodymium:YAG active medium is a solid crystal of yttrium-aluminum-garnet, doped with neodymium atoms, a metal of the group of rare earth elements. The stimulation of the crystal happens, thanks to a powerful flash lamp (free-running pulse mode). The emission of energy is therefore really pulsed, with each pulse having a quick start, a peak, and an end; between each pulse, there is a time of latency. The controller (software) permits to control the parameters, the repetition rate of the pulses (pulse frequency).

The neodymium:YAP laser has a crystal of yttrium, aluminum, and perovskite, doped with neodymium as active medium.

The delivery systems of the near-infrared lasers are flexible optic fibers, available in different diameters and ending with different type of handpieces (see Figs. 3.2, 3.9, 3.15).

3.5.4 Medium-Infrared Laser

In the infrared spectrum, there are the wavelengths of 2,100 nm of the holmium:YAG, used in urology and orthopedics, and those of 2,780 and 2,940 nm of the erbium laser family, extensively used in medicine such as dermatology, orthopedics, and dentistry. The erbium laser was introduced in dentistry at the end of the 1980s and the beginning of the 1990s, with the idea of substituting the drill for caries removal.

The erbium laser active medium is a crystal of yttrium, aluminum, and garnet, doped with erbium atoms, a metal of the group of rare earth elements.

The crystals of Er:YAG and Er,Cr:YSGG lasers emit photons of wavelength of 2,940 and 2,780 nm, respectively.

The stimulation of the YAG and YSGG crystals is supplied by powerful flash lamp (free-running pulse mode) making this laser really "pulsed" laser; this characteristic, in particular the pulse duration and shape, controlled by a software, permits to have different interactions with tissues, with more or less thermal effect. This part will be extensively debated in Chap. 4.

The erbium:YAG laser energy is delivered to a terminal handpiece through different systems, among which the optic fiber and articulated arm are still in use (see Figs. 3.2 and 3.9).

The erbium, chromium:YSGG laser energy is delivered to a terminal handpiece through an optic fiber (see Figs. 3.4, 3.5, and 3.6).

Thanks to their affinity with water in the tissues, erbium lasers find a large area of applications in dentistry, on both soft and hard tissues, and are therefore called "all-tissue" lasers.

3.5.5 Far-Infrared Laser

In the far-infrared spectrum, there is the CO_2 family of lasers (9,300–9,600 and 10,600 nm), the surgical laser par (for) excellence, used in dental surgery and experimentally in caries prevention.

Lately a new CO_2 laser at 9,300 nm was proposed for use on both hard and soft tissues (see Figs. 3.7 and 3.8).

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4 Laser–Hard Tissue Interaction

Giovanni Olivi and Matteo Olivi

Abstract

Hard dental tissues (enamel, dentin, and carious tissues) are composed of different percentages of hydroxyapatite, water, and collagen matrix. On an optical point of view, these components are defined as chromophores and have specific affinity with medium-infrared wavelengths, specifically the erbium, chromium:yttrium–scandium–gallium–garnet laser (Er, Cr:YSGG at 2,780 nm) and the erbium:yttrium–aluminum–garnet laser (Er:YAG at 2,940 nm), the only wavelengths capable of being greatly absorbed by water within the dental tissues for clinical procedure in restorative dentistry. The chapter emphasizes the difference in water content of the various hard tissues (enamel, dentin, and carious tissue) and the differences in composition between primary and permanent teeth, which explain the different absorption coefficients and thresholds of ablation of different tissues and the different laser energy settings for the tooth ablation. The affinity of water to the erbium laser explains also the selective interaction of laser for dental caries. The erbium laser–hard tissue interaction is the result of a complex mechanism, which involves primarily the photothermal effect and, secondarily, the photomechanical and photoacoustic effects that occur rapidly. The water participates in the ablative process of the erbium family laser not only as a target chromophore but also for its cleansing and cooling action, for rehydration, which affects the quality of the ablation of the hard tissue. Microscopically, the laser-irradiated enamel shows an etched-like pattern, more or less irregular; the dentin presents a typical chimney-like appearance, an effect of ablation prevalent

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in the intertubular level, more rich in water, with protrusion of peritubular dentinal tubules, and more mineralized, with open orifices and smear layer mainly absent. The lased surface is also highly decontaminated up to a depth of 300–500 µm.

The use of laser for caries removal and cavity preparation in restorative dentistry involves the use of wavelengths that are suitable for interacting with the dental tissues, enamel, and dentin.

The interaction of laser light with a target tissue follows the rules of optical physics: a laser beam can be reflected, absorbed, diffused (or scattered), and transmitted (Fig. 4.1). When the affinity between a wavelength and a target tissue is high, the greater the quantity of light energy absorbed, the greater the selectivity of action. The lower the affinity, the greater the quantity of light energy reflected and or transmitted.

Reflection is an optical phenomenon resulting from the lack of affinity of the light with the target tissue, which will repel it. The proportion of laser radiation reflected is generally low (5 % of the emitted radiation) and represents that aspect of laser therapy that involves the safety measures (safety glasses with filter for each specific wavelength). Laser radiation is in fact potentially harmful to the structures of the eye (retina, cornea, lens, aqueous humor) (see Appendix).

Absorption is, on the opposite, the expression of high affinity between the light and the target tissue, which will keep the light in the point of interaction. The portion of the laser energy absorbed by the tissues is responsible for the majority of the therapeutic effects: it is converted locally into photochemical energy, photothermal energy, and photomechanical–photoacoustic energy, depending on the type of laser, the parameters, and the emission mode used.

Scattering, typical of a limited spectrum laser light (in the visible and especially near-infrared spectrum), is the ability of the light to spread more in depth and in a disorderly manner in the target. The portion of light energy diffused in the tissues is responsible for the photochemical and/or photothermal effects of these laser wavelengths, which allow, for example, biostimulation and decontamination effects deeply in the tissue, at a distance from the point of interaction.

Transmission is the passage of light through a non-affine tissue or body without interaction on it and therefore without producing physical or biological effects.

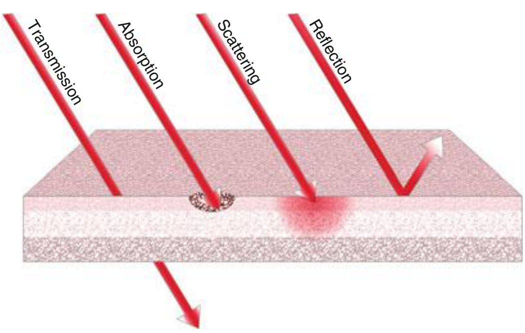

Fig. 4.1 Laser–tissue interaction: laser light can be reflected, scattered, absorbed, or transmitted

4.1 The Wavelength

The first laser to be studied for application to the hard dental tissues was the ruby laser (visible red at 694.3 nm) [1]. The lack of cooling effect and the low affinity of the ruby laser for hard dental tissues led to discouraging results for the ablation of dental tissues (charring, melting, and cracking), and this wavelength was soon abandoned in restorative dentistry.

Subsequently, the carbon dioxide (CO_2) laser (in the far-infrared spectrum of light, at 10,600 nm) [2], the excimer (XeCl) laser (in the ultraviolet spectrum of light at 308 nm) [3], and the neodymium:yttrium–aluminum–garnet (Nd:YAG) laser (in the near-infrared spectrum of light, at 1,064 nm) [4–6] have been studied for use in restorative dentistry, with poor clinical

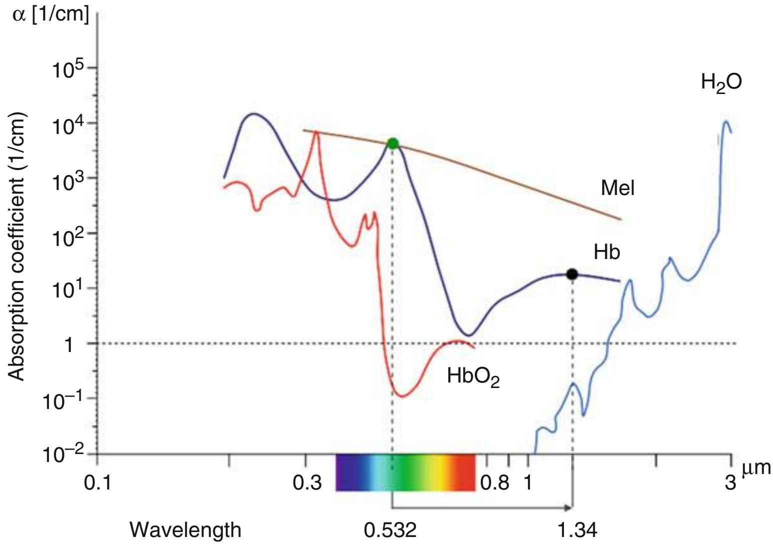

Fig. 4.2 Visible and near-infrared laser wavelengths in the electromagnetic spectrum of light and relative absorption in soft tissue chromophores. *Mel* melanin, *Hb* Hemoglobin, *HbO*$_2$ Oxyhemoglobin, H_2O water

outcomes because of the poor absorption in the enamel and dentin and the excessive damage caused by heat [7, 8].

Due to the absorption of Nd:YAG laser in pigmented areas, it was proposed in the past to apply pigment or dark ink to the enamel of pits and fissures of posterior teeth for sealant or class 1 cavity preparation. The unwanted thermal damage on the irradiated surface (cracks, melting, bubbles, and recrystallization of mineral dental structures) discouraged the continued research on the use of Nd:YAG laser in restorative dentistry [9, 10].

The lasers in the near-infrared light spectrum (from 810 to 1,340 nm) have high affinity for hemoglobin and melanin but minimal or absent affinity for hard dental tissues. When irradiating a tooth with safe clinical parameters, there is no ablative interaction with the enamel and dentin, but only the release of thermal energy that diffuses deeply toward the pulp tissue, rich in their absorbing chromophore, the hemoglobin (Fig. 4.2).

The deep thermal effect of these wavelengths produces decontamination of a deep cavity [11] and also melting of the superficial dentin that can be carefully used for the treatment of dentinal hypersensitivity (see Fig. 4.67). Its interaction with hemoglobin also allows its possible use in vital pulp therapy (see Chap. 8).

The other wavelengths used in dentistry also have a limited utility when used in restorative dentistry.

In the visible light spectrum (from 532 to 675 nm), we find other lasers with high affinity for hemoglobin and melanin. The green light of the KTP laser (532 nm) is mainly used in surgery for its excellent ability to cut and for coagulation; in esthetic dentistry, it can be used for dental bleaching [13, 14] (see Fig. 4.2).

The lasers in the red spectrum of visible light (630–675 nm) are used for pain therapy, biostimulation, and anti-inflammatory therapy (low-level laser therapy, LLLT); for their affinity with specific photosensitizers with bactericidal activity, they are also used for the deep decontamination of the endodontic system and of periodontal pockets (photodynamic therapy (PDT) or photo-activated disinfection (PAD)) and have also been proposed for possible conservative use in deep dentin decontamination [15].

After the first experimental studies on CO_2 laser at 9,300 nm [16, 17], in recent years, new studies have revived this wavelength for the ablation of enamel and dentin [18, 19].

4.1.1 Medium-Infrared Lasers

Due to the specific affinity of water with medium-infrared wavelengths [20], specifically the erbium, chromium:yttrium–scandium–gallium–garnet laser (Er, Cr:YSGG at 2,780 nm) and the erbium:yttrium–aluminum–garnet laser

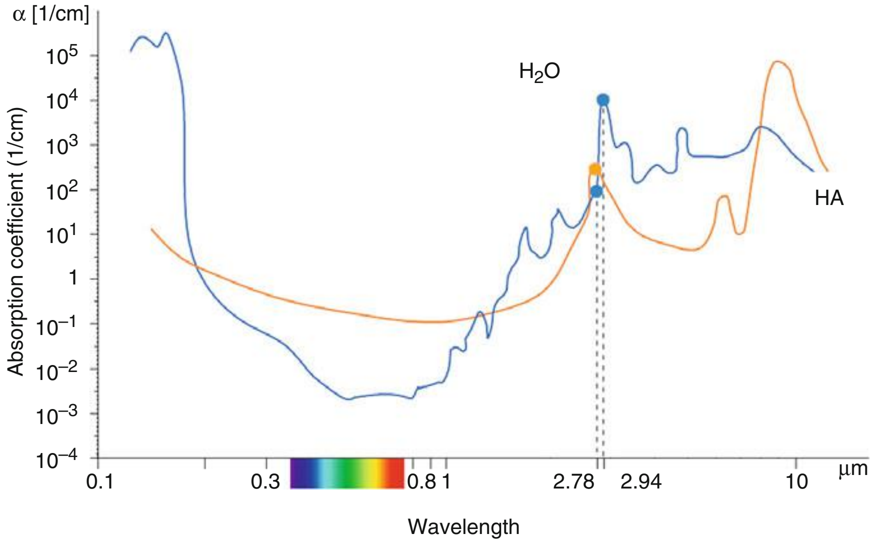

Fig. 4.3 Relative absorption of erbium wavelengths in hard tissue chromophores: hydroxyapatite (*orange line*) and water (*blue line*)

(Er:YAG at 2,940 nm), now called erbium family laser, these are currently the only two wavelengths capable of being greatly absorbed within the dental tissues when used with safe and accepted clinical parameters [21–24] (Fig. 4.3).

The Er:YAG laser wavelength operates into the peak of absorption of water, at 2,940 nm, while the Er, Cr:YSGG laser wavelength is absorbed slightly less by water (300 % less) at 2,780 nm [23, 25] (Fig. 4.4).

The difference in the absorption coefficients leads to a difference in the penetration depths of the two erbium laser wavelengths in dental tissues. The Er:YAG laser wavelength penetrates approximately 7 µm in the enamel and 5 µm in the dentin; the Er, Cr:YSGG laser wavelength penetrates three times deeper, 21 µm in the enamel and 15 µm in the dentin [26] (Fig. 4.5). As a result of the very superficial absorption and due to the specific optical properties of these wavelengths, the diffusion phenomenon is negligible.

Furthermore, the wavelength 2,780 nm falls into the second peak of the absorption curve of the hydroxyl group of hydroxyapatite in dental hard tissues [27–31], but its role in the ablation of hard tissues is secondary (see Fig. 4.3); it is the stronger water absorption of 2,940 nm (Er:YAG) and 2,780 nm (Er, Cr:YSGG) that plays the dominant role in dental laser ablation [10, 31]. Clinically, the different absorption in water of the two wavelengths is scarcely relevant in quantitative terms of speed of ablation of the hard tissues.

4.2 The Target Tissue

Substances present in most tissues of the human body, such as water, hydroxyapatite, collagen protein substances, melanin, and hemoglobin, are widely represented in the hard and soft oral tissues.

In restorative dentistry, the main target tissues are the dental hard tissue (enamel, dentin, and decayed tissue), composed of different percentages of hydroxyapatite, water, and collagen matrix. From the point of view of optical physics, these components are defined as "chromophores" and have selective affinity for the wavelengths 2,780 nm and 2,940 nm of the medium-infrared spectrum [23, 26–30].

It is important to know the difference in water content of the various hard tissues (enamel, dentin, and carious tissue) and to consider the differences in composition between primary and permanent teeth to understand the different absorption coefficients and thresholds of ablation of different tissues when considering the energy setting of laser for dental ablation [23].

Because of the dental–periodontal relationship and its involvement in the proximal subgingival carious lesions, in the carious and non-carious lesions of the neck of the tooth (class 5 cavities)

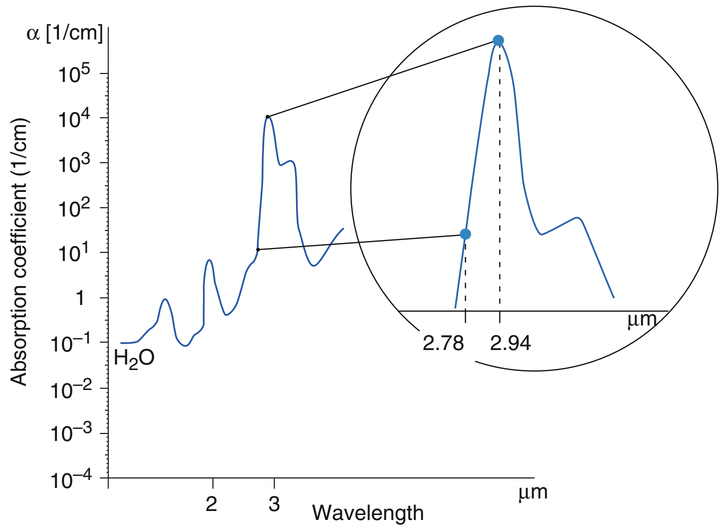

Fig. 4.4 Different absorption in water of different erbium lasers

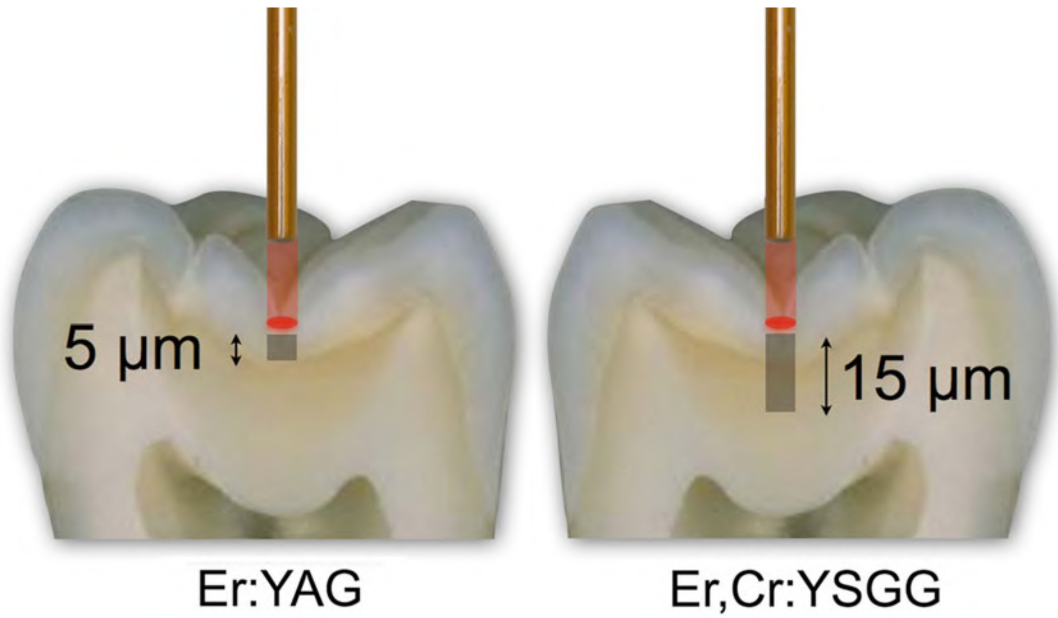

Fig. 4.5 Different penetration depth of erbium and erbium, chromium laser in dentin

and in dental trauma, this chapter will also discuss the periodontal soft tissue (gum), which is also composed of a different percentage of water, protein fibrous matrix, melanin, and hemoglobin.

4.2.1 Water and Hydroxyapatite Content of Dental Tissues

The enamel is the hard and white external covering of human teeth, characterized by a prismatic structure with radial orientation (orthogonal) to the tooth surface. The enamel has a thickness ranging from 2 to 3 mm at the tip of the cusps and 1–1.3 mm on buccal and lingual surfaces. In deciduous teeth, enamel has a thickness of 1 mm or less.

A healthy enamel is a highly mineralized tissue composed of 93–96 % hydroxyapatite, 3–5 % water, and 1 % organic tissue by weight and 85 % hydroxyapatite, 12 % water, and 3 % organic tissue by volume [32] (Fig. 4.6). Some authors reported a different value for the hydroxyapatite 96–98 % by weight or 89–91 % by volume and the remaining proportion of tissue volume being occupied by the organic matrix and water [33–37].

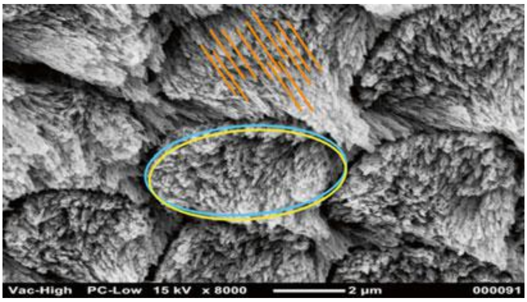

Fig. 4.6 Enamel ultrastructural morphology and erbium laser target: hydroxyapatite crystals are the core of the enamel prism (*orange line*); water (*blue line*) and organic tissues (*yellow line*) are on the periphery of the prism

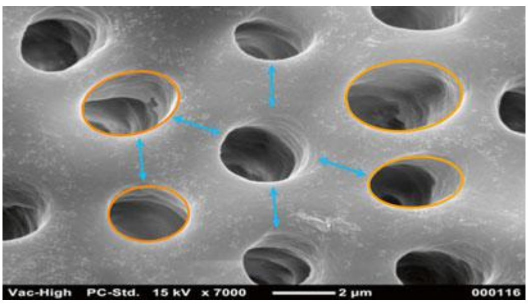

Fig. 4.7 Dentin ultrastructural morphology and erbium lasers target: the peritubular dentin is more mineralized (hydroxyapatite, *orange line*); the intertubular dentin is less mineralized and richer in water (*blue arrows*)

The dentin is a mixture of mineralized collagen fibers that determine the architecture of the dentinal tubules, which extend from the pulp to the enamel (see Chap. 1).

A healthy dentin is less mineralized than enamel; it is composed of only 65–70 % of mineral, with a higher content of organic tissue (18–20 %) and water (10 %) by weight. In volume, the proportions of mineral are 45–47 %, 30–33 % of organic tissue, and 20–24 % of water [32–34] (Fig. 4.7).

The water content of carious tissue is higher than in healthy tissues (from 27 to 54 %) depending on the stage of the caries lesion [38] and highly and selectively absorbs the medium-infrared wavelengths, resulting in a faster ablation (Fig. 4.8).

The percentage composition in hydroxyapatite, water, and organic tissue also varies from individual to individual, depending on the age of the tooth, in case of parafunctions (grinding, bruxism), in vital teeth compared to non-vital teeth. Also, intrinsic factors, such as the fluoride content of the hydroxyapatite crystals in the enamel, influence the hardness of hard tissue and thus the speed of ablation.

The ultrastructure of the deciduous teeth is different from that of permanent teeth. In primary dentition, the enamel structure appears disorganized and the prisms are large and irregular, with a superficial layer of aprismatic tissue, explaining the whiter and more opaque aspect of primary teeth. Furthermore, deciduous teeth have higher

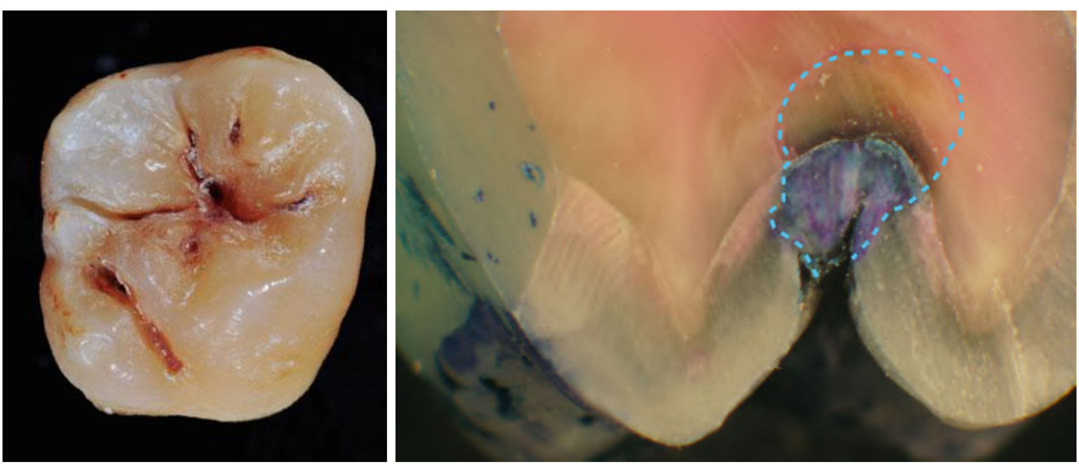

Fig. 4.8 Carious tissue and erbium laser target: occlusal face and assial section show the distribution and penetration of pit and fissure decay in enamel and dentin; the carious tissue is demineralized and richer in water (*blue line*)

water content, and the thickness of the enamel is thinner, with widely expanded pulp chamber. The dentinal tubules are smaller in diameter and more widely spaced with a lower number of dentinal tubules per unit area compared to permanent teeth [33, 34].

Since water is the main chromophore that absorbs the laser wavelengths of 2,780 and 2,940 nm, the different water content of dental tissues should be taken into account when adjusting the setting for laser ablation of dental tissues. Even the pulp tissue has a higher water content than hard tissues; therefore, care must be taken in deep cavity ablation close to the pulp chamber.

In addition to the absorption of erbium laser energy by water, there is a small amount of energy that is absorbed by the hydroxyl group of hydroxyapatite found in dental hard tissue [25], which is considered negligible for the purposes of clinical trials, in comparison to the higher water absorption [10, 31].

4.2.2 Water and Hemoglobin Content of Soft Tissues

Oral soft tissues are mainly composed of water, hemoglobin, melanin, and organic tissues (collagen and elastic fibers). Gingiva has a variety of types, such as keratinized and nonkeratinized gingiva and gingiva with thick or thin biotype; other differences are dependent on tissue location (free or attached gingiva), on the health of the tissue (healthy or inflamed), on vascularization and hydration, and on pigmentation [39] (Figs. 4.9, 4.10, and 4.11).

Best results will occur when the appropriate wavelength is matched to the main chromophore (water or hemoglobin or melanin) within the target tissue, maximizing the absorption.

Inflamed tissue that contains more blood and therefore more hemoglobin will react favorably (easily and faster) with wavelengths in the visible and near-infrared regions (see Fig. 4.2). Therefore, it is necessary to consider that the use of local anesthesia with a vasoconstrictor affects the vascularization, causing ischemia of the tissue. The distribution of melanin pigment varies from individual to individual, depending on the skin phototype (according to Fitzpatrick) and on race (Figs. 4.12 and 4.13).

Healthy or minimally vascularized tissue, where water is the principal component, is efficiently vaporized by medium- and far-infrared wavelengths [12, 39] (see Fig. 4.3).

Fig. 4.9 Healthy gingiva with thin biotype

Fig. 4.10 Inflamed, highly keratinized gingiva with thick biotype

Fig. 4.11 Inflamed, keratinized gingiva

Fig. 4.12 Fitzpatrick skin phototype 4 (moderate *brown skin*) shows dark pigmentation of the gingiva and mucosa

Fig. 4.13 Fitzpatrick skin phototype 6 (*brown* to *black skin*) shows black adherent and keratinized gingiva and pink mucosa

4.3 Mechanism of Interaction of the Erbium Family Lasers on Hard Tissues

The interaction of the erbium laser with the hard tissue is the result of a complex mechanism, which involves primarily the photothermal effect and, secondarily, the photomechanical and photoacoustic effects that occur rapidly.

4.3.1 Thermal Effect

The first effect that determines the ablative action of the erbium family laser is a direct thermal effect on the water molecules within the dentin and enamel.

The rapid temperature increase up to the boiling point of water (100 °C), trapped within the dental interstitial structure, causes an increase of pressure when it exceeds the structural tension of the surrounding tissue, leading to a micro-explosion within the tissue [29, 30, 40–43]. The richer the tissue is in water, the more quickly it reacts with laser energy [23].

4.3.2 Photomechanical and Photoacoustic Effects

The phenomenon that follows the primary thermal effect and the explosion of the water molecules inside the dental tissues is a secondary photomechanical effect, with a rapid shock wave that causes an expansion of the volume of the disrupted tissue, which results in the destruction of the surrounding mineral matrix that explodes and is removed from the irradiated surface, thus removing the tooth structure [23, 25, 41–43] (Fig. 4.14). The micro-explosion of the water molecules of the spray coaxial to the laser beam generates a pressure so high that it mechanically removes the hard tissues already irradiated and exploded by the effect of thermomechanical laser, thus participating in the ablative mechanism, with a cooling and cleansing effect [23, 44]. The products of the ablation of hard tissue, vaporized, go to form a suspension of microparticles (cloud), which in turn interferes with the ablation itself [45] (Fig. 4.15).

4.4 Role of the Water in Hard Tissue Ablation

The water participates in the ablative process of the erbium family laser not only as a target chromophore but also by its cleansing and cooling action, for rehydration, which affects the quality of the ablation of the hard tissue [23, 46].

The water spray appears to be important for its action on the tissue, because it removes the products of micro-explosion (cleaning effect) [47],

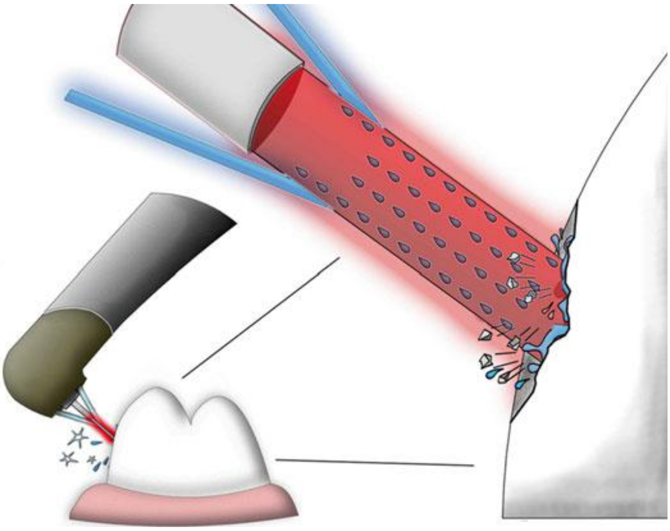

Fig. 4.14 Interaction of the erbium laser beam with the target creates a cloud of debris

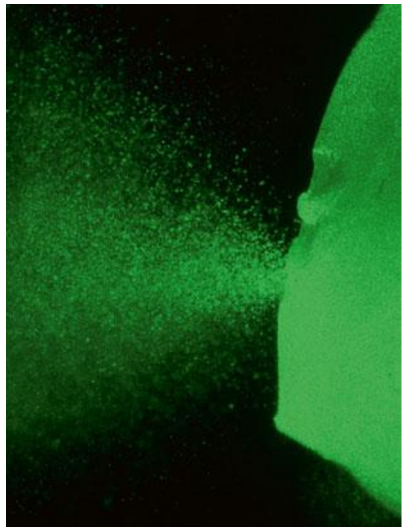

Fig. 4.15 Scattering of the laser beam after the interaction with a cloud of debris, which is formed following the ablation of dental tissues (Courtesy of M. Lukac, Slovenia)

modulates the laser energy directly absorbing it before interacting with the tissue (reducing the photothermal effect) [46], and cools the tissue (cooling effect) [46, 47]; this enables undesirable structural thermal changes of the enamel to be avoided.

An ablative "hydrokinetic" model has also been proposed; however, it is not widely accepted [48–52].

4.4.1 Water Within the Dental Tissue as Absorbent Chromophore

The primary role of water in the ablation of hard and soft tissues is as target chromophore. The greater the water content, the greater the absorption of the wavelengths 2,780 and 2,940 nm.

Studies of [53] reported that only the water content of dentin significantly influences the volume of ablation ($p < 0.0001$) of the Er:YAG laser. On the other hand, the ablative efficiency of the Er:YAG laser on the enamel is not affected by the few (minimal) water content of the enamel. The ablation volume of the Er, Cr:YSGG laser also would not be influenced by the water content of the dentin enamel [53].

This result can be explained by the low water content of the enamel and the ablative mechanism of the Er, Cr:YSGG laser (2,780 nm) that could also involve the interaction with the hydroxyapatite rather than with the water (see Fig. 4.3) and/or even greater possible hydrokinetic effect of the water spray energized by the laser [48–50].

The concept of selectivity of the interaction of the laser with the tissue or material richer in water (enamel, dentin, decayed tissue) allows the management both of the mini-invasiveness of the procedure and its speed, with the modulation of the applied energy. In this regard, Lizarelli et al. (2003) compared also the ablation rate between composite resins and dental hard tissues (enamel and dentin) after Er:YAG laser irradiation, to distinguish the energy used to remove the composites so as to protect the dentin and enamel from unwanted ablation; while the idea of ultraconservative dentistry seems to be fully applicable for the enamel, it is not applicable for the dentin, because the dentin's composition and water content make the Er:YAG laser ablation equal or superior in rate compared with the used resins (nano- or microfilled, microhybrid, and condensable) [52].

4.4.2 Water Spray as a Cleaner and Cooler

The water spray is important not only for being the main absorber and for its possible ablative action [48, 51] but also, above all, for its ability to remove the products of micro-explosion (cleaning effect), cool the tissue (cooling effect), and modulate the laser energy acting on the tissue (reducing the photothermal effect) [46]; this enables to avoid undesirable structural thermal changes in the dentin and enamel.

Many studies demonstrated the importance of the water spray to avoid micro- and macrostructural damage to the enamel, dentin (cracks, melting, and bubbles produced by thermal damage, with melting and recrystallization) [54–60], and pulp tissue [61].

4.4.3 Water Spray's Effects on Pulp Temperature

The interaction of erbium lasers with the water content of dental tissues and the instantaneous rise in temperature (up to 100 °C) within the tooth itself during the laser ablation process may be a concern, and unanimous consent considers water cooling to be mandatory for the safety of the pulp during the ablation of dental tissues.

One of the first studies to evaluate the safety of Er:YAG laser ablation of dental tissues was carried out by Dostálová et al. (1997), which evaluated, in vivo, on human premolars scheduled for extraction during orthodontic therapy and the pulpal response to Er:YAG laser cavity preparation. After extraction, the teeth were processed for light microscope observation that revealed no inflammatory reaction in the pulp and showed normal vascularity with the odontoblasts presenting the usual starlike cell shape [54].

Eversole et al. (1997) found no pulpal inflammatory responses either immediately or 30 days after Er, Cr:YSGG cavity preparation [62], and also Rizoiu et al. (1998) showed that pulp temperature did not increase and even decreased by 2 °C during tooth preparation with an erbium, chromium:yttrium–scandium–gallium–garnet (Er, Cr:YSGG) laser system. As a comparison, conventional burr preparation resulted in a 3–4 °C rise [63].

Glockner et al. (1998) confirmed the temperature drop after a few seconds of erbium:YAG laser preparation, from 37 to 25 °C to 30 °C, due to the water spray's cooling effect. In comparison, conventional preparation showed a higher rise in pulp temperature [64].

However, Armengol et al. (2000), Louw et al. (2002), and Cavalcanti et al. (2003) found no significant difference in the Er:YAG laser and high-speed handpiece groups when water spray was used to prepare class 5 cavities [65–67].

Other studies investigated the in vitro intrapulpal temperature variation during Er:YAG laser ablation. Oelgiesser et al. (2003) reported a rise in temperature that was lower than 5.5 °C (degrees Celsius) which is considered as the critical value for pulp vitality [68], while Attrill et al. (2004) reported a rise in temperature that was lower than 4.0 °C [69].

Other studies compared the intrapulpal temperature increases produced by a high-speed turbine and Er:YAG laser and concluded that Er:YAG laser generated a lower temperature rise but without statistical differences with both low- and high-torque handpieces groups [70, 71].

Krmek et al. (2009) examined the temperature variations in the pulp chamber during cavity preparation with an Er:YAG laser (2,940 nm) using a very short pulse duration (100 μs), at different depths (enamel and dentin) and different settings with a 1-mm-diameter tip. The highest rise in temperature in the pulp was achieved after enamel irradiation with 400 mJ and 15 Hz (2 °C) and the lowest was after irradiation with 320 mJ and 10 Hz (0.7 °C).

In dentin, the highest temperature increase was achieved with 340 mJ and 10 Hz (1.37 °C) and the lowest was with 200 mJ and 5 Hz (0.43 °C). It appears evident that both energy level and pulse frequency affected the temperature rise; however, the two-way analysis of both enamel and dentin showed that the influence of energy on temperature increase was stronger than that of frequency [72].

4.4.4 Water Spray's Influence on Dental Ablation

The effect of water spray on dental hard tissue ablation efficiency using the erbium lasers is still a subject of study.

Rizoiu and DeShazer (1994) and Kimmel et al. (1996) have suggested the role of a hydrokinetic effect as a fundamental ablative mechanism of hard dental tissues [48, 49].

Freiberg and Cozean (2002), comparing the effect of a water spray with that of a superficial film of water in mediating the ablative action of the erbium laser, concluded that if a hydrokinetic effect exists, it does not cause a volumetric increase in tissue ablation [73].

Kim et al. (2003) reported that when using Er:YAG laser, effective hard tissue ablation requires that the appropriate water flow rate corresponds properly to irradiation conditions. They found that at 250 mJ, the most effective ablation resulted from a water flow rate of 1.69 mL/min in both the enamel and dentin. At 400 mJ/pulse, a different water flow rate (6.75 mL/min) is required for enamel ablation, while dentin does not require more water for better ablation [74].

Meister et al. (2006) reported that the external supplied water always has a significant influence on the effectiveness of the ablation process and that only the water content in dentin influences the efficiency of Er:YAG laser ablation. He found no significant relation between dentin and enamel's water content and Er, Cr:YSGG ablation efficiency [53].

Kang et al. (2007, 2008) found a 60 % higher ablation threshold for spray-associated irradiation due to water spray absorption during irradiation. The enhanced acoustic peak pressures were six times higher, and the ablation volume of the spray-assisted process was up to two times larger compared to dry ablation, as a result of rapid water vaporization, material ejection with recoil stress, interstitial water explosion, and possibly liquid-jet formation [47, 51]. In both studies, they concluded that dry ablation exhibited severe carbonization due to excessive heat accumulation while spray induced slightly reduced efficiency but also provided significant beneficial effects, such as clean-cutting with augmented material removal and cooling effects during laser ablation.

A study by Olivi et al. (2010) described the role of water spray as modulator of the laser energy to avoid the undesirable structural thermal changes to dental tissues; a safer and more effective irradiation of the enamel was found at high percentages of air and water (Er, Cr:YSGG 92 and 80 %: 56 mL/min). The authors reported the important role of the water flow rate to obtain a qualitatively better ablation, both reducing the thermal effect of the laser interaction and increasing the tissue, cooling, and cleaning action [46]. Different percentages of the air/water spray, with wider range between air and water, appeared to slightly increase the ablative action by increasing the photothermal effect of the laser beam, but to the detriment of the quality of the ultrastructural morphology [46] (Figs. 4.16, 4.17, and 4.18).

Lately, Kuščer and Diaci (2013) studied the efficiency of the erbium laser ablation of hard tissues under different water cooling conditions. They found that the use of a continuous water spray during laser irradiation of hard dental tissues reduced the laser ablation efficiency in comparison with laser irradiation in dry mode. The phenomenon of ablation stalling can primarily be attributed to the blocking of laser light by the loosely bound and recondensed desiccated minerals that collect on the tooth surface during laser ablation. Also no evidence of the influence of the water absorption shift on the hypothesized increase in the ablation efficiency of the Er, Cr:YSGG wavelength was observed. Another positive function of the water spray during erbium laser irradiation is that it rehydrates the minerals within the tooth, thus sustaining the subsurface expansion ablation process [45].

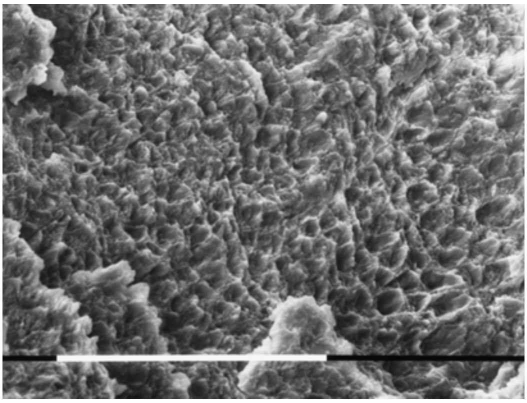

Fig. 4.16 Enamel ablation with Er, Cr:YSGG laser at 5.5 W, 20 Hz, 225 mJ, 140-μ pulse duration, 600-μm tip, with 92/80 % air/water spray presented a more regular aspect of the prismatic structure (type I or type II Silverstone) (Reprinted with permission from Olivi et al. [46])

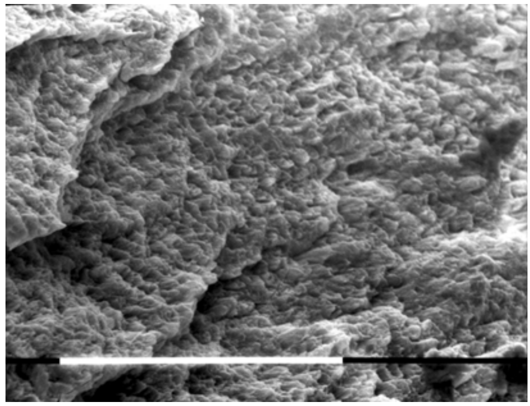

Fig. 4.17 Enamel ablation with Er, Cr:YSGG laser at 5.5 W, 20 Hz, 225 mJ, 140-μ pulse duration, 600-μm tip, with 95/70 % air/water spray showed a more disordered prismatic structure, due to prevalent destruction of the superficial prismatic structure (type III Silverstone) (Reprinted with permission from Olivi et al. [46])

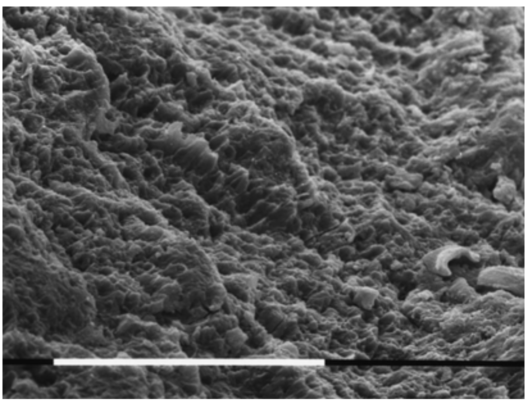

Fig. 4.18 Enamel ablation with Er, Cr:YSGG laser, at 5.5 W, 20 Hz, 225 mJ, 140-μ pulse duration, 600-μm tip, with 82/70 % air/water spray presented an intermediate outcome, with moderate presence on the surface of exploded products of ablation and few areas of melting (type II or type III Silverstone) (Reprinted with permission from Olivi et al. [46])

4.5 Mechanism of Interaction of Different Lasers on Soft Tissues

The different composition of the gum tissue in melanin, hemoglobin, water, and protein matrix (non-operator-dependent factors) determines the different interaction with the selected wavelength.

Therefore, the choice of wavelength is the most important operational factor (operator-dependent factor): visible, near-, medium-, or far-infrared lasers all interact with the soft tissues, but with different modalities (scattering or absorption), different target chromophores (hemoglobin and melanin or water), and different penetration depths (deeper or superficial) (see Fig. 4.2).

The lasers in the visible and the near-infrared spectrum are absorbed predominantly by melanin and hemoglobin. The lasers in the visible spectrum (532-nm KTP) have an optical behavior of absorption–diffusion to 50 %, with less deep penetration in the soft tissue. The lasers in the near-infrared spectrum are spread more in depth with the increase of their wavelength.

The medium-infrared (Er, Cr:YSGG and Er:YAG) and far-infrared lasers (CO_2) are absorbed by the water within tissues; the CO_2 laser has a moderate surface absorption in tissue.

The erbium:YAG laser is much more shallow, having a maximum absorption in the aqueous component of the gingiva, mucosa, and dental pulp. The absorption wavelength of 2.78 μm is lower, with greater penetration into the soft tissue; this translates, for the same energy emitted, in a higher ablative efficiency for the soft tissues.

It is the author's experience a lower power usage for the Er, Cr:YSGG laser (from 50 to 75 mJ) compared to the Er:YAG (from 100 to 150 mJ) during the incision and/or vaporization of soft tissues; this clinical experience supports the physical basis of the higher absorption in water of the Er:YAG laser compared to the Er, Cr:YSGG laser (Figs. 4.19 and 4.20). Also to be considered is the proportion of energy absorbed by the water spray, which limits the efficiency of Er:YAG soft tissue vaporization.

Whatever are the wavelengths, the laser energy absorbed by the target chromophore produced a photothermal effect on the target that generates incision and vaporization of the soft tissues. However, a stable coagulation is only obtained after visible or near-infrared lasers' interaction with hemoglobin (Figs. 4.21 and 4.22).

4.6 Laser Parameters

The laser–tissue interaction depends on the wavelength and the target tissue. The consequent effects on tissue are closely influenced by the parameters used [23, 41].

In this chapter, we consider only the use of erbium lasers in restorative dentistry.

Erbium lasers are called "free-running pulsed" lasers because they emit pulses that have a specific beginning, peak, and end; pulsed emission concentrates the amount of energy and time in a

Fig. 4.19 Laser gingivectomy to expose subgingival class V decay

Fig. 4.20 Incision performed with an Er:YAG laser at 130 mJ, 20 Hz, 300-μ pulse duration, 600-μm conical tip, air/water spray

Fig. 4.21 Laser gingivectomy to expose subgingival class V decay

Fig. 4.22 Incision performed with a 810-nm diode laser at 1 W in CW, 400-μm tip: near-infrared laser in continuous wave performed an incision with a very good coagulation and few carbonization

defined space (temporal and spatial profile), at defined intervals.

The parameters of laser used that influence the effects on the tissue are:

- The *energy* emitted and its density (*fluence*)
- The *frequency of pulses* in the time unit
- The *average power* emitted and its density (*power density*)
- The *pulse duration* and *peak power*

Also important are the temporospatial characteristics of the single pulse (temporal and spatial pulse profile) and the modality and operative technique of the clinician (distance, angle, speed, and time of irradiation) because they also influence the parameters and they will be discussed later (see Sect. 4.7).

4.6.1 Energy and Threshold of Ablation

Energy is the ability of the system to perform a task. The term comes from the Greek word "energheia" (ἐνέργεια), used by Aristotle to express effective action: it is composed of "en" (ἐν) which means "intensive particle" and "ergon" (ἔργον), meaning "ability to act." The term therefore expresses the ability of a laser to emit particles of energy (quantum) that can perform a given work (job), in our case the ablation of dental tissues.

The energy density (fluence) is the amount of energy emitted per unit of irradiated surface in a unit of time (expressed in J/cm^2). It is a value affected by the amount of irradiated surface covered in the unit of time, which also is closely related to the speed of hand movement when using the laser. This value is difficult to assess clinically and is best suited for experimental evaluations and for various applications for therapeutic purposes (LLLT). It is more useful, clinically, to consider the energy density in relation to the diameter of the fiber tip to use. At the same amount of energy emitted, the smallest fibers emit energy at a higher density; to

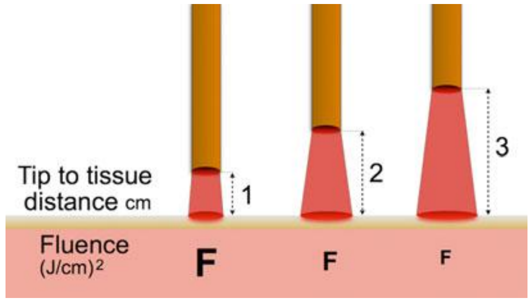

Fig. 4.23 Fluence and working distance; using the same fiber diameter and the same energy, the fluence decreases with the working distance

have the same energy density, a larger-diameter tip requires a greater amount of energy, while less energy is needed for a smaller tip. Other parameters that affect the fluence are focusing or defocusing the laser beam, which, respectively, increases or decreases the density of the energy. As the distance between the laser tip and the target tissue increases, the fluence decreases precipitously. At 2-mm tip-to-tissue distance, fluence is calculated to decrease by 68 % from its level at the tip surface. At 3 mm, it decreases by 78 % [23, 32] (Fig. 4.23).

The minimum energy required to generate a clinical effect, ablation or vaporization, is called the "threshold of ablation."

The energy that does not reach the ablation threshold is called sub-ablative.

When considering an erbium laser and water, its target chromophore contained in the dental tissues, the ablation threshold of the enamel was approximately calculated by Apel et al. (2002) in values of 9–11 J/cm^2 for the Er:YAG laser and slightly higher at 10–14 J/cm^2 for the Er, Cr:YSGG laser [75].

Lin et al. (2010) have calculated that the threshold values for the ablation of dentin are approximately 2.97–3.56 J/cm^2 for the Er:YAG and 2.69–3.66 J/cm^2 for the Er, Cr:YSGG laser [76].

Also, Majaron and Lukac (1996) have calculated the values of the ablation threshold for the dentin in 4 J/cm^2 for the Er:YAG laser [77].

The ablation threshold also depends on pulse duration, and it decreases toward shorter pulse duration. Experiments by Apel et al. (2002) revealed that when pulses of shorter duration are used, the limit at which ablation starts is reduced by up to approximately 3 J/cm^2. This expands the ablation threshold range of Er:YAG laser radiation to between 6 and 10 J/cm^2 [78]. This is due to the fact that for shorter durations, the energy has little time to escape from the ablated volume and so less heat is diffused into the surrounding tissue [79, 80]. However, although the ablation threshold of the dental enamel can be changed by varying the pulse duration of the Er:YAG laser, no clinical consequences can be expected, as the shift is only slight [78].

So, a good knowledge of the energy values to use is necessary for a selective ablation of the enamel, dentin, and decayed tissue, bearing in mind the individual variability of mineral composition of the tooth. The more energy applied, the greater the effect produced on the tissue. Only energy above what is needed to reach the threshold is used for ablation. Lower ablative energy (just above the threshold of ablation) can be used to smooth and condition the hard tissue surface through macroroughening and cleansing of the enamel and dentin (often incorrectly called laser etching; see Sect. 4.8).

Here, it is important to recall one of the basic concepts of laser therapy:

Apply the minimum effective energy, that is, the energy capable of causing the desired clinical effect, limiting the undesirable ablative effects related to higher energy used.

4.6.2 Pulse Repetition Rate

Also called pulse frequency or improperly frequency, expressed in Hz and/or more correctly in pulses per second (pps), it is an expression of the number of pulses emitted per unit of time. Numerous pulses per second increase the speed and power of the interaction; the more numerous the pulses in the time unit, the smaller the interval between one pulse and the other, with less time for tissue cooling.

4.6.3 Power

Power expresses the speed with which a certain amount of work is produced. The average power of the laser is determined by the energy emitted in the unit time (second). It is determined by the value of the energy of each single laser pulse (expressed in J) multiplied by the number of pulses in a second (pulse repetition rate or pulse frequency, expressed in Hz or pps).

Power (W) = energy (J) × pulse repetition rate (Hz or pps)

The greater the power applied, the faster the effect on the tissue.

Power density is determined by the power emitted per unit of surface area of the fiber tip or tip (expressed in Watts/cm^2).

Furthermore, other parameters influence the result of laser irradiation:

4.6.4 Pulse Duration and Peak Power

The peak power of each pulse is calculated by the energy emitted by a single pulse divided by its duration (pulse duration); it determines the effectiveness of the pulse output. The shorter the pulse duration, the more energy is concentrated in the unit time and the more effective is the ablative action with minimum thermal effect (Fig. 4.24). Short pulses cause a high peak power and lead to better efficiency for ablation of hard tissues. Pulse duration is the duration of each pulse that determines the thermal effect and the ablative efficiency of the pulse. Usually, the pulse is not variable in its length, being determined by the hardware components used in the pulse forming network (PFN) [25, 82]. Long pulses have a higher emission of thermal energy on the tissue and are more effective for the vaporization of soft tissues (see Fig. 4.24). Short pulses have better efficiency for hard tissue ablation.

Consequently, for an erbium laser, the possibility to vary and control the pulse duration is critical for the success of laser dental treatments [82].

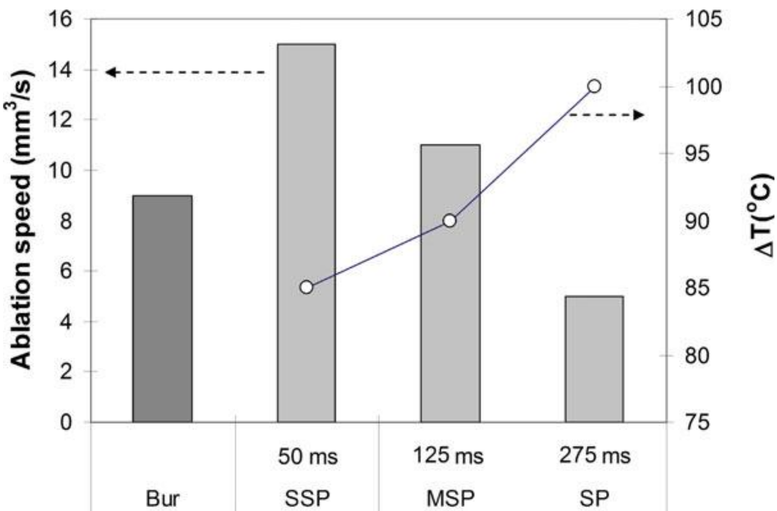

Fig. 4.24 Ablation rate (in mm^3/s) of caries in dentin for different Er:YAG pulse duration modes of Fotona Fidelis laser in comparison with a steel burr. Shorter pulse durations result in lower heat deposition and higher ablation rate (Reprinted with permission from Lukac et al. [81])

Table 4.1 summarizes the main operating parameters of the erbium laser.

By learning how to set these parameters and operating modes, you can manage and influence the quantity and quality of irradiation on the tissue, being able to predict the resulting biological effects.

Table 4.1 Main operating parameters of the erbium laser

Energy (E): J
Fluence or energy density (Fl): J/cm^2
Pulse repetition rate or frequency (F): Hz o pps
Average power (P): Watt = E (J) × F (Hz o pps)
Power density (Pd): W/cm^2
Peak power (PP): W = E (J) ÷ pulse duration (s)

4.7 Laser Effects on Hard Tissues

The interaction of the erbium lasers (2,780 and 2,940 nm) with the hard dental tissues causes the typical photothermal and photomechanical effects.

Macroscopically, we can observe superimposed (overlapped) craters, dispersed over the prepared area, which give the irradiated hard tissue a characteristically rough, white-opaque aspect; the whitish color is characteristic of the irradiated tissue due to the disruption of the prismatic structure of enamel and of the organic-mineral matrix of the dentin that consequently produces a low reflection-refraction of light, hence the opacity (Figs. 4.25 and 4.26).

Microscopically, the enamel has an etched-like pattern, more or less irregular (Figs. 4.27, 4.28, and 4.29); the dentin shows the typical chimney-like appearance, an effect of ablation prevalent in the intertubular level, more rich in water, with protrusion of peritubular dentinal tubules, and more mineralized, with open orifices and smear layer mainly absent (Figs. 4.30, 4.31, 4.32, and 4.33). The microscopic appearance can vary greatly according to the different parameters used, the angulation of irradiation, and the position of the lased surface, all critical factors for the adhesion of composite systems (see Chap. 5) (Figs. 4.34 and 4.35).

4.7.1 Influence of Laser Parameters on Hard Tissue Irradiation

There are many parameters involved that determine the effects of laser radiation on the hard tissues.

Energy: higher energy produces "deeper craters" with an ablative effect that is more pronounced. The photothermal effect and the photoacoustic effect are proportional to the energy emitted;

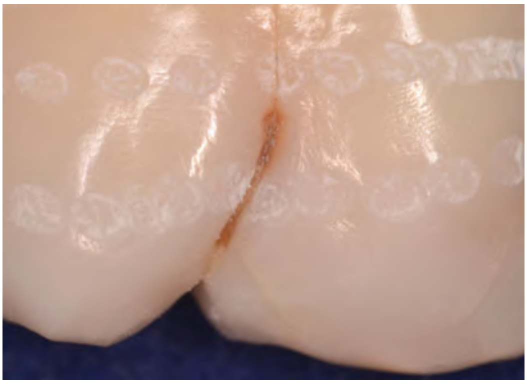

Fig. 4.25 Palatal surface of upper molar with two lines of Er:YAG irradiation: the *whitish* and opaque laser spots on the enamel surface show no reflection of the incident flashlight, due to the disorganization of the enamel prisms

Fig. 4.26 Noncomplicated enamel–dentin fracture of tooth 11. Erbium laser preparation of the surface shows a whitish and opaque surface

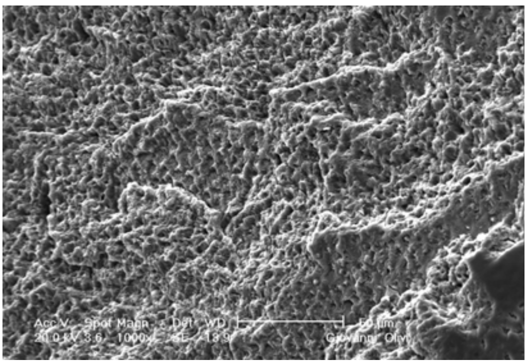

Fig. 4.27 SEM image (1,000×) of enamel surface irradiated with an Er, Cr:YSGG laser (Biolase Waterlase MD) at 300 mJ, 10 Hz, 1,100-μm tip, with 90/80 % air/water spray shows a clean surface from the exploded products of ablation and partially thermally affected surface: the prism profiles are rounded

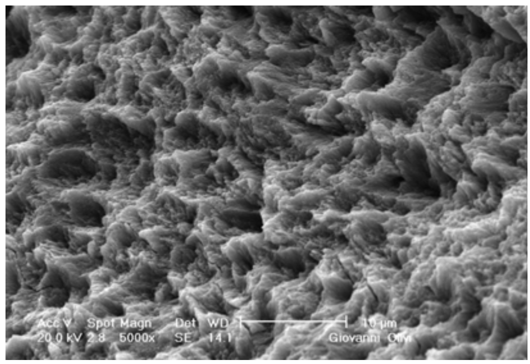

Fig. 4.28 SEM image (5,000×) of enamel surface irradiated with an Er:YAG laser (Fotona, LightWalker AT), QSP mode at 450 mJ, 10 Hz, tipless handpiece 1-mm spot, with 6/5 air/water spray ratio. The high magnification shows typical Silverstone type 1 pattern, with sharp prism profile

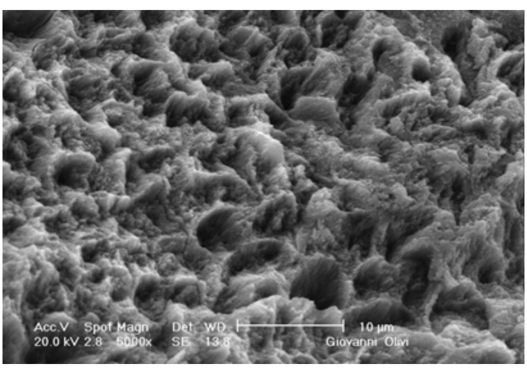

Fig. 4.29 SEM image (5,000×) of enamel-irradiated surface with the same parameters as the previous but with SSP mode (50 μs); the high magnification shows typical Silverstone type 1 pattern, with sharp prism profile

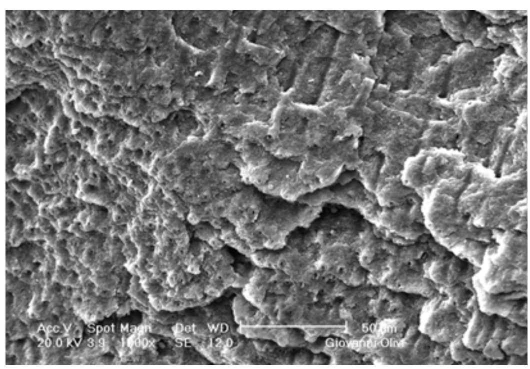

Fig. 4.30 SEM images (1,000×) of dentin surface. Laser irradiation performed perpendicularly to the crown axial wall with an Er, Cr:YSGG laser at 125 mJ, 10 Hz, 140 μs, 1,100-μm tip, with 90/80 % air/water spray; typical scaly surface appearance, due to prevalent ablation in the intertubular dentin which is more rich in water, with open orifices and smear layer mainly absent

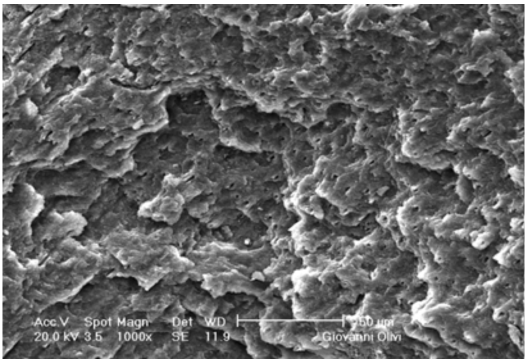

Fig. 4.31 SEM images (1,000×) of dentin surface of a different sample irradiated with an Er, Cr:YSGG laser with the same parameters as the previous show the same typical pattern of laser irradiation

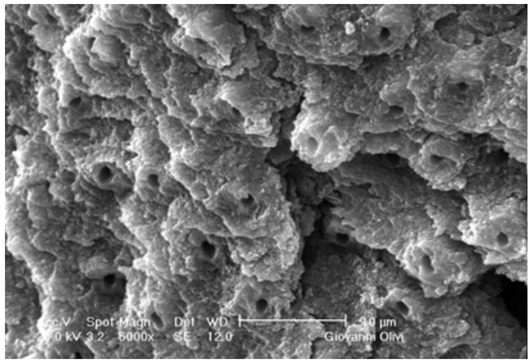

Fig. 4.32 SEM images at higher (5,000×) magnification of Fig. 4.30; typical chimney-like appearance, an effect of ablation prevalent in the intertubular level with protrusion of peritubular dentin, less rich in water; the orifices are opened with no smear layer. The surface shows superficial thermal damage

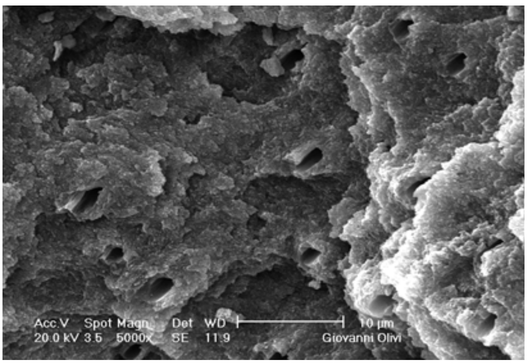

Fig. 4.33 SEM images at higher (5,000×) magnification of Fig. 4.31; higher magnification shows the typical chimney-like appearance of the lased dentin, with opened orifices and no smear layer. The surface shows superficial thermal damage

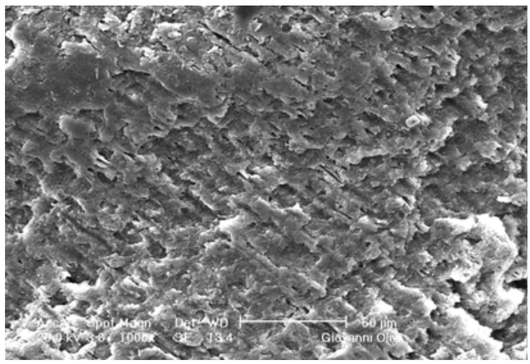

Fig. 4.34 SEM image (1,000×) of dentin surface. Laser irradiation performed perpendicularly to the crown axial wall with an Er:YAG laser (Fotona, LightWalker AT) at 160 mJ, 10 Hz, with 600-µm conical tip and high air/water spray ratio: smear layer-free surface that partially shows the dentin tubules' path

the increased intensity of the acoustic effect is easily perceived by varying the energy during the ablation of dental tissues.

A study by Olivi and Genovese (2007) reported that Er:YAG laser irradiation of human enamel, at energy of 350 mJ, was associated with a greater depth of craters and uneven and less defined spot–crater margins. The study described both the qualitative and quantitative morphological differences of the irradiated surface as a result of the higher thermal effect when using high energy levels as 350 mJ/pulse (Figs. 4.36 and 4.37). Lower energy levels of 250 and 80 mJ, for enamel ablation and conditioning, respectively, were found to produce a

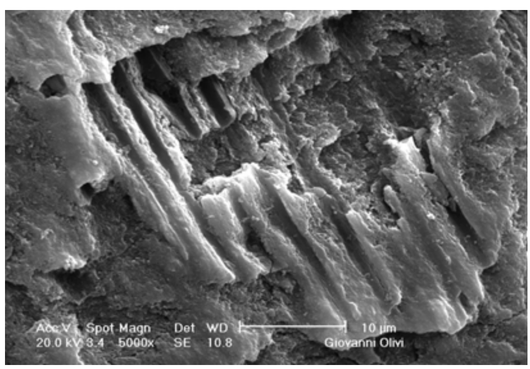

Fig. 4.35 SEM image (5,000×) of dentin-irradiated surface with the same parameters as the previous; higher magnification shows dentin tubules' section and signs of thermal irradiation

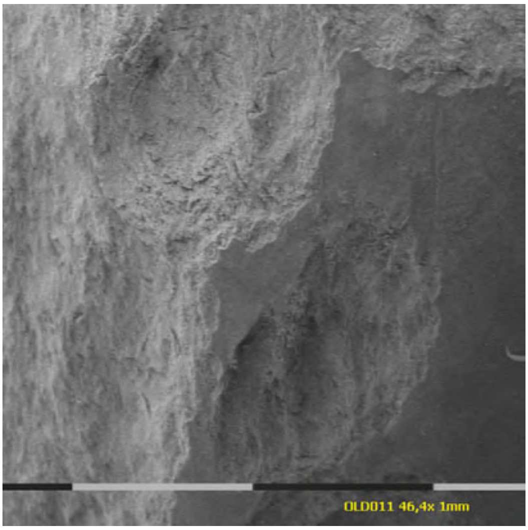

Fig. 4.36 SEM image (46.4×) of enamel surface irradiated with Er:YAG laser, 250 µs pulse duration, at 350 mJ, 3 pps: the margins of the overlapping spots are uneven (Reprinted with permission from Olivi and Genovese [83])

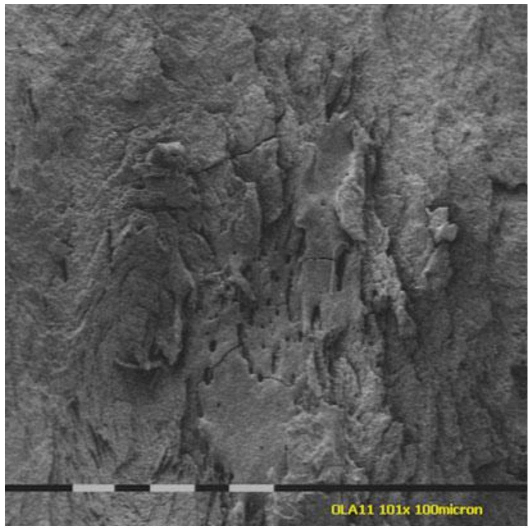

Fig. 4.37 SEM image (101×) of enamel surface irradiated with Er:YAG laser, 250 µs pulse duration, at 350 mJ/pulse, 3 pps: the crater shows an irregular rough surface, flakes, and areas of melting. These parts are loosely adherent to the surface and can lead to microleakage (Reprinted with permission from Olivi and Genovese [83])

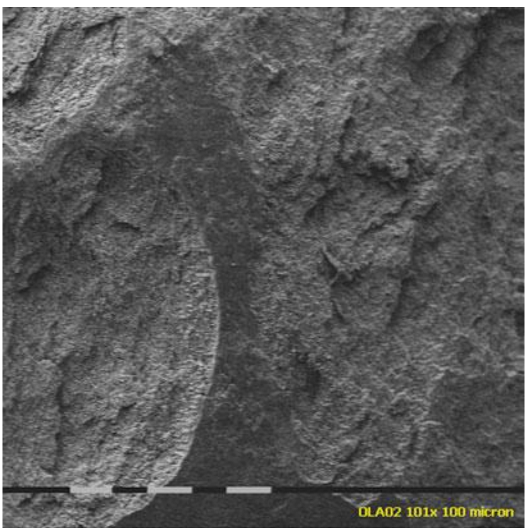

Fig. 4.38 SEM image (101×) of enamel surface irradiated with Er:YAG laser, 250 µs pulse duration, at 80 mJ/pulse, 10 pps, 600-µm tip: crater with better defined margins (Reprinted with permission from Olivi and Genovese [83])

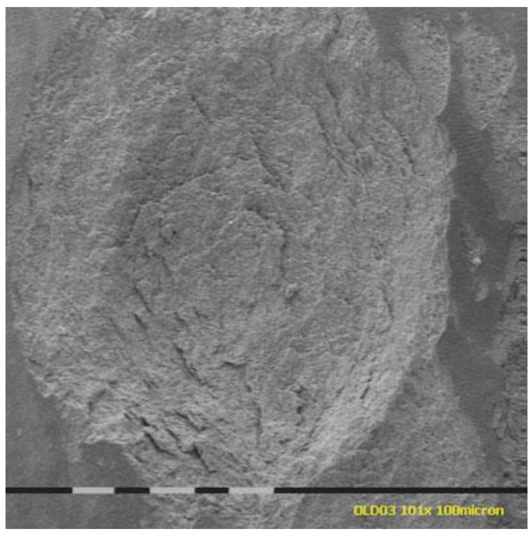

Fig. 4.39 SEM image (101×) of enamel surface irradiated with Er:YAG laser, 250 µs pulse duration, at 80 mJ/pulse, 10 pps, 600-µm tip: the crater shows rough, scaly surface and flakes and melting is absent (Reprinted with permission from Olivi and Genovese [83])

better surface for the adhesive restorative materials [83] (Figs. 4.38 and 4.39). The energy emitted is also conditioned by the diameter of the tip: a smaller tip diameter will emit more energy per unit of irradiated surface (fluence) with a greater ablative efficiency (Figs. 4.40 and 4.41).

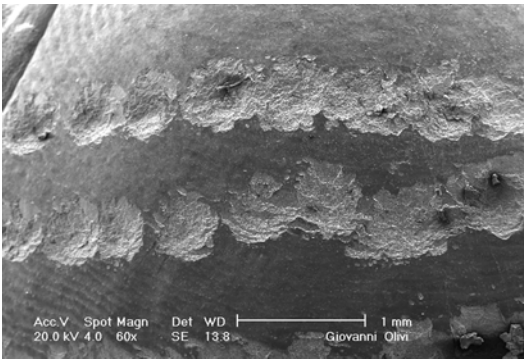

Fig. 4.40 SEM image (60×) of a series of Er, Cr:YSGG laser spots irradiating the enamel surface at 300 mJ, 10 Hz, 140 µs pulse duration, MZ10 1,100-µm tip, and 90/80 % air/water spray: lower fluence performed better craters with scaly surface and very irregular margins

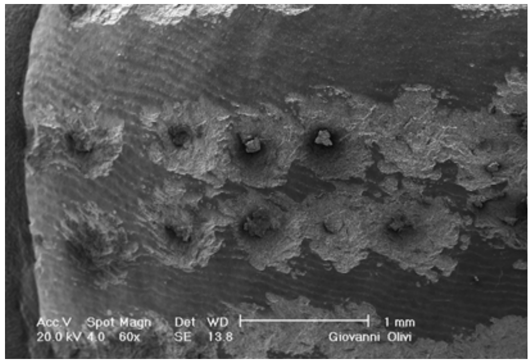

Fig. 4.41 SEM image (60×) of a series of Er, Cr:YSGG laser spots irradiating the enamel surface at 300 mJ, 10 Hz, 140 µs pulse duration, MG6 600-µm tip, and 90/80 % air/water spray: the higher fluence caused deeper interaction with some loosely attached flakes in the center of the craters' surface

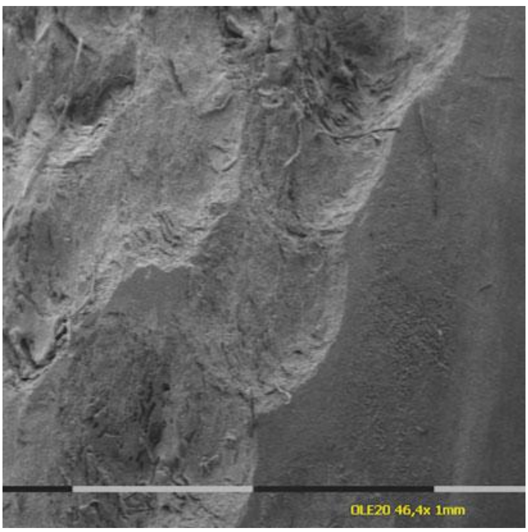

Fig. 4.42 SEM image (46.4×) of a series of Er:YAG laser overlapped spots, irradiating the enamel surface. Energy of 125 mJ and high pulse repetition rate of 25 Hz allow for a continuous preparation of the surface

Pulse repetition rate: the pulse frequency influences the control and accuracy of irradiation, the continuity of the ablation, and the sensitivity to pain of the patient.

A higher pulse repetition rate produces spots that are closer together or overlap, with the continuity of ablation covering the entire irradiated surface; during conservative dentistry, finishing of cavities should be performed at a high pulse repetition rate from 30 to 50 pps, with low energy, to have a continuous smoothing effect but more superficial (Fig. 4.42); on the opposite, lower pulse repetition rate could in fact leave areas of tissue untouched.

Pulses at a lower repetition rate (lower than 15 pps) also allow a long time for thermal relaxation between one pulse and the next (following), time necessary for the tissue to dissipate the thermal energy stored at 50 % of the initial temperature. Accordingly, working on dentin, it is preferable to choose a low repetition frequency, to reduce the thermal effect on dentin and have a surface more suitable for adhesive procedures.

Varying the repetition frequency also improves visual and manual control of the irradiation with more ease; when the pulse repetition rate is reduced (5–20 pps), control and precision are higher, compared to a train of pulses that come closer together (30–50 pps). With the same energy output, more frequent pulses are less tolerated by the patient when compared with lower repetition rate pulses in the time frame; this increased sensitivity is due to a greater stimulation of nerve fibers.

Pulse duration: also pulse duration is a parameter that characterizes the photothermal and/or photomechanical effects of the laser irradiation.

With the same energy output, a short pulse duration leads to a high peak power, with higher ablative efficacy and fewer thermal side effects (see Fig. 4.24). Table 4.2 shows the different peak power resulting from the same energy level using different devices with different pulse duration.

A study from Baraba et al. (2013) reported that at an energy of 80 mJ at 10 pps (Er:YAG laser), the use of 300 μs and 100 μs pulse duration produced more suitable results than super short pulses at 50 μs, for dentin surface conditioning prior to bonding procedures, when using one-step self-etch adhesive [84].

Table 4.2 Peak power results

Energy (mJ)	Pulse duration (μs)	Peak power (W)
200	50	4,000
200	100	2,000
200	140	1,428
200	250	800
200	300	666

Temporal and spatial beam profile: in addition to the duration of the single impulse, the temporal and spatial beam profiles of the pulse are very important for the efficacy and efficiency of the laser ablation.

The temporal profile describes how the laser pulse develops in time, i.e., the starting time and end time of the single pulse. Traditional erbium lasers typically use a conventional method for generating a high-energy laser pulse (pulse forming network); the PFN has a typical pulse temporal shape with a fast rise and a long declining tail, with a drop of ablation efficacy during the final part of the pulse [85]. In recent years, the development of variable square pulse (VSP) pumping technology for Er:YAG lasers [80, 82–85] has allowed the creation of the square wave pulse used for a broad spectrum of pulse duration. The energy emitted through a "square pulse" has a more homogeneous distribution over time and space, with a more efficient effect. The ability to vary the duration over a wide range of pulse durations permits wide possibilities of clinical protocols operating with different characteristics, allowing the optimization of the speed and precision and to control the heating during laser–tissue interaction (Fig. 4.43).

The spatial profile describes the energy distribution of the laser beam on the treated surface (TEM00, TEM 31, top-hat, etc.), which affects the amount of ablation and the amount of heat diffusion during the irradiation. The conventional laser beam is emitted in fundamental transverse

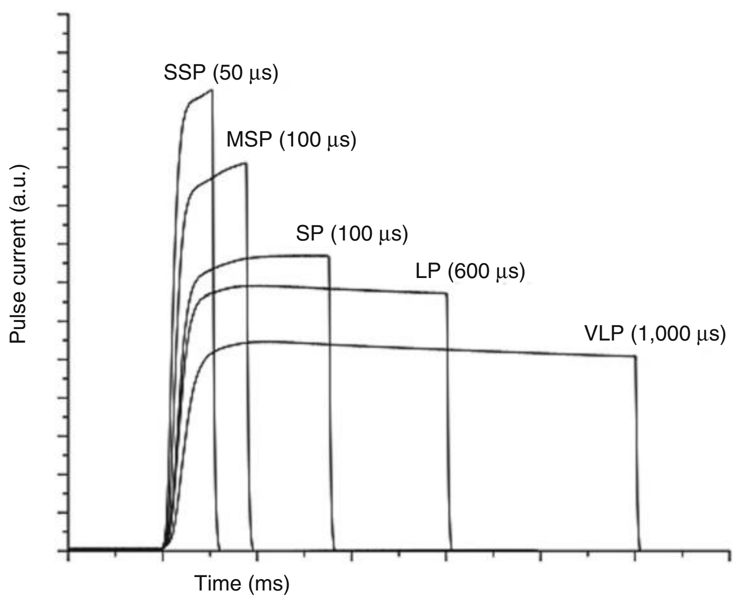

Fig. 4.43 VSP pulse shapes for different pulse durations of Fotona dental laser. The rise and fall times are approximately the same for all the pulse durations; the pulse durations have no relationship with the rise and fall times (Reprinted with permission from Diaci and Gaspirc [25]). *SSP* super short pulse, *MSP* medium short pulse, *SP* short pulse, *LP* long pulse, *VLP* very long pulse

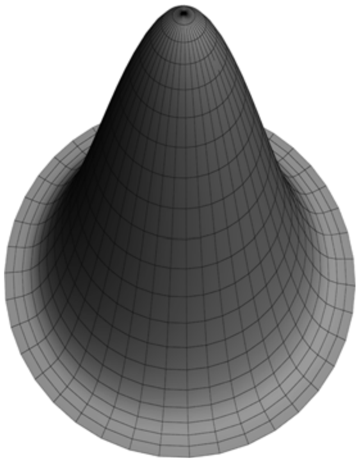

Fig. 4.44 A symmetric bell-shaped curve is typical of the laser beam emitted in TEM00 mode (Gaussian profile)

Fig. 4.45 Er:YAG laser-ablated cavities in dentin with a standard VSP pulse; note the ablation depth and the uneven margins of the cavity (Courtesy of M. Lukac, Slovenia)

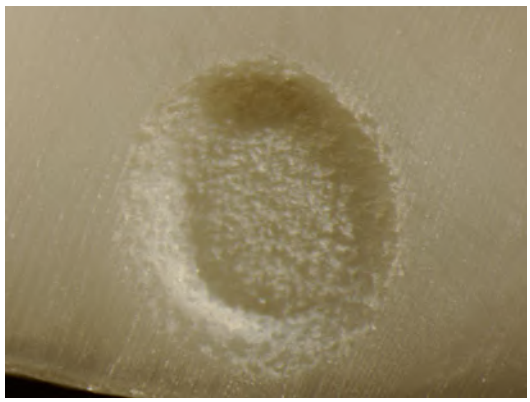

Fig. 4.46 Comparison of the quality of laser-ablated cavities in dentin with a QSP pulse of the same pulse energy as the previous Fig. 4.45. Note the difference in the ablated depth and the sharpness of the cavity edges (Courtesy of M. Lukac, Slovenia)

mode (TEM00), represented by a Gaussian profile with a typical symmetric bell-shaped curve (Fig. 4.44).

However, many clinical applications require different modes of emission, defined as "top-hat shaped" or "multi-mode transverse mode," which guarantee a more homogeneous tissue thermal radiation across the beam profile, while in conventional treatments with TEM00 emission mode, the intensity of the laser energy emitted is concentrated at the center of the laser beam.

The laser pulse "top-hat shaped" with very short duration (<100 μs) generates a high peak power with a more homogeneous tissue thermal radiation across the beam profile that results in a high photomechanical effect, with minimum thermal dispersion and a high ablative efficiency. Observing at low magnification the laser craters (from 33 up to 200× magnification) resulting from a single pulse of laser irradiation emitted by a different transmission mode (TM00 or top-hat), the different spatial distribution of the emitted laser beam, with interactions that are more or less precise, with sharp or uneven edges, become evident (Figs. 4.45, 4.46, and 4.47).

An evolution of the emission of the laser pulse is represented by QSP (quantum square pulse) modality. This technology is produced for a specific erbium:YAG laser (LightWalker, Fotona) and is composed of a long pulse (600 μs) consisting of five very short pulses (VSP), defined as "pulse quanta," which occur at an optimized frequency [81, 86, 87]. Each pulse quanta has a square profile and is very short (VSP at 50 μs), allowing an efficient and homogeneous tissue thermal radiation across the beam profile (Figs. 4.48, 4.49, and 4.50). The short pulse duration overcomes the problem of the interaction of the laser beam with the cloud of debris produced during the ablation; indeed, the duration of each "pulse quanta" is

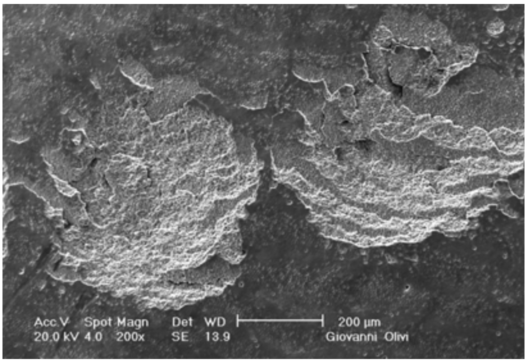

Fig. 4.47 SEM image (33×) of a couple of Er, Cr:YSGG laser spots at 150 mJ, 10 Hz, with a 550-µm tip and 90/80 % air/water spray. Due to the typical pulse temporal shape with a fast rise and a long declining tail, the PFN pulse generates uneven and less precise margins of the overlapped spots

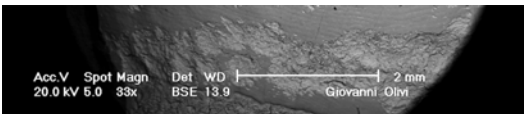

Fig. 4.48 SEM image (200×) of a series of Er, Cr:YSGG laser spots at 300 mJ, 10 Hz, with a 1,100-µm tip and 90/80 % air/water spray. Note the uneven and less precise margins of the craters due to the TM00 spatial distribution of the laser beam

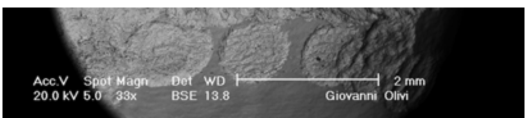

Fig. 4.49 SEM image (33×) of a series of Er:YAG laser (Fotona, LightWalker AT) spots at 450 mJ, 10 Hz, SSP mode, with tipless handpiece 1-mm spot diameter and high air/water spray ratio (6/5). The SSP mode at 50 µs allows efficient laser emission: the craters are more outlined

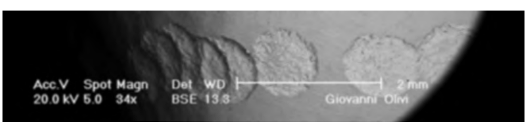

Fig. 4.50 SEM image (34×) of a series of Er:YAG laser (Fotona, LightWalker AT) spots at 450 mJ, 10 Hz, QSP mode, with tipless handpiece 1-mm spot diameter and high air/water spray ratio (6/5). The QSP mode permits higher efficient laser emission and very sharp and even margins of the craters

lower than the time of formation of the cloud of debris derived from the hard tissue ablation; the interval between a pulse and the other is also longer than the decay time of the cloud, thus avoiding the interaction of the "pulse" with the "cloud," allowing the emission of lower energy with higher efficiency, with high peak power and higher speed of ablation (Figs. 4.51a, b).

Water spray: erbium lasers also work with a spray of water integrated with multiple functions such as tissue rehydration, cleaning, and cooling [45]. Olivi et al. (2010) described the modulator role of the water spray on the laser energy to avoid the undesirable structural thermal changes to dental tissues [46]. High water spray ratio induced clean-cutting with slightly reduced efficiency, providing significant beneficial effects such as augmented material removal and cooling/cleaning effects during the irradiation. A varied ratio of the air/water spray, with a wider range between air and water, appeared to increase the ablative action by increasing the photothermal effect

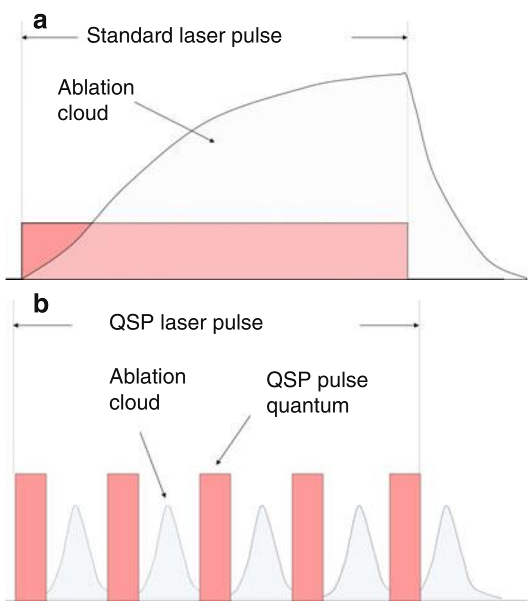

Fig. 4.51 (**a**) Due to the duration of a standard laser pulse and of formation of a cloud cycle, the laser beam interacts with the cloud of debris, with loss of efficiency during the ablation process. (**b**) QSP mode's major advantage is the reduction of the undesirable effects of laser beam scattering and absorption in the cloud of debris during tissue ablation. The duration of each pulse quanta (50 µs) is shorter than the cloud of debris' rise time, while the separation between the pulse quanta is longer than the cloud of debris' decay time (Courtesy of M. Lukac, Slovenia)

of the laser beam, but to the detriment of the quality of the morphological aspects [46] (see Figs. 4.16, 4.17, and 4.18).

4.7.2 Influence of Laser Technique on Hard Tissue Irradiation

Speed: the speed of application is important as it enables better control over the release of energy on the tissue. Also a very slow movement of the hand allows a greater energy release per unit of surface area over time; on the contrary, a fast movement could lead to an ineffective ablation.

Working distance and focus: the distance from the target affects the density of energy and power. Furthermore, different handpieces have different focal distances from the tissue, depending on the construction; focusing or defocusing the laser beam increases or decreases the energy density and power. As the distance between fiber/tip and target increases, the density of energy emitted decreases. Selting (2009) reported that at 2-mm tip-to-tissue distance, fluence has decreased by 68 % from its level at the tip surface; at 3 mm, it has decreased by 78 % [23, 31] (see Fig. 4.23).

Angulation: the ideal angulation for interaction of the erbium laser on the enamel is perpendicular to the orientation of the prisms and therefore with different angle of irradiation to the dental surface. The percentage of ablation is nearly constant when maintaining a radiation angle of 45° on the dental surface; variations of up to 90° do not seem to be a critical factor for the clinical ablation of hard tissues [23, 31]. Qualitative variations, in terms of adhesion, on the surface of the prismatic structures of the enamel are appreciable with a change in the angle of inclination [46]. Therefore, it is essential to have visual control during irradiation. The use of loops or an operative microscope allows a magnified view of laser–tissue interaction and permits a check on the correct execution of tissue irradiation; hand speed, as well as the angulation, or focusing or defocusing during irradiation can be increased or decreased depending on the result desired and obtained [88].

4.8 Enamel Conditioning and Ablation

When the appropriate laser wavelengths (2,780 and 2,940 nm) interact with the dental surface, absorption in water and hydroxyapatite produces several effects on the enamel and dentin, resulting from the parameters used.

The difference between laser ablation and conditioning is closely related to the laser energy/fluence used. In addition, the air/water spray volume and ratio, the duration of the pulse, and the different spatial and temporal beam profiles of the pulse contribute to a more or less evident laser thermal effect on the target tissues.

Sometimes, the inappropriate term “laser etching” is used to describe a reduced ablative effect on the enamel surface, which has the purpose to produce surface modifications similar to orthophosphoric acid etching.

According to other authors, the more accurate term laser “conditioning” [89, 90] is used in this text to describe the laser procedures of smoothening the enamel cavity margins before adhesive procedures.

The ideal pattern of the enamel surface for the adhesion procedures is produced by 37 % orthophosphoric acid for 20–30 s. Silverstone (1981) described and classified this surface pattern as type 1 [91] which still remains the “gold standard” in adhesive dentistry. Macroscopically, the etched enamel with orthophosphoric acid loses its shine, becoming slightly opaque; microscopically, a Silverstone type 1 surface is visible, with a homogeneous prismatic structure that is well preserved in peripheral areas with prismatic bumps demarcating a concave cuplike central area, as a result of a chemical decalcification mainly produced in the central zone of the prism (more calcified) [91] (Fig. 4.52). Mid-infrared lasers produce similar

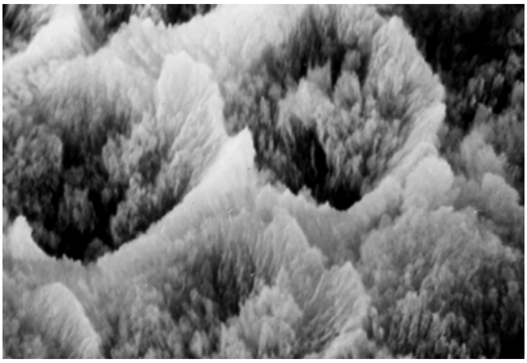

Fig. 4.52 Typical SEM image of 37 % orthophosphoric acid-etched enamel. The enamel pattern is of Silverstone type 1 classification (original magnification 6,500×) (Courtesy of Prof. Vasilios Kaitsas, Italy)

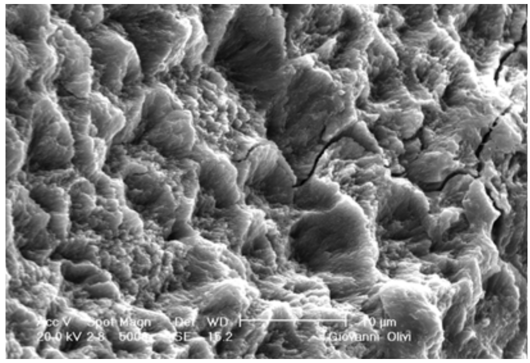

Fig. 4.53 SEM image (5,000×) of enamel surface irradiated with Er, Cr:YSGG laser at 250 mJ, 10 Hz, 140 µs, shows Silverstone types 1 and 2 pattern of the enamel

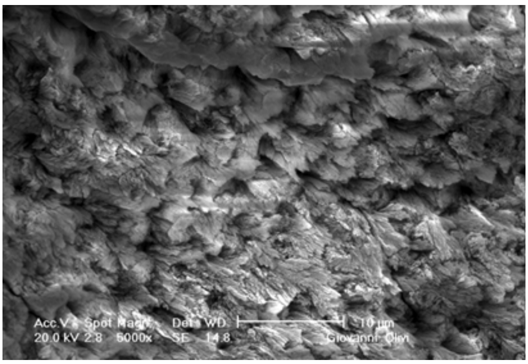

Fig. 4.54 SEM image (5,000×) of enamel surface irradiated with Er:YAG laser, at 450 mJ, 10 Hz, 50 µs, plus 80-mJ conditioning shows a more conserved enamel pattern with peripheral prismatic bumps

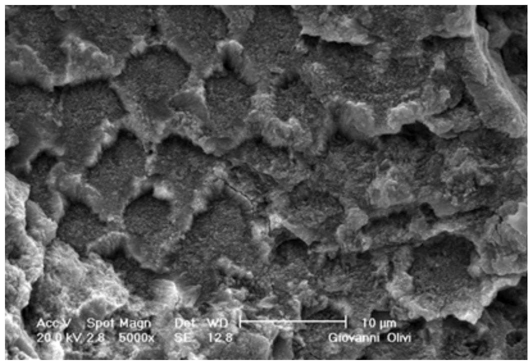

Fig. 4.55 SEM image (5,000×) of enamel surface irradiated with Er:YAG laser at 450 mJ 10 Hz, 50 µs shows the typical Silverstone type 2 pattern, with flat surface and few peripheral prismatic bumps

surface modifications to acid etching, but more irregular. The laser spots and craters are macroscopically more or less outlined, expressing the interaction of the laser with the enamel. The surface is very opaque from the complete absence of reflection resulting from the disorganization of the prismatic pattern. Microscopically, Er:YAG and Er, Cr:YSGG laser irradiation are rarely able to produce enamel modification with Silverstone type 1 pattern because laser interaction works more on the peripheral interprismatic structure, which is more rich in water, than in the central zone of the prism; as a result, Silverstone type 2 pattern is more commonly observed after laser irradiation, characterized by a flatter surface with fewer peripheral prismatic bumps [46] (Figs. 4.53, 4.54, and 4.55). Also the angulation of the irradiation affects the pattern of the enamel surface [46]; indeed, the orthophosphoric acid always works on the enamel surface with a complete surface contact, while the laser angulation changes according to the tooth surface orientation and the laser's position in the mouth (Figs. 4.56, 4.57, 4.58, and 4.59).

When high water spray is used during laser irradiation, the typical pattern of laser-treated enamel is visible; the prismatic structures are partially preserved; the surface is characterized by grooves, shelves, and flakes, aspects more indicative of micro-explosion than of melting [46] (see Figs.4.16, 4.17, 4.18, 4.28, and 4.29).

Fig. 4.56 Intraoral preoperative image shows irregular and unesthetic margins of two *upper* central incisors; agenesia of lateral incisors

Fig. 4.57 Er:YAG laser conditioning of distal margins of the central incisors and of the mesial margin and incisal surface of 21 to be aligned with composite; the cuspids have been restored with indirect porcelain veneers

Fig. 4.58 Orthophosphoric acid etching of the irradiated teeth shows a more uniform rough surface, ready for the bonding procedure

When lower water spray is used and the thermal effect is higher, cracks and melting appear, with a glazed surface; the structure of the enamel is completely disorganized, both in the center of the prism and the periphery, with production of a Silverstone type 3 surface pattern [46].

When laser ablation is performed at high energy (>150 mJ) and there is insufficient water cooling, it can produce deep craters with presence of flakes and detached particles that leave unsupported enamel prisms on the irradiated surface (Figs. 4.60 and 4.61). Consequently, laser conditioning is performed at the end of the ablation with lower energy (<100 mJ) and high repetition rate; it allows to obtain a refinishing

Fig. 4.59 Esthetic results of the combination of noninvasive direct composite restoration and indirect porcelain veneers

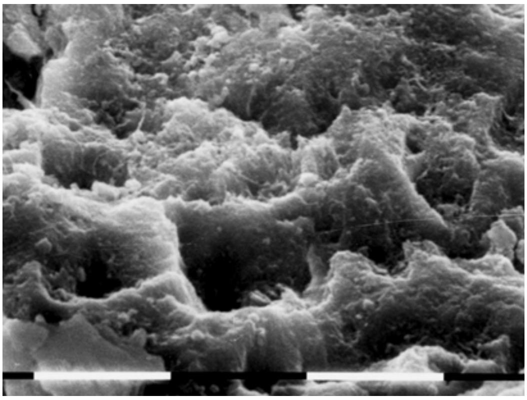

Fig. 4.60 SEM image (6,000×) of Er, Cr:YSGG laser-irradiated enamel at 250 mJ, 20 Hz, with 600-µm tip at low air/water spray ratio. Insufficient cooling of the ablated surface produced some superficial melting

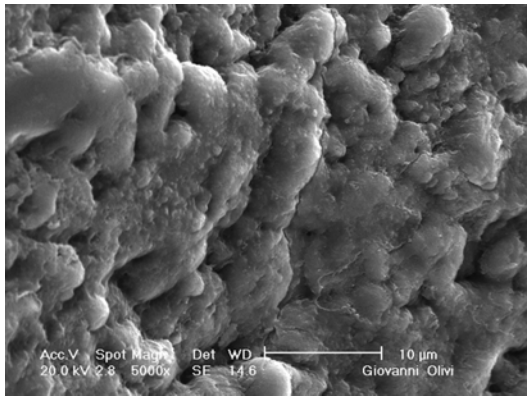

Fig. 4.61 SEM image (5,000×) of enamel surface irradiated with Er:YAG laser at 450 mJ, 10 Hz, 50 µs. High energy and insufficient air/water cooling produced melting of the enamel surface

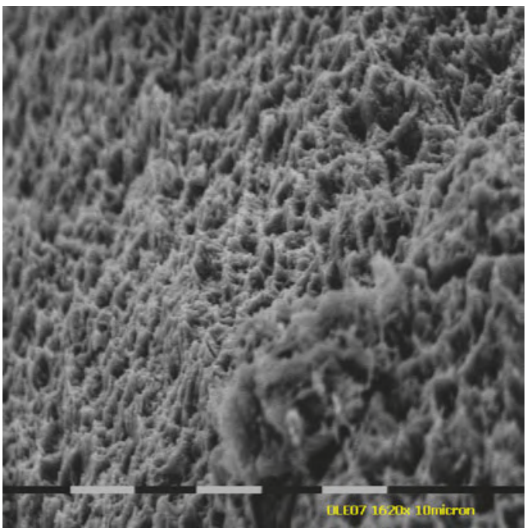

Fig. 4.62 SEM image (1,620×) of enamel surface irradiated with Er:YAG laser at 80 mJ, 10 Hz. The surface presents an etched-like aspect of the enamel prismatic structure (Reprinted with permission from Olivi and Genovese [83])

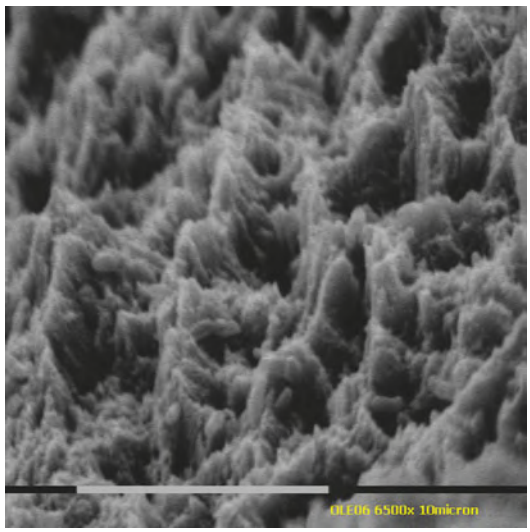

Fig. 4.63 SEM image (6,500×) of enamel surface irradiated with Er:YAG laser at 80 mJ, 10 Hz. The surface shows an etched-like aspect of the enamel prismatic structure; no melting or cracks are present (Reprinted with permission from Olivi and Genovese [83])

of the enamel with production of shallower craters. The thermal effect is less pronounced, and the result is a leveling of the irradiated surface and preparation margins, with a smoothening-finishing effect.

Given that the ablation threshold of the enamel was calculated approximately by Apel et al. (2002) [75] in values of 9–11 J/cm^2 for the Er: YAG laser and slightly higher at 10–14 J/cm^2 for the Er, Cr:YSGG laser, using a 600-µm tip, a minimum energy of 25–30 mJ for Er:YAG and 28–40 mJ for Er, Cr:YSGG is required to smooth the enamel margins. In the clinical practice, energies ranging from 35 to 70 mJ for the Er:YAG laser and from 50 to 80 for the laser Er:Cr:YSGG are proposed by the author for this purpose.

Safer, effective, and qualitatively better conditioning of the enamel was found at 80 mJ and high percentages of air and water (Er, Cr:YSGG 92 and 80 %: 56 mL/min) [46] (Figs. 4.62 and 4.63).

To obtain a standard and better result in terms of finishing and then of marginal adaptation of composite materials that results in less marginal leakage (and infiltration) and better bond strength of composite materials, a mechanical smoothening (finishing) of the enamel surface and margins is also recommended. The etching with orthophosphoric acid will help to uniform the surface for a better adhesion.

4.9 Dentin Ablation and Conditioning

The laser–dentin interaction occurs when the mid-infrared lasers (2,780 and 2,940 nm) irradiate the dentin surface and are absorbed by the water in dentin. The photothermal and photomechanical effects result in dentin ablation with debris and smear layer removal, producing the typical cuff-like appearance. The laser-dentin pattern is the result of prevalent ablation in the intertubular dentin, which is richer in water with protrusion of open orifices of dentinal tubules; the thermal effect also results in vaporization and denaturing of the collagen fibers in the superficial layers of the dentin (see Figs. 4.32 and 4.33). This typical dentin surface aspect is subject to many variations depending on the energy, pulse duration, and pulse repetition rate used.

When ablation is performed at energy levels greater than 150–200 mJ and water cooling is insufficient, macrostructural thermal alterations are more commonly visible, resulting from water vaporization; the dehydration results in cracks, flakes, and melting (Figs. 4.64 and 4.65). The thermal alteration zone on the dentin is superficial, ranging from 38 to 76 μm [92]. The thermal damage also affects the organic dentin network with disorganization and vaporization of collagen fibers of lased dentin, which is the main cause of reduced adhesion and bond strength in comparison to nonirradiated dentin; accordingly, the removal of this thermally affected layer is suggested to enhance the quality of dentin bonding [93].

Olivi et al. (2011) suggested the conditioning of dentin surface after dentin ablation using the Er:YAG or Er, Cr:YSGG laser with a 600-μm tip at reduced energy (40–50 mJ), just above the respective ablation threshold (8–14 J/cm^2), and with conspicuous water spray in the final steps of cavity preparation to improve the cleansing of debris and smear layer, also reducing the thermal impact and the vaporization of the collagen fibers and subsequently minimizing the underlying dentinal damage [23].

A dye infiltration study reported that the application of a 5 % NaOCl solution on Er:YAG-irradiated cavities significantly improves the marginal adaptation of the composite restoration [94]. However,

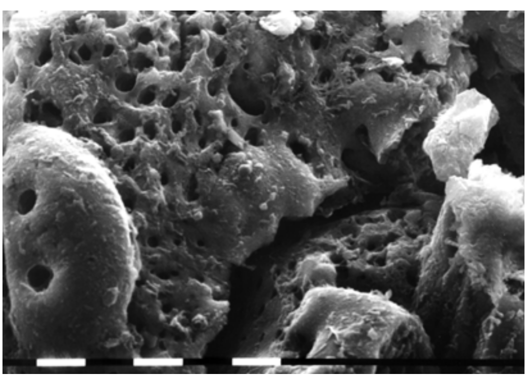

Fig. 4.64 SEM image (5,000×) of dentin surface irradiated with an Er, Cr:YSGG laser at 200 mJ, 20 Hz, and low air/water spray ratio (30–20 %): cracks, melting, and reformed amorphous hydroxyapatite are present

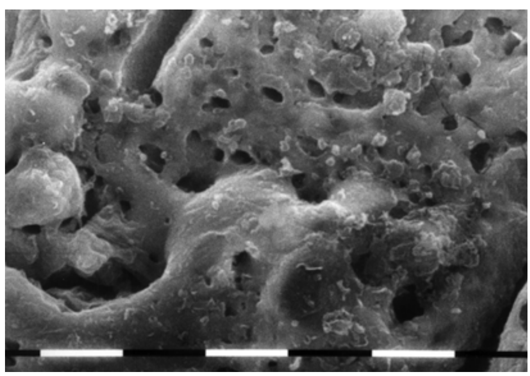

Fig. 4.65 SEM image (4,000×) of dentin surface irradiated with an Er, Cr:YSGG laser at 200 mJ, 20 Hz, and low air/water spray ratio (30–20 %): cracks, melting, and reformed amorphous hydroxyapatite are present

the use of sodium hypochlorite does not produce improvement in bond strength, while the conditioning with orthophosphoric acid provided higher bond strength values than erbium laser [95].

In addition to a proper fluence and an efficient air/water spray, recent studies indicate that the pulse duration is a very important parameter for an efficient dentin ablation. Staninec et al. (2006) reported that high bond strengths can be achieved using shorter laser pulse duration (50 μs) that minimizes peripheral thermal damage [96].

A study from Baraba et al. (2013) reported opposite results; at energy of 80 mJ, at 10 pps, the use of 300 μs and 100 μs pulse duration of an Er:YAG laser produced more suitable results than a shorter pulse at 50 μs, for dentin surface conditioning prior to bonding procedures, when using one-step self-etch adhesive [84].

Also the pulse repetition rate can influence the thermal effect and the quality of the surface. Raucci-Neto (2012) analyzed with a scanning electron microscope the morphological alterations on healthy and decayed dentin surface after Er:YAG laser irradiation at 200 mJ and different pulse repetition rates of 4, 6, and 10 pps. All the pulse frequencies promoted irregular surface in the sound dentin and flatter surface in carious dentin. No difference in temperature was found with 4 and 6 Hz, while the highest temperature rise was achieved with 10 Hz. The study concluded that with the parameters used in the study, a safe removal of caries lesions produces no significant morphological alterations on dentin surface [97].

When used with care and proper parameters, the thermal effect generated by several lasers can be used for generating a superficial melting of dentin surface, useful for both treatment of deep dentin decay and dentinal hypersensitivity [11] (Figs. 4.66 and 4.67).

Finally, a gentle scrub of the lased dentin surface, followed by rubbing with cotton pellets infused with sodium hypochlorite and by using 37 % orthophosphoric acid for 20 s, allows the removal of dentin flakes and the disorganized collagen matrix, with exposure of intact collagen fibers; when observed at high magnification, this procedure showed more evident peritubular dentin [23] (Figs. 4.68 and 4.69). The critical steps of the mechanical and chemical treatment of enamel and dentin will be detailed in the operative section (see Chap. 7).

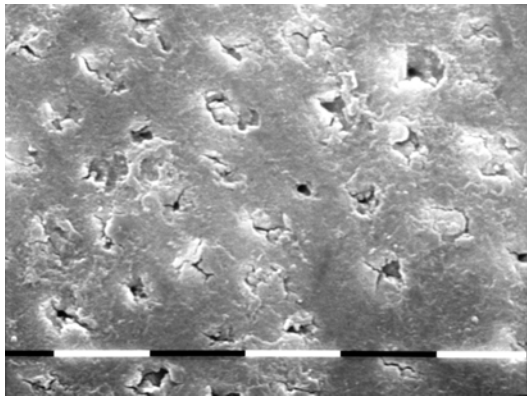

Fig. 4.66 SEM image (1,960×) showing a superficial melting and partial closure of dentin tubules achieved using an Er, Cr:YSGG laser at 0.5 W, 25 mJ, and 20 Hz with a 600-μm tip and low air/water spray rate in defocused mode (Reprinted with permission from Olivi et al. [12])

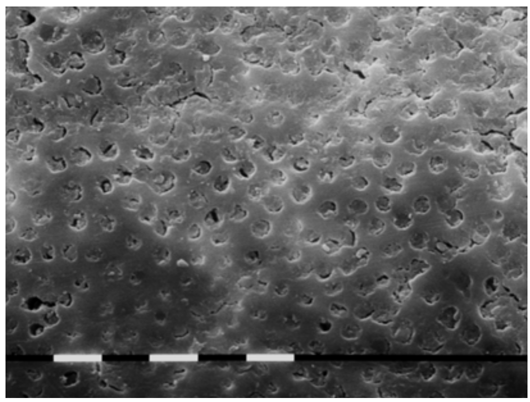

Fig. 4.67 SEM image (1,020×) showing the results of deep dentin sealing treatment performed with 810-nm diode laser at 0.5 W in CW, with a 400-μm fiber in defocused mode (Reprinted with permission from Olivi et al. [12])

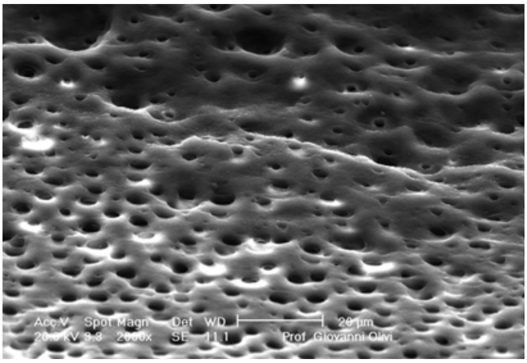

Fig. 4.68 SEM image at 2,000× of dentin irradiated with Er:YAG laser, with 50 µs pulse, at 160 mJ, 10 Hz: a final rubbing with cotton pellets infused with a 5 % sodium hypochlorite and 37 % orthophosphoric acid etching for 20 s allows the removal of dentin flakes and of disorganized collagen matrix, with exposure of intact collagen fibers

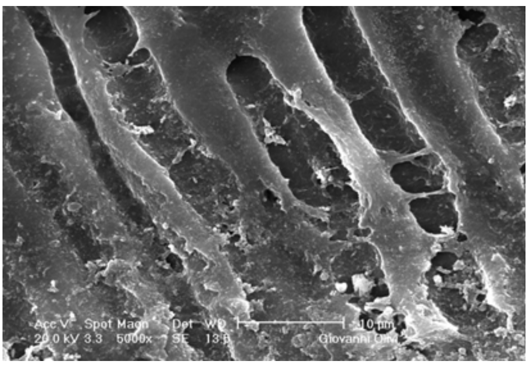

Fig. 4.69 SEM images at 5,000 of dentin irradiated with Er:YAG laser, with the same parameters as the previous image: the cross section of dentinal tubules shows the collagen matrix, with exposure of intact collagen fibers; debris are the result of cutting and splitting the root

4.10 Laser Effects on Bacteria

One of the main advantages of using erbium family lasers in restorative dentistry is bacteria reduction [98]. Using a laser for cavity preparation creates a substrate that is almost bacteria-free, statistically decreased in number compared to the bacteria in conventional mechanical preparation [99].

A study by Hibst et al. (1996) showed that bacteria below the surface preparation are killed during Er:YAG laser cavity preparation to a depth of 300–400 µm [100].

A study by Franzen et al. (2009) showed that the Er, Cr:YSGG radiation at a low pulse energy of 3.13 mJ, delivered at an incidence angle of 5° to the dentin slice surface, resulted in significant bacterial reduction up to a dentin thickness of 500 µm [101].

Both the thermal effect and shockwave of mid-infrared lasers generate an important decontamination effect via structural change in bacterial cells [102]. At 75 mJ, the effects of laser energy damage the cell walls of the bacteria, leading to an alteration of the osmotic gradient and finally cell swelling and cell death [103].

4.11 Laser Effects on Soft Tissues

The thermal effects resulting from the interaction of the selected wavelength on tissue are different and also depend on the operating mode and the usage of the parameters chosen by the operator [12, 39, 104].

Diffusion and absorption depend on the optical behavior of the selected wavelength. The visible and near-infrared laser operate within the so-called therapeutic window of the electromagnetic spectrum (635–1,000 nm) because of the maximum penetration of light into the tissues. In contrast, the mid-infrared lasers have a superficial interaction with absorption prevalence in water tissue [105].

The photonic energy absorbed and/or scattered in the tissue generates photothermal and photochemical effects. The photochemical effect is induced by low-energy lasers that photoactivates biochemical reactions in the tissue. All laser radiations, although in different ways, generates photochemical effects. In particular the wavelengths from 635 to 675 nm and from 810 to 1,064 nm to generate photochemical effects that can produce analgesic effects, biostimulation, anti-inflammatory effects, and muscle relaxation in irradiated tissues characteristic of LLLT (low-level laser therapy); these effects occur when the laser light is emitted at low power, with a long exposure time, in continuous and defocused mode.

The laser energy is converted at the cellular level; the primary mechanism is the conversion of photonic energy into biochemical energy (photochemical effect); the secondary mechanisms are attributable to the biochemical changes induced by the primary mechanism at the subcellular level. The laser irradiation increases the metabolism of endorphins, acetylcholine, serotonin, and cortisol, resulting in reduced perception of pain (analgesic effect). Laser irradiation increases the release of growth factors and cytokines; increased production of ATP (30 %) and protein synthesis take place in the mitochondria. This explains the better healing of tissue (bio-stimulating effect).

Laser irradiation modifies the blood flow and lymphatic drainage and induces neoangiogenesis by stimulating endothelial growth factors, thus reducing inflammation (anti-inflammatory).

During a laser gingivectomy, for instance, the healing of tissue is affected by a bio-stimulating and anti-inflammatory effect, also correlated to laser irradiation.

The photothermal effect represents the best known effect of laser radiation (an effect common to all wavelengths) emitted in a variable range of exposure times (from ms to μs), at variable power (from 0.5–0.6 W up to 15–20 W), in continuous mode or gated or free-running pulsed mode.

In the visible (argon and KTP) and near-infrared (diode and Nd:YAG) spectrum of light, laser energy is absorbed by the pigment hemoglobin/oxyhemoglobin content in the gingiva, mucosa, and pulp, diffusing at varying depths in the tissue, and is used for surgical incision, vaporization, and modeling of soft tissue and for tissue coagulation.

The modes of operation, continuous wave, gated, or super pulsed, determine the thermal interaction, with greater or lesser coagulation and collateral thermal effects.

Using erbium lasers, the control of rise in temperature is performed by controlling the emitted energy, the pulse repetition rate (low frequency allows a longer relaxation time), and the pulse duration (long or short) and by using the air/water spray that reduces and limits the thermal damage to the tissue, avoiding any peripheral necrosis in the tissue [106]. Besides its cooling and cleaning action, the water spray partially hinders tissue coagulation and hemostasis of erbium lasers.

Table 4.3 Thermal effects of laser energy on soft tissue

Tissue temperature (°C)	Observed effect
>37	Hyperthermia
45–50	Development of edema – blanching
>50	Nonsporulating bacteria inactivated
>60	Coagulation and protein denaturation
>100	Vaporization or incision
>200	Carbonization

The thermal effect is also responsible for an important *decontaminating effect* in the treated area, with breadth and depth varying according to the different absorption and penetration of the different laser radiations.

The thermal effect on the target tissue produces various changes according to the temperature reached within the tissue: the vaporization or incision of soft tissue takes place at a temperature of the irradiated tissue around 100 °C; the production of areas of carbonization (black) is the expression of temperature higher than 100 °C, while the production of smoke is the expression of temperature exceeding 200 °C.

Coagulation of tissue is achieved around 60 °C; the whitish area peripheral to the area of vaporization is the expression of lateral thermal diffusion at temperatures around 45–50 °C (blanching or warming) (Table 4.3).

Achieving different working temperatures and therefore different therapeutic results is closely related to the parameters and methods used.

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5 Adhesion and Erbium-Lased Enamel and Dentin

Roeland De Moor, Katleen Delmé, and Filip Keulemans

Abstract

The quality of bonding to the enamel and dentin is of utmost importance for the long life of adhesive filling materials. At present, adhesive systems have evolved in a positive way. Much is the result of a better understanding of the interaction between adhesive system and substrate. Both the dentin and enamel have different surface characteristics after laser preparation with erbium lasers as compared to conventionally bur-cut surfaces. For some, the characteristic irregularity and retentiveness of lased surfaces permit to adhere without etching. In the mean time, investigations have demonstrated that it is better to etch the lased surface (both the enamel and dentin) before bonding with non-self-etching systems. Also here, the original 'gold standard', i.e. a three-step etch-and-rinse system, results in clinically acceptable bond strengths. Furthermore, two-step 'mild' self-etch adhesives containing 10-MDP used with enamel etching and without dentin etching appear to perform at least equally well. As the quality of the adhesion is also influenced by the substrate, it has to be emphasised that it is recommended not to rely on enamel laser conditioning (previously called laser etching) and to finish the dentin at low fluency before adhesion. At present, there is insufficient information to take a position for glass ionomers.

5.1 Introduction of Resin Composites in Restorative Dentistry

At present, the classic concepts of cavity preparation [1] advocated in the early 1900s by G.V. Black have changed dramatically. Whereas geometrically shaped cavities with retentive features such

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as convergence and retention grooves were needed to retain restorative materials in the past, today a more conservative approach based on only replacing diseased tooth tissue followed by direct bonding of the restorative material to remaining sound tooth substance is adopted [2].

The introduction of the acid etch technique by Michael Buonocore in the mid-1950s [3] (improving the resin-enamel bond) and the development of Bis-GMA or Bowen's resin as an organic matrix for resin composites by Bowen in the early 1960s [4] (with important advantages, including reduced polymerisation shrinkage and the ability to form cross-links during polymerisation), initiated the adhesive revolution and led towards the concept of tooth tissue preservation also known as minimal invasive or intervention dentistry [5, 6].

Since the experiments on hard tissue ablation with a ruby laser by Stern and Sognnaes in the mid-1960s [7], the use of lasers in restorative dentistry became the most explored field in laser dentistry. Unfortunately, the initially explored wavelengths, i.e. Nd:YAG (1.064 μm), CO_2 (9.6 μm) and Ho:YAG, (2.12 μm) had to be abandoned as they resulted in massive thermal side effects leading to dangerous temperature rises in the pulp as well as to carbonisation and the formation of microcracks [8].

An ablation mechanism with a small penetration depth and a better control on the temperature (no thermal heating of the pulp) had to be found. Both the excimer laser (within the ultraviolet range) [9, 10] and the erbium laser (within the infrared range) [11, 12] could be used with small thermal side effects. Because of ablation and technical reasons, the erbium lasers (Er:YAG at 2.94 μm and Er,Cr:YSGG at 2.78 μm) have become the most appropriate tools for removal of dental hard tissues. The use of erbium lasers for cavity preparation and tooth surface modification is described in detail in Chap. 7.

The preparation/ablation of the enamel and dentin with erbium lasers results in a very specific surface morphology (see Chap. 4). The optical affinity with water is the key parameter for their effectiveness, selectivity and minimal invasiveness during enamel and dentin ablation. Moreover, the presence of water also plays an important role in the effectiveness of dental adhesive systems.

5.2 Adhesion

The American Society for Testing and Materials (specification D 907) defines adhesion as 'the state in which two surfaces are held together by interfacial forces which may consist of valence forces or interlocking forces or both [13].

Adhesion also refers to the propensity of dissimilar particles and/or surfaces to adhere or bond to one another [14]. Adhesion also indicates the formation of an adhesive joint between two substrates. In dentistry, these substrates are in most cases the dental adhesive and the tooth (enamel, dentin, cementum). Hence, a dental adhesive is a material that joins and solidifies two substrates (e.g. tooth substance and restorative material or two restorative materials) together. This adhesive should also be able to transfer a load from one surface to the other [14]. An example of adhesion is the direct bonding of glass ionomer cement to tooth substance.

5.2.1 Basics of Adhesion

Three basic types of adhesion can be described:

1. *Specific*: molecular attraction between surfaces in contact
2. *Mechanical*: adhesion arising from mechanical interlocking between the adhesive and the substrate surface
3. *Effective*: optimal bonding between adhesive and substrate surface due to combined effects of specific and mechanical adhesion

Factors influencing adhesion are:

1. Surface *wetting* of the substrate by the adhesive
2. *Viscosity* of the adhesive
3. Surface *roughness* of the substrate

Wetting indicates the ability of a liquid to cover and form an interface with a solid surface. The contact angle formed between the liquid and the solid substrate surface is an indication for the degree of wetting: the smaller the contact angle and the lower the surface tension of the liquid, the greater the degree of wetting and the better the spreading of the liquid across the surface of the solid. Materials that wet against each other tend to have a larger contact area than those that do not. So, wetting is influenced by the relative surface energies of the adhesive and substrate materials, meaning that the surface tension of the adhesive should be lower than the surface energy of the substrate. Low surface energy materials such as the enamel do not wet and are difficult to bond without surface conditioning.

The conclusion for dental adhesion, hence, is that the adhesive (dental adhesive or adhesive material, e.g. glass ionomer cement) must wet the surface of tooth substance or restorative material (create contact areas).

In this respect, it certainly needs to be emphasised that attention has to be paid to the following factors with impact on the creation of optimal adhesion between substrate and adhesive: (1) cleanliness of the substrate, (2) presence of moisture, (3) surface roughness and contamination, (4) surface conditioning and (5) the adhesive material itself (viscosity).

5.2.2 Mechanisms of Adhesion in Adhesive Dentistry

The strength of the adhesion between two materials depends on the interactions between the two materials and the surface area over which the two materials are in contact.

There are four mechanisms of adhesion: (1) mechanical adhesion, (2) physical adhesion, (3) chemical adhesion and (4) diffuse adhesion.

5.2.2.1 Mechanical Adhesion

Mechanical adhesion occurs if adhesive materials fill the voids, pores or rugosity of the surfaces and hold substrates together by interlocking. Another example of mechanical adhesion is the interlocking of chains and fibres.

A typical example in adhesive dentistry is the creation of micro-irregular enamel surface by acid etching. The resin adhesive flows across the conditioned surface into the irregularities to create resin tags. The effectiveness of enamel bonding is dependent on the wetting of the substrate by the bonding liquid. Low viscosity is required for the flow into the surface irregularities (rheological or flow properties of the adhesive). Next to viscosity, electrostatic forces may be operating between the adhesive and the microtopography of the substrate. Thixotropy of a liquid (temporary transformation to lower viscosity due to mechanical activation and exhibiting a better flow than with the fluid in its static state) is another influencing factor.

5.2.2.2 Physical Adhesion

Physical adhesion occurs when the adhesive and the substrate are held together by means of secondary bonding forces such as van der Waals forces or hydrogen bonds. In order to establish secondary bonds, the adhesive and substrate should be able to come in close proximity; in other words, the adhesive should easily wet or adsorb onto the substrate.

Two types of physical adhesion can be distinguished:

Electrostatic Adhesion

Some conducting materials may pass electrons to form a difference in electrical charge at the joint. An attractive electrostatic force is created between the materials.

Dispersive Adhesion

In dispersive adhesion, also defined as physisorption, interatomic and intermolecular forces such as van der Waals forces or hydrogen bonds hold two materials together if sufficient intimate contact is achieved at the interface. The molecules involved are polar with respect to the average charge density and have regions of net positive and net negative charge [15].

Although physical adhesion is reversible in nature, it can be seen as a precursor of chemical adhesion. This can be illustrated by the interaction between a silane coupling agent and a glass surface. Initially, hydrogen bonds are formed between the silane and the glass surface resulting in reversible physical adhesion. After drying, a condensation reaction occurs, and a stable chemical bond is created by the formation of a covalent bond between silane and the glass surface.

5.2.2.3 Chemical Adhesion

Chemical adhesion indicates the chemical bonding between adhesive and adherend forming a compound at their union or interface; it occurs if the molecule changes its identity through ionic or covalent bonding with the atoms or molecules of the other material [15].

In order to obtain high strength and short lengths of the chemical bonds, the surfaces have to be brought in very close contact. Moreover, these surfaces also have to stay in proximity to each other for the bond to remain stable. Bond lengths decrease in the following order: Van der Waal forces (0.45 nm), metallic bond (0.4 nm), ionic bond (0.25 nm), hydrogen bond (0.2 nm) and covalent bond (0.15 nm); average bond energy of the forces involved increases in the following order: Van der Waal forces, hydrogen bond, metallic bond, covalent bond and ionic bond [14]. Chemical bonding mainly occurs between the inorganic component (hydroxyapatite) or organic components (mainly type I collagen) of tooth tissue and functional monomers (e.g. 10-MDP) from dental adhesives or the carboxyl groups of polyalkenoic acid from glass ionomers with the calcium of the hydroxyapatite.

5.2.2.4 Diffusive Adhesion

Some materials may blend, merge or intermingle by diffusion at the bonding interface. In this situation, adhesion is considered to be a three-dimensional volume process, rather than a two-dimensional surface process. It is possible if the molecules of both materials are mobile and soluble in each other. A nice example of diffusive adhesion is the formation of a hybrid layer created when the demineralised collagen matrix of dentin is infiltrated by resin monomers of the adhesive.

Another example of diffusive adhesion is sintering. Here, atoms diffuse from one particle to the next to produce a solid mass after compression and heating of metal and ceramic powders.

5.3 Critical Thinking with Regard to Adhesion: Durable Dental Bonding

Over the last 60 years, starting from 1955 with Buonocore's experiments and the introduction of enamel bonding, dental bonding systems have evolved with variations in chemistry, mechanisms, application, techniques, efficacy and efficiency.

In Table 5.1, an overview of the history of bonding agents is given based on the classification in generations. We have ended up with simplified 'all-in-one' adhesives that combine etch, primer and bonding in a single solution. These one-step self-etch adhesives (1-SEAs) are clearly more user friendly and less technique sensitive, but there are still a number of shortcomings. The bond strength of 1-SEAs is lower than for multistep self-etch and etch-and-rinse adhesives. Due to their high hydrophilicity, HEMA-rich 1-SEAs behave as a permeable membrane so that increased water sorption and water movement across the adhesive layer occurs [16]. On the other hand, HEMA-free/-poor 1-SEAs experience phase separation, whereby water bubbles are formed onto the adhesive layer [17]. These phenomena make both HEMA-rich and HEMA-free/-poor 1SEAs more prone to bond degradation, which compromises their long-term bonding performance [17]. At present, the group of one-step adhesives comprises two component 1-SEAs (to be mixed prior to application), single component 1-SEAs (the only true all-in-one adhesives) and

Table 5.1 Overview of the different generations of adhesives

1960s first generation
Development of the surface-active comonomer NPG-GMA
No recommendation for dentin etching
Relied on adhesion to the smear layer through chelation
Weak bonding strength (no wetting of the dentin and did not penetrate the entire depth of the smear layer) 2–3 MPa
End of the 1970s and beginning of the 1980s second generation
Introduction of phosphate ester dentin-bonding systems
No recommendation for dentin etching
Relied on adhesion to the smear layer through chelation
Weak bonding strength (no wetting of the dentin and did not penetrate the entire depth of the smear layer) 5–6 MPa
1980s third generation
Acid etching of the dentin
Preservation of a modified smear layer with slight demineralization of the underlying intertubular dentin
Separate primer
Increased bond strength 3–8 MPa
Mixed clinical results
Early 1990s fourth generation
Three-step total-etch systems
Phosphoric acid/a primer containing reactive hydrophilic monomers in ethanol, acetone or water/ unfilled or filled resin-bonding agent
Hybrid layer (resin-dentin interdiffusion zone) and penetration of open dentinal tubules, forming resin tags
Increased bond strength 13–30 MPa
Technique sensitivity
Mid-1990s fifth generation
Simplification of bonding procedure: 'one-bottle' system (primer and adhesive in one bottle)
Maintenance of high bond strengths 3–25 MPa
User friendlier system
Late 1990s – early 2000s sixth generation
Self-etching primer systems
Reduced incidence of postoperative sensitivity
Bond strength lower than fourth and fifth generations, except for Clearfil SE Bond
Late 2002 seventh generation
'All-in-one' systems
Combines etching, priming and bonding
Mild self-etching approach leads to good bond strength
Enamel etching with phosphoric acid is still recommended
End 2000s eighth generation
Still a matter of debate

the group of universal or multimode adhesives. Moreover, also self-adhesive composites have been put on the market.

5.3.1 Scientific Classification of Modern Adhesives

A more simple and straightforward way to classify adhesives is to follow the classification according to their adhesion strategy towards the enamel and dentin [18] and refer to:

- Etch-and-rinse (E&R) adhesives (a): three-step E&Ra/3E&Ra (fourth generation) and two-step E&Ra/2E&Ra (fifth generation)
- Self-etch (SE) adhesives (A): two-step SEA/2SEA (fifth generation) and one-step SEA/1SEA (seventh generation, …) (both 2SEA and 1SEA are further subdivided in 'mild' and 'intermediately strong' (1/2SEA-m), with a $Ph \geq 1.5$, and 'strong' (1/2SEA-s), with a $Ph < 1.5$.)
- Glass ionomers (GI) (the classification of Table 5.3 will be used in this chapter)
- The degree of substance exchange differs amongst these adhesives. The degree of exchange induced by etch-and-rinse adhesives exceeds that of self-etch adhesives. Today, however, systems exist with an intensive interaction with both the enamel and dentin.

In 2014, Peumans et al. [19] came to the following conclusion in a systematic review with regard to the clinical effectiveness (annual failure rate – AFR) of contemporary adhesives for the restoration of non-carious cervical lesions: *the lowest AFR scores [mean (SD)] were recorded for GI* [2.0 (1.4)] *shortly followed by 2SEA-m* [2.5 (1.5)], 3E&Ra [3.1 (2)] and *1SEA-m* [3.6 (4.3)] (Tukey Contrasts: $p > 0.05$). *Significantly higher AFR scores were recorded for 1SEA-s* [5.4 (4.8)], *2E&Ra* [5.8 (4.9)], *and 2SEA-s* [8.4 (7.9)] ($p > 0.05$). *In addition, significant differences in AFR were noticed between adhesives of the same class* (Kruskal–Wallis sum test: $p > 0.05$), *except for GI* ($p = 0.7$) and 2SEA m ($p = 0.1$).

5.3.2 'Smear Layer-Removing' and 'Smear Layer-Modifying' Adhesives

5.3.2.1 From the Beginning Up to the Third-Generation Adhesives

Many attempts were made to 'bond' the adhesive to the unetched dentin substrate. Most of these, however, remained disappointing. Phosphoric acid etching of dentin was established by Fusayama et al. in 1979 [20]. This dentin acid-etching technique was discouraged in Europa and America until the end of the 1980s because of its thought pulp-irritating nature. So, most of the third-generation adhesives were still designed not to remove the entire smear layer, but rather to modify it and allow penetration of acidic monomers such as phenyl-P.

Surface-Active Comonomer NPG-GMA and the First-Generation Adhesives

NPG-GMA (N-phenylglycine glycidyl methacrylate), a surface-active comonomer, was the basis of Cervident (S.S. White, Lakewood, NJ, USA), the first commercially available dentin-bonding agent [21]. This comonomer could chelate with calcium on the tooth surface and was able to generate water-resistant chemical bonds to dentinal calcium [22, 23]. The in vitro dentin bond strengths of the first-generation dentin adhesives were in the range of 2–3 Mpa [24].

Phenyl-P (2-Methacryloxy Ethyl Phenyl Hydrogen Phosphate) and the Second-Generation Adhesives

Several phosphate ester dentin-bonding systems were introduced in the early 1980s. These products were based on phosphorous esters of methacrylate derivates. The mechanism of action was based on enhanced surface wetting and ionic interaction between negatively charged phosphate groups in the resin and positively charged calcium in the smear layer [24]. Clearfil Bond System F[c] (Kuraray, Osaka, Japan) was recognised as the first product of the second generation of dentin adhesives (phenyl-P and hydroxyl methacrylate [HEMA] in ethanol). Bond strengths ranged between 1 and 6 Mpa [25–27] as a result of a lack of dentin wetting (large contact angles) [28]. Moreover, the entire depth of the smear layer was not penetrated up to the dentin to establish ionic bonding or create resin extensions into the dentinal tubules [26]. Inadequate hydrolytic stability in the oral environment was also described [29, 30].

10-MDP (10-Methacryloyloxy Decyl Dihydrogen Phosphate) and the Third-Generation Adhesives

In 1984, Clearfil New Bond (Kuraray, Osaka, Japan) was introduced and with this the concept of phosphoric acid etching of dentin before the application of a phosphate ester-type bonding agent. This phosphate-based material contained HEMA and a 10-carbon molecule known as 10-MDP, which includes long hydrophobic and short hydrophilic components [31].

Most other third-generation materials, however, were designed not to remove the entire smear layer.

4-META (4-Methacryloxyethyl Trimellitic Anhydride) and the Third-Generation Adhesives

In 1982, Nakabayashi described the hybrid layer as an interconnection zone between adhesive and dentin based on a micromechanical bonding mechanism as still used by the present-day adhesive systems [32]. Extensive research in Japan had shown that strong, long-lived bonds between resin and living dentin could be formed when a monomer such as 4-META, which contains both hydrophilic and hydrophobic chemical groups, penetrated the dentin and polymerised in situ. This resin impregnation creates the so-called transitional 'hybrid' layer, that is neither resin nor tooth, but a hybrid of the two. The thin layer of resin-reinforced dentin locks the two dissimilar substances together on a molecular level, sealing the surface against leakage and imparting a high degree of acid resistance. Dentin was etched with an aqueous solution of 10 % citric acid and 3 % ferric chloride. After rinsing and drying, an aqueous solution of 35 % HEMA and a self-curing adhesive resin containing 4-META, MMA (methyl methacrylate) and TBB (tri-n-butyl borane) was applied.

5.3.2.2 The Present Generations of Adhesives: Etch-and-Rinse and Self-Etch Adhesives

At present, adhesives are marketed as four different systems: three bottles or the three-step etch-and-rinse adhesives (3E&Ra); two bottles, be it an etch-and-rinse system (2E&Ra) or a two-bottle self-etch system (2SEA); and one bottle or the ‘all-in-ones’ (1SEA).

Three-Step Total-Etch Adhesives

The total-etch approach originated in Japan, where the application of a phosphate ester type of bonding followed an etch procedure with phosphoric acid [20]. Research during the begin period of the 3E&Ra did not demonstrate improvement in bond strengths, most probably as a result of the hydrophobic nature of the phosphonated resin [33]. Today, however, in vitro tensile bond strengths between 20–50 Mpa for enamel and 13–80 for dentin are demonstrated [34].

Acid etching alters the mineral content of dentin and changes its surface-free energy [35, 36]. The etched dentin (the resultant collagen network depleted of high surface energy hydroxyapatite) ends up as a low surface energy substrate. The primer in a 3E&Ra is needed to increase the critical surface tension of the dentin [34]. Both primer and bonding resins impregnate the intertubular dentin and a resin-dentin interdiffusion zone of hybrid layer is formed. Both resins also penetrate the dentinal tubules and form polymerised resin tags.

Two-Step Etch-and-Rinse Adhesives

The 2E&Ras (fifth-generation adhesives) were a simplification of the adhesive system. Most of these systems have fallen somewhat short of their objective, but still, comparable bond strengths to those of the 3E&Ra (fourth-generation adhesives) are achieved [16].

Two-Step Self-Etch Adhesives

A further demand for simplification resulted in the development of systems without a separate conditioning phase. This sixth generation consists of systems with a self-etching primer and a separate adhesive resin and those that combine the conditioner, primer and adhesive resin but require mixing and hence, the confusion when using the classification based on generations.

This group of adhesives use the smear layer on the enamel and dentin as bonding substrate as was seen with the second-generation adhesives. The acidity of the primer, however, is the main difference between the two generations. This generation adhesives contain acidic monomers such as 4-MET and 10-MDP [37, 38] which renders these adhesives much more hydrophilic compared to previous hydrophobic adhesive systems [39, 40].

The self-etching primers (SEPs) have been classified in three groups: mild, moderate and aggressive. Mild SEPs appear to provide excellent dentin bond strengths and poorer enamel bonds. Aggressive SEPs provide the reverse.

One-Step Self-Etching Adhesives

This generation of adhesives combine conditioning, priming and application of adhesive resin. Adhesives belonging to this generation are mixes of hydrophilic and hydrophobic components [41]. Furthermore, these all-in-one adhesives contain uncured ionic monomers that bind to composite restorative materials directly [42, 43].

All-in-one adhesive systems must be acidic enough to demineralise the enamel and the dentin smear layer. As a consequence, the hydrophilicity of their resin monomers is high and might result for some insusceptibility for water degradation [44]. Due to the complex nature of the mixed solutions, these adhesives are prone to phase separation and formation of water droplets within their adhesive layers [41]. The adhesive layers can also act as semipermeable membranes, permitting bidirectional water currents [45]. Lower bond strengths were registered with the all-in-one systems as compared to the 3E&Ra and the 2E&Ra [45, 46]. More recent investigations demonstrate higher bond strengths to dentin for 2SEA (Clearfil SE Bond) as compared to 1SEA. The performance of one-step self-etch systems to dentin appears to be material dependent [47, 48].

5.3.3 Recommended Approach

Today (2015), a choice can be made between the etch-and-rinse and the self-etch approach [49]. Investigations have demonstrated that *micromechanical interlocking, as created by the etch-and-rinse approach, remains of paramount importance for enamel adhesion* [2]. In spite of functional monomers in self-etch adhesives designed to chemically interact with hydroxyapatite, the structure, size, and orientation of enamel hydroxyapatite crystals appear to provide insufficient chemical bonding sites to achieve durable bonding to enamel. The *chemical interaction of functional monomers with hydroxyapatite following a 'mild' self-etching approach results in an improved bond durability to dentin.* Examples of these functional monomers are 10-MDP and 4-MET [50, 51].

The advocated protocol in '2015' is as follows [49]:

- *Cavity margins* are finished with a *bevel* taking into account the orientation of the *enamel* prisms. The ends of the enamel rods, exposed by bevelling, are more effectively etched than otherwise occurs when only the sides of the enamel rods are exposed to the acid etchant.
- *Selective etching of the enamel* during 15 s with phosphoric acid (35–37 %) followed by rinsing. Etching of the dentin should be avoided, though some contact is not detrimental.
- *A 10-MDP-based mild self-etching primer* is actively rubbed onto the etched enamel and the unetched dentin for 15 s minimum. The primer film is air thinned until the film no longer moves (10-MDP ionically bonds to hydroxyapatite and self-assembles into nanolayers).
- A *solvent-free adhesive resin* (bonding layer) is applied, air thinned and light cured.

5.4 Erbium Laser Irradiation of the Enamel and Dentin and the Resultant Surface Changes

Lasing of the enamel and dentin results in a very specific surface morphology. Erbium laser irradiation of enamel and dentin yields an anfractuous surface (fractured and uneven) and open tubules without smear layer, both apparently ideal for adhesion [52]. Typical, lased enamel surfaces are irregular with typical keyhole-shaped prisms and rods; lased dentin shows protrusion of dentinal tubules with a cuff-like appearance (more intertubular than peritubular dentin is removed) [52–54].

The described characteristic topography of lased dentin and enamel is the result of specific 'erbium laser-tissue' interaction. The energy delivered by the Er:YAG (2.94 μm) and the Er,Cr:YSGG (2.78 μm) is well absorbed in the endogenous water and has a high affinity for hydroxyapatite (Chap. 4). The mechanism of enamel and dentin removal is referred to as 'photothermal fragmentation' or 'ablation'.

A number of investigations have demonstrated that the presence of endogenous water is not sufficient to remove the enamel and dentin. Moreover, it has been demonstrated that Er:YAG and Er,Cr:YSGG behave differently in this respect. The small penetration depth of the Er:YAG laser generates a high spatial energy density, hence making the tissue more sensitive to interaction with the radiation. The penetration depth of the Er,Cr:YSGG laser is greater, and therefore, the corresponding spatial energy density is lower. Important to emphasise is that ablation could not be observed using the Er:YAG laser and the Er,Cr:YSGG laser in dental enamel and the Er,Cr:YSGG laser in dentin, without an external water spray [55]. Melting, cracking and carbonated hydroxyapatite mineral occurred as a result of the photothermal interaction, but also resulted in final high surface temperatures.

Er,Cr:YSGG laser radiation is stronger absorbed by the mineral of the dental enamel than Er:YAG laser radiation, but in contrast, the volumetric content of hydroxyapatite is much higher than that of water. Therefore, the absorbed radiation of an Er,Cr:YSGG laser is distributed to a large volume in the enamel, which leads to substantially lower spatial energy densities [55].

Supplying water externally makes it possible to reduce the thermal stress on the surrounding tissues and rule out damage [56, 57]. At the same time, it was demonstrated that the water spray also serves to maintain the ablation process. Different hypotheses are described and favoured,

Table 5.2 Material characteristics and physical factors affecting the efficiency and quality of Er:YAG laser ablation

Relevant material characteristics for biological hard tissues:
Coefficient of absorption (α)
Reflectivity of the tissue surface (R)
Specific heat capacity (cp) of the absorbing constituents in the tissue
Tissue capability for heat conduction (thermal diffusivity κ)
Distribution of water within the tissue
Properties of laser light:
Wavelength (λ)
Pulse energy (Ep)
Pulse duration (τp)
Temporal beam profile (pulse shape)
Spatial beam profile (TEM/transverse electromagnetic modes)

such as the formation of channels and the collapse of which causes cavitation bubbles, which in turn generate shock waves, or also so-called recoil-induced material expulsion [58]. The externally supplied water spray, or rather the water film applied by it, is the actual mediator of the ablation process and solely an absorber.

In Chap. 4, it was emphasised that a number of material characteristics and physical factors affect efficiency and quality of erbium laser ablation (Table 5.2). However, it needs to be emphasised that the role of water is very crucial. Next to endogenous water, the external water supply is of paramount importance for the ablation efficiency [55] and at the end also for the quality of the adhesion between lased tooth surfaces and adhesive restorative materials [59, 60]. Factors such as water film thickness [61] and the amount, the flow rate and the type of water spray have to be related to the energy and the pulse repetition rate [62–64].

Based on this summary, it is clear that the ablation efficiency is influenced by an extensive number of parameters employed (following parameters are mostly provided in scientific publications: energy, energy density, power, frequency (Hz), beam diameter (mm), pulse duration, water flow rate, water delivery). Unfortunately, not all studies provide this information and omit important parameters (such as energy density, power, laser beam diameter, and the water delivery mode) that jeopardise inter-study comparisons [64].

5.5 Adhesion to Erbium-Lased Enamel and Dentin

5.5.1 Investigations with Etch-and-Rinse Adhesives

5.5.1.1 Enamel

De Moor and Delmé [14] concluded in their review of 2009 that acid etching with phosphoric acid remained mandatory on laser-irradiated enamel with respect to bond strength and marginal seal.

There was no value-added benefit of laser etching of the enamel after laser preparation. It has to be mentioned that laser etching is an insufficient term; laser conditioning is a more accurate term. Laser conditioning is a term used to describe a reduced ablative effect obtained with energy just above the threshold of ablation (15 J/cm^2 for Er:YAG and 20 J/cm^2 for Er;Cr:YSGG) (Figs. 5.1, 5.2, 5.3 and 5.4). In general, these investigations on laser etching were performed with etch-and-rinse adhesives. At that time, there was insufficient information on the effect of self-etching systems on the lased enamel.

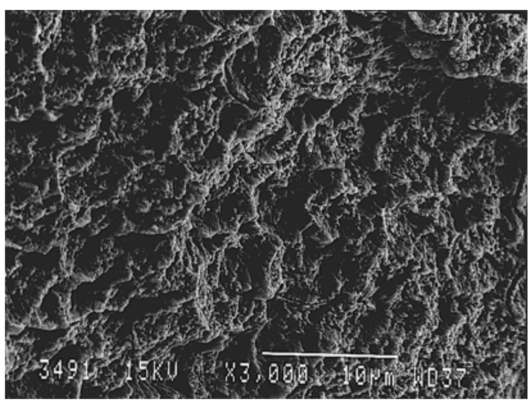

Fig. 5.1 Er:YAG laser-irradiated enamel (350 mJ, 10 Hz, 100 µs, 7 mm distance, 0.9 mm spot size) (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

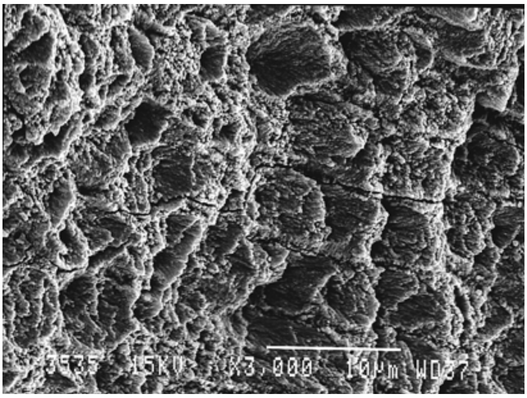

Fig. 5.2 Er:YAG laser-conditioned enamel (150 mJ, 10 Hz, 100 µs, 7 mm distance, 0.9 mm spot size) (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

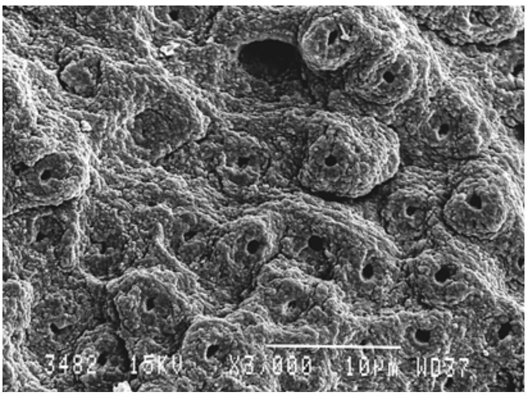

Fig. 5.3 Er:YAG laser-irradiated dentin (200 mJ, 10 Hz, 100 µs, 7 mm distance, 0.9 mm spot size) (Courtesy Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

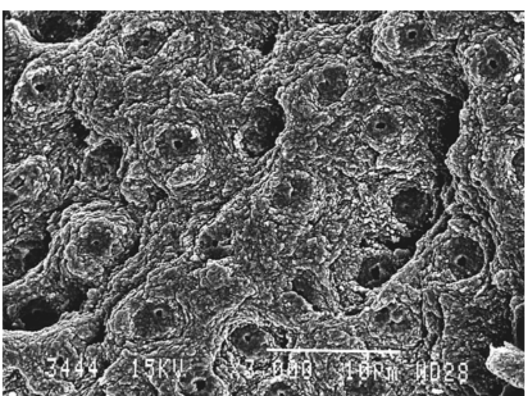

Fig. 5.4 Er:YAG laser-conditioned dentin (80 mJ, 10 Hz, 100 µs, 7 mm distance, 0.9 mm spot size) (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

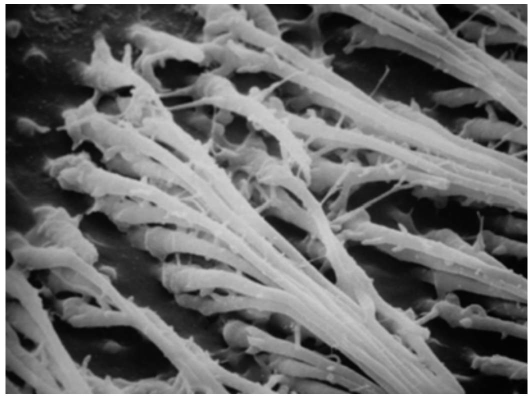

Fig. 5.5 SEM image (1,300×) of resin tags in the dentin (middle crown) in young third molar treated with etch-and-rinse bonding system (3M Scotchbond) (Courtesy of Prof. Luciano Fonzi and Prof. Vassilios Kaitsas, Siena, Italy)

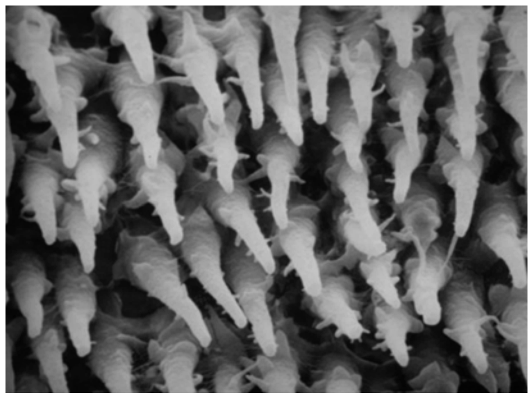

Fig. 5.6 SEM image (1,600×) of resin tags in the dentin (close to border enamel-dentin junction) in young third molar treated with etch-and-rinse bonding system (3M Scotchbond) (Courtesy of Prof. Luciano Fonzi and Prof. Vassilios Kaitsas, Siena, Italy)

5.5.1.2 Dentin

The hybrid layer created with etch-and-rinse adhesives after erbium laser irradiation of dentin and after subsequent acid etching is thinner as compared to acid-etched bur-cut dentin (Figs. 5.5, 5.6, 5.7 and 5.8).

Different explanations have been put forward for the less profound hybridization:

- Increase of the Ca and P because organic components are selectively removed [64].
- Reduction of the carbon-to-phosphorus ratio leading to more stable and less acid-soluble compounds [65].

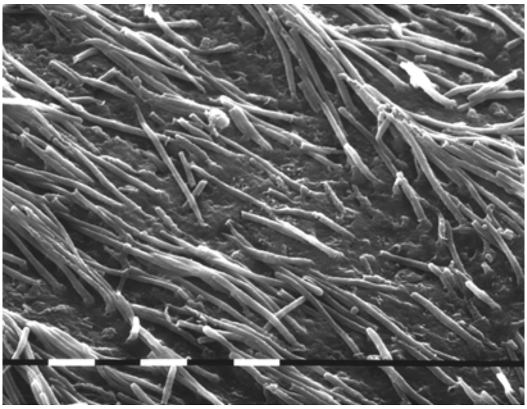

Fig. 5.7 SEM image of resin tags in the dentin (middle crown) using self-etch bonding system (Xeno V) after Er,Cr:YSGG preparation at 2.0 W, 20 Hz, 100 mJ, 600 μm tip, high air/water ratio (92/80 %) (Courtesy of Prof. Luciano Fonzi and Prof. Vassilios Kaitsas, Siena, Italy)

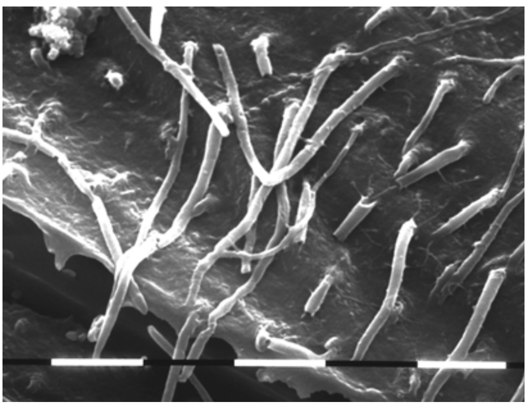

Fig. 5.8 SEM image of resin tags in dentin (middle crown) using self-etch bonding system (Xeno V) after Er,Cr:YSGG preparation at 2.0 W, 20 Hz, 100 mJ, 600 μm tip, lower air/water ratio (35/25 %) (Courtesy of Prof. Luciano Fonzi and Prof. Vassilios Kaitsas, Siena, Italy)

- Creation of a more acid-resistant enamel and peritubular dentin [66–68].
- More intensive loss of carbonate at subablative energy densities, with complete loss at 1,000 °C [69, 70].
- The chemical composition is altered under influence of factors such as pulse duration, output energy and water coolant [70–73].
- Heat during laser irradiation may cause denaturation of the collagen network and decrease of the dentin permeability [71–74].
- Formation of a modified superficial layer in which collagen fibres are poorly attached to the underlying dentin substrate [75].
- Thermal effects also extend in the dental subsurface, impairing interdiffusion zone formation [76].
- Melting and recrystallisation leave the surface hypermineralised and less permeable, which can affect the acid resistance [77–81].

It was concluded that there is a reduced thickness of the hybrid layer after erbium laser irradiation even though phosphoric acid was used. Subsurface damage is thought to be responsible for the decrease in bond strength and cohesive failure in the subbonding layer in dentin [82–84].

Also with self-etching adhesives, both subsurface damage and the thinner or absent hybrid layer resulted in low tensile bond strengths. It was recommended in 2,009 not to use ‘non-rinse’ or ‘self-etch’ adhesives. Higher microleakage at the enamel and dentin margins was also observed [14].

In recent years, however, more attention has been paid to the laser parameters (see Sect. 5.5.2) [85–89]. The latter explains the changed approach at present for the sixth-generation or two-step self-etch adhesives.

5.5.2 Adhesion to the Erbium-Lased Enamel and Dentin: Investigations with Self-etch Adhesives

Most of the research from 2010 was focused on dentin adhesion. More attention was also paid to the laser irradiation mode, i.e. emphasis on low energy [87, 88], shorter pulse duration time (100 μs, but no 50 μs) [88, 90] as mentioned in 5.5.1.2 and repetition rate [85, 86]. In fact, laser treatment could enhance or impair μTBS to the enamel and dentin depending on the pulse duration used and additional acid application.

5.5.2.1 Enamel

Pulse duration of the erbium lasers is related to the laser ablation ability and surface morphology, which are a very important factor for bond strength of adhesives to both the enamel and dentin [90]. Furthermore, one study demonstrated higher microtensile bond strength (μTBS) for Er:YAG than for Er,Cr:YSGG in combination with two-step etch-and-rinse adhesives (2E&Ra) (fifth generation) [91].

In general, acid etching of enamel margins resulted in better tensile bond strengths than the sole use of two-step self-etch adhesives (2SEA) (sixth generation). Only laser-pretreated enamel surfaces appeared not to achieve clinically acceptable values due to the more acid-resistant-lased surface. These findings also coincide with the present-day recommendations still to rely on the use of phosphoric acid to etch the lased enamel margins.

5.5.2.2 Dentin

Investigations with two-step self-etch adhesives (2SEA) demonstrated that treatment of lased dentin with these 2SEA in general still resulted in lower μTBS values as compared to conventionally bur-prepared dentin surfaces [92–94]. The reduction in bond strength for Clearfil SE Bond self-etching adhesive (SEA), however, was lower than for a 2E&Ra [93]. The latter accounts for both Er:YAG and Er,Cr:YSGG [92]. These studies have in common that there is a superior adhesion for the adhesive system with 10-MDP, which has the potential to chemically interact with interfacial hydroxyapatite [93, 94].

Increasing etching time was also not able to increase the bonding strength of a 2E&Ra to irradiated dentin [92]. This is in contrast with 2E&Ra where etching during the 90 seconds resulted in increased bond strength as compared to 30 and 15 s [95]. In this respect, previous studies had already reported an increase in acid resistance of the enamel and dentin after laser irradiation [96–98]. An additional cleaning after with NaOCL after the etch procedure was also proposed [93] in order to improve the penetration of adhesive monomer into the irradiated dentin, as little or no hybrid layer formation was reported in previous studies [99, 100].

Research in the 2010s considered laser pretreatment again. Finishing the dentin at low fluency after laser cavity preparation resulted in higher bond strength then without an additional finishing for 2SEAs [101]. Depending on the formulation, a number of 1SEAs (seventh generation) demonstrate identical bond strengths on lased dentin as compared to bur-cut dentin [102]. In general, these adhesives belong to the group of 'mild' self-etch adhesives. More research however is needed, to explain these apparently unexpected different effects.

5.5.3 Recommendations

At present, the same approach as with bur-cut dentin can be advocated. The original 'gold standard', a three-step etch-and-rinse (3E&Ra) (fourth generation) with a water/ethanol-containing primer, results in clinically acceptable bond strengths. Laser conditioning of the enamel (due to the enamel structure and composition changes as the result of lower water content than the dentin) is not recommended, and the enamel has to be etched with phosphoric acid. Finishing of the dentin at low fluency is also recommended.

As two-step self-etch adhesives (2SEA) (sixth generation) perform better than two-step etch-and-rinse adhesives (2E&Ra) (fifth generation) and equally well or better than three-step etch-and-rinse (3E&Ra) (fourth generation) on the level of dentin adhesion, their use is to be advocated. The enamel margins still have to be etched, though, without laser conditioning. The dentin walls have to be finished at low fluency, no acid etching is needed and a 10-MDP containing two-step 'mild' self-etch adhesive (2SEA-m) is selected, in order to promote stable long-term dentin bonding.

Today, it is too early to take a position for the one-step self-etch or all-in-one adhesives (seventh generation). Nevertheless, acceptable clinical bond strengths to dentin finished at low fluency have been demonstrated.

5.6 Glass Ionomer Cements

5.6.1 Classification

Glass ionomer cements were first introduced in 1972 by Wilson and Kent [103]. They were marketed in Europe in 1975 and in the USA in 1977.

Table 5.3 Classification of glass ionomer cement compomer and resin composite according to Saito et al.

Material	Basic composition	Setting reaction	Structure of set material
Glass ionomer cement	Powder: fluoroaluminosilicate glass	Acid-base reaction	Filler: fluoroaluminosilicate glass powder
	Liquid: polyacrylic acid, polybasic carboxylic acid, water		Matrix: polyacid salt
Resin-modified glass ionomer cement	Powder: fluoroaluminosilicate glass	Acid-base reaction	Filler: fluoroaluminosilicate glass powder
	Liquid: polyacrylic acid, water-soluble methacrylate monomer (HEMA, etc.), catalyst	Polymerisation	Matrix: polymer acid salt, methacrylate polymer
Compomer	Paste: filler (containing fluorine, etc.), methacrylate monomer, acidic monomer, catalyst	Polymerisation	Filler: filler containing fluorine
			Matrix: methacrylate polymer, acidic polymer

Based on data from Ref. [104]

The first glass ionomer consisted of an ion-leachable aluminosilicate glass and an aqueous solution of a copolymer of acrylic acid. The setting reaction is an acid-base reaction between the acidic polyelectrolyte and the aluminosilicate glass. Because both components are materials of wide chemical diversity, the range of glass ionomer cements is very wide. Material setting purely on an acid-base reaction is referred to as conventionally setting GIC (Table 5.3).

There are different types of CGIC (8):

1. GICs for direct restoration: these are typical acid-base reaction materials consisting in general of a calcium aluminosilicate glass powder and a liquid containing polyalkenoic acid.
2. Reinforced GICs: the powder contains a fluoroaluminosilicate glass and the chemical composition of the glass is modified.
   - Disperse-phase glasses: modification by means of phase separation of the glass.
   - Fibre-reinforced GIC: incorporation of alumina fibres and other fibres such as silica fibre, glass fibre, carbon fibre, etc. to the existing glass powder.
   - Metal-reinforced GIC: addition of metal powder (amalgam alloy) or fibres.
   - Cermet-ionomer cements: the glass is sintered with silver or gold. Only a silver containing GIC (Ketac Silver) was marketed.
3. Highly viscous GICs: these materials are more viscous than the classic GIC as a result of the addition of polyacrylic acid to the powder and finer grain-size distribution. They were developed as an alternative to amalgam for posterior preventive restorations.
4. Low-viscosity GICs, which have been developed as liners, fissure protection materials, sealing materials for hypersensitive cervical areas and endodontic materials.

Resin modification of glass ionomer was done in the late 1980s and early 1990s in order to have a better control of the work and also to solve the problem of moisture sensitivity of the first generation of glass ionomers (conventionally setting glass ionomer cements – CGIC). These materials set by both acid-base reaction and a second curing process, which are initiated chemically or by light. If only one polymerisation mechanism is used, the resin-modified glass ionomer (RMGIC) is considered to be a dual-cure cement; if both mechanisms are used, the material is referred to as a tri-cure cement. The tri-cure mode consists of an acid-base reaction between the functionalised polyacid and the fluoroaluminosilicate glass, light polymerisation or a free radical light cure (light and HEMA) and a chemically activated or self-cure reaction, i.e. an oxidation-reduction dark cure (redox catalysts – HEMA). All RMGICs retain a significant acid-base reaction. Based on the resin incorporation and polymerisation, two types of RMGIC can be defined: (1) RMGIC Class I: The cement contains the addition of a small quantity of resin component such as hydroxyethyl methacrylate (HEMA) or Bis-GMA in the liquid of the conventional glass ionomers. Some of the water component of the conventional glass ionomer cement is replaced by a water/HEMA mixture. Two separate setting reactions take place, i.e. the initial set of the resin-modified glass ionomer cement is the result of formation of a polymer matrix, and the acid-base reaction serves to harden and strengthen the formed matrix. The matrix consists of two different interpenetrating networks. (2) RMGIC Class II: The polyalkenoic acid is modified with side chains that can be polymerised by a light-curing mechanism. The result is a matrix consisting of one network as a result of both the polymerisation reaction and the acid-base reaction.

Both types of GIC cannot be confused with polyacid-modified resin composites (PAMRC) or compomers (Table 5.3). Here, an acid monomer polymerises in the presence of fluoraluminosilicate glass. A PAMRC or compomer is mainly a resin composite with fluoride-releasing potential. The amount of fluoride released cannot be compared with fluoride-releasing potential of GIC and should therefore not be overemphasised. PAMRCs have no potential to self-adhere to tooth structure.

5.6.2 Glass Ionomer Adhesion

Glass ionomers have a self-adhesion potential, though pretreatment with a weak polyalkenoic acid conditioner significantly improves adhesion to the tooth structure [105]. The conditioner is needed in the presence of a smear layer. An application of at least 10–20 s is advocated, after which the gel is rinsed off followed by gentle air-drying without dehydration of the conditioned surface.

The conditioner is used as a ‘cleaning agent’ to remove smear layer and debris. Smear props are removed from the entrance of the dentinal tubules. The application also results in ‘partial demineralization’ further increasing the surface contact area and the number of microporosities. Furthermore, the use of the conditioner results in depletion of hydroxyapatite from the collagen fibrils resulting in ‘hydroxyapatite-coated collagen fibres interspersed by pores’ the whole not deeper than 1 μm. It has also to be emphasised that the conditioning gel is not always completely rinsed off [106] resulting in a 0.5 μm thick attached layer.

The adhesion of GIC is based on (1) micromechanical interlocking in the dentin (tubules and microporosities) as a result of infiltration by the polyalkenoic acid and by shallow hybridisation of the microporous network of hydroxyapatite-coated collagen fibrils (RMGIC) and (2) chemical interaction of the polyalkenoic acid with the hydroxyapatite [107]. This chemical self-adhesion is the result of true primary chemical bonding through formation of ionic bonds between the carboxyl groups of the polyalkenoic acid and calcium of hydroxyapatite of the substrate.

It is postulated that an intermediate adsorption layer of calcium and aluminium phosphates and polyacrylates is formed at the GIC-hydroxyapatite interface.

Depending on the product, an up to 0.5 μm thick layer of polyalkenoic remains attached to the tooth. This results in a persisting ‘gel phase’ at the interface. Formation of calcium polyacrylate salt resulting from either the polyalkenoic acid conditioner or the glass ionomer material itself was seen [106].

5.6.3 Glass Ionomer Adhesion and Laser Dentistry

Most of the studies evaluating GIC shear bond strength or microtensile bond strength are performed with RMGIC; CGICs are brittle materials and are not always representative because failure frequently occurs within the material [108]. Tensile and shear bond strengths of GIC have been limitedly investigated in association with laser preparation.

Higher bond strengths are registered for RMGIC adhering to bur-cut dentin surfaces as compared to high-power cavity preparation with erbium lasers [109] (Er:YAG – 350 mJ/2Hz). This was also found after dentin conditioning at low power [110] (Er,Cr:YSGG – 50 mJ/20 Hz) for CGIC Fuji II and not for RMGIC, where the values were similar between the bur-cut and laser-conditioned dentin, though without the use of a conditioner. In this study, the use of a conditioner decreased the bonding strength.

Lasing at high power in the study of Delmé et al. [84] and Cardoso et al. [111] resulted in the absence of a hybrid layer and a gel phase and impaired the interaction of RMGIC with the dentin negatively influencing its bonding effectiveness.

An exception was the study of Ekwarapoj et al. [112] (Er,Cr:YSGG – up to 300 mJ/20 Hz) with Fuji IX and Ketac Molar (CGIC) placed after laser dentin preparation and the use of dentin conditioner, as compared to bur-prepared dentin and dentin conditioning. The values, however, did not differ between the bur-cut dentin and laser-ablated dentin when no conditioner was used. This was also confirmed in the study of Jafari et al. [113] where the adhesion of Fuji IX to lased enamel (Er:YAG – 350 mJ/10 Hz) was found to be better than to bur-cut enamel. No conditioner was used in this study.

A number of studies on erbium-lased dentin adhesion emphasise the need of the use of low-power laser conditioning for better adhesion [114, 115]. Preparation of enamel is also best followed by conditioning [116].

Long-term water storage and thermocycling did not affect shear bond strength of GIC to Er:YAG laser-prepared dentin [117].

5.6.4 Laser-Prepared Cavities and Marginal Seal with Glass Ionomer Cements

It has been demonstrated that both CGIC and RMGIC require pretreatment procedures with a conditioner to establish good adhesion to both the dentin and enamel [8]. The conditioner a.o. is needed to remove smear layer and debris from bur-cut cavity walls [107]. Erbium-lased cavity walls are free of smear layer on both the enamel and dentin, and it can be questioned whether pretreatment with a conditioner after laser conditioning is needed to improve marginal adaptation.

Studies on microleakage in the permanent teeth associated with GIC fillings after laser preparation remain scarce. It was concluded by De Moor and Delmé [8] that both CGIC [118–123] and RMGIC [104, 118, 120–122, 124–126] could not prevent microleakage in erbium-lased cavities. Making comparisons between the studies is difficult due to the heterogeneity of the study design and drawing conclusions even more difficult. In general, it can be seen that leakage was higher at the gingival margin (dentin/root cementum) than at the occlusal enamel margins. Leakage was scored in both erbium-lased cavities and bur-cut cavities, coming to the conclusion that the mode of preparation was of no influence. The use of a conditioner before insertion of the GIC filling, however, is recommended (Figs. 5.9, 5.10, 5.11, 5.12, 5.13 and 5.14). Conditioning leads to rounding of the enamel prisms and smoothening of the lased dentin surface with removal of the higher mineralized peritubular dentin.

During the recent years, studies have focused also on primary teeth, nevertheless, their number is limited [127–131]. Higher leakage score were found with CGIC as compared to RMGIC in class V cavities [127, 129]. Leakage in class V erbium-lased cavities was higher gingivally than occlusally and more extensive than in bur-cut cavities [129]. Other

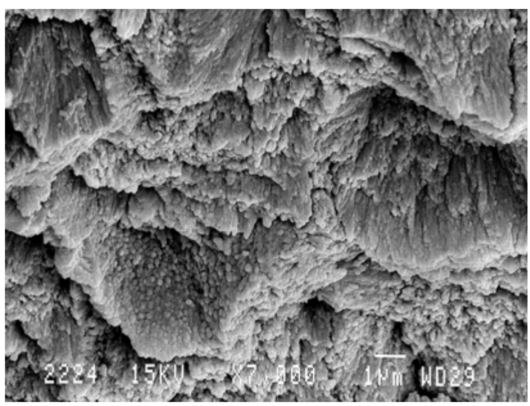

Fig. 5.9 Scanning electron microscope (SEM) picture of enamel surface after laser preparation showing irregular surface with sectioned enamel prisms (×3,000). Scale bar = 10 μm (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

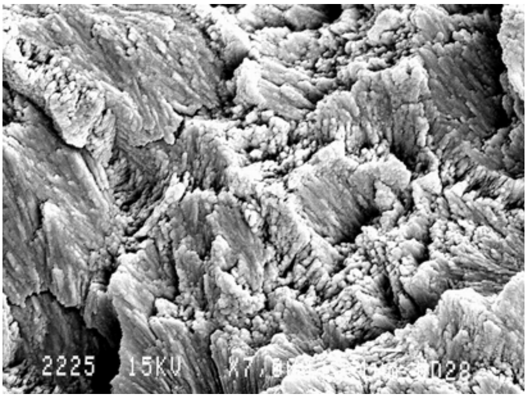

Fig. 5.10 Scanning electron microscope (SEM) picture of enamel surface after Er:YAG laser preparation and conditioning with Ketac conditioner. Rough surface was seen (×3,000). Scale bar = 10 μm (Courtesy of Prof. Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

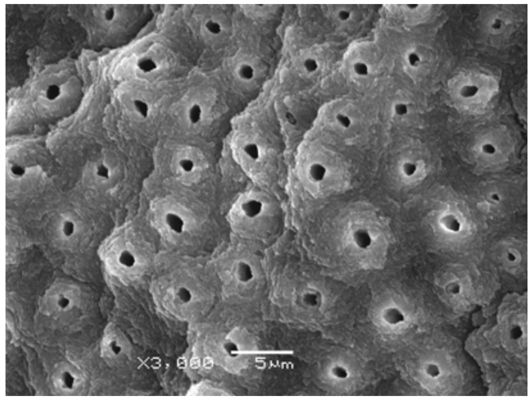

Fig. 5.12 Scanning electron microscope (SEM) picture of dentin surface after Er:YAG laser preparation showing surface free of smear layer and open tubules (×8,000). Scale bar = 5 μm (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

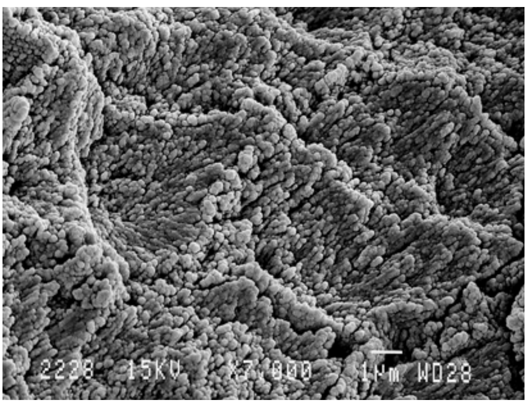

Fig. 5.11 Scanning electron microscope (SEM) picture of enamel surface after Er:YAG laser preparation and conditioning with GC conditioner. Enamel prisms were rounded off (×3,000). Scale bar = 10 μm (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

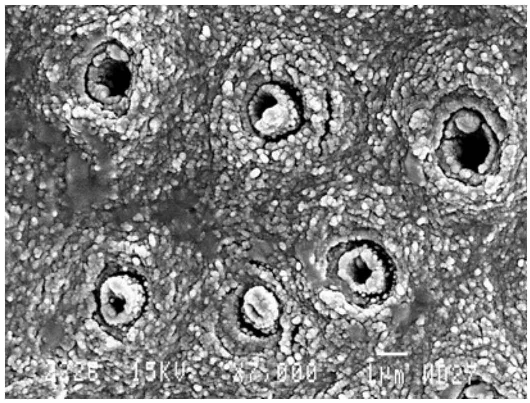

Fig. 5.13 Scanning electron microscope (SEM) picture of dentin surface after Er:YAG laser preparation and conditioning with Ketac conditioner. Tubules' orifices were partially closed (×8,000). Scale bar = 1 μm (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

studies demonstrated no difference in leakage between bur-cut and erbium-lased class V cavities filled with a RMGIC [127, 128, 131]. A study comparing microleakage between class I cavities prepared by chemomechanical caries removal (Apacaries gel), ART (atraumatic restorative treatment) and Er:YAG laser lased revealed higher leakage for the preparations made using the Er:YAG laser [130]. Once again, comparison between these studies was impossible due to the heterogeneity of the methods and materials.

5.6.5 Recommendations

Studies on glass ionomer adhesion in erbium-lased cavities are limited and mostly confined to RMGIC. Adhesion with RMGIC is achieved in the same way as with resin composites with their resinous components. Pretreatment with a conditioner is advised in order to obtain a good marginal seal. Laser conditioning appears to have a positive influence on adhesion. Enamel microleakage is in general lower than gingival dentin microleakage. Insufficient

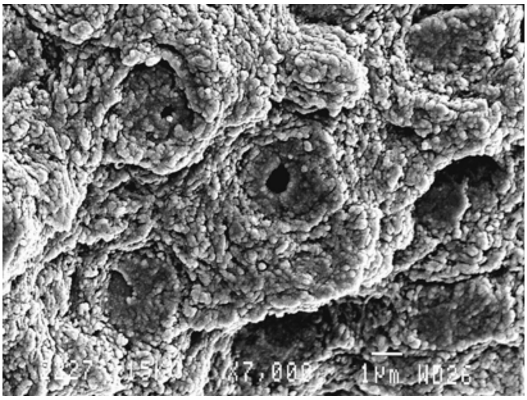

Fig. 5.14 Scanning electron microscope (SEM) picture of dentin surface after Er:YAG laser preparation and conditioning with GC conditioner. Most tubules' openings were closed (×8,000). Scale bar = 1 μm (Courtesy of Dr. Katleen Delmé and Prof. Dr. Roeland De Moor, Belgium)

information is available on tensile bond strength.

The information on adhesion of CGIC is scarcer than for RMGIC. No reliable information is available of the effects of erbium-lased cavity walls on the bond strength of CGIC. For as far as the sealing ability of CGIC is considered, it appears that pretreatment with a conditioner might not be needed with the smear layer-free surfaces. As long as there is no convincing information, CGICs are placed after laser conditioning and conditioning of the tooth surfaces.

At present, there is no convincing proof that adhesion of GIC on erbium-lased dentin and enamel is at least equivalent with three-step etch-and-rinse adhesives (3E&Ra) and two-step mild self-etch adhesives containing 10-MDP (SEA-m).

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Part III

Clinical Applications

Failure

Failure is simply the opportunity to begin again, this time more intelligently.

–Henry Ford

Success

Success does not consist in never making mistakes but in never making the same one a second time.

–George Bernard Shaw

6 Laser Applications for Caries Diagnosis and Prevention

Giovanni Olivi and Maria Daniela Genovese

Abstract

Early diagnosis and monitoring of occlusal caries over time is difficult. The most effective diagnostic mean is the combination of several techniques, including laser fluorescence. Pit and fissure sealant is the most common preventive procedure together with fluoride application. Lasers have many uses in preventive dentistry. Laser fluorescence (LF) diagnosis and erbium laser conditioning or ablation can improve the outcome of fissure sealant or preventive resin restoration, making the procedure personalized. LF can direct the procedure towards a laser conditioning only of the fissure or towards a minimal enamel ablation and decontamination. When visual inspection and LF values indicate a caries, erbium laser can directly prepare the cavity only varying the energy applied; a final fissure sealant completes the so-called preventive resin restoration (PRR). Other preventive measures include the laser modification of enamel to produce increased acid resistance of enamel and to improve the remineralization process; the far infrared laser demonstrated, in vitro, significant results. Also other wavelengths in combination with APF, specifically 810 nm, 1064 nm, 2780 nm, and 2940 nm, demonstrated to be suitable for preventive applications. Finally the MIH lesion of enamel can have advantage from erbium laser preparation due to the minimal and favorable modifications produced by the laser. Also the minor discomfort produced by the laser in comparison with conventional instrumentation makes this procedure elective for children and anxious patients.

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6.1 Diagnosis and Preventive Dentistry

Preventive dentistry is a branch of operative dentistry closely related to the restorative part. After diagnosis and caries risk assessment, younger

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and older patients receive different personalized preventive and follow-up programs; these include periodic recall sessions at 3–6 or 12 months.

Early diagnosis and/or monitoring of occlusal caries is difficult. Fissure probing alone has a minor diagnostic value. Visual close inspection can direct the attention in different areas of the dental surface, and the presence of white spots is more indicative of progressive demineralization stage when compared to dark spots (Figs. 6.1 and 6.2).

Even the periapical or bitewing intraoral x-rays cannot show initial enamel caries (grade I); the radiographs may instead be an important aid in the diagnosis of proximal caries when carious process extends in dentin (grade II and III).

Furthermore, caries risk patients that undergo clinical checks every 3–6 months are possibly exposed to an excessive radiation dose summation, and also pregnant women cannot receive x-rays, so exploring alternative noninvasive methods is necessary.

Lasers have many uses in preventive dentistry for the following purposes [1]:

– Caries detection: laser fluorescence (LF) has been used for preoperative diagnosis of caries (DIAGNOdent, KaVo) in both primary and permanent teeth and as an intraoperative diagnostic tool (SIROInspect, Sirona).
– Caries prevention: several infrared laser wavelengths have been used to provide increased enamel surface resistance to acid attack as experimental methods of caries prevention.
– Sealants: erbium lasers irradiation are used to provide enamel surface modifications that are suitable for the application of pit and fissure sealants.

6.2 Laser for Caries Detection

Laser for caries diagnosis is the most widely investigated laser application in pediatric dentistry. In the last 15 years, several technologies were developed and investigated for different diagnostic purposes, including preoperative, intraoperative, and postoperative diagnosis. Laser fluorescence (LF) device using 655 nm light (DIAGNOdent and

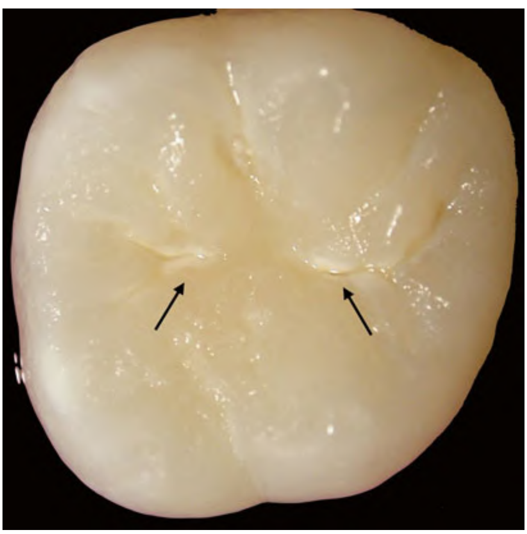

Fig. 6.1 Visual close inspection can direct the attention in different areas of the dental surface to identify the presence of initial demineralization and/or caries; white spots on molar fissures, that are indicative of progressive demineralization stage (*black arrows*) (Reprinted with permission from Olivi et al. [1])

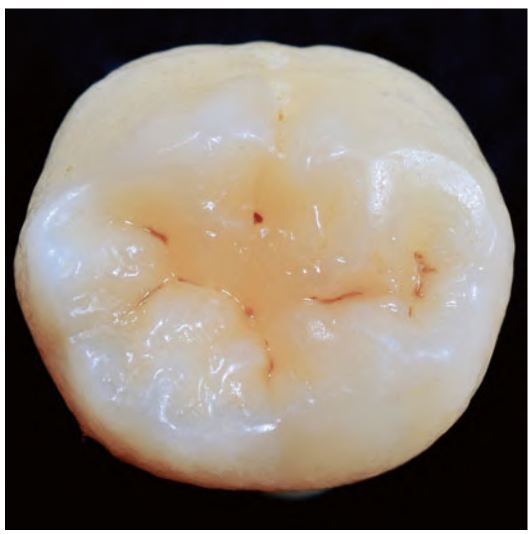

Fig. 6.2 Visual close inspection shows the presence of dark spots, normally not associated with enamel demineralization; probing, x-ray, and LF diagnosis will give a more precise diagnosis

DIAGNOdent-pen; KaVo, Germany) is the more studied technology for preoperative diagnosis. Laser fluorescence at 405 nm (SIROInspect, Sirona, Germany) is a recent technology for intra-operative check of remaining carious tissue during excavation. The quantitative light fluorescence (QLF) uses a blue light, while the optical coherence tomography (OCT) uses near-infrared light at 1310 nm for preoperative diagnosis. Also the transillumination imaging diagnostic method uses laser light at 780 nm (DIAGNOcam) to produce proximal lesion images that are reported as comparable to bitewing radiographs.

6.2.1 Laser Fluorescence: The DIAGNOdent

Laser fluorescence (LF) is the most widespread laser diagnostic technology; it is a non-ablative laser device that emits a visible, red light at 655 nm.

When the light is directed towards the occlusal fissures of posterior teeth, it is easily transmitted through the enamel and is absorbed by a specific target. Effectively, bacteria by-products and porphyrins within the carious lesion absorb and simultaneously reflect a red fluorescent light that is detected and rated at a digital display and as an acoustic signal [2, 3] (Figs. 6.3, 6.4, and 6.5).

Iwami et al. reported the relationship between bacterial infection of carious dentin and LF detection (polymerase chain reaction). The values of the LF increased as the bacteria detection rates increased, reinforcing the concept of the relationship between fluorescence values of caries and rates of bacteria by-products and porphyrins present [4]. Later on, Neuhaus et al. also reported that the quantitative measure of

Fig. 6.3 LF detects with higher sensitivity and good specificity occlusal fissure caries; first the laser identifies the fluorescence value of healthy enamel (e.g., the enamel of a cusp)

Fig. 6.4 DIAGNOdent detects then the fluorescence of occlusal pits and fissures

Fig. 6.5 DIAGNOdent registers a numerical rate of the detection, reporting on the left the initial value of the healthy enamel and on the right the actual value detected (e.g., 99 is indicative of deep dentin caries)

fluorescence of the tooth was related more to the presence of bacterial by-products than to the mineral loss subsequent to the development of a caries lesion [5].

Several studies compared different caries detection methods: visual inspection alone, visual inspection with magnification, bitewing x-ray, and laser fluorescence with different results.

Lussi and Francescut confirmed the very high reliability and the diagnostic validity (sum of sensitivity and specificity) of LF for occlusal caries detection and also reported it, as higher than bitewing radiography for proximal caries diagnosis in primary teeth. The authors concluded that LF could be used as an additional tool in the detection of occlusal caries in deciduous teeth and its good reproducibility should enable the laser device to monitor the caries process over time [6]. Another study reported that the reliability, predictability, and the reproducibility of the detection did not result as dependent on operator factor [7].

Olmez et al. (2006) evaluated the sensitivity and specificity of DIAGNOdent, visual examination, and bitewing radiography. Sensitivity measures the proportion of actual positives which are correctly identified as such (e.g., the percentage of decayed teeth who are correctly identified as having the condition). Specificity measures the proportion of negatives which are correctly identified as such (e.g., the percentage of healthy teeth who are correctly identified as not having the condition). Sensitivity and specificity for DIAGNOdent, visual examination, and bitewing radiography were 0.86/0.80, 0.69/1.00, and 0.36/1.00, respectively. The LF showed lower specificity than visual inspection and bitewing radiographs but on the contrary demonstrated significantly higher sensitivity for caries lesions than other conventional methods. Consequently, in case of doubtful diagnosis after clinical examination, LF having high sensitivity may be a useful adjunct to visual inspection with a high specificity to formulate the proper diagnosis of occlusal caries [8, 9].

Chu et al. compared three different methods for fissure caries detection in second permanent molars of young adults (visual examination, bitewing radiographs, and DIAGNOdent) and concluded that the combined approach of the LF and visual examination produced the better results [10].

Fig. 6.6 Occlusal view of an upper permanent molar showing dark spots on pits and fissures (Courtesy of Prof. Vasilios Kaitsas, Italy)

Diniz et al. conducted an in vivo study to determine clinical cutoffs for a DIAGNOdent, a DIAGNOdent-pen, and a DIAGNOcam (fluorescence camera, FC) and to evaluate the clinical performance of these methods and conventional methods in detecting occlusal caries in permanent teeth. The International Caries Detection and Assessment System (ICDAS), the LF device, and the LF pen demonstrated good performance in helping detect occlusal caries in vivo. BW radiography and FC had the lowest performances in helping to detect the lesions. The study concluded that occlusal caries detection should be based primarily on visual inspection. Fluorescence-based methods may be used to provide a second opinion in clinical practice [11] (Figs. 6.6, 6.7, 6.8, 6.9, 6.10, and 6.11). Recently an in vivo study reported that caries lesions may be detected more accurately by laser fluorescence devices than by clinical visual inspection [12].

Laser fluorescence has been proposed also for monitoring and for appropriate management of dental caries in both primary and permanent molars.

An in vitro study by Mendes et al. reported that LF was neither able to detect the remineral-

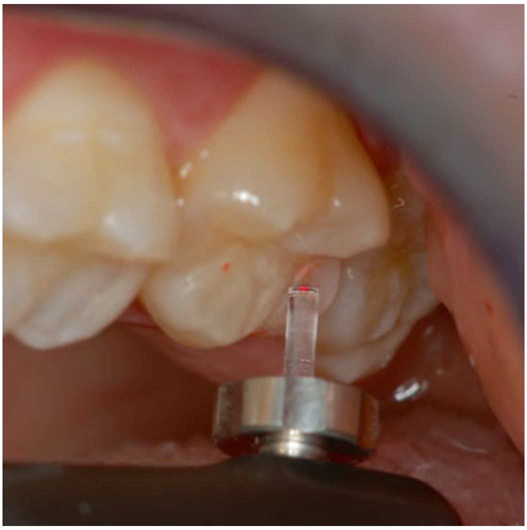

Fig. 6.7 DIAGNOdent-pen first detects the healthy enamel fluorescence (e.g., the enamel of a cusp) (Courtesy of Prof. Vasilios Kaitsas, Italy)

Fig. 6.8 DIAGNOdent-pen detecting successively the fluorescence of enamel pits and fissures (Courtesy of Prof. Vasilios Kaitsas, Italy)

Fig. 6.9 Histology of an extracted molar, presenting similar very narrow fissure with apparently intact occlusal opening; enamel caries extending in dentin is difficult to identify (Courtesy of Prof. Vasilios Kaitsas, Italy)

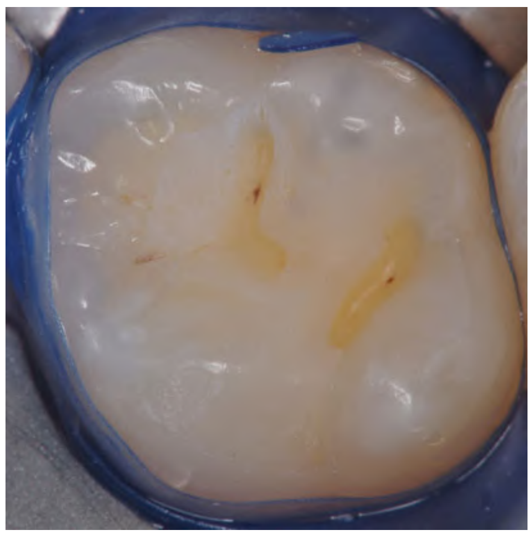

Fig. 6.10 Minimal preparation of the fissures followed the combined visual and LF diagnosis (Courtesy of Prof. Vasilios Kaitsas, Italy)

ization of incipient caries lesions of primary teeth nor to monitor the quantification of mineral loss in caries lesion development in primary teeth [13]. In a following study of the same group, Braga et al. reported that LF device performed better at the dentin threshold than at the enamel threshold; accordingly the study concluded that LF performed better in predicting the depth of the caries lesions (dentin caries) than the initial mineral loss (early enamel caries) [14].

Khalife et al. in an in vivo study also assessed the correlation between the depth and volume of caries and DIAGNOdent readings and concluded that the DIAGNOdent should be used only as an

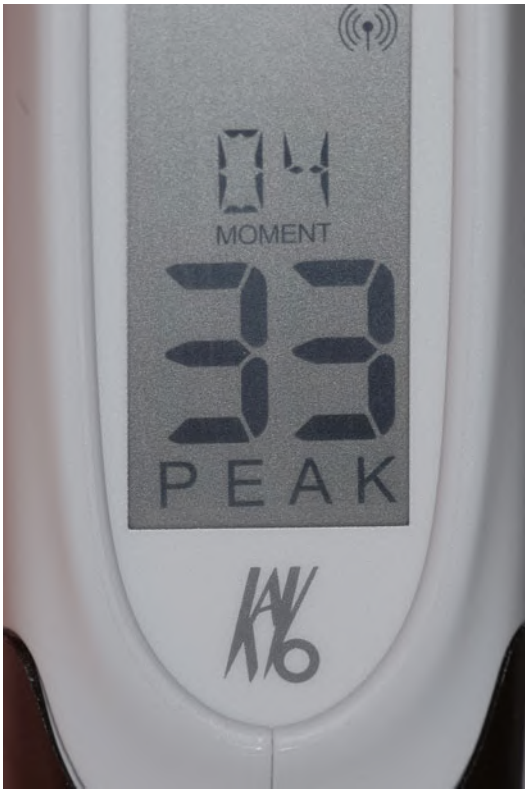

Fig. 6.11 DIAGNOdent-pen detection related to Fig. 6.8 shows high value peak (Courtesy of Prof. Vasilios Kaitsas, Italy)

adjunct to the diagnosis and treatment planning process [15].

Also a more recent in vitro study by Bahrololoomi et al. concluded that LF is an appropriate method for detection of demineralization in smooth enamel lesions, but it was not so efficient in the detection of remineralization [16].

Besides occlusal caries detection performed with DIAGNOdent, a more recent version (DIAGNOdent-pen) has different tip shapes that enable an advanced proximal caries detection.

Novaes et al. compared the performance of various methods for proximal caries detection in primary molars. Both the LF pen and radiographic examination exhibited similar performance in the detection of cavitations on proximal surfaces of primary molars [17].

A recent study investigated in vitro a newly developed LED fluorescence device for proximal caries detection in comparison with DIAGNOdent-pen, bitewing x-rays, and visual inspection (International Caries Detection and Assessment System, ICDAS). Reliability data scored fair to moderate for the LED fluorescence device and good for bitewing radiography and laser fluorescence pen. However, it is the combination of different methods that gives better results, with association of visual inspection (ICDAS) and radiography yielding the best diagnostic performance at the dentine threshold [18] (Figs. 6.12, 6.13, 6.14, and 6.15).

Several studies investigated particular factors that could negatively influence the detection and must be kept in mind when combining the visual inspection and laser fluorescence detection.

The presence of brown or dark spots on fissures tends to overscore specific discolored areas of fissures, giving false positive detection [19].

The presence of plaque or toothpaste residual after teeth cleansing worsens the performance registering false readings [20, 21]; therefore, a careful preparation must precede the laser detection.

The laser reading under whitish dental sealants is unreliable due to inaccurate detection caused by intrinsic fluorescence of sealant material [22, 23]. However, it has been recently reported the possibility of monitoring the sealant procedure over time, when clear sealant is used [24].

To conclude this brief overview on laser diagnostic device guidelines, a study by Mendes et al. was included to give a complete and objective point of view. This study reported that adjunct methods of caries detection would not significantly improve the detection of primary molar lesions in comparison to visual inspection alone. The sensitivity, specificity, accuracy, and utility of diagnostic strategies were calculated. Simultaneous combined strategies increased sensitivities but decreased specificities, and, furthermore, no differences were observed in accuracy and utility, parameters more influenced by caries prevalence. The study concluded that present clinical guidelines should be re-evaluated [25]. In agreement with other studies [11, 18], it is personal opinion of the author that LF may be considered a valuable tool in combination to visual inspection,

Fig. 6.12 LF detection of proximal surfaces in upper bicuspids using DIAGNOdent-pen and new tip-probe (chisel or conical) (Courtesy of Prof. Vasilios Kaitsas, Italy)

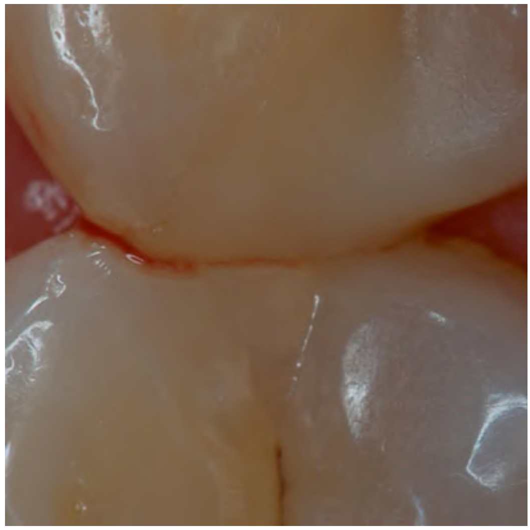

Fig. 6.13 Close proximal contact point among two bicuspids hides a proximal caries that is not visible at visual inspection or probing but is detected by LF (Courtesy of Prof. Vasilios Kaitsas, Italy)

Fig. 6.14 Initial opening of cavity from occlusal ridge shows the proximal caries (Courtesy of Prof. Vasilios Kaitsas, Italy)

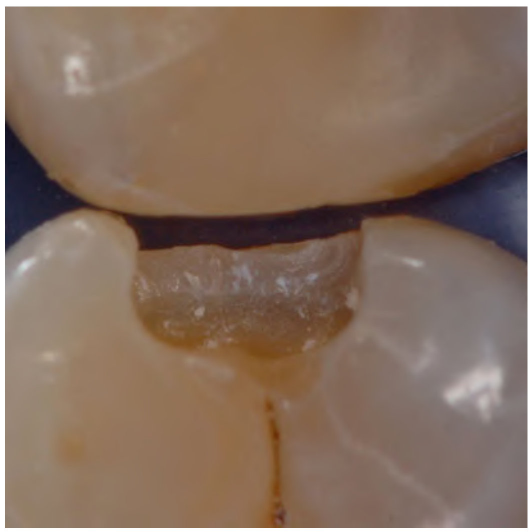

Fig. 6.15 The cavity preparation is completed with conventional instruments (Courtesy of Prof. Vasilios Kaitsas, Italy)

for caries detection as well as for longitudinal monitoring of caries and for assessing the outcome of preventive interventions during recall session in caries risk patients; LF allows to space out the x-ray examinations, so reducing the radiation dose summation (Tables 6.1, 6.2, and 6.3).

6.2.2 Laser Fluorescence: The SIROInspect™

Bacteria present in the infected carious dentin release metabolic products (porphyrins) that emit visible red fluorescence when lighted with a violet laser light (405 nm). Healthy

Fig. 6.16 SIROInspect with orange filter fit on the probe

Table 6.1 Shows the DIAGNOdent values of occlusal fissures detection

DIAGNOdent™ readings according to the manufacturer
0–10 = Healthy tooth structure
11–20 = Outer half enamel caries
21–29 = Inner half enamel caries
30+ = Dentin caries

Table 6.2 Shows the DIAGNOdent-pen values of occlusal fissures detection

DIAGNOdent-pen™ readings according to the manufacturer
0–12 = Healthy tooth structure
13–24 = Outer half enamel caries (initial demineralization)
>25 = Inner half enamel caries (severe demineralization)

Table 6.3 Shows the DIAGNOdent-pen values of proximal detection

DIAGNOdent-pen™ readings according to the manufacturer
0–7 = Healthy tooth structure
8–15 = Initial demineralization
>16 = Severe demineralization

tooth tissue differs in this respect by fluorescing green.

During caries excavation, one of the main problems is to avoid over-excavation saving healthy dentin to be removed. This is also more important when approaching deep caries for the possibility to create a pulp exposure (this topic is discussed in Sects. 7.7.2, 7.7.3, and 8.2.3). SIROInspect utilizes a patented technology (FACE, fluorescence-aided caries excavation) to illuminate the tooth cavity with violet light (405 nm). The advantage of intraoperative laser fluorescence technology is that the dentist can see which areas are carious and which are not, during excavation with a much greater degree of certainty than with dye detector or visual inspection or tactile feedback alone.

The light is delivered through a handy probe that presents an attachable filter fit and aligned on it (Fig. 6.16); this allows to filter out light with wavelengths below 500 nm, making the light with higher wavelengths to remain visible when the tooth is exposed to violet light. Few studies are present in literature on this topic.

The studies of Lennon et al. investigated the ability of fluorescence-aided caries excavation (FACE) to detect and remove infected dentin in primary teeth compared to conventional methods (tactile excavation criteria or a caries detector dye). The quantitative confocal microscopy and histologic investigations showed significantly less remaining infected dentin in FACE samples compared to conventional excavation, resulting in more effective excavation than conventional in removal of infected dentin [26, 27]. The author's experiences are very positive on the utility of this device as an adjunct valuable instrument to perform minimal invasive cavity preparation.

6.3 Pit and Fissure Treatment

Most of the increased dental caries in children and adolescents are confined to pit and fissure surfaces of first molars. Sealants are one of the methods of primary prevention of dental oral diseases introduced in the 1960s, specifically to prevent fissure decays of posterior teeth [28–31]. Sealants fill the fissures of the dental surface closing the access into the deep enamel fissure of residual food and bacteria, preventing the possible carious process to begin, and therefore is a recommended preventive procedure for all the children.

A systematic review conducted in 2013 reported the efficacy of sealant in reducing caries up to 48 months when compared to no sealant groups; however, after a longer follow-up period the quantity and quality of the evidence is reduced [32]. Therefore follow-up sessions are fundamental for monitoring the conditions of teeth in young patients and to perform the prompt corrective measures (Figs. 6.18 and 6.19).

Also topic fluoride varnishes have been extensively used as adjunct measures to prevent dental caries in caries risk patients. In 2013 an updated review confirmed the caries-inhibiting effect of fluoride varnish in both permanent and primary teeth; however, the quality of the evidence assessed was moderate [33].

In 2010, another systematic review compared the effectiveness of pit and fissure sealants with fluoride varnishes in the prevention of dental decay on occlusal surfaces. The results of the study reported evidence on the superiority of pit and fissure sealants over fluoride varnish application in the prevention of occlusal decay [34].

Accordingly, the application of sealant is the preventive procedure of choice for all the children. The application of fluoride varnishes could follow after some weeks of the application of sealant, to reinforce the smooth and proximal enamel areas that cannot be protected by the sealant. Fluoride varnish can be applied periodically every 3–6 months in case of high-risk patients with poor diet and bad oral hygiene habits and attitudes (see Sect. 2.4.1). It must be emphasized that fluoride inhibits the polymerization of the adhesive and composite systems and cannot be used before, but rather must follow the adhesive procedures.

Considering the different anatomy of different fissures, different pretreatment enamel techniques are used before the application of sealants Figs. 6.17, 6.18, 6.19, 6.20, 6.21, and 6.22:

Fig. 6.17 First upper quadrant of patients underwent to sealant application on bicuspids and molars 25 years before. The follow-up permits to check the sealing of the teeth and propose the amalgam removal (microcrack on distal wall)

Fig. 6.18 Second upper quadrant of patients underwent to sealant application on first bicuspid, PRR on second bicuspid, and composite restoration on first molar 20 years before. The follow-up permits to check the sealing of the teeth and to diagnose proximal decay on second molar

- Noninvasive techniques using acid etching of the occlusal fissures
- Noninvasive techniques using air abrasion followed by 37 % orthophosphoric acid etching of the occlusal fissures
- Invasive techniques using diamond bur and high-speed drill to open the narrow fissures (fissurotomy), followed by the etching procedure with 37 % orthophosphoric acid.

When the occlusal surface presents small fissure and/or pit caries, a selective removal of any affected enamel and/or dentin without any preparation of the neighbor intact fissures is the treatment of choice. The prepared cavity is restored with composite resin, and a sealant is placed over the remaining intact fissures and pits, completing the minimally invasive procedure with a preventive procedure for the remaining healthy enamel. This technique was introduced by Simonson and is called preventive resin restoration (PRR) technique [35].

6.3.1 Laser Assisted Fissure Sealant (LAS)

Although there is evidence of sealants' effectiveness, one major obstacle on its use is the concern of sealing over active caries lesions, and the decision of whether or not to place a sealant depends largely on the dentist's assessment of the depth of the occlusal fossae (Figs. 6.23, 6.24, 6.25, and 6.26). Effectively pediatric dentists' perception (visual examination and tactile perception) of fossa depth in permanent molars correlates moderately well with the actual fossa depth [36], so that clinical and anatomical consideration in combination with laser diagnostic values must be considered before the sealant procedure, because

Fig. 6.19 Buccolingual hemi-section of recently extracted third molar shows a very narrow anatomy of the fissure

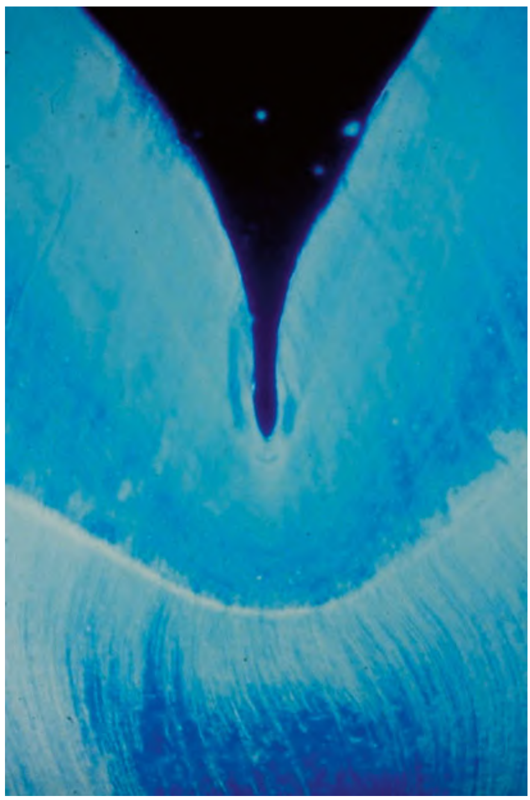

Fig. 6.20 Buccolingual hemi-section of extracted third molar shows a narrow healthy fissure

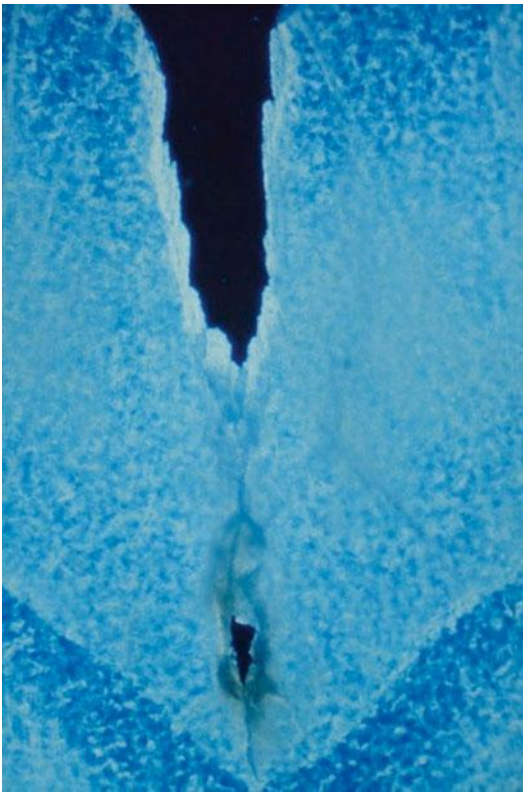

Fig. 6.21 Buccolingual hemi-section of extracted third molar shows a fissure with demineralization in depth very close to the enamel-dentin junction

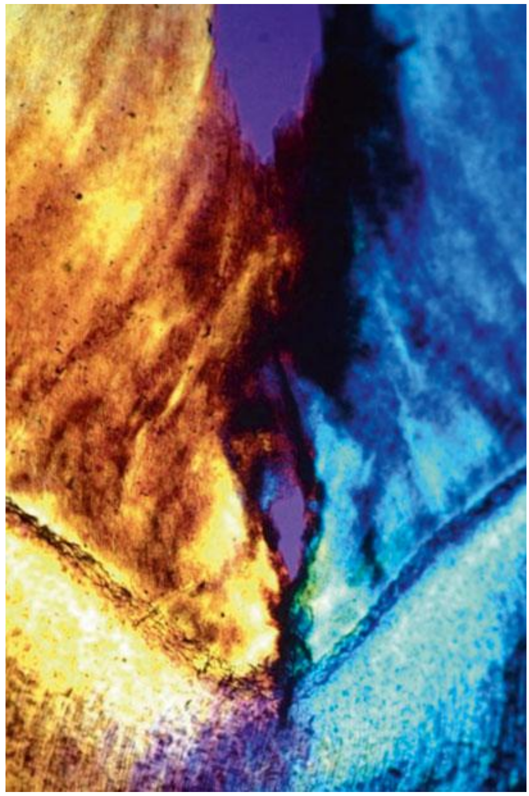

Fig. 6.22 Buccolingual hemi-section of extracted third molar shows a fissure with demineralization in depth very close to the enamel-dentin junction

they condition both the clinical choice and the operative procedure, making the treatment plan more reliable (Figs. 6.27 6.28, 6.29, 6.30, 6.31, and 6.32). Anatomical and clinical considerations include the following:

- Age of the tooth eruption (just erupted or erupted for several months or years)
- Visual perception of pit and fissure anatomy (deep, retentive)
- Presence of dark or white spot on the fissures (demineralization)
- LF values between 0–20 and 0–24 (DIAGNOdent or DIAGNOdent-pen*)

LF permits to diagnose the condition of the fissure and pits, addressing the procedure towards a preventive or therapeutical treatment (see Tables 6.1 and 6.2) (Figs. 6.33 6.34, 6.35, 6.36, 6.37, and 6.38).

When fluorescence diagnosis is combined with erbium lasers (2780 and 2940 nm), it is possible to individualize (personalize) the treatment of the fissure. Erbium lasers can be used as:

- Noninvasive technique for conditioning pretreatment of healthy pits and fissures before acid etching and sealant (LAS) (see Table 6.4)
- Minimally invasive technique for decontamination and conditioning pretreatment of deep fissures or with initial demineralization before acid etching and sealant (LAS) (see Table 6.4) (Figs. 6.39, 6.40, 6.41, 6.42, 6.43, 6.44, and 6.45)
- Minimally invasive ablative technique for white spot or caries removal, followed by healthy fissure conditioning, before acid etching, bonding, composite, and sealant in the preventive resin restoration (PRR) (see Tables 6.4 and 6.5).

The main advantages of using erbium lasers for these applications are the cleansing [37] and

Fig. 6.23 Buccolingual hemi-section of extracted third molar following 24-h dye application. Image of fissure conditioned with orthophosphoric acid and sealed with no filled resin

Fig. 6.24 A magnification of the previous image shows presence of dye under the sealant as for initial enamel demineralization in the depth of the fissure; dentin is not involved in the process

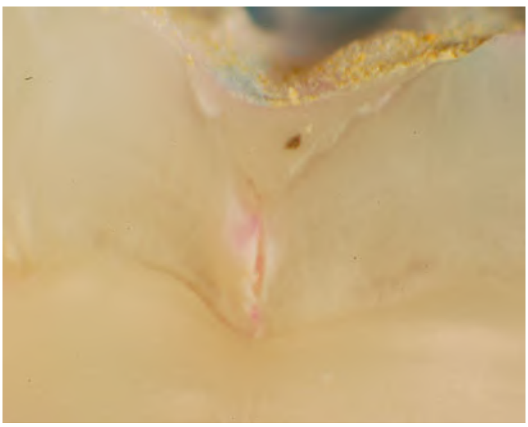

Fig. 6.25 Buccolingual hemi-section of extracted third molar following 24-h dye application. Image of fissure conditioned with orthophosphoric acid and sealed with no filled resin

Fig. 6.26 A magnification of the previous image shows traces of dye under the sealant, in the depth of the fissure that also present initial demineralization of the enamel (clear area); dentin is not involved in the process

decontamination [1] of the fissures associated to the conditioning pretreatment or to the ablation of enamel fissures and pits [1]. Most of the debris are removed by erbium laser treatment, whereas some fissures remain not cleaned by bristle brush (Figs. 6.46, 6.47 and 6.48). Laser technique facilitates good adaptation of resin sealant to enamel, because of an increase in surface roughness and favorable surface characteristics [38].

Still debated is if laser pretreatment may help to improve the quality of the margins and the adhesive strength of the sealant to the enamel, in order to avoid secondary decay, so ensuring a longer duration of the seal [38–41]. However, there is a consensus on the use of acid etching after laser irradiation to improve the adaptation of sealant and bonding results of LAS [42–46] (Fig. 6.49).

Recent study confirmed the role of the combination of Er:YAG laser pretreatment (125 mJ, 20 Hz) followed by 37 % orthophosphoric acid (15 s) in reducing the microleakage of fissure sealants in permanent molar teeth in vitro; however, the difference among the two groups was not statistically significant [47] (Table 6.3).

Fig. 6.27 Occlusal surface of extracted upper third molar presenting complicated fissure anatomy; also white demineralization areas are visible

Fig. 6.28 Occlusal surface of extracted lower third molar presenting complicated fissure anatomy; also white demineralization areas are visible

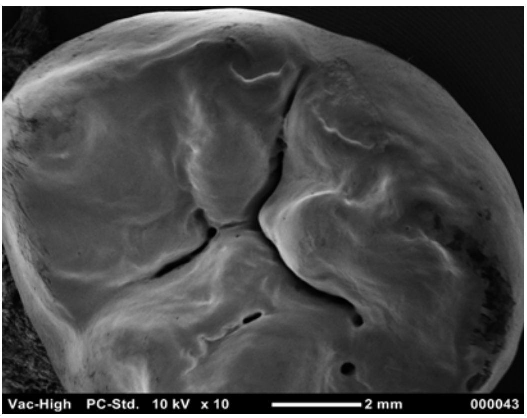

Fig. 6.29 SEM images (10×) of occlusal surface of upper third molar presenting complicated fissure anatomy

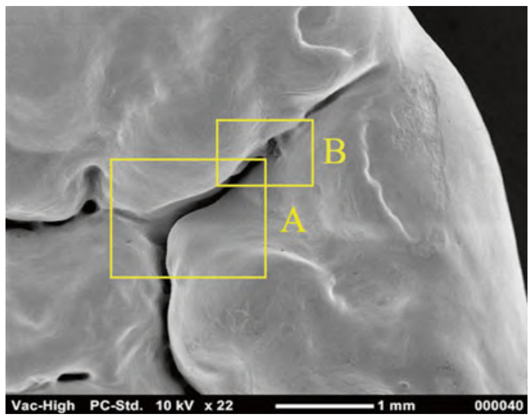

Fig. 6.30 SEM images (22×) of the same tooth show the influence of the magnification on the visual inspection. Three different areas (*A*, *B*) are deeply explored

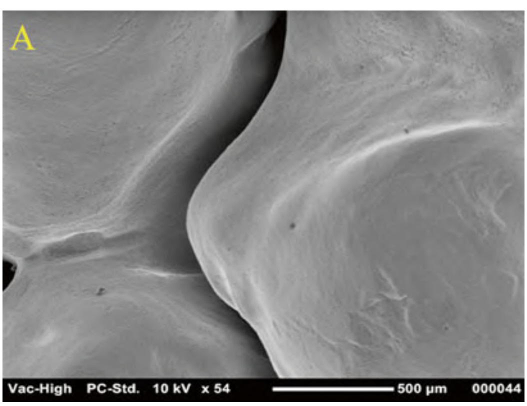

Fig. 6.31 SEM images (54×) of the A area of Fig. 6.30. The narrow anatomy of the tooth is clearly visible by magnification

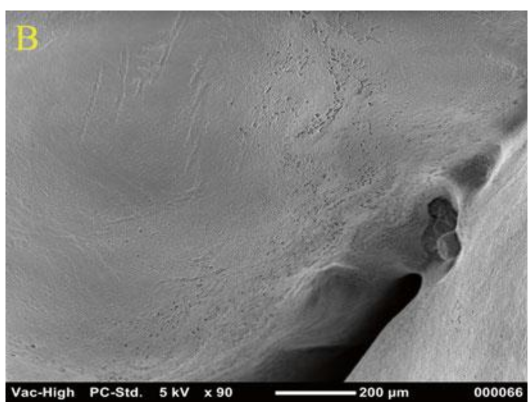

Fig. 6.32 SEM images (90×) of the B area of Fig. 6.30. The narrow and deep anatomy of the tooth explains the difficulty in cleaning the fissure before the sealant application

Fig. 6.33 Clinical intraoperative image shows apparently healthy second bicuspid and first molar of a 13-year-old boy, before sealant application

Fig. 6.34 DIAGNOdent-pen fluorescence detection of the enamel of mesial cusp

Fig. 6.35 DIAGNOdent-pen fluorescence detection of the fissures to assess the type of fissure treatment before sealant application

Table 6.4 Suggested parameters for use laser assisted fissure sealant (LAS)

Accurate diagnosis of the fissures: inspection and probing under magnification and fluorescence detection (value refers to DIAGNOdent-pen*, KaVo)
Healthy fissures
Fluorescence detection values: 0–10 (0–12*)
Appropriate energy/fluence in order to cleanse and condition: *35 > 50 mJ–20 Hz*
High air/water spray – short pulse duration – pulse rate may be increased if needed
Fissures with initial demineralization
Fluorescence detection values: 11–20 (13–24*)
Appropriate energy/fluence in order to cleanse, condition, and decontaminate
Decontamination (first): *75 mJ–20 Hz*
Cleansing and conditioning: *35 > 50 mJ–20 Hz*
High air/water spray – short pulse duration
Accurate irradiation of fissures includes: correct focus, correct inclination, precise irradiation in order to avoid irradiation of the healthy enamel of ridges, and cusps using small diameter tip >400–600 µm tip. Close contact handpiece allows a better control and precision

6.3.2 Laser for Preventive Resin Restoration (LPRR)

The indications for a preventive resin restoration include the following:

- The presence of pit and/or fissure caries or of caries at pit/fissure base detected by a catch with the explorer or by laser device (value 21–29; >25)
- Incipient caries demarcated by a chalky, opaque appearance along the fissures and pits (white spot) (Table 6.4)

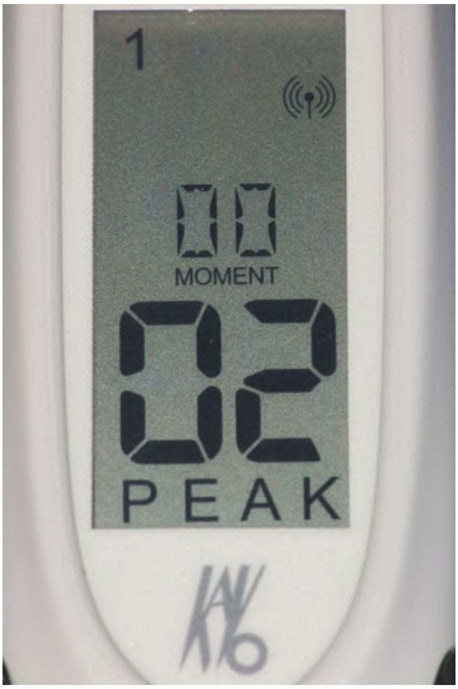

Fig. 6.36 DIAGNOdent-pen detection value of healthy enamel

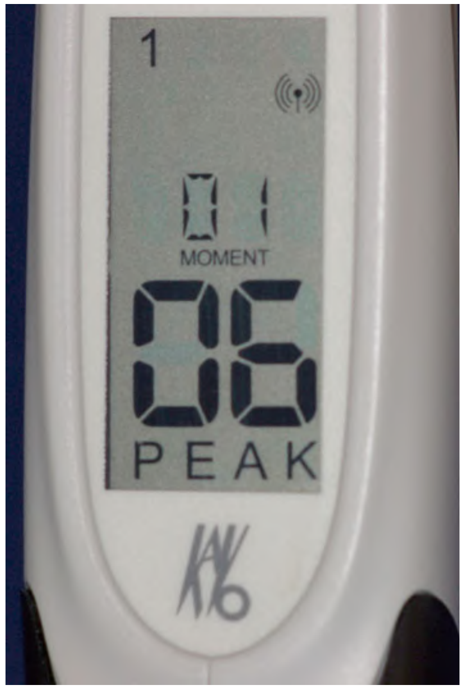

Fig. 6.37 DIAGNOdent-pen detection value of the healthy fissure

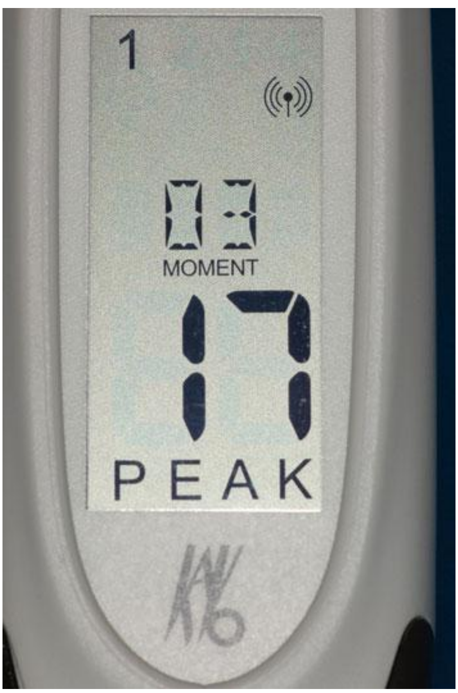

Fig. 6.38 DIAGNOdent-pen detection value of the initially demineralized fissure

6.4 Laser for Caries Prevention

Several laser wavelengths, including visible, near, medium, and far infrared lasers, have been investigated for superficial ultrastructural modifications and acid resistance increase.

Stern et al. first demonstrated the possibility of using laser irradiation to improve the resistance of dental enamel to acid attack. A carbon dioxide (CO_2) laser irradiation (10,600 nm) was used to melt the external enamel structure through heating [48, 49].

Even if the potential use of laser irradiation for caries prevention was demonstrated, a definitive mechanism of action was not precisely established, and the conditions used at time of first experiments were far from being suitable for clinical application. Numerous laboratory studies have been done with various wavelengths, but limited in vivo studies were performed.

In order for laser to modify the enamel structure and/or composition, the laser light may be strongly absorbed by the tissue, as the basis for any mechanism of action [50] (see Chap. 4).

Fig. 6.39 Rubber dam application before the clinical procedure

Fig. 6.40 Er,Cr:YSGG laser irradiation of pit and fissures before sealant application: different parameters permit to differently condition or minimally prepare different areas, according to LF values detected

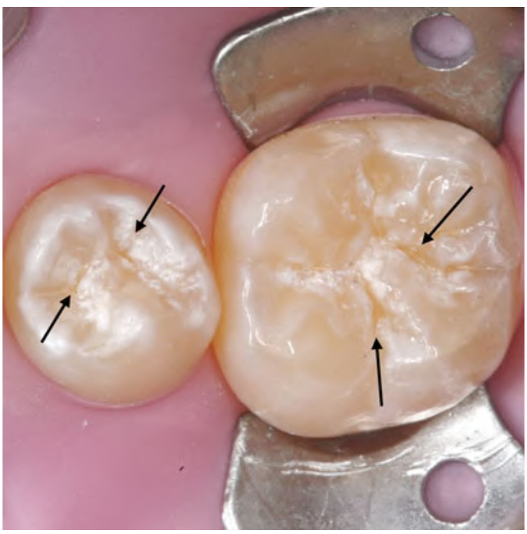

Fig. 6.41 The *black arrows* show the deeper and wider area of fissures with higher LF detection values that were treated at higher fluence (ablation)

Fig. 6.42 Orthophosphoric acid etching following laser conditioning and ablation permits to improve the enamel pattern for bonding

The absorbed light is transformed into heat, sufficiently to transform the carbonated hydroxyapatite into a permanently less soluble form. The wavelengths suitable for this mechanism must be closely matched to the absorption characteristics of the calcium phosphate mineral, more in the 9000–11,000 nm (CO_2 lasers) spectrum than in the 2700–2900 nm (erbium lasers) spectrum of light. The absorption curve of oxydril group (OH−) and free water present peaks at 2700 and 2900 nm; the

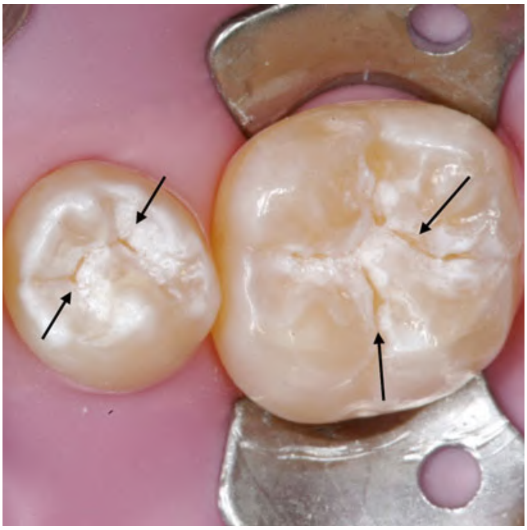

Fig. 6.43 After acid etching the lased surface appears more clean and uniform before sealing. The *black arrows* show the exposed dentin after laser irradiation and more evident after orthophosphoric acid etching

Fig. 6.44 Flowable composite with lower viscosity (medium filled) was used to fill the ablated and the conditioned fissures

Table 6.5 Suggested parameters for laser preventive resin restoration (PRR)

Accurate diagnosis of the fissures: inspection and probing under magnification, and fluorescence detection (DIAGNOdent or DIAGNOdent-pen*, KaVo)
Healthy fissures
Fluorescence detection (DIAGNOdent, KaVo; Germany) values: 0–10 (0–12*)
Appropriate energy/fluence in order to cleanse and condition: *35 > 50 mJ–20 Hz*
High air/water spray – short pulse duration – pulse rate may be increased if needed
Affected fissures or pits
Fluorescence detection (DIAGNOdent, KaVo; Germany) values: 21–29 (>25*)
Appropriate energy/fluence in order to:
Decontamination: *75 mJ–20 Hz*
Ablation: *>200 mJ–20 H*
Condition: *35 > 50 mJ*
High air/water spray – short pulse duration
Caries in dentin
Fluorescence detection (DIAGNOdent, KaVo; Germany) values >30 (>30*)
Reduce the energy up to *200 > 100 mJ–15 Hz*
High air/water spray – short pulse duration – reduce the pulse rate if necessary
Accurate irradiation of fissures includes: correct focus, correct inclination, precise irradiation in order to avoid irradiation of the healthy enamel of ridges, and cusps using small diameter tip >400–600 μm tip. Close contact handpiece allows a better control and precision

Fig. 6.45 Postoperative image

absorption peak at 9600 nm is coincident with the phosphate group in the molecule. Effectively, studies showed that much lower fluence is required to reduce enamel solubility when the 9300 or 9600 nm wavelengths were used instead of the conventional 10,600 nm [51–53].

Also the Er:YAG (2940 nm) and Er,Cr:YSGG (2780 nm) lasers, strongly absorbed by water and oxydril groups within the enamel and

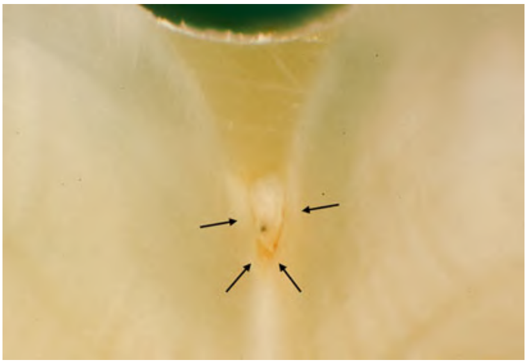

Fig. 6.46 Hemi-section of molar with sealant applied with conventional procedure (acid etching); the *black arrows* show debris and unclean area under the sealant

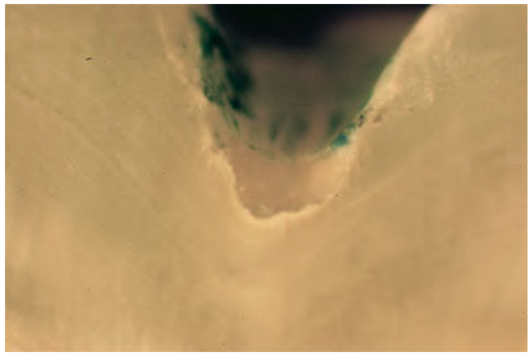

Fig. 6.47 Buccolingual hemi-section of recently extracted third molar following 24-h dye application. The enamel fissures underwent mid-infrared radiation prior to sealant placement. Application of fourth-generation resin bonding and flowable low viscosity composite without acid etching. No microleakage is present (Reprinted with permission from Olivi et al. [1])

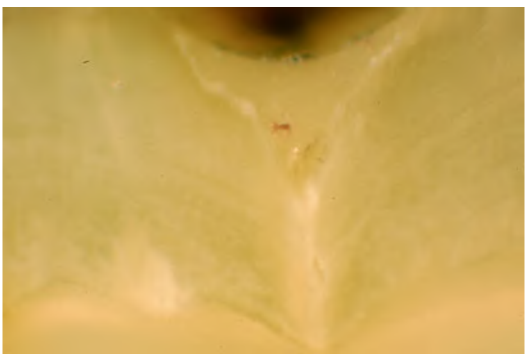

Fig. 6.48 Buccolingual hemi-section of recently extracted third molar following 24-h dye application. The enamel fissures underwent mid-infrared radiation prior to sealant placement. Application of unfilled resin sealant (no acid etching). No microleakage is present (Reprinted with permission from Olivi et al. [1])

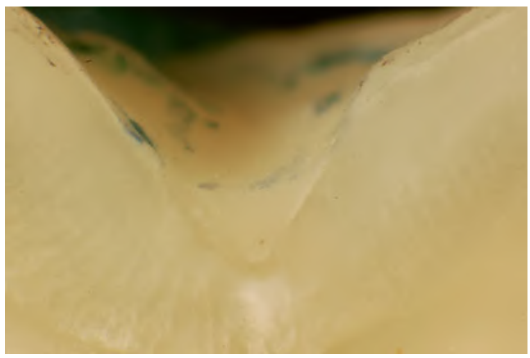

Fig. 6.49 Buccolingual slices from a recently extracted third molar following 24-h dye application. The enamel fissures underwent mid-infrared radiation as well as acid etching prior to application of fourth-generation resin bonding and flowable low viscosity composite. No microleakage is present. Note the better adaptation of the resin bonding and of the flowable composite to the acid-etched enamel of the fissures (Reprinted with permission from Olivi et al. [1])

dentin, have shown their potential to modify the enamel structure and to inhibit acid dissolution [54], but also their ability to ablate the dental hard tissues [55, 56]. Accordingly, a compromise between fluence values for producing acid resistance and for reaching ablation threshold had to be found.

On the opposite, enamel is essentially transparent to the diodes, the Nd:YAG and Argon laser wavelengths, so that a unique, common mechanism for different laser wavelengths cannot be considered [57]. These laser wavelengths have shown an increased acid resistance effect when used with other substances and typically with fluoride components.

The following summarizes the results of several of the studies that have been published for a variety of laser wavelengths.

6.4.1 Near-Infrared Laser Irradiation

The enamel is essentially transparent to the Nd:YAG laser at 1064 nm and researches were aimed to the use of a chromophore that could absorb the near-infrared energy superficially. Accordingly, Sato used in vitro a black dye on the surface of the enamel to absorb the Nd:YAG laser light and consequently efficiently heating the enamel to the point where it melted and transformed to an acid-resistant mineral [58]. The black dye absorber was essential step to the production of acid resistance, and without it there was no effect, unless the fluence (energy/surface area) is raised to high, unsafe, levels.

More recently, the researches were aimed to the use of near-infrared lasers in combination with fluoride gel or varnish.

Zezell et al. utilized in vivo a Nd:YAG laser irradiation in combination with topical application of acidulated phosphate fluoride (APF) as a preventive measure of enamel demineralization. After 1 year period, the clinical effects of this combined treatment resulted in a significant reduction of caries (39 %) and of white spot formation in the laser group when compared with the control group. The study concluded that the combination of Nd:YAG laser irradiation and topical fluoride application was effective for reducing the incidence of caries in vivo [59].

Vitale et al. (2011) evaluated in vitro the effect of a 810 nm diode laser radiation (2 W, 2 times × 20 s) in combination with fluoride gel application on the fluoride uptake on enamel surfaces.

Diode laser treatment showed statistically significant increase of fluoride uptake of enamel in comparison to fluoride gel application alone, providing protection to enamel surface from acid attack [60].

6.4.2 Visible Argon Laser Irradiation

Several studies, almost all from same group of researchers, have been published investigating the argon laser effects (488–541 nm) in caries prevention.

Enamel is almost transparent to light in this wavelength region; nevertheless, the studies by Powell and coworkers have showed a positive remineralization [61] and acid resistance effect [62] and increased enamel microhardness, following the irradiation by argon laser light alone or in combination with acidulated phosphate fluoride treatment (APF) or with zinc fluoride [63]. However, as of today, the use of these wavelengths in dentistry is almost abandoned.

6.4.3 Medium Infrared Laser Irradiation

Delbem et al. reported that the Er:YAG laser in combination with application of acidulated phosphate fluoride (APF) influenced the deposition of calcium fluoride on the enamel, exhibiting a superficial anticariogenic action [64].

Researches by Apel et al. also reported that the erbium laser wavelengths used at sub-ablative energy have the potential to increase acid resistance, without severe alterations of the enamel, but the differences were not statistically significant [65–67].

A study by Ying et al. seemed to confirm the mechanisms of laser-induced blocking of organic matrix in the micro-diffusion pathway in enamel, as one of the organic blocking theory in caries prevention of Er:YAG laser [68].

A study by Ana et al. evaluated the effect of Er,Cr:YSGG laser irradiation in combination with fluoride (APF) application on enamel demineralization and on fluoride formation and retention and concluded that laser treatment at 8.5 J/cm^2 was able to reduce the enamel demineralization, increasing the formation and retention of CaF2 on dental enamel [69].

A recent study by Colucci et al. evaluated the effect of Er:YAG laser parameters on the development of caries-like lesions adjacent to dental restorations and concluded that the parameters employed for cavity preparation influenced the acid resistance of the irradiated substrate, allowing to control of development of caries-like lesions around composite resin restorations [70].

In summary, several studies showed the potential of erbium lasers irradiation alone or in combination with fluoride application to provide caries resistance to enamel or remineralization potential, but there is limited and no definitive proof if they are suitable for clinical application.

6.4.4 Far Infrared Laser Wavelengths

Following the early studies of Stern and coauthors [48, 49], Featherstone and his group conducted numerous experiments over the last 30 years searching for the ideal protocol for caries prevention. These experimental studies definitively proved the mechanism of laser for imparting acid resistance to enamel.

When used at fluences less than 5 J/cm^2, CO^2 laser irradiation of dental enamel altered the composition of the enamel from a highly acid soluble carbonated hydroxyapatite to an acid-resistant hydroxyapatite-like mineral [71–74].

The inhibition of caries progression, obtained by using 9.3 and 9.6 μm (1–3 J/cm^2), was of 70 %, comparable with the inhibition produced with daily fluoride dentifrice treatments; such a low fluence produced only minimal subsurface temperature elevation (<1°C at 2 mm depth) [75, 76].

Another study reported no thermal damage to the pulp in humans at the fluences investigated [77].

Other studies investigated the protective effect of CO_2 laser associated with a high frequent fluoride therapy, resulting in reduced subsurface enamel demineralization [78]. Also the combination of CO_2 laser irradiation with fluoride treatment was more effective in inhibiting caries than either one alone confirming the reduced acid reactivity of the mineral [79].

Chen and Huang (2009) studied the effects of Nd:YAG and CO_2 lasers and acidulated phosphate fluoride (APF) on the acid resistance of decalcified enamel.

The CO_2 and Nd:YAG laser groups exhibited melted surfaces and crater-like holes. The authors concluded that lasers and fluoride on decalcified enamel appear to increase the acid resistance of the enamel. The effects of the lasers were better than the fluoride treatment alone [80].

Another study confirmed the ability of low-fluence irradiation (0.3 J/cm^2, 5 μ, 226 Hz for 9 s) to increase caries resistance up to 81 % compared to the control and significantly better than fluoride application (25 %, $p<0.0001$). Scanning electron microscopy examination did not reveal any obvious damage caused by the laser irradiation [81].

Recently, de Melo et al. investigated in vitro the effect of CO_2 laser on the inhibition of root surface demineralization around composite resin restorations and concluded that the CO_2 laser was effective in inhibiting root demineralization around composite resin restorations in comparison to conventional methods [82].

Although there are many promising studies showing the potential of carbon dioxide laser treatment to increase acid resistance and hence increase caries protection, studies in human teeth are very few.

An in situ study showed similar caries protection in the mouth to that which the same group found in the laboratory [83].

Rechmann et al. reported, for the first time in vivo, that the short-pulsed CO_2 laser (9600 nm) irradiation successfully inhibits demineralization of tooth enamel in humans [84].

Again Rechmann et al. reported that CO_2 laser irradiation (9600 nm, 20 μ pulse duration, 4.5 ± 0.5 J/cm^2 at 20 Hz, beam spot of 800 μm) markedly inhibits, in vivo, caries progression in pits and fissures of second molars of 14 years young patients, in comparison to fluoride varnish alone, over 12 months period [85].

Several clinical trials will be needed to definitively prove that clinical validity of this technology for long term caries prevention.

6.5 Molar and Incisor Hypomineralization (MIH)

Molar incisor hypomineralization (MIH) is defined as a hypomineralization of systemic origin of one to four permanent first molars; it is frequently associated, in 70 % of cases, with affected hypomineralization of incisor teeth [86, 87].

The prevalence considerably vary depending on the studies, varying from a low percentage of MIH reported in a study from China (2.8–3.6 %) to a higher prevalence up to 40 % in Demark and Brazil [88, 89].

This enamel-dentin alteration is often associated to systemic causes. Among several possi-

Fig. 6.50 Lower first molar presenting yellow-brown defect on the buccal aspect of the surface

ble causes, there are asthma, pneumonia, upper respiratory tract infections, otitis media, tonsillitis and tonsillectomy and exanthematous fevers of childhood, amoxicillin, and dioxins in mother's milk [87, 90]. The majority of the medical conditions involved may produce hypocalcaemia, hypoxia, and prolonged pyrexia to the child or the mother [91].

Also elevated exposure to fluoride was mentioned as a possible associated cause [92]. However, despite the higher prevalence of enamel defects in children living in areas richer in F of Australia, the prevalence of MIH was similar in Australian and British children populations coming from lower-fluoride concentration areas [88]. On the opposite, a Swedish study on children 7–8 years old from a low-fluoride area showed development enamel defects (hypomineralized opacities) of permanent teeth in 18.4 % of the children (average of 3.2 teeth per child, of which 2.4 were first molars) [93]. These opposite results support the view that the etiology of MIH is not associated with F concentration in water. As a today, the etiology of MIH remains unclear [94].

According to the localization of the defect, it was estimated that the timing of the amelogenesis disturbance ranges from the birth up to the first 6–7 months of age [94, 95].

Morphological studies revealed that the hypomineralized enamel areas are mainly located in the occlusal half of the crown, especially the mesiobuccal cusps of first molar; the cervical half of the crown results in most cases well mineralized, however different scenarios are possible. The alteration starts at the enamel-dentin junction and continues towards the enamel surface. MIH is a qualitative alteration of the enamel mineralization; the ameloblasts form enamel of normal thickness, but their maturation is altered [94]. Defect may appear as yellow-brown and white-yellow opacity areas. The yellow-brown defect is more porous than white-yellow opacity

Fig. 6.51 Lower first molar showing yellow-brown defect on the mesiolingual cusp; the cervical area is more affected than the occlusal. Breakdown of the defect is evident

Fig. 6.52 MIH of anterior teeth associated to yellow-brown defect of molar; the central incisor shows a smoother white-yellow opacity areas, while the lateral shows a more extended, porous, yellow-brown defect

Fig. 6.53 Mild hypomineralization limited to the anterior teeth

Fig. 6.54 Mild hypomineralization treated with laser bleaching when the patient was 18 years old

Fig. 6.55 One week post-op image shows the masking effect resulted from the laser bleaching

area and extends through the entire thickness of enamel; differently, the white-yellow opacity is only located in the deepest part of the enamel, maintaining a superficial smoother aspect [96] (Figs. 6.50, 6.51, and 6.52). Mild areas of hypomineralization show only a change in color, while the moderate MIH presents loss of enamel. In cases of severe MIH, the loss of tissue also involves the dentin. Lesions tend to worsen with age, and often the molars go early to meet the so-called post-eruptive breakdown, while the incisors never present structural post-eruptive collapse.

The European Academy of Paediatric Dentistry defined criteria for diagnosis and treatment of MIH, and treatment options vary from prevention, to restoration, or to extraction depending on the severity of the conditions, the patient's dental age, and the child/parent's social background and expectation [97]. A successful treatment of MIH includes an early diagnosis, the risk identification, the use of re-mineralizing agents for caries and posteruption breakdown prevention, or a restoration [92, 95]. The maintenance of the result includes follow-up at 3–6 months at early stages and later at 1 year.

6.5.1 Laser Treatment for Molar Incisor Hypomineralization (MIH)

There are no evidence-based studies on the use of laser irradiation on MIH teeth.

Mild cases of MIH present typical white-yellow opacity that can be treated with desensitizing toothpastes or re-mineralizing gels. The possibility to increase the resistance of enamel structure with laser through heat and melting of enamel surface could be explored, and also the associated application of fluoride gel that already demonstrated to increase the uptake of fluoride in normally formed enamel may be interesting [59, 60, 64, 69, 78–82].

When front teeth are affected by white-yellow opacity, a cosmetic improvement may require different type of intervention. External bleaching might be the minimal treatment of choice to mask minimal defects. The treatment must be delayed until growth completion (18 years), and unless there are specific esthetic concerns expressed by

Fig. 6.56 Extensive defects on anterior teeth, varying from white spots to yellow-brown defect

Fig. 6.57 Teeth bleaching at 18 years and composite resurfacing on lateral teeth were used to improve the esthetics

Fig. 6.58 Erbium:YAG laser removal of the defect

Fig. 6.59 The erbium:YAG preparation extended for few hundred microns within the enamel and arrived just to the base of the hypomineralization close to the dentinoenamel junction. Note the rough surface more suitable for adhesive restoration that will be smoothened on the margins

the patient or parents (Figs. 6.53, 6.54, 6.55, 6.56, and 6.57). When the defect varies from mild to moderate hypomineralization, the affected incisors require a surface preparation and restoration using composites. Adhesive restorations of hypomineralized teeth appear to fail frequently, due to altered enamel surface. Studies reported a little improvement when affected anterior teeth were treated with microabrasion [87]. Erbium laser preparation may contribute to modify the surface pattern while minimizing the thickness of tissue removal (Figs. 6.58, 6.59, 6.61, and 6.62). The surface resulted from laser irradiation is rough and more suitable for bonding than conventional burr preparation. The laser energy needed for the procedure is generally much lower than that needed for healthy enamel ablation, so that minimal energy is required (100>70 mJ) just to remove and condition few layers of enamel. The surface margins must be finished with a bur and smoothened with silicone bur, to allow a good adaptation and esthetic matching of composite. According to other authors, before the acid etching step, a pretreatment with 5 % sodium hypochlorite (brushing per 1 min) could be used to remove the altered surface proteins, enhancing the morphologic pattern

Fig. 6.60 MIH affecting the anterior teeth associated to first molars. Different seriousness and extension of the defect is present in different teeth (Fig. 6.52)

Fig. 6.61 Er,Cr:YSGG preparation of the defects

Fig. 6.62 Acid etching conditioning improve the pattern for bonding

Fig. 6.63 Esthetics improved after the restorations are completed

created by erbium lasers and the following 35 % orthophosphoric acid etching [98]. This intervention is normally very well accepted by patients without need of anesthesia (Figs. 6.60, 6.61, 6.62, 6.63, 6.64, and 6.65). The incisors almost never degenerate towards enamel breakdown, and when adults are affected, higher esthetics may require to cover the teeth with porcelain veneers.

Permanent first molars more frequently present yellow-brown defects, with more or less mineral loss, that worsen with age. Furthermore, the porosity of exposed subsurface enamel and dentin may promote bacterial penetration into the dentin resulting in chronic inflammation of the pulp and dentin hypersensitivity [99, 100]. Consequently the child could avoid a correct toothbrushing and become more anxious about treatment, needing considerable behavioral management. Hence, ideal treatment options may not be possible, and conservative treatment may be delayed permitting with time possible complications such as enamel collapse and breakdown in first permanent molars. In this case, restorative treatment varies from microabrasion in mild cases to extensive enamel removal and filling in moderate-severe cases or to crown. Erbium lasers allow for minimal cavity preparation with limited discomfort. The surface modification and the minimal invasive removal allow for preparation suitable for bonding and composite (Figs. 6.66) (also see Fig. 6.51). In cases of very severe MIH, early extraction of the first permanent molars may allow healthy second molars to erupt into their position.

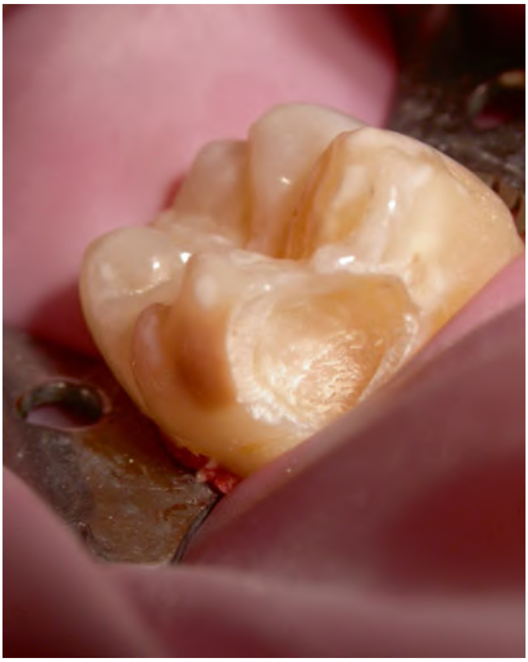

Fig. 6.64 Extensive cusp preparation of defect on lower first molar (Case of Fig. 6.51)

Fig. 6.65 Acid etching of enamel; a self etch adhesive was used on dentin

Fig. 6.66 Final restoration

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7 Laser Application for Restorative Dentistry

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Abstract

Laser technology is used in restorative dentistry as an alternative to traditional tools or a complementary one, adding many therapeutic advantages. The first and most important is the selectivity for carious tissues and so its minimally invasive action. Laser increases the surface for bonding retention and so it may improve the adhesion of restorations if all the additional steps are carefully followed. All the "secrets" of laser technique are described with step-by-step illustrations of all the Black's classification of cavities. Also, lasers can be used on both hard and soft tissues, including the pulp where they perform high decontaminating and coagulating effect during vital pulp therapy and on the gum, which can be vaporised for aesthetic or periodontal needs. Laser provides safe and comfortable therapy due to the absence of contact of rotating instruments with the tooth and consequently are less painful; in many cases, the use of local anaesthetics can be avoided, providing a favourable psychological impact on phobic and paediatric patients. Many particular clinical aspects of restorative dentistry, including the cracked tooth syndrome, the preparation for indirect restoration, and gingivectomy, are presented and discussed.

7.1 Laser Wavelengths on the Electromagnetic Spectrum Used in Restorative Dentistry: Erbium Family of Lasers

Chapter 4 introduced the basic concepts of laser tissue interaction and affinity between a wavelength and a target chromophore. The choice of the ideal wavelength for tooth cavity preparation

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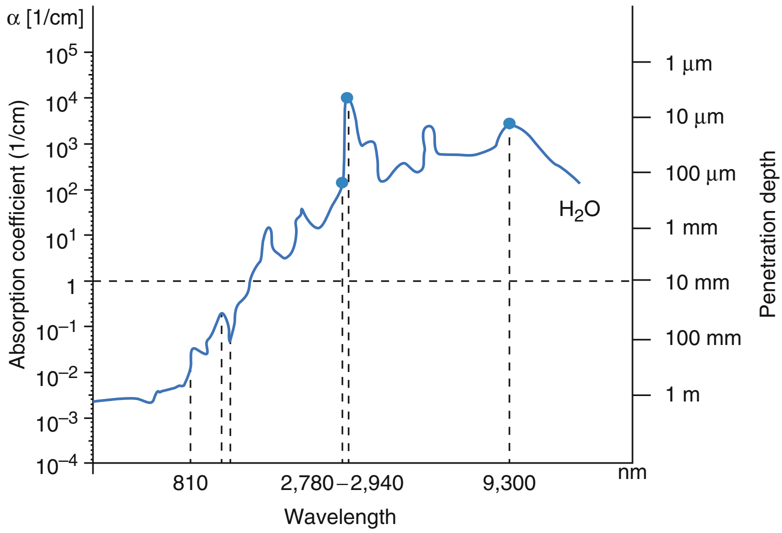

Fig. 7.1 Absorption in water (*blue line*) of Er,Cr:YSGG; Er:YAG; and CO_2 lasers. Penetration depth in water of laser at different wavelengths (*horizontal dotted line*)

and carious removal falls uniquely on the erbium family of lasers because of the selective interaction with the target chromophore (water). The use of CO_2 laser, with selective absorption on a second peak of the absorption curve of water at 9,300 nm and in hydroxyapatite, is promising but not yet supported by an extensive enough body of experimental and clinical researches to be considered today in this book (Fig. 7.1).

7.2 Laser Advantages in Restorative Dentistry

Laser technology may be used as a complementary technique as well as an alternative to traditional tools, adding many therapeutic advantages in restorative dentistry. Among them, we can consider the following advantages:

- It has high affinity for carious tissues and so is selective and minimally invasive.
- It creates macrocraters that improve the surface for bonding retention.
- It can be used on both hard and soft tissues, including the pulp.
- It has strong decontaminating effect.
- It is safe due to the absence of the use of rotating instruments in the mouth.
- It provides comfort because it works without contact and vibration on the surface.
- It is less painful, and in many cases, the use of local anaesthetics can be avoided.
- It has a favourable psychological impact on phobic and paediatric patients.

Table 7.1 illustrates the operative and clinical advantages of laser technology in restorative dentistry.

Table 7.1 Advantages of laser technology in restorative dentistry

Operative advantages	
Safety	No rotating or cutting instruments used in the mouth
Comfort	No contact and no vibration on the tooth
Painless	Reduction of need for local anaesthesia or no anaesthesia
Acceptance	High and improved patient compliance
Clinical advantages	
Minimally invasive	Selective for carious tissue
Decontaminating effect	Deeply in dentin
Macro-retentive surface	Rough, clean surface, no debris and smear layer
Less rise in temperature	In pulp and periodontal surface during irradiation
Direct pulp capping indication	Coagulation/decontamination in case of pulp exposure
Soft tissue application	Exposure of sub-gingival tooth margins during cavity preparation

7.3 No Pain Dentistry: Theoretical Aspects

Laser was wrongly proposed in the past to be a "painless" tool. The reality is slightly different and it has to be known in order to optimise the clinical results and the expectations of the operator and of the patient. Only if the mechanism of the perception of pain, the concept of analgesia and its induction in operative dentistry are known can laser therapy allow the execution of complex interventions without the use of local anaesthesia and with benefits for the patient.

7.3.1 Pain Perception and Laser Approach

The absence or the perception of pain is the result of a mixture of subjective and objective factors; both subjective and objective factors are variable and make "pain a personal experience that no one has in common" [1] Fig. 7.2.

Among the *subjective factors*, we find the peripheral limit of pain perception which is almost constant in people and characterises the threshold of pain and the threshold of suffering which is the individual tolerance of pain [2].

The individual tolerance of pain is based on the psychological interpretation of pain which depends on individual factors, such as the patient's memory of pain (cognitive component), on the emotional status of the patient (emotional component) and on the social behaviour (behavioural component), that is, the individual willingness to react to pain [1]. The psycho-emotional status of the patient is also conditioned by previous negative medical or dental experience; also negative experiences transmitted by parents and relatives can contribute to a considerable state of anxiety, and this could influence the level of tolerance as well as the ability to effectively cooperate with the operator. All these factors characterise the threshold of suffering that describes the individual tolerance of pain [1, 2] (Fig. 7.3).

Among the *objective factors*, we must consider the type and the seriousness of the lesion (e.g. simple enamel decay or a deep cavity with

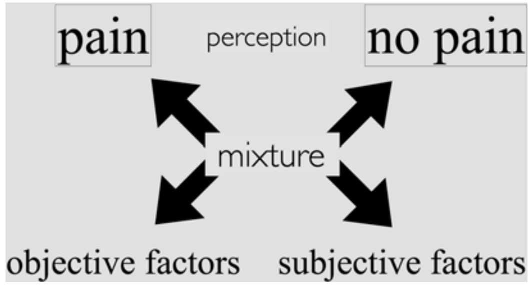

Fig. 7.2 The perception of pain is a mixture of several objective and subjective factors

Fig. 7.3 Subjective factors of pain perception include the personal threshold of pain that is almost constant in people and the threshold of suffering, that is, the individual tolerance to pain

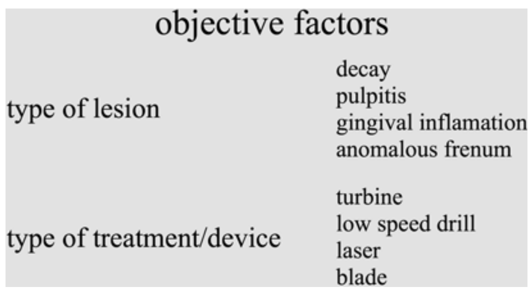

Fig. 7.4 Objective factors of pain include the different seriousness of lesions and the different types of treatment

pulp exposure), the dentist's knowledge and skill, and the technique and instruments used, a turbine or blade or a laser [1] (Fig. 7.4).

The lasers work without contact and vibrations (see the operative advantages of laser technology reported in Table 7.1) and are able to raise the threshold of pain (analgesic effect) so conditioning the objective factors of pain. The lasers also influence the subjective factors of pain, because the reduction of painful experiences, of anxiety or fear related to previous negative personal or family experience when needles, drills, scalpels, suture etc. are used. These factors influence the cognitive and emotional status of the patient and so his/her threshold of sufferening [1, 3].

For these reasons, the use of laser in restorative dentistry has been proven to be a valid method of intervention, with a good level of patient acceptance reported during hard and soft tissue therapy [4–14].

7.4 No Pain Dentistry: Basic Concepts

Irradiation of the operative site, with low laser energy prior to any surgical or nonsurgical procedure, generates an analgesic effect in the area caused by a temporary loss of conductance of the nervous impulse.

Laser irradiation initiates the disruption of the NA+/K+ pump of the cell membrane of the nervous fibre, causing membrane hyperpolarisation that results in loss/decrease of impulse conduction; as a result an analgesic effect is produced, and in order to initiate a potential action, a stimulus of greater intensity is needed [1, 15, 16], thus raising the *threshold of pain* [1].

All the wavelengths at sub-ablative power, especially those of the near-infrared laser (803–980 nm), can produce analgesia at the irradiated site when used in defocused mode, with a scanner technique and by slowly raising the laser energy.

In the early 1990s, a pre-emptive laser analgesia was first noted with the use of the neodymium-doped yttrium aluminium garnet (Nd:YAG) laser and has received more widespread acceptance with the clinical use of erbium lasers (Er:YAG and Er,Cr:YSGG). When used at pulse rates of 15–20 Hz and at low pulse energies, below the ablation threshold of tooth structure (9–14 J/cm^2) (see Sect. 4.6.1), the erbium laser's energy will penetrate the tooth along the hydroxyapatite crystals towards the dental pulp, where laser frequencies coincide with the natural bioresonance frequency of type C fibre and other nerve fibres in the dental pulp [3, 17]. There is evidence that laser irradiation may selectively target fibres conducting at slow velocities, especially afferent axons from nociceptors (pain receptors). This low-level laser therapy achieves an analgesic effect in the dental pulp prior to restorative procedures, with duration of approximately 15 min, temporarily improving the *threshold of pain*. No adverse pulpal changes have been reported, either clinically or histologically, over a short or long period of time.

7.4.1 Laser Analgesia: Clinical Procedures

There are several techniques that can be used by the operator to induce laser analgesia.

Naturally, to keep pain below the threshold and to avoid betraying the patient's trust, we must continue the treatment using the minimal effective energy and power, thus avoiding surpassing the *threshold of pain*.

7.4.1.1 Margolis Technique

Margolis proposed a laser analgesia technique for erbium laser dental preparation using a tip defocused at 4 mm from the tooth surface and then run slowly across the facial surface of the anterior teeth or the occlusal face of the posterior teeth at 1.5 W, 20 Hz, for 30 s. When metal restoration is present, the laser beam can be aimed at the tip of a cusp instead of the central groove of the tooth. The procedure is repeated for another 15 s at 3.0 W, 20 Hz, before starting ablation at the focused working distance [18].

7.4.1.2 Olivi-Genovese Technique

This technique was initially suggested for the erbium-chromium (Er,Cr:YSSG) laser because of its lower absorption in water and consequently deeper penetration (through the gingiva) into hard dental tissues compared to the Er:YAG laser; it is used today by the authors for both wavelengths. The laser tip is positioned defocused 10 mm farther from the gum-tooth surface (this data depends on the focus distance of different hand-pieces) and is run slowly around the neck of the tooth at the gingival margin for

Table 7.2 Clinical parameters for anterior teeth

	Er,Cr:YSGG				Er:YAG			
	Energy	Pulses(s)	Pulse duration	Tip	Energy	Pulses(s)	Pulse duration	Tip/mirror
Enamel ablation	200 > 250 mJ	20 > 15 pps	140 µs	1.1 mm 600 µm	200 > 250 mJ	20 > 15 pps	50 µs QSP	0.9 mm 800 µm
Dentin ablation	180 > 100 mJ	20 > 15 pps		600 µm	200 > 120 mJ	20 > 15 pps	50–100 µs	0.9 mm 800 µm
Dentin decontamination	75 mJ	10 pps		600 µm	75 mJ	10 pps	50 µs	0.9 mm 600 µm
Carious removal	<150 mJ	20 > 15 pps		600 µm	<150 mJ	20 > 15 pps	50–100 µs	600 µm
Enamel conditioning	50–75 mJ	25 > 50 pps		1.1 mm 600 µm	35–80 mJ	25 > 50 pps	50 µs	0.9 mm 600 µm
Dentin conditioning	40–50 mJ	15 > 10 pps		600 µm	40–50 mJ	15 > 10 pps	50–100 µs	0.9 mm 600 µm

Table shows the range of clinical parameters suggested for Er,Cr:YSGG laser (MD and iPlus, Biolase; CA, USA) and Er:YAG laser (Fidelis and LightWalker, Fotona; Slovenia) for the anterior teeth in restorative treatment

Table 7.3 Clinical parameters for posterior teeth

	Er,Cr:YSGG				Er:YAG			
	Energy	Pulses(s)	Pulse duration	Tip	Energy	Pulses(s)	Pulse duration	Tip
Enamel ablation	200 > 300 mJ	20 > 15 pps	140 µs	1.1 mm 600 µm	200 > 350 mJ	20 > 15 pps	50 µs QSP	0.9 mm 800 µm
Dentin ablation	200 > 100 mJ	20 > 15 pps		600 µm	220 > 120 mJ	20 > 15 pps	50–100 µs	0.9 mm 800 µm
Dentin decontamination	75 mJ	10 pps		600 µm	75 mJ	10 pps	50 µs	0.9 mm 600 µm
Carious removal	<150 mJ	20 > 15 pps		600 µm	<150 mJ	20 > 15 pps	50–100 µs	600 µm
Enamel conditioning	50–75 mJ	25 > 50 pps		1.1 mm 600 µm	35–80 mJ	25 > 50 pps	50 µs	0.9 mm 600 µm
Dentin conditioning	40–50 mJ	15 > 10 pps		600 µm	40–50 mJ	15 > 10 pps	50–100 µs	0.9 mm 600 µm

Table shows the range of clinical parameters suggested for Er,Cr:YSGG laser (MD and iPlus, Biolase; CA, USA) and Er:YAG laser (Fidelis and LightWalker, Fotona; Slovenia) for the posterior teeth in restorative treatment

40–60 s at very low energy (25–50 mJ) and low pulse repetition rate of 10–15 Hz, with a low air-water ratio; the energy level is gradually increased to 75–80 mJ after the first 60 s, always in a defocused mode. Later on the laser beam, still not in focus, is aimed directly at the carious lesion, still at 75–80 mJ. The low pulse repetition rate (10–15 Hz) allows minimal nerve stimulation, permitting a longer thermal time of relaxation. A lower pulse repetition rate (10, 8 pulses for second), with a gradually improved energy (>100 mJ), is more acceptable for the patient than a lower energy with higher pulse frequency, at the same power. When the analgesia is well established, it is possible to increase the pulse repetition to 20 Hz, the air-water spray flow and the energy up to the minimum effective level (see Tables 7.2 and 7.3) and to focus the laser beam on the target, allowing ablation to begin [18] (Figs. 7.5, 7.6 and 7.7).

Other techniques advocate faster or slower approach to induce analgesia using a high power setting of 3.0–4.5 W, 15 Hz (rabbit technique), or low power setting 0.25 W, 20 Hz (turtle technique). Many laser users have found that a fast approach is often less comfortable for the patient, requires a longer treatment time and provides less patient and dentist satisfaction [18, 19].

Fig. 7.5 Olivi-Genovese laser analgesia technique: the laser tip is positioned defocused 10 mm farther from the gum-tooth surface (note that the focus distance is different for different hand-pieces) and run slowly around the neck of the tooth at the gingival margin for 40–60 s at very-low-energy and low pulse repetition rate and low air-water ratio

Fig. 7.6 Olivi-Genovese laser analgesia technique: laser on the laser beam, still not in focus, is aimed directly at the carious lesion, still at 75–80 mJ. The low pulse repetition rate allows minimal nerve stimulation

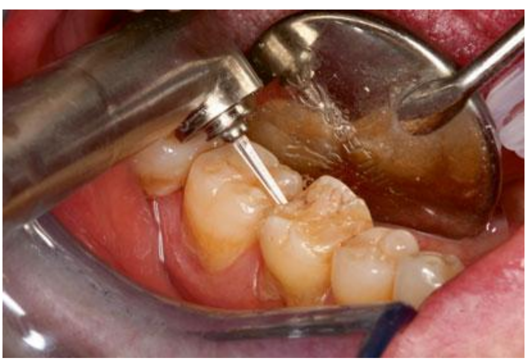

Fig. 7.7 Laser ablation: when the analgesia is well established, it is possible to increase the pulse repetition, the air-water spray flow and the energy up to the minimum effective level and to focus the laser beam on the target, allowing ablation to begin

7.5 Selective Interaction of Erbium Laser

The research of a system for cavity removal, both efficient and selective and minimally invasive, is still the object of various studies.

A study by Neves Ade et al. used micro-CT scanning to evaluate the relative volume of residual caries and the mineral density at the cavity floor, before and after dentin caries removal, using different systems [20].

The rotative instruments used, with their mechanical action, removed both the healthy and the demineralised part of the tissue, without any distinction; the use of the caries detector increased the risk of over-excavation [20]. On the other hand, the utilisation of less invasive systems, such as the ceramic burs (CeraBur; Komet-Brasseler) and sono-abrasion burs (Cariex; Kavo), left more caries on the cavity floor and on the cavity walls, respectively. The chemo-mechanical system for caries removal used chemical solutions, sodium hypochlorite-based solution (Caridex-Carisolv) and enzyme-based solution (SFC-V and SFC-VIII, 3 M-ESPE), in order to selectively dissolve the affected dental tissue in association with different mechanical systems and metal and plastic excavators, for the affected tissue removal. These methods are mostly selected in removing caries while preserving sound tissue. However, it is the manual mechanical removal with metallic instruments which determined the caries removal effectiveness, whereas the association with plastic excavators did not lead to complete caries removal. The erbium laser system used in this study has a feedback system based on tissue fluorescence that reads the different levels of fluorescence in the same or affected tissue, to control the emission of laser energy; while some specimens revealed many residual caries, others showed over-excavation into sound dentin, so that the Er:YAG laser resulted in non-selective caries removal presenting the lowest minimal invasiveness potential [20]. This study investigated the mini-invasive potential of laser preparation, based on the fluorescence feedback of dental tissue and not on the selective action of Er:YAG. Based on the result,

Fig. 7.8 Lower first molar with a large, open cavity on the distal proximal side: the carious tissue is directly exposed to the laser beam, making the interaction easier and faster

Fig. 7.9 Er:YAG laser preparation is completed in a few minutes, carious tissue is removed by laser at 150–180 mJ, 12–15Hz (tipless hand-piece, 0.9 mm), and enamel margins mechanically smoothened

the Er:YAG laser has not been proved to be neither precise nor selective.

The author proposal for a selective and effective carious removal is based on the use of different laser parameters for the different tissues to be treated (see Chap. 4), on the microscopical intraoperative control and the consequent adjustment of the most appropriate energy setting during cavity preparation, in order to confer to laser technology its minimally invasive potential.

Conventional techniques or chemo-mechanical ones require some further steps for the smear layer removal (etching with orthophosphoric acid) and for decontamination (benzalkonium chloride phosphate, sodium hypochlorite).

On the contrary the irradiated laser surface is already highly decontaminated and it does not present smear layer. When laser preparation is also associated with successive procedures of mechanical finishing and chemical conditioning, which improve the adhesive properties of the irradiated surface (see Sect. 7.7), laser represents the most effective and efficient system for selective caries removal. If these procedural steps are not taken into consideration, laser preparation provides inferior adhesion in comparison to conventional preparation, explaining the different results reported by the research using laser in restorative dentistry.

Considering the different content in water of dental tissues (enamel and dentin), the irradiation of erbium laser is selectively absorbed by those with a higher water content. In this way a minor amount of energy is required for the ablation of dentin that is more rich in water [21–23] and even less for caries [24], while a greater amount is required for the ablation of decayed or highly mineralised enamel.

When correctly used, modulating the emitted energy depending on the area to irradiate, laser is a physical tool that works selectively. The optical affinity with water is the key concept of the selectivity and minimal invasiveness of laser preparation in restorative dentistry. Consequently, the choice of the ideal parameters of use must be made keeping this principle in mind. Tables 7.2 and 7.3 show the range of clinical parameters suggested for the Er,Cr:YSGG laser (MD and iPlus, Biolase; CA, USA) and Er:YAG laser (Fidelis and LightWalker, Fotona; Slovenia) (Tables 7.2 and 7.3).

Access to the demineralised tissue can also include the removal of healthy tissue, enamel and dentin which preclude access.

Open cavity lesions, directly accessible in the oral cavity, such as occlusal, buccal or proximal surfaces, are more easily aimed by laser irradiation. In this case the vaporisation of the caries tissue, directly exposed, is simple, quick and selective using lower parameters for the caries tissue, saving the surrounding healthy tissue (Figs. 7.8 and 7.9).

Fig. 7.10 Upper first and second molars show the decayed pits and fissures (Reprinted with permission from Olivi et al. [85])

Fig. 7.11 Er,Cr:YSGG laser class 1 preparation on the upper molars shows very deep decay; enamel ablation required more energy (250 mJ, 20 Hz, 600 μm tip) and more time than the previous case. A mechanical margin finishing will complete the laser preparation (Reprinted with permission from Olivi et al. [85])

Fig. 7.12 Upper first molar with infiltrated old amalgam filling: following laser analgesia on the neck of the tooth and around the filling, on the cusps, the filling is removed with high-speed rotative instruments

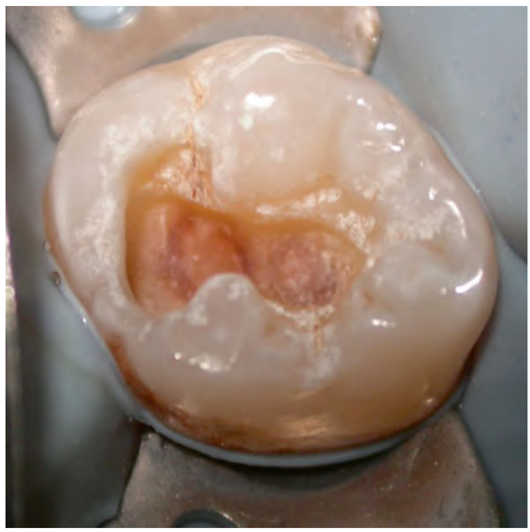

Fig. 7.13 Cavity preparation and carious removal are completed with Er,Cr:YSGG laser at 150 and 125 mJ, 20 Hz

When the occlusal or proximal cavities do not present an evident and large opening to the oral cavity, the approach towards caries requires the elimination of the healthy tissue in order to access the demineralised tissue affected by the carious process, using first the parameters for enamel and then progressively reducing the parameters for dentin and carious tissue (Figs. 7.10 and 7.11); this phase could be long and hard because of the high level of enamel mineralisation in some tooth. When the carious lesion is relapsing or contiguous to previous work in amalgam, which will be included in the preparation, the filling removal will be performed with conventional technique (rotative high-speed drill), while the removal of the decay will be performed using a laser with specific parameters (Figs. 7.12 and 7.13). The composite materials could be removed com-

Fig. 7.14 Lower first molar presents a decay on the proximal distal wall close to an occlusal composite filling with "coloured" borders; note a microcrack coming from distal to the occlusal surface

Fig. 7.15 Er:YAG laser preparation includes the ablation of affected enamel of the distal proximal wall (250 mJ) and the removal of dentin caries (at 150–120 mJ) and infiltrated composite filling: note the tertiary dentin on the roof of pulp chamber as a dentin reaction to the deep decay

Fig. 7.16 Lower first and second molars show secondary caries due to infiltration on the periphery of old composite fillings

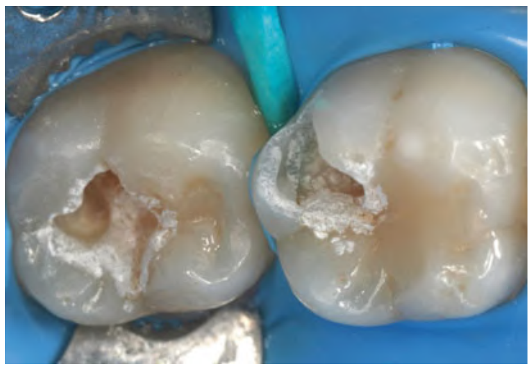

Fig. 7.17 Er:YAG laser preparation includes the ablation of enamel, composite and decayed dentin. A close inspection allows the intraoperative decision to completely remove or not the old filling; note the whiter aspect of the irradiated composite after the complete caries removal

pletely or partially with erbium lasers, according to the clinical situation. However, the complete laser procedure is not advisable because the micro-exploded remains contain microparticles of quartz, glass or zirconium that could damage the tip or the mirror of the laser hand-piece (Figs. 7.14, 7.15, 7.16 and 7.17).

The ablation of healthy hard tissue, occlusal and/or proximal enamel, requires a variable range of energy that goes from 200 to 350 mJ, while a slightly inferior amount of energy is required for the ablation of the healthy underlying dentin (from 100 mJ up to 220 mJ) in order to access the demineralised carious tissue. Less energy is required to vaporise the decayed tissue (<150 mJ) (see Tables 7.2 and 7.3). Not changing the energy while irradiating healthy enamel or decayed dentin during the preparation will result to a quicker but not selective ablation, with an overpreparation of the healthy tissue surrounding the cavity. Close attention should be exercised in very deep cavities, in order to avoid an accidental and involuntary pulp exposure.

The definition of a standard parameter to use is a significant limit to comprehension of the use of laser technology nowadays. Different tissues have different ablation threshold. Moreover, different laser systems in the same range of wavelength and energy parameters have different power of ablation, in relation to the delivery system (articulated arm or optic fibre), the handpiece (with or without tip), the technology and modality of energy emission. Moreover, the operator's manual technique influences the result (focusing or defocusing, angulation and speed of irradiation).

7.6 New Cavity Design Concept: A Minimally Invasive Cavity Preparation

Modern adhesive dentistry brought gradual changes in the rules of cavity preparation. The transition (passage) from amalgam restoration to the composite one, the improvement of adhesive materials and the evolution of composite materials from macro filled and micro filled to microhybrid and nano filled brought a successive change in the cavity preparation design. This change takes into consideration both the teeth's biomechanical characteristics and its adhesive peculiars and the material ones. Laser is a different system of preparation compared to the conventional ones, which perfectly match the minimally invasive concepts of contemporary restorative dentistry, allowing for selective carious removal, preventing the unnecessary removal of healthy tissue. Laser preparation must be completed with an accurate finishing in order to better adapt the surfaces and margins of the cavity to the adhesive material used.

7.6.1 Outline Form and Convenience Form

The modern cavity preparation design involves carious and demineralised tissue removal with maximum conservation of the healthy tissue. The selective use of laser allows to perform the preparation for direct restoration of all Black's cavity classes, outlining a form that corresponds to the caries process extension (Figs. 7.18, 7.19, 7.20, 7.21, 7.22, 7.23, 7.24, 7.25, 7.26 and 7.27). However, cavity preparation includes also the ablation of enamel tissue which is not supported by enough healthy dentin; this principle must take into consideration the anatomical (localisation) of the cavity (working or not working cuspids, proximal walls). The bottom of the cavity does not have to be plane anymore, but can gently follow the depth and the extension of the carious process.

The preparation of the cavity for indirect restoration (inlay, onlay and veneer) on the other hand requires a precise outline form, obtained using the drill and diamond burs with a specific shape and size. The correct outline form permits the insertion of the restoration without undercuts, with the removal of dental substance of adequate thickness, especially in the areas exposed to mastication load (working or centric cuspids). In these cases the use of laser is advisable only for the phase of caries tissue removal; a successive composite build-up will permit the filling of the undercuts, leaving more residual dental tissue and bonded composite for the conventional finishing with rotative or ultrasonic tools, which will define the shape.

7.6.2 Retention Form

The old concept of extending the preparation of a decayed occlusal pit into the neighbour fissures or to the proximal surface wall, in order

Fig. 7.18 Lower second molar with class 1 cavities on the occlusal fissures

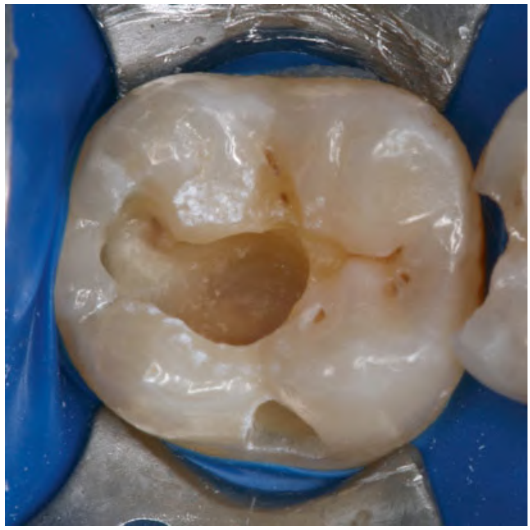

Fig. 7.19 Er,Cr:YSGG ablation allows selective ablation of the caries; the outline form follows the extension of the decay without enlarging in healthy tissue

Fig. 7.20 Upper first molar with class 2 proximal mesial decay; note microcracks on the enamel ridge due to caries undermining the healthy occlusal enamel

Fig. 7.21 Erbium lasers allow a selective removal of the affected tissues without extending the cavity design on the occlusal fissure

Fig. 7.22 The pre-existing diastema between the upper central incisors allows a direct access to a “pure” class 3 cavity on the mesial side

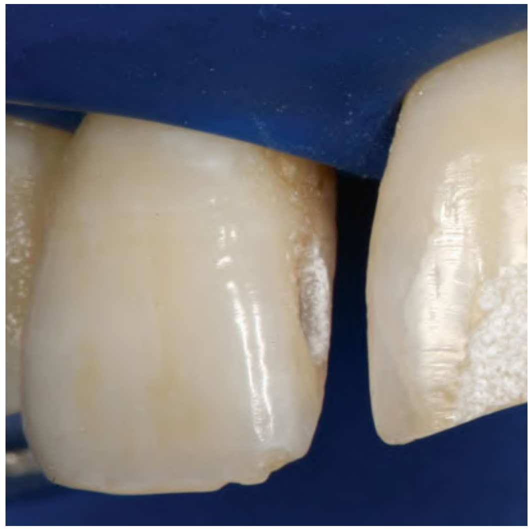

Fig. 7.23 Er,Cr:YSGG laser irradiation and caries removal of the proximal decay without any extension in healthy tissue

Fig. 7.24 Wear and fracture of the incisal margin of the upper central incisor

Fig. 7.25 Minimal tissue removal after Er,Cr:YSGG irradiation just to clean, decontaminate and condition the enamel and dentin surfaces

to prevent a possible relapse, is definitively abandoned. The use of adhesive techniques no longer requires the preparation of mechanical retention with undercuts and accessory retentions (dovetails).

7.7 Finishing of the Cavity

The preparation and treatment of the dentin surface as well as the enamel margins of a cavity are some of the most critical steps in restorative

Fig. 7.26 Lower premolar shows a cervical decay (class 5)

Fig. 7.27 Er:YAG laser class 5 cavity preparation allows minimal, selective and precise carious removal at 150>120 mJ; note the absence of any overpreparation both on the enamel and in dentin

dentistry, because they involve carious removal, final decontamination and protection of deep dentin or pulp capping in case of small pulp exposure before restoration and better adaptation of the restorative material to the tooth. Conventional instrumentations also produce smear layer and debris during cavity preparation, elements that affect adhesion during bonding procedures, while laser preparation produces other morphological alterations of the surface that must be considered and modified to reach a more stable and predictable result of the restoration.

7.7.1 Carious Removal and Deep Dentin Decontamination

It has sometimes been suggested to possibly leave a minimum quantity of demineralised tissue on the bottom of the cavity, considering that some technology in use nowadays (laser, ozone therapy) would be able to neutralise the deep dentin and pulpal contamination and that also bacteriostatic and bactericidal medication could work in that way (stepwise and indirect pulp capping techniques).

Considering the difficulty to establish if and how much tissue must be removed or left in the cavity, it is opportune to always precede to complete removal of the caries/demineralised tissue (see also Sect. 8.2).

Sometimes with the aim of removing all the carious tissue, the cavity is overprepared, leading to hypersensitivity or pulp micro-exposure (see also Sect. 8.3).

Erbium lasers decontaminate the bottom of the cavity through the dental walls to a different depth [25–27] and reduce this risk; however, the dental surface at the end of laser preparation must be hard.

The final cleansing and disinfection in the conventional restorative dentistry is usually performed using chemical agents, such as benzalkonium chloride phosphate and sodium hypochlorite, detergents such as EDTA, or a combination of them. The use of these disinfectants, with a suggested contact to the dental surface of 30–60s, could not be enough for deep decontamination.

Fig. 7.28 Er:YAG laser cavity preparation: the irradiated dentin shows the typical whitish aspect due to laser micro-explosions. The bottom of the cavity must be finished, probed and checked for residual caries

Türkün et al., experimentally, found no significant differences in the antibacterial activity of 0.75 W and 1 W Er,Cr:YSGG laser power outputs and a chlorhexidine gluconate-based cavity disinfectant [28].

Franzen et al. used very low Er,Cr:YSGG energy of 3.13 mJ, delivered at an incidence angle of 5° to a dentin slice surface, to produce significant bacterial reduction up to a dentin thickness of 500 μm [27].

At the end of cavity preparation, an irradiation at 75 mJ with a tip of 600 μm, with a high water spray for 20–30s, is efficient in order to reduce the bacteria's load [26, 27, 29]. Also other wavelengths demonstrated ability of deeper disinfection in dentin [26, 30] (see Sects. 4.10 and 8.2).

7.7.2 Conditioning and Medication of the Bottom of the Cavity

The cavity prepared with laser, even if it has been thoroughly cleansed and decontaminated, should be finished and conditioned anyway with sodium

Fig. 7.29 Er:YAG laser cavity preparation: the irradiated dentin also shows the orange-brown colour, typical of tertiary sclerotic dentin. The bottom of the cavity must be probed and checked for residual caries; margins must be smoothened

Fig. 7.30 Er:YAG laser cavity preparation: when an amalgam filling is removed, the dentin may also appear dark black, due to the deep amalgam pigmentation. The bottom of the cavity must be probed and checked for residual caries; margins must be finished

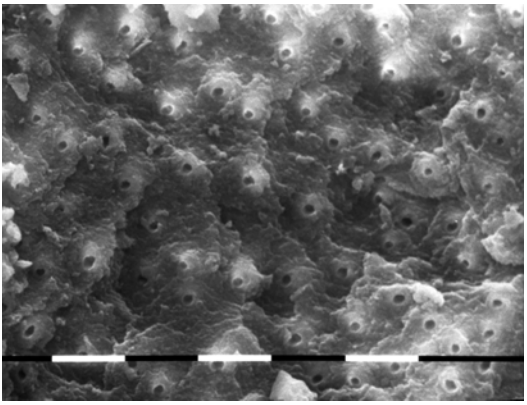

Fig. 7.31 SEM image of Er,Cr:YSGG laser-irradiated dentin at 175 mJ, 20 Hz, 3.5 W, 1.5 mm distance and a 600 μm tip. Air-water spray is 45/35 %. This is a typical image of laser-ablated dentin; the surface is scaly, clean and debris-free with intertubular and peritubular dentin creating depressions and reliefs with open orifices at the top (original magnification × 1,160). Organic collagen matrix has been vaporised by laser ablation

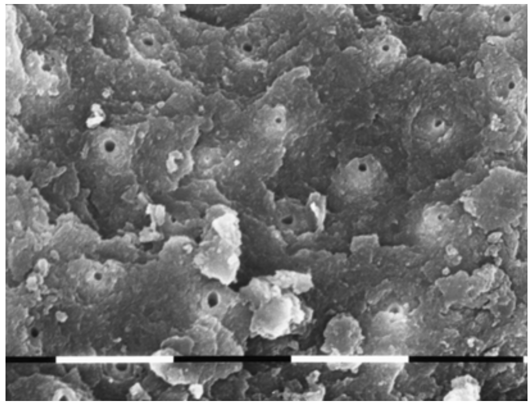

Fig. 7.32 SEM image of Er,Cr:YSGG laser-irradiated dentin at 150 mJ 20 Hz, 3.0 W, 1.5 mm distance and a 600 μm tip. Air-water spray is 30/20 %. The lower air-water flow did not allow thorough cleaning of dentin surfaces: the surface is scaly, some debris are still present and there are some unsupported flakes of dentin (original magnification × 1,280)

hypochlorite before the application of adhesive systems to improve bonding and adaptation of the restorative materials.

At macroscopic inspection, the laser-prepared dentin shows a typical whitish aspect expression of the laser microexplosions (see Sect. 4.7) (Fig. 7.28). Sometimes the dentin presents a dark orange colour, because of the tertiary sclerotic dentin, or blackish, in case of amalgam pigmentation, and it should be probed with an explorer to verify the complete removal of the demineralised dentin (Figs. 7.29 and 7.30).

Microscopically the laser-prepared surface is generally without smear layer that is well vaporised during laser ablation and presents open dental tubules. Many studies showed the improvement of dental porosity and the smear layer removal, which are two factors that are potentially positive for a good adhesion of the composites to the substrate [31–34] (Fig. 7.31); in contrast the surface could present flakes of dentin tissue, partially adherent to the dental surface, which contribute to creating the characteristic whitish colour and a possible decrease of the adhesion (Fig. 7.32).

Toro et al. investigated the correlation between the remaining demineralised dentin and the dentin permeability of cavities prepared with conventional and Er:YAG laser techniques and concluded that laser produced an increase in permeability that was directly proportional to the amount of removed demineralised tissue [35].

The majority of studies on the adhesion of the irradiated and lased dentin reported yet negative results in terms of improvement of the adhesion [36–39]. This depends on the ultrastructural modifications of the irradiated dentin which include denaturation of the organic matrix (collagen) [40] and the production of flakes on the surface; these modifications if have not been treated with an accurate final finishing produce inferior bonding to the substrate as reported in the quoted studies [36–39].

Some experimental studies and the clinical and experimental experience of the author regarding ultrastructure modifications after laser irradiation and the chemo-physical treatment of the substrate confirmed that finishing of the surface after irradiation contributes to achieving a more efficient adhesion.

The treatment of dentin with low laser energy (laser conditioning at 40–50 mJ) and/or hand excavator permits removal of dentin particles loosely adherent on the surface (flakes), producing a surface which is more homogeneous and suitable for adhesion.

Also de Souza et al. reported that the irradiation in defocused mode at 17 mm resulted in a

Fig. 7.33 At the end of laser cavity preparation, the use of scalpels or hand excavators helps in removing loosely adherent dentin flakes from the cavity surfaces; a Black's scalpel is showed here for distal proximal margin finishing

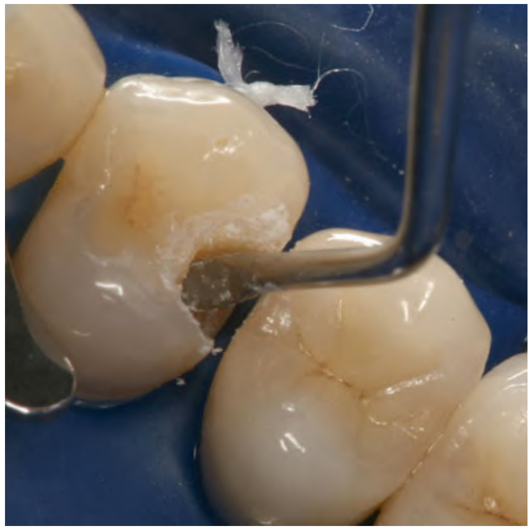

Fig. 7.34 At the end of laser cavity preparation, a hand excavator is used to remove flakes and dentin chips from the lased cavity

more homogeneous appearance of the surface than those irradiated at closer distances to the focus. The authors also confirmed that subsequent acid etching on the lased surfaces decreased the superficial irregularities with partial exposure and enlargement of dentin tubules, in all the tested irradiation distances [41].

Mechanical excavation was reported to have a greater influence in dentin than enamel; the combination of excavation and longer etching time (30 s) also exhibited significantly better results in dentin [42] (Figs. 7.33 and 7.34).

SEM and TBS analysis from Chen et al. demonstrated that both low-level laser energy pretreatment and acid etching reduced irregularities and produced a more homogeneous surface, significantly increasing the tensile bond strength of adhesion to the irradiated dentin [43].

Chousterman et al. reported significant increase in tensile bond strength of the samples when the etching time was prolonged up to 90 s [44].

In addition scrubbing out with cotton pellets soaked with sodium hypochlorite can be undertaken to partially remove the denatured collagen layer produced by the thermal effect of the laser or to alter its configuration [40, 45].

A study of Lahmouzi et al. reported that the application of a 5 % NaOCl solution on Er:YAG-irradiated cavities can significantly improve the marginal quality of composite bonding [46] (Figs. 7.35, 7.36, 7.37, 7.38 and 7.39).

Fig. 7.35 Upper cuspid shows a class 5 with abrasion of the cervical neck and concomitant abfraction: part of the enamel is conserved between the different lesions

Fig. 7.36 Er:YAG laser cavity preparation was performed separately on the two lesions: one cervical and the other more coronal

Fig. 7.37 To have a better aesthetic result, laser preparation was then extended on both cavities in dentin and enamel to create a unique cavity design; the surface of the bottom of the cavity is quite uniform

Fig. 7.38 A final scrubbing with cotton pellets imbedded with 5 % NaOCl solution after erbium laser preparation and the following orthophosphoric acid etching significantly change the aspect of the surface

Fig. 7.39 The micro-hybrid composite filling at 1-month follow-up

Fig. 7.40 Lower molar cavity preparation completed (see case Figs. 7.14 and 7.15). After a scrub with 5 % NaOCl, acid etching is performed only on the enamel, because of the chosen self-etching adhesive system

Fig. 7.41 Cavity prepared and conditioned

Fig. 7.42 Self-etching adhesive system applied

Fig. 7.43 Composite filling completed

The use of sodium hypochlorite also contributes to the decontamination of the cavity surface. The association of mechanical finishing, of the scrub with sodium hypochlorite and of the chemical pretreatment of dentin with orthophosphoric acid before the adhesion procedures makes the obtained results of conventional technique and laser technique uniform [36, 42, 43, 47] (Figs. 7.40, 7.41, 7.42 and 7.43 (for the initial case, see also Figs. 7.14 and 7.15) Figs. 7.55, Fig. 7.56, 7.57 and 7.58).

Finally, dentin hypersensitivity may be avoided by performing a procedure that creates a superficial melting in the proximity of the roof of the pulp chamber (Figs. 7.44 and 7.45) and by paying close attention during the bonding procedures [48].

The application of a protective liner or bioactive dentin substitute product is advisable just in case of close proximity or exposure of the pulp chamber (Figs. 7.46, 7.47 and 7.48). The laser produces clean and decontaminated surface also in the deeper area, and in case of pulp microexposure during erbium laser cavity preparation, the bacteria's load is already considerably reduced and also the risk of pushing infected dental chips into the pulp chamber is inferior to conventional procedures [49–51] (see Sect. 8.3) (Figs. 7.49 and 7.50).

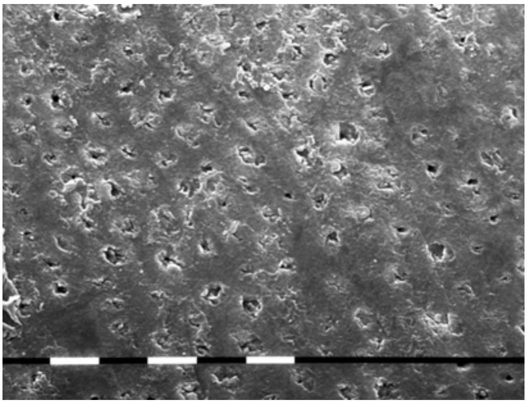

Fig. 7.44 Scanning electron microscopic (SEM) image shows the result of deep dentin sealing treatment performed with mid-infrared laser. Superficial melting and partial closure of dentin tubules were achieved using Er,Cr:YSGG laser treatment at 0.5 W, 25 mJ and 20 Hz with a 600 μm tip and low air-water spray rate in defocused mode (original magnification ×1,000)

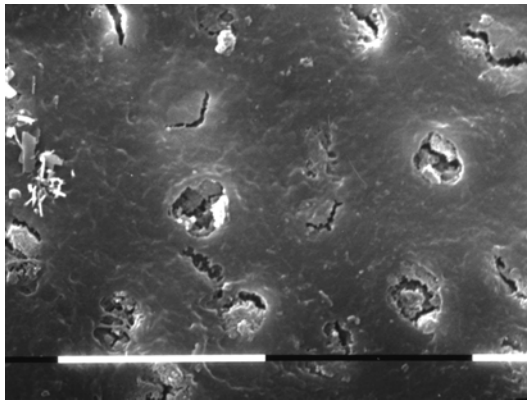

Fig. 7.45 Scanning electron microscopic (SEM) image shows the result of deep dentin sealing treatment performed with laser. Superficial melting and partial closure of dentin tubules were achieved using Er,Cr:YSGG laser treatment at 0.5 W, 25 mJ and 20 Hz with a 600 μm tip and low air-water spray rate in defocused mode (original magnification ×2,300)

7.7.3 Macro-retentive Surface for Bonding Procedures

The laser-prepared cavity has macro-roughened surfaces that increase the area for the bonding of adhesive resins for retaining composite restorations. The cavity does not require the preparation of accessory mechanical retentions.

Besides the conservative approach to the dental tissues, the modern restorative dentistry must consider the physical characteristics of dental composite and adhesive materials to be used.

The laser-prepared cavity leaves a scaly dental surface, with macrocraters on the enamel, with a depth of 5–15 μm on the enamel and of 7–1 μm on the dentine [52]. These must be reduced with final finishing of the bottom and axial walls and the margins of the cavity, in order to improve the adjustment of the chosen adhesive system anad filling. Different procedures are available to improve the quality of the dentin-adhesive-composite interface and bonding.

The choice of an adhesive that uses or not orthophosphoric acid etching (etch and rinse or self-etch) can resolve this issue. Furthermore, to use one or another adhesive system depends on the presence of the type of dentin, fresh or sclerotic, on the bottom of the cavity.

Jaberi Ansari et al. reported that the use of orthophosphoric acid would be recommended if erbium lasers are used for cavity preparation [53].

The application of the adhesives must be thin and uniform, and a gap of more than 10 μm on the bottom of the cavity could compromise adhesion.

The physical characteristics of modern composite materials are more similar to that of ceramic than resin materials. Because of the high elastic module and rigidity and hardness of the composite, the cavity design requires an adequate support on the bottom of the cavity. Accordingly, the use of different liners, suitable for the different areas, such as glass ionomeric cement [54], bioactive dentin substitute [55–57] or flowable composite, can be advisable because they allow both good protection and biostimulation of the deep dentin-pulp complex and good adaptation at the floor of the cavity, reducing the negative effects of the shrinkage of the restoration materials [58, 59], levelling the contact surface between dentin and composite or ceramic. Also, composites and ceramic require different minimal thickness (at least 1 mm

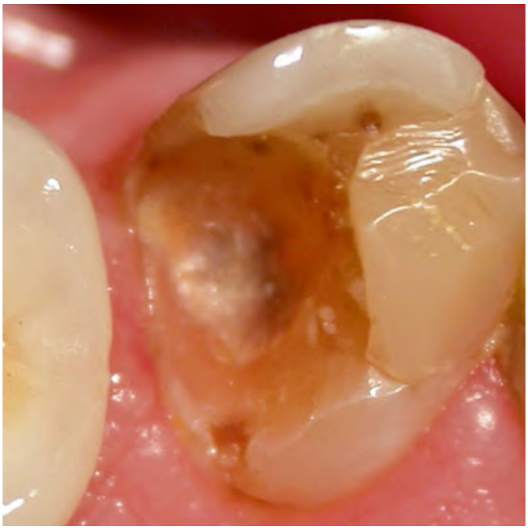

Fig. 7.46 Upper cuspid with deep class 3 cavity

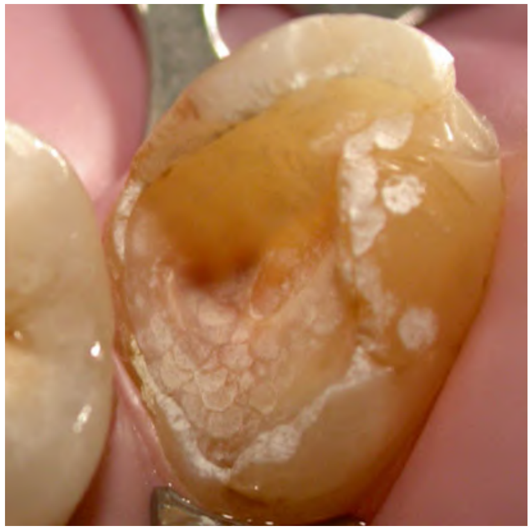

Fig. 7.47 Upper cuspid: after Er,Cr:YSGG laser preparation and carious removal, a superficial dentin sealing (melting) is performed at 1 W, 20 Hz, air-water 25/15%, 600 µm tip, in defocused mode (Reprinted with permission from Olivi and Genovese [49])

Fig. 7.48 Upper cuspid: a base of self-hardening calcium hydroxide is positioned on the deep dentin, close to the pulp (Reprinted with permission from Olivi and Genovese [49])

for the composite and 1.5 mm for the ceramic) that should be considered during the preparation regardless of the choice of restoration material and the extension and depth of the cavity.

7.7.4 Finishing and Conditioning of the Margins of the Cavity

The macro-roughened surface of the laser-prepared enamel presents some superficial morphological alterations with micro-prisms detached during ablation, which are barely adherent to the surface and hardly removable by acid etching. Moreover, as for the treatment of the bottom of the cavity, a finishing-smoothening of the enamel margins is suggested; this is another critical step to obtain bonding results that overlap those of conventional techniques [40, 42, 46, 47]. Few of the numerous studies in the scientific

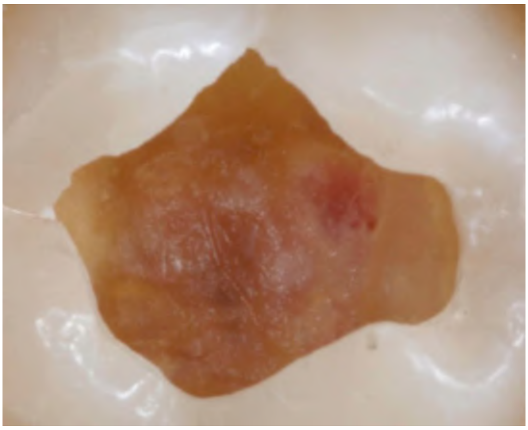

Fig. 7.49 Lower molar with deep class 1 cavity; after a final scrub with pellets imbedded of 5 % NaOCl, a small exposure of pulp tissue occurred

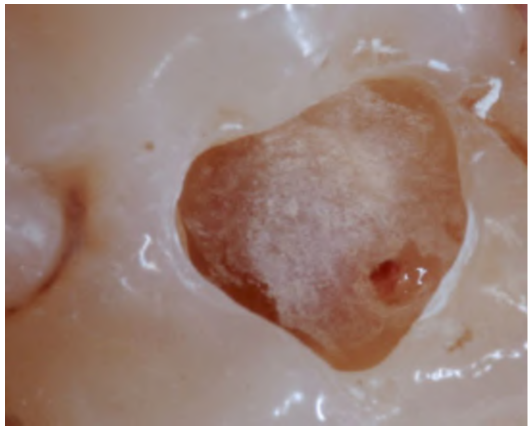

Fig. 7.50 Upper molar with deep class 1 cavity laser prepared; small exposure of pulp tissue and melting of the deep dentin surface

literature take into consideration this step; the simple finishing of the enamel allows the realisation of a laser-prepared cavity with a macro-retained surface on the bottom and walls in dentin and smoothened peripheral margins on the enamel, depending on the finishing technique used [40]. The use of the orthophosphoric acid as the final step completes the conditioning, producing a micro-roughened surface more suitable for the bonding systems [53].

Depending on the localisation and biomechanical characteristics of both tooth and restoration, the margins must be flat on the occluding surface (palatine surface of upper anterior teeth and palatine cusps on the upper arch and buccal cusps on the lower arch) or rounded with a chamfer, when better aesthetic and chromatic matching are required (cervical-buccal surfaces). In the area dedicated to the different Black's classes, the different types of finishing line will be examined (see Sect. 7.10).

The proposed procedure foresees all the advantages of the conventional technique and of the laser technique and can be performed using different modalities, depending also on the type of surface involved.

Low-energy laser irradiation at 35–80 mJ for the laser Er:YAG and from 50 to 75 mJ for the laser Er:Cr:YSGG allows a more delicate interaction with the enamel with very superficial spots. A high frequency pulse, more than 25 pps or Hz (up to 50 pps or Hz), permits the levelling of the micro-craters created during the ablation with a smoothening effect (Fig. 7.51). Another way to control the energy delivered to the target is defocusing the distance of irradiation; as a result slight morphological alterations are produced in comparison to the focus mode. Defocused mode irradiation is therefore more suitable for enamel conditioning than focused irradiation, and the subsequent acid etching on the lased surface partially removed the disorganised tissue [60].

- The contouring and finishing discs (Soflex and Soflex XT, 3 M) allow to smooth and refine the contours and margins of flat surface of class 4 cavity (angle of anterior tooth)

Fig. 7.51 Different procedures for enamel and dentin conditioning: an Er,Cr:YSGG laser with a 400 µm tip is used at 50 mJ to condition the enamel incisal margin after laser preparation; the defocused irradiation at low energy makes the surface more uniform and suitable for adhesive systems

Fig. 7.52 Different approaches for enamel smoothening: a blue Sof-Lex Pop-On is used to smooth the flat enamel incisal margin after laser preparation

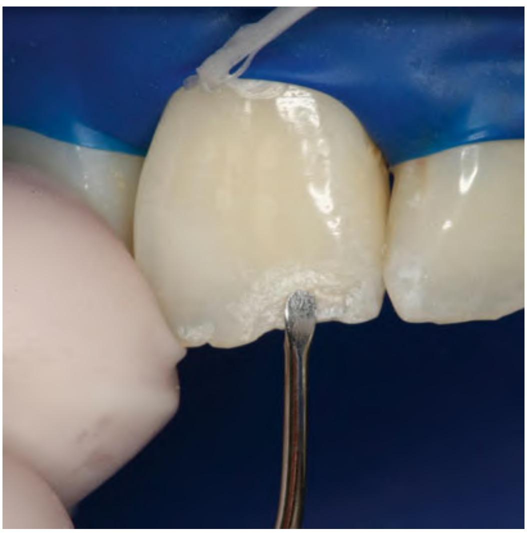

Fig. 7.53 Different approaches for enamel smoothening: a hand excavator is used to remove loosely adherent prisms from the flat surface after laser preparation

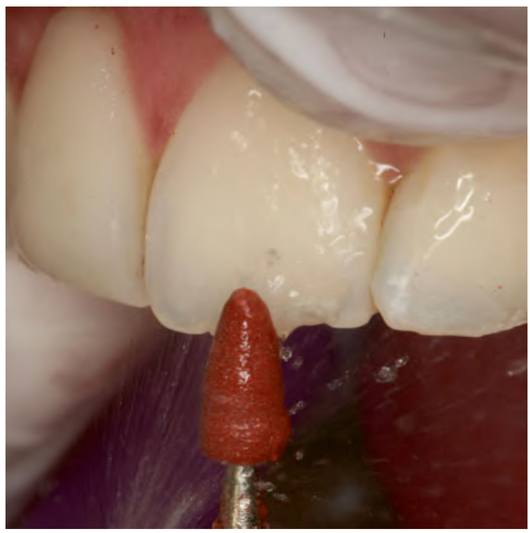

Fig. 7.54 Different approaches for enamel and dentin conditioning: as an alternative to hand excavators or scalpels, a brown silicon tip is used to smooth the surface

Fig. 7.55 Different approaches for enamel and dentin conditioning: a gentle scrub with cotton pellets imbedded of sodium hypochlorite is very useful to remove the denatured superficial collagen layer and unsupported prisms

Fig. 7.56 Different approaches for enamel and dentin conditioning: 20 s orthophosphoric acid etching

Fig. 7.57 Upper central incisor after laser preparation, finishing, conditioning and etching, ready for the bonding procedures

Fig. 7.58 Upper central incisor restoration completed (micro-hybrid composite)

Fig. 7.59 Different approaches for enamel smoothening: mesial proximal enamel slice of class 2 cavities is smoothened with blue Sof-Lex Pop-On

Fig. 7.60 Different approaches for enamel smoothening: changing the angulation of the hand-piece, the distal proximal enamel slice of class 2 cavities is smoothened with blue Sof-Lex Pop-On

Fig. 7.61 Different approaches for enamel smoothening: hand scalpel (Black, 79/80) is used to refinish the gingival margin of the class 2 cavity

(Fig. 7.52) and the slices of the proximal box in class 2 cavity (see Figs. 7.59 and 7.60).

- The use of excavators or scalpels is also very effective in the removal of unsupported prisms: excavators can be used for flat enamel buccal surfaces (Fig. 7.53) (see also Figs. 7.33 and 7.34), while mesial and distal Black scalpels (77–78 and 79–80) are used to produce proper finishing lines on the enamel margins of proximal cavities (Figs. 7.61 and 7.62).
- The sonic tips are also very useful for finishing of the occlusal and proximal surfaces in premolars and molars as well as for margin finishing for indirect ceramic veneering.
- The fine or ultrafine grit diamond burs are used to smooth and finish the occlusal margins in class 1, class 2 and class 5 cavities (Figs. 7.63, 7.64 and 7.65). Different shapes are used depending on the different areas to be treated; round-shaped or chamfer burs are used in the aesthetic buccal areas, and long, thin, or cone-shaped diamond burs are used in scarcely reachable areas. Silicone conical tips are also used for the same purpose (see Fig. 7.54).
- Orthophosphoric acid etching is used to create a micro-roughened surface of the mechanically smoothened margins [53, 60] (Figs. 7.66 and 7.67).

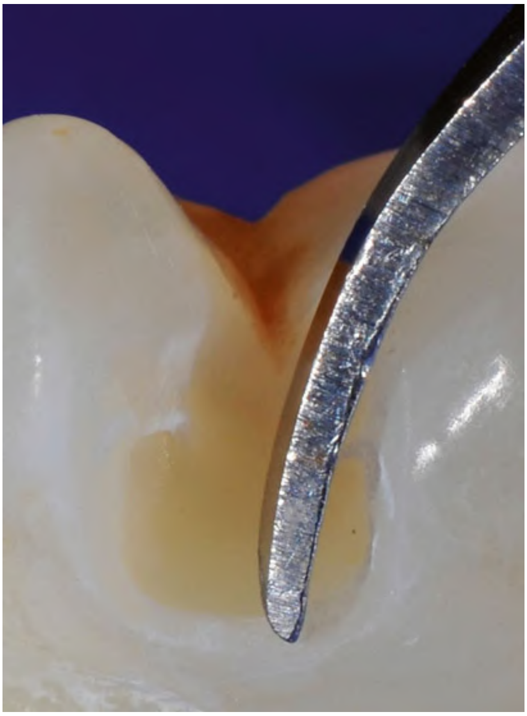

Fig. 7.62 Hand scalpel for enamel smoothening: higher magnification shows the elimination of unsupported prisms from the enamel gingival margin of a proximal box

Fig. 7.63 Red ring fine grit burs with different shapes are used to refinish the cavity walls and margins

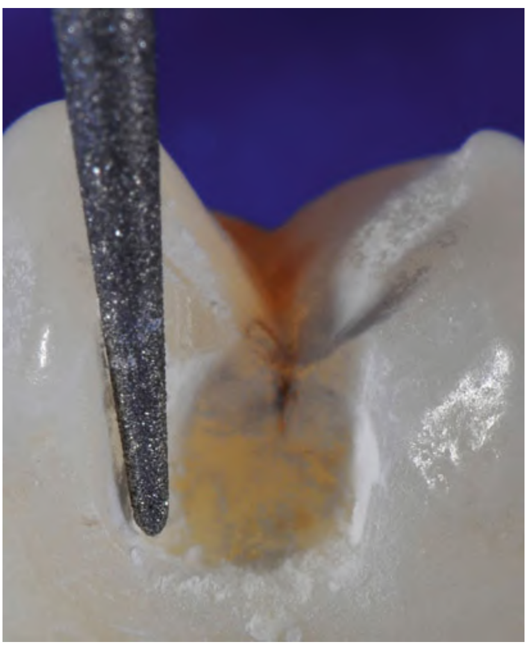

Fig. 7.64 Red ring, fine grit, conical-shaped bur is used to smooth the slice of proximal box of the cavity

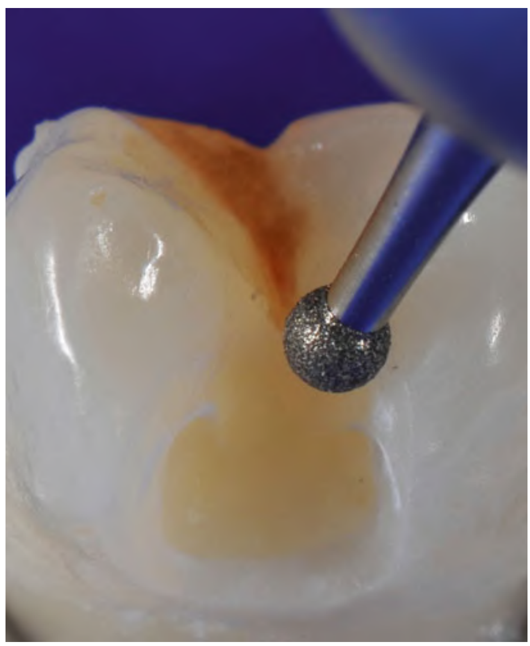

Fig. 7.65 Red ring, fine grit, round-shaped bur is used to smooth the margins of cavosurface

Fig. 7.66 Orthophosphoric acid etching is used to totally etch the tooth or to only etch the enamel margins, depending on the bonding system used

Fig. 7.67 Laser-prepared cavity as it appears after smoothening, conditioning and etching procedures: the cavity is clean and the margins are smooth

7.8 Erbium Laser Cavity Preparation

Erbium:YAG and erbium, chromium:YSGG lasers are used in restorative dentistry for the preparation of cavities in all Black's classes and also for the preparation of indirect restoration in combination with conventional rotative instruments.

7.8.1 Class 1 Cavity Preparation

Class 1 cavity, based on Black's topographic criteria, includes the caries of the occlusal surfaces of all the anterior and posterior teeth: the 2/3 extension of the buccal and lingual surface of molars and premolars (fissures and buccal pit) and the palatal surface of upper incisors and canines (palatal pit).

The diagnosis takes place after inspection, semeiotic tests, and intraoral x-ray examination. The use of DIAGNOdent (KaVo, Germany) is very effective in close forms. Modern cavity preparation does not foresee the use of the conventional principles of retention and prevention; the walls do not have to present parallelism and the regularity of the bottom of the cavity does not have to be created.

Laser preparation permits:

- The removal of the caries tissue and eventual healthy tissue from the occlusal surface in order to access the carious lesion.
- The conservation, thanks to selectivity of action, of healthy dentin reducing the weakening of the tooth (dentin is elastic and discharges the forces under the enamel, supporting it). Modern restorative materials, strongly adhesive on the dental structure, have an elastic module very similar to that of natural dentin and they contribute to the reinstatement of tooth's resistance.
- The preparation of the bottom of the cavity (follows) the extension, in depth and width, of the caries, limiting overpreparation. Deep cavities in particular benefit from laser preparation, due to the fact that, during conventional

mechanical preparation, vicinity to pulp (horn) could lead to an accidental exposure of the pulp (see Figs. 7.49 and 7.50), while laser, slowly working on dentin, is safer.

Removal of caries from the undercuts could be performed using laser when the cavity is very wide (with the loss of one or more cuspids or walls) so allowing the insertion of laser tips that can better fit inside the cavity. The use of a low-speed drill with round multiblade bur, of different diameters, is very useful for the removal of caries from undercuts and for the completion of preparation (Figs. 7.68, 7.69, 7.70, 7.71 and 7.72). For the parameters of use, see Table 7.3.

7.8.1.1 Large Cavity

A large cavity, already open on the occlusal surface, is the easiest to treat because the mineralised healthy occlusal enamel does not need to be treated. After a first initial irradiation with low-energy and low-wavelength impulses, necessary for establishing analgesia, or after anaesthesia, the laser is set progressively on a sufficient amount of energy for caries removal (150 mJ), starting from the parameters for dentin ablation 220–200 mJ up to 120–100 mJ to 20 > 15 pps, to decrease towards the healthy dentin in depth. Selective laser ablation of the caries tissue is the reason for the minimal invasiveness of this procedure. The laser beam can be directed at the caries surface with ample opportunity to change angle because of the width of the caries cavity. As reported in Chap. 4, the energy emitted is different and should be adjusted when it comes from a more efficient tipless hand-piece or a hand-piece with a different tip diameter that works closer to the teeth (close contact hand-piece at 1–2 mm). The energy should be set taking into consideration the hand-piece or the tip used and the diameter of the tip (fluence), reducing it progressively towards the end of the cavity; the minimum efficient amount of energy should be used for dentin ablation (see threshold of ablation, Sect. 4.6.1) and for decontamination in order to avoid cavity overpreparation (see Sect. 4.10). An efficient water spray will help the cleansing and the cooling of the irradiated tissue.

Fig. 7.68 Lower second molar with class 1 cavity prepared with laser; note some irregularities of the margins

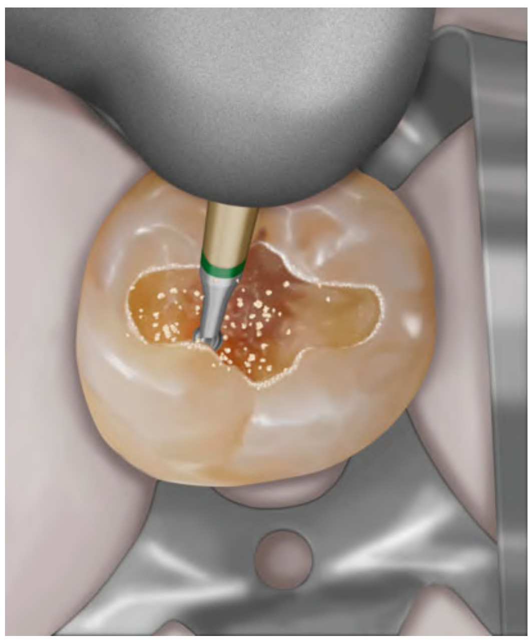

Fig. 7.69 Graphic rendering of carious removal in the undercuts using low-speed drill; the bur can work in the undercuts where the laser beam cannot reach, saving healthy tissue on the surface to be removed

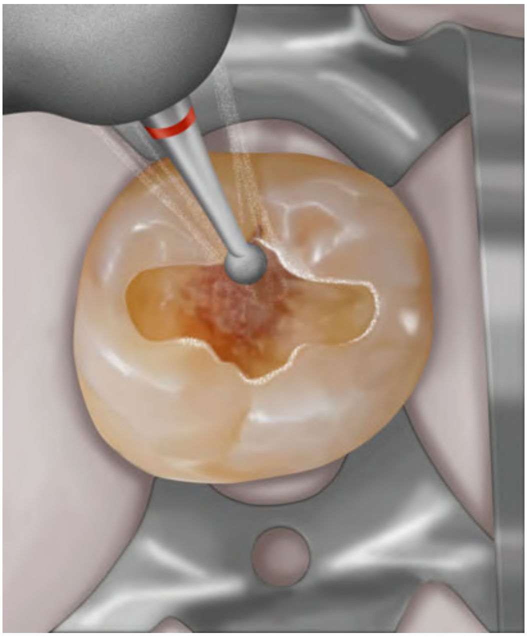

Fig. 7.70 Graphic rendering of the high-speed drill margin finishing with a fine grit, round-shaped bur

Fig. 7.71 Orthophosphoric acid etching

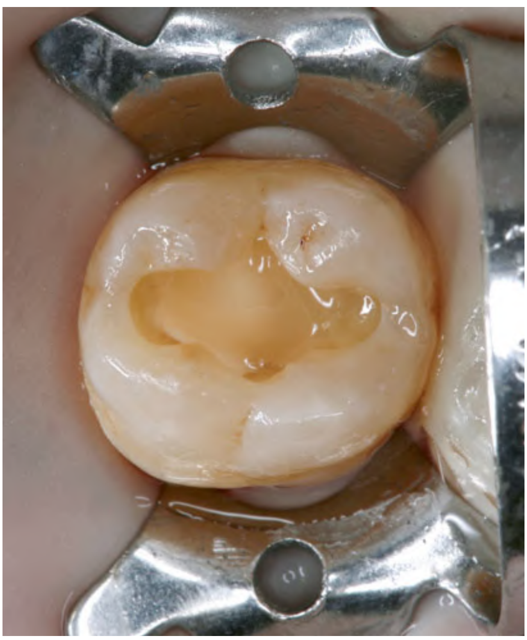

Fig. 7.72 A layer of flowable highly filled composite is used on the bottom of the cavity above the calcium hydroxide

7.8.1.2 Mine Cavity

Mine cavity, that is, with a minimum opening and development and enlargement of the caries in depth, requires the utilisation of higher energy for opening the cavity. The occlusal undermined enamel must be irradiated with more energy than the dentin (200>350 mJ), first perpendicularly to the surface and to the orientation of the prisms, then changing the angle of irradiation, making it parallel to the prism of the enamel, to complete the opening of the cavity. In this cavity, the removal of the decayed dentin can be carried out with hand excavators, exposing more easily the underlying decayed dentin which will be irradiated and vaporised with erbium laser with the correct energy (220>150 mJ), progressively reduced towards the bottom in a healthy cavity (>120>100 mJ). The residual carious tissue inside the undercuts can be removed with a low-speed drill with multiblade spherical cutters with the right diameter, if the dimensions of the opening of the cavity do not permit the insertion of laser points (Figs. 7.73, 7.74, 7.75, 7.76 and 7.77).

Fig. 7.73 Lower premolar: small decay on the distal part of the occlusal fissure; diagnosis performed with DIAGNOdent, KaVo

Fig. 7.74 Er,Cr:YSGG laser was used for the preparation of class 1 cavity

Fig. 7.75 Caries excavation using a hand excavator completes the carious removal

Fig. 7.76 The probe shows the depth of the cavity

Fig. 7.77 Cavity restoration completed with nano-filled composite

7.8.1.3 Small Cavity

A small cavity is the most difficult to treat. Different erbium lasers have fibres of different diameters, from 400 to 1,100 μm, but the smallest barely sustains the amount of exit energy required for enamel removal (<250 mJ). Small dot-shaped cavities that go from the central pit and from the occlusal fissures of the molars in apical direction must be treated separately, keeping the occlusal enamel healthy. In this case, the combined use of rotative means is advisable. Small diamond burs for micro-preparation (ISO 006–008), assembled on high-speed drill (turbine), are very useful because they allow, working on contact, great precision with focused removal of the tissue; finally the use of a laser with fibres with reduced diameter (400–600 μm) can be used to complete cleansing and cavity decontamination, using less energy (100 > 50 mJ). It should be noted that this type of cavity, deep and narrow, does not afford the possibility to angle the fibre which works only on the final part, perpendicularly to the target and parallel to the walls. It neither affords the possibility to irrigate the bottom of the cavity with the spray (Figs. 7.78, 7.79, and 7.80). Close attention must be paid on the use of a tipless hand-piece for the preparation or finishing of deep and small cavities, because of the difficulty of controlling a precise irradiation and interaction of the laser beam on the cavities' walls of small dimension, which would be overprepared.

Fig. 7.78 Upper lateral incisor showing class 1 cavity on the pit of the palatal surface

Fig. 7.79 Cavity preparation is performed by an Er,Cr:YSGG laser and smoothened with rotative instrumentation

Fig. 7.80 Upper lateral incisor restored with nano-filled composite

The removal of old fillings in amalgam requires the use of rotative instruments (see Figs. 7.12 and 7.13). The composite filling, after initial removal with rotative diamond burs, can be easily removed with laser from the bottom of the cavity, thanks to the photomechanical action that detaches entire portions of filling due to the weakening of the bonding strength (see Fig. 7.14).

Class 1 cavities must be finished on the bottom and on the margins; the toilette of the bottom of the cavity should be realised with manual excavators and the bottom treated with pellets soaked with sodium hypochlorite or clorexidina. Finishing of the enamel margins has to be carried out with ultrasonic tools or high-speed red grit burs (thin pointed, thin pointed conical, or round in shape) (see Fig. 7.70).

7.8.2 Class 2 Cavity Preparation

Black's class 2 cavity involves the proximal surface of the posterior teeth. Usually the caries starts under the contact surface that often shows areas of mild decalcification from rubbing with gradual wear of the proximal surface because of the tooth's movement during chewing and occlusal stress. A microcrack of the proximal enamel ridge can also be a path for the entrance of bacteria and a start of a carious process.

Hess classified different types of class 2 cavity:

- *Pure class 2 or class 2A*: with direct access to the lesion because of the lack of the contiguous tooth
- *Class 2B*: primary or secondary involvement of the marginal ridge and of the proximal surface (M mesial or D distal cavities)
- *Composed class 2 cavity*, which expects the contemporaneous involvement of the two proximal surfaces separately (M and D cavities) or the proximal and occlusal surfaces together (OM, OD and MOD cavities)

Excluding the pure form, the contact surface is generally involved in cavity preparation. The proximal contact surface has many functions, and it also involves periodontal problems for the safety of periodontal tissue from the vertical impact of food and occlusal problems due to the disto-mesial distributions of mastication force, progressively from the molars to the incisors, contributing to the stabilisation of the teeth in the dental arches. So the reconstruction of a correct interproximal contact is important.

Class 2 cavity preparation often involves composed preparation which also includes the occlusal surface. When the occlusal surface is not involved, the adhesive techniques of restoration do not make necessary occlusal extension for retention. For the parameters of use, see Table 7.3.

7.8.2.1 Pure Class 2

Class 2A or pure class 2 is aimed directly with the laser beam hitting the carious surface with different angulations (buccal, palatal, lingual or occlusal) (Figs. 7.81, 7.82 and 7.83). After analgesy is established, the laser is set on specific parameters for dentin and for carious tissue (200 mJ > 150 mJ); energy setting is reduced as ablation goes in depth. When it is not possible to irradiate the target for the presence of undercuts with difficult access or angulation of the laser beam, and the choice is to save the more healthy tissue as much as possible, residual caries in eventual undercuts in the proximal walls or in the marginal ridge can

Fig. 7.81 Upper first molar shows a pure class 2 cavity, easily visible after the extraction of the second premolar

Fig. 7.82 Class 2 cavity restored with micro-hybrid composite

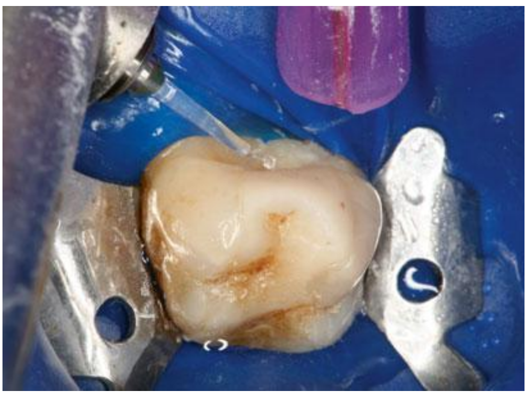

Fig. 7.83 Cavity preparation using Er:YAG laser and conical 600 µm tip approaching the cavity with buccal angulation

Fig. 7.84 A conical 600 µm tip of Er:YAG laser irradiates the cavity from the palatal side

Fig. 7.85 Graphic rendering of the same clinical case: low-speed drill is used to remove carious tissue from the undercuts scarcely irradiated by the laser

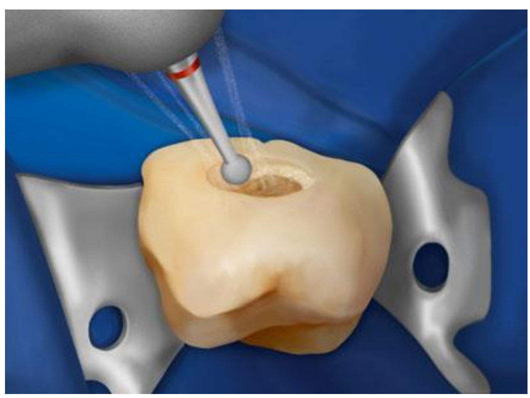

Fig. 7.86 Graphic rendering of the same clinical case: high-speed drill margin finishing using a round-shaped fine grit bur

Fig. 7.87 Lower second molar showing a pure class 2 cavity

Fig. 7.88 The missing tooth allows an easy irradiation of the proximal cavity without preparing the enamel ridge

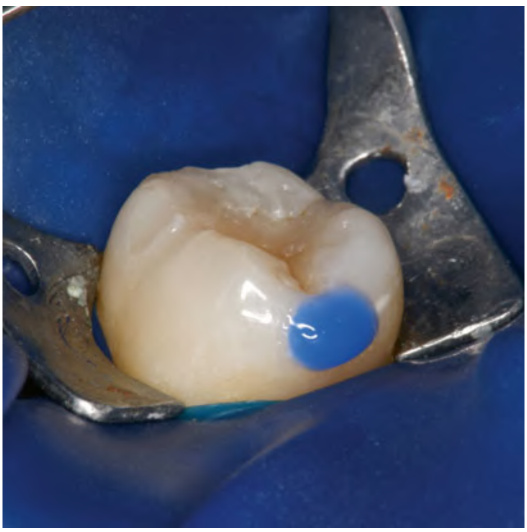

Fig. 7.89 Cavity prepared, refinished and acid etched

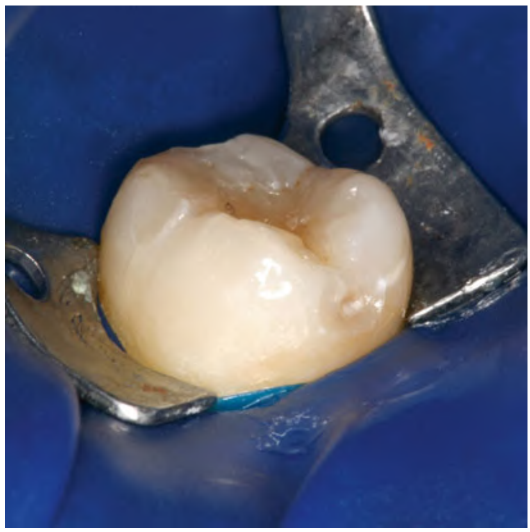

Fig. 7.90 Cavity ready for bonding procedures

be treated with hand excavators or with low-speed drill and tungsten carbide round-shaped bur (Fig. 7.84). Margin finishing is performed with a fine grit round-shaped bur and/or silicone tips (Figs. 7.85 and 7.86, 7.87, 7.88, 7.89, 7.90, 7.91 and 7.92).

7.8.2.2 Tunnel Preparation

Mc Lean (1987) defined tunnel preparation as a cavity preparation with occlusal access from the mesial or distal pit which leaves the marginal ridge intact, allowing the removal of the proximal caries extended under the contact point [61]. In contrast with the advantage of being a very conservative technique, there are some technical difficulties due to poor visibility, few operative space, difficult control of caries removal and possible low resistance of the marginal ridge not supported by the residual amount of dentin.

7.8.2.3 Slot Preparation

Roggenkamp (1982) defined slot preparation as a cavity preparation which allows buccal (vestibular) or lingual access to the proximal caries, without any removal of the marginal ridge [62].

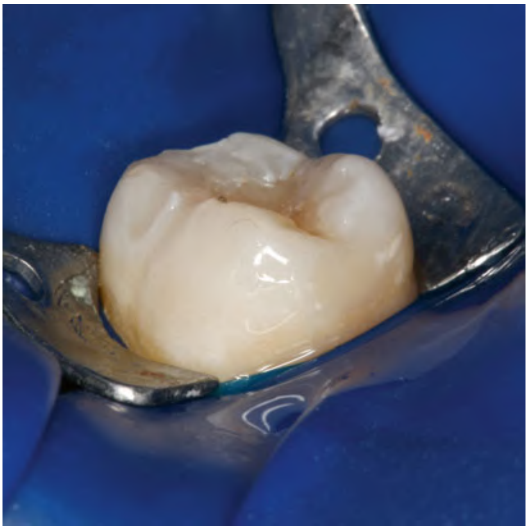

Fig. 7.91 Cavity restored with micro-hybrid composite

Fig. 7.92 1-month follow-up

Fig. 7.93 Class 2 OD cavity on the first upper premolar

Fig. 7.94 Cavity restored with nano-filled composite

This technique is possible only if:

- The margins of the cavity do not affect the area of contact.
- The complete removal of caries is possible.
- There is sufficient thickness of healthy dentin under the marginal ridge.

Slot preparation is particularly indicated when the caries involves two contiguous teeth (preparation is easier), permitting a more aesthetic restoration, thanks to the conservation of the occlusal surface and of the marginal ridge. This technique lends itself well to erbium laser preparation with access through a longer (cylinder-conical) and thinner (400–600 μm) tip at 200 mJ, progressively reduced to 150 > 100 mJ on carious dentin; low-speed hand-piece with tungsten carbide round bur helps the excavation of the carious dentin in eventual undercuts. Finishing of the enamel margins is possible with a thin, fine grit, pointed, conical-shaped bur.

7.8.2.4 Class 2B

In class 2B, the cavity access is realised irradiating the marginal ridge perpendicularly to the surface, using the parameters for the enamel. In case of difficulty for highly mineralised enamel, resistant to laser ablation, conventional high-speed drill can be used with a tungsten carbide or diamond, long, pear-shaped bur. Sometimes, at cervical level, the floor of the proximal box is too close to the neighbour tooth and the separation from the adjacent tooth is necessary, using a thin, pointed, cone-shaped bur (to avoid damaging contiguous teeth, use a protective metallic matrix). All the

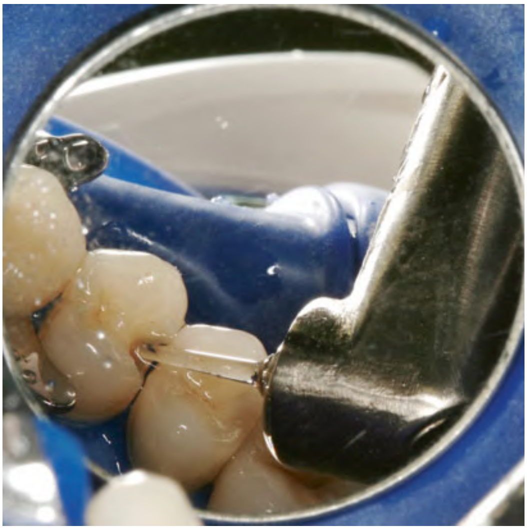

Fig. 7.95 Er:YAG laser with a conical 600 μm tip irradiating the distal cavity

Fig. 7.96 Er:YAG laser is rested with the side part of the tip on the healthy enamel ridge of the neighbour premolar; the resting allows the operator to precisely aim the beam on the distal cavity controlling the movement, the focus and the angulation

Fig. 7.97 Cavity laser preparation completed, just prior to margin finishing

interproximal contacts should be removed, in buccal, lingual or gingival side, until reaching a separation from the next teeth of about 0.5 mm (Figs. 7.93, 7.94, 7.95, 7.96 and 7.97).

7.8.2.5 Composed Class 2

In the complex forms (OM, OD or MOD), the preparation begins at occlusal level, as for the first class, and then it will extend to the proximal area. The area of passage between the occlusal cavity and the proximal cavity (isthmus) is a “locus minoris resistentiae” where the antagonist teeth discharge the mastication forces, so it is more susceptible to fracture. This zone has to be smoothed and rounded in order to eliminate angles that can create a possible wedge effect towards the filling material, reducing the remarkable risks of fracture and having a more homogeneous distribution of occlusal stress. The axial or pulp wall must follow the caries extension, without any need of wall parallelism also avoiding possible exposure of the pulp. The connection between the axial wall and cervical step must be gradual. The margins of the cervical step have the enamel prisms that follow radially the tooth walls; in correspondence of the cervical area, prisms have a horizontal evolution or are oblique towards the outside. This is the most critical zone in cavity preparation that must be linear; the maintenance of well-supported prisms in this area reduces the risk of marginal fractures and infiltration (Figs 7.98, 7.99, 7.100 and 7.101).

The positioning of the cervical step should be carried out, if possible, above or at the same level as the free gingival margin. When an extensive cervical cavity extends under the gum, it is necessary to resort to a laser gingivectomy to rebuild

Fig. 7.98 Multiple cavities in the upper arch

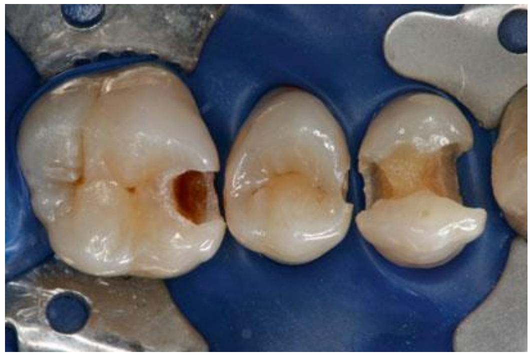

Fig. 7.99 Class 2 cavity performed on the molar (mesial), second premolar (mesial) and first premolar (mesio-occlusal-distal) and class 3 performed on cuspid (distal)

Fig. 7.100 The cavity preparations are completed. The occlusal, cervical and proximal enamel margins are finished, and the deep dentin is excavated also with a hand excavator and cleaned with sodium hypochlorite; note the change in colour of the dentin before (*brown*) and after deep excavation and cleaning (*orange*)

Fig. 7.101 Cavities restored with nano-filled composite

the correct dental-periodontal relationships. In case of alteration of the biological width, treatment with erbium laser must be performed on both the gum and the crestal bone, to re-establish the correct relations between hard and soft periodontal tissues.

Finishing of class 2 cavities requires laser conditioning at low energy, the use of hand excavators and cleansing of the cavity with pellets soaked with sodium hypochlorite or clorexidina. Finishing of the enamel margins is realised with ultrasonic or rotative instruments with fine grit bur (Figs. 7.102, 7.103, 7.104 and 7.105). The enamel prisms of the cervical step must be refined manually with Black's scalpel, orientated from the inside to the outside and from up to down in order not to weaken the prisms.

7.8.3 Class 3 Cavity Preparation

Black's class 3 cavity involves the proximal surfaces of canines and incisors, without including the angle.

The class 3 cavities can be divided into:

- *Pure class 3*. In the case of diastema or the lack of proximal teeth, the cavity is directly accessible for preparation (see Figs. 7.22 and 7.23).

Fig. 7.102 Hidden cavities on the proximal walls of upper premolars (Reprinted from Olivi and Genovese [86])

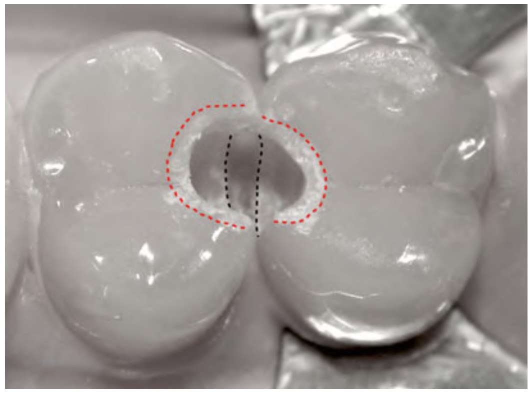

Fig. 7.103 Cavities prepared with Er,Cr:YSGG laser

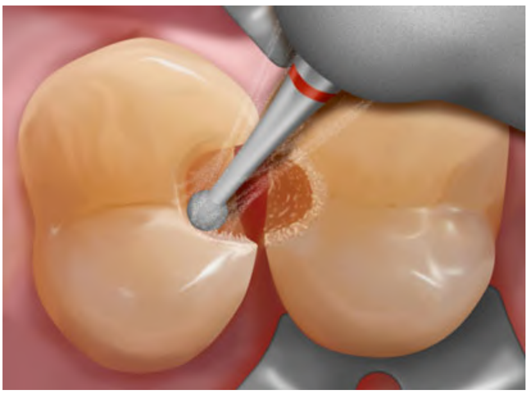

Fig. 7.104 Graphic rendering of the same clinical case: high-speed drill margin finishing using fine grit round bur

Fig. 7.105 Cavities completed and finished

- *Hidden class 3*. The lesion starts at the level or under the contact surface of the proximal zone and it goes deeper in the dentin without affecting the buccal or the palatal enamel. It can be revealed by transillumination, throughout the enamel transparency, both buccally and lingually, as a zone that could vary from opaque white to dark-blackish (Figs. 7.106, 7.107, and 7.108).
- *Deep class 3*. The carious lesion involves extensively the palatal and/or buccal (vestibular) enamel (Figs. 7.109 and 7.110).

Laser cavity preparation overlaps the traditional preparation with rotative instruments and it is extremely conservative; it follows the spatial extension of the carious lesion. Retentions and undercuts are not necessary. The anterior tooth's enamel is less thick than one of the posterior teeth and usually less energy is required for its removal (see Table 7.2). Operative magnification tools (loops or microscope) are fundamental to visualise the laser-tissue interaction, and to control the focus and angulation of the irradiation. The affected softened dentin is removed before with manual excavators of appropriate size and then irradiated again.

The access to the cavity depends on the localisation and extension of the lesion, and it should satisfy also aesthetic needs and biomechanical properties of the teeth and of the restoration.

In *hidden class 3*, the access is from the palatal side for the upper teeth (for aesthetic reason) and the buccal side for the lower teeth (less sacrifice of healthy tissue, easier instrumentation and better visibility) (Figs. 7.111, 7.112, 7.113, and 7.114). The enamel is irradiated (200>250 mJ)

Fig. 7.106 Hidden cavity on the upper central incisor (buccal view)

Fig. 7.107 Hidden cavity on the upper central incisor; the palatal view shows an old restoration on the left incisor (right side in the picture with mirror) and a hidden mesial lesion on the right central incisor

Fig. 7.108 Class 3 cavities prepared with a palatal approach: round-shaped smoothening of the margins

starting in proximity of the carious lesion, then lasing deeply following the major absorption from the carious tissue, progressively slowing down the energy.

In the open *pure form*, the laser beam could be easily directed on all the cavity walls because of the more available space, starting with other parameters for dentin and caries (>150 mJ) (Figs. 7.115 and 7.116).

The open and *deep lesions* are easily treatable; the wide cavity permits wide possibility of movement and angulation of the laser tips (Figs. 7.117, 7.118 and 7.119).

Fig. 7.109 Deep class 3 cavities on lateral and central incisors involving all the width of the teeth, from buccal to palatal side

Fig. 7.110 After cavity preparation the deep class 3 cavities are open both on the palatal and buccal side

Fig. 7.111 Hidden class 3 cavity on the lower incisor

Fig. 7.112 Because of the extension of the carious lesion, the cavity is opened from the buccal side

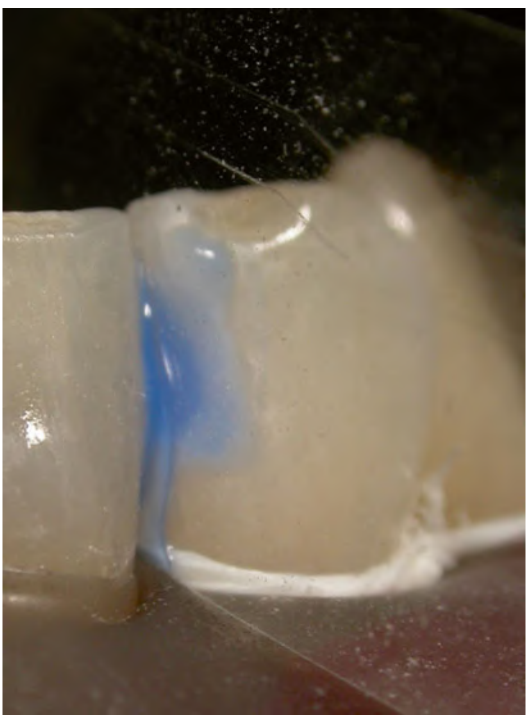

Fig. 7.113 The cavity is finished and acid etched

Fig. 7.114 Cavity restoration completed with micro-hybrid composite

Fig. 7.115 The pure class 3 cavity is approached from the mesio-palatal side (see pre- and post-op. images of Figs. 7.22 and 7.23)

Fig. 7.116 Er,Cr:YSGG laser irradiating the pure class 3 cavity from the mesio-buccal side, using a 400 μm tip

Fig. 7.117 Er:YAG laser with very ergonomic curve tip irradiating the proximal cavity of central incisor (see pre- and post-op. images on Figs. 7.109 and 7.110) (Reprinted with permission from Olivi and Genovese [86])

Fig. 7.118 Er:YAG laser with very ergonomic curve tip irradiating the proximal cavity of the lateral incisor (see pre- and post-op. images on Figs. 7.109 and 7.110)

Final cleansing of the cavity is performed with hand excavators and/or laser conditioning at low energy in defocused mode; the bottom can be also treated with pellets soaked with sodium hypochlorite or clorexidina. Depending on the chosen adhesive system, total etch or self-etch, the acid etching includes both the enamel and dentin or just the enamel.

Peripheral smoothening with round-shaped bur is advisable on the anterior restorations, both for permitting a better adaptation of the materials to the teeth and guaranteeing a better aesthetic result (Figs. 7.120, 7.121, 7.122, 7.123, 7.124, 7.125, 7.126 and 7.127). For this reason a round-shaped bur (ISO 012–014) on

Fig. 7.119 Cavities restored with micro-hybrid composite

Fig. 7.120 Multiple class 3 cavities on two lateral incisors

Fig. 7.121 Final view of completed restoration of the frontal teeth

Fig. 7.122 Close-up of the upper right lateral incisor with class 3 cavity open on the buccal side

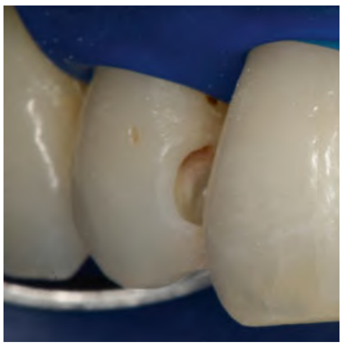

Fig. 7.123 Cavity preparation performed with Er:YAG laser and finished on the margins with a round-shaped fine grit bur

Fig. 7.124 Cavity restored with micro-hybrid composite

Fig. 7.125 Close-up of the upper left lateral incisor with class 3 cavity open on the buccal side

Fig. 7.126 After carious removal, the mesial angle of the tooth is ablated; the buccal margin is finished with a round bur and the palatal margin with a thin conical tip. Also the distal wall of the neighbour central incisor is prepared

Fig. 7.127 Cavity restored with micro-hybrid composite

Fig. 7.128 Multiple class 3 cavities on upper right frontal teeth (Reprinted with permission from Olivi et al. [87])

Fig. 7.129 Postoperative images showing final polishing and smoothening [Reprinted with permission from Olivi et al. [87])

Fig. 7.130 Cavities prepared with an Er,Cr:YSGG laser (Reprinted with permission from Olivi et al. [87])

Fig. 7.131 Cavities restored with micro-hybrid composite

the buccal side (see Figs. 7.110 and 7.122) and the same or a football-shaped bur on the palatal side are used (see Figs. 7.116 and 7.125). The proximal areas, hardly reachable, are refinished with high-speed drill with thin, pointed, conical-shaped, fine grit burs, or Sof-Lex Pop-On (Figs. 7.128, 7.129, 7.130 and 7.131).

7.8.4 Class 4 Cavity Preparation

Black's class 4 cavity affects the angle(s) of incisors and canines and can also extend to the proximal surface and to the incisal margin. Class 4 is often the evolution of a neglected class 3. At other times, it is the result of trauma and dental fracture, and in this case, it entails a different level of seriousness which is classified by the WHO (1978) classification of traumas of hard tissues, revised and amplified in 1992 following the guideline of Andreasen's school [63, 64]. Table 7.4 summarises the different types of traumatic injuries to the tooth and supporting tissues. Indeed traumatic injuries can also concern the support tissues of the teeth (gingiva and bone, together with the mucosa and lips) and, in that case, involve all branches of dentistry (restorative, endodontics, periodontics, oral surgery, orthodontics) (Figs. 7.132, 7.133, and 7.134); therefore, traumatology can be considered multidisciplinary (Figs. 7.135, 7.136 and 7.137). For the purpose of this book, only the noncomplicated

Table 7.4 Classification of traumatic injuries

1. Traumatic injuries to hard dental tissue and pulp
Crown infraction Uncomplicated crown fracture
Complicated crown fracture
Uncomplicated crown-root fracture[a]
Complicated crown-root fracture[a]
Root fracture: in the apical, middle, coronal third[a]
2. Traumatic injuries to the periodontal tissues[a]
Concussion
Subluxation
Extrusive luxation
Lateral luxation
Intrusive luxation
Avulsion
3. Injuries to the supporting bone[a]
Comminution of the maxillary alveolar socket
Comminution of the mandibular alveolar socket
Fracture of the maxillary alveolar socket wall
Fracture of the mandibular alveolar socket wall
Fracture of the maxillary alveolar process
Fracture of the mandibular alveolar process
Fracture of the maxilla
Fracture of the mandible
4. Injuries to gingiva or oral mucosa[a]
Laceration of gingival or oral mucosa Contusion of gingival or oral mucosa

[a]Injuries to the pulp-radicular system and to the periodontal and supporting bone structures will not be discussed in this book

dental fractures will be treated in this chapter. For traumatic injuries involving the vitality of the tooth, refer to Chap. 8, and for the injuries involving supporting tissues (luxation-avulsion) of the tooth, refer to other specific texts [65, 66].

7.8.4.1 Crown Infraction

The enamel infraction is represented by micro-cracks in the enamel without macroscopical loss of substance. It is the most common accident among dental traumas. Sometimes it is associated with trauma to supporting tissues (concussion, luxation) and could be associated with irreversible pulp pathology (see Figs. 7.134 and 7.135). It is diagnosed by inspection and transillumination. In the case of favourable prognosis, tests for sensitivity and the peri-apical radiographic tests are often negative during the first 48 h, and then only post-trauma hypersensitivity can be present, due to the microscopical

Fig. 7.132 Trauma to the upper central right incisor and to the upper and lower lips (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.133 Trauma to the upper frontal teeth and concomitant trauma with abrasion of cutaneous tissue on the chin and upper lip (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.134 Bike accident and trauma to the frontal teeth and concomitant trauma with tumour of the lips

Fig. 7.135 Same clinical case of Fig.7.136; note the complicated fracture on tooth 2.1 with pulp exposure and the enamel-dentin fracture of 1.1 and 2.2. Both these teeth had concomitant luxation and multiple infractions (see also Figs. 8.39, 8.40, 8.41, 8.42, 8.43 and 8.44)

exposition of dental tubules throughout the not visible microcracks at a cervical level (cement-enamel junction). Low laser energy delivered in defocused mode (all the wavelengths described in Chaps. 3 and 4 are useful for this procedure) reduces the enamel-dental hypersensitivity [66–68]. The procedure can be repeated at 7 or 15 days from the first intervention (Table 7.5).

Follow-up examinations involve sensitivity test at 3 and 12 months and x-ray examination after 12 months.

7.8.4.2 Uncomplicated Crown Fracture

It is the most frequent event in dental traumatology, regarding especially the superior incisors (70 %). Usually, the uncomplicated fracture of the enamel or of the enamel-dentin is represented by an oblique fracture of the mesial or distal angle of the incisors [64–66] (Figs. 7.138, 7.139, 7.140 and 7.141). It is often associated with soft tissue trauma of the lips and frenula (Figs. 7.132, 7.133 and 7.134). Sometimes the dental fragment is recuperated, sometimes it is lost, and the

Fig. 7.136 Laser-assisted debridement of the pocket after trauma using an Er:YAG laser with long thin tips (other therapies on Figs. 8.39, 8.40, 8.41, 8.42, 8.43 and 8.44)

Fig. 7.137 Laser-assisted decontamination of the traumatic pockets using a Nd:YAG laser with 300 μm fibre (other therapies on Figs. 8.39, 8.40, 8.41, 8.42, 8.43 and 8.44)

Table 7.5 Clinical parameters for tooth fracture preparation

	Er,Cr:YSGG				**Er:YAG**			
	Energy	Pulses(s)	Pulse duration	Tip	Energy	Pulses(s)	Pulse duration	Tip
Dentin decontamination	75 mJ	10 pps	140 µs	400 µm	75 mJ	10 pps	50 µs	600 µm
Enamel-dentin conditioning	50–75 mJ	10–15 pps 25 > 30 pps		400 µm	35–80 mJ	10–15 pps 25 > 30 pps	50 µs	600 µm
Fragment conditioning	40–50 mJ	15 > 10 pps		400 µm	40–50 mJ	15 > 10 pps	50 µs	600 µm
Dentin sealing	25 mJ	10 pps		400 µm	25 mJ	10 pps	100 µs	600 µm
No or minimal water spray	Defocused							

Table shows the range of clinical parameters suggested for Er,Cr:YSGG laser (MD and iPlus, Biolase; CA, USA) and Er:YAG laser (Fidelis and LightWalker, Fotona; Slovenia) for treatment of anterior teeth in traumatic restorative treatment

Fig. 7.138 Enamel fractures of the mesial angles of the two central incisor

Fig. 7.139 Not complicated enamel-dentin fracture of the angle of the upper left central incisor, involving most of the mesial wall and of the incisal margin (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.140 Not complicated enamel-dentin fracture of the angle of the lower left central incisor

Fig. 7.141 Uncomplicated enamel-dentin fracture of the mesial angle of central incisors (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.142 Hot pulp vitality test using warm gutta-percha on the traumatised tooth and also on the neighbour teeth

Fig. 7.143 Cold pulp vitality test using freezing compressed gas on the traumatised tooth and also on the neighbour teeth

Fig. 7.144 Two different teeth fragments recovered after dental trauma, well conserved in saline solution

Fig. 7.145 Tooth fragment recovered after dental trauma, conserved in milk and stored in the refrigerator before the dental session

possibility of dislocation in the soft tissues must be investigated.

Diagnosis includes objective test and x-ray examination. The sensitivity test could show normal or slightly increased results.

Treatment depends on the quantity of dentin exposed, and in case of deep enamel-dentin fractures, an immediate intervention is important in order to prevent pulp contamination and/or irritation. The therapy involves restoration with composite resins or reattachment of the fragment (if found and in a good condition).

Checks involved x-ray examinations and sensitivity tests after 1 month and then every 6–12 months for 2 years (Figs. 7.142 and 7.143).

Fig. 7.146 Young patient with discolouration of the upper left central incisor due to bonding of a tooth fragment that was not previously re-hydrated

Fig. 7.147 Enamel-dentin not complicated fracture of upper left central incisor; the fragment was recovered and stored

Fig. 7.148 Fragment assessment. Indications for reattachment include the presence of sharp edges of tooth and fragment margins and the dimension of the fragment; all these allow for a good fitting

Fig. 7.149 Enamel-dentin not complicated fracture of the upper right central incisor; the fragment was recovered and stored (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.150 One week post-op. control (Reprinted with permission from Caprioglio et al. [66])

Follow-up is important to check the pulp condition and to intercept possible discolouration, often also on surrounding elements not diagnosed for trauma before.

Laser irradiation of the exposed enamel and dentin is minimal; however, preparation of the margin of the fractured tooth is different if it requires composite restoration or reattachment of the recovered teeth.

7.8.4.3 Reattachment of the Tooth Fragment

The recovered fragment must be conserved in a physiological solution, saliva or milk, in a specific container kept in the fridge of the dentist's clinic, labelled with the name of the patient and the date of the trauma (Figs. 7.144 and 7.145). This is to avoid dehydration and dyschromia (Fig. 7.146).

Indications for reattachment are the presence of sharp edges of the tooth and fragment margins and the dimension of the fragment that must be suitable for correct manipulation during the reattachment procedure. Obstacles to reattachment are the presence of a small fragment, more than one fragment, change of the colour of the fragment and the need to devitalise the teeth (Figs. 7.146, 7.147, 7.148, and 7.149).

The procedure involves cleansing the fragment, first with a water spray, to remove the presence of remains, then using erbium laser to condition the surface of the exposed enamel-dentin with minimal energy and maximum conservation of dental substance, at 40–50 mJ (400–600 μm tip) (Fig. 7.150).

Cleansing the margins of a tooth can be a symptomatic procedure for a patient recently exposed to a trauma. Traditional techniques require just

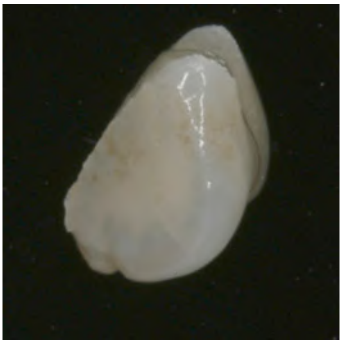

Fig. 7.151 The tooth fragment, rehydrated after storing in a container with milk, is ready for the bonding procedure (Reprinted with permission from Caprioglio et al. [66])

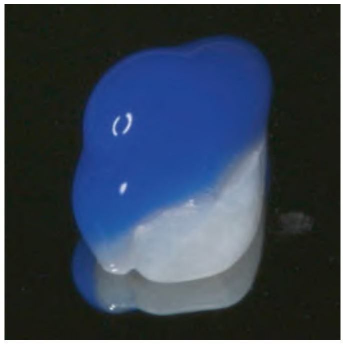

Fig. 7.152 The tooth fragment, already cleansed and laser conditioned, is etched with orthophosphoric acid (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.153 The cleansed and etched fragment is ready for the application of thin layer of adhesive and final bonding to the tooth surface (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.154 Same clinical case of Fig. 7.152; palatal surface was irradiated at very low energy level and in defocused mode (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.155 The irradiated palatal surface of the tooth was etched with orthophosphoric acid (Reprinted with permission from Caprioglio et al. [66])

anaesthesia. Using laser technology, the analgesia of the traumatised tooth is slowly induced, irradiating with a low energy (25>50 mJ), in defocused mode and with a low pulse repetition (10>15Hz) in the cervical zone, around the gingival contour of the tooth, moving towards the exposed dentin later on. At this moment there will be a clear perception of a decrease in sensitivity in the patient, and it is possible to get closer to the tooth until reaching the correct focus mode; slowly increasing the energy (50>70 mJ) and the frequency of pulses allows for cleaning and conditioning the enamel and dentin surface; the clean and decontaminated area can be restored, showing a smear-layer-free and finely etched surface, without loss of substances and suitable for receiving the fragment to be reattached. It is very important not to lose the correct focus, since pre-focalisation can cause overheating phenomenon with dentin dehydration up to carbonisation (underlined as a dark black burned spot). In case of congruent fragment to the tooth, with sharp edges on both the surfaces, reattachment must be executed without any preparation of the tooth. The surface is cleansed again at the end with cotton pellets soaked with sodium hypochlorite. The fragment bonding follows the procedure of etching with 37 % orthophosphoric acid for 20s and the application of adhesive resin on both tooth surface and recovered fragment (Figs. 7.151, 7.152, 7.153, 7.154 and 7.155). The two parts are united by a thin layer of heated composite (dentin mass of correct colour); keeping the fragment in position, the excess of composite is eliminated with a little spatula and light cured on both sides (palatal and buccal or vestibular) (Figs. 7.156, 7.157, 7.158, 7.159, 7.160, 7.161 and 7.162).

Fig. 7.156 Primer application on the tooth (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.157 Adhesive application on the tooth: no curing (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.158 Composite, just heated at 35 °C, application on the tooth: no curing (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.159 The fragment is placed in the correct position; a thin transparent polyester strip is positioned to contour the mesial wall of the tooth and to avoid any displacement of composite to the neighbour tooth (Reprinted with permission from Caprioglio et al. [66])

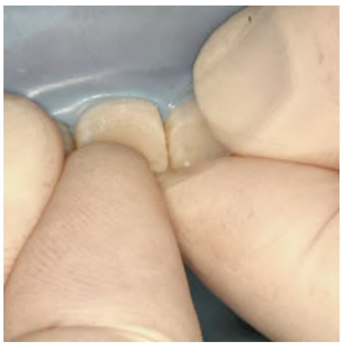

Fig. 7.160 The fragment is kept in position with the fingers, the excess of composite is eliminated with a little spatula and finally the tooth is light cured on both sides (Reprinted with permission from Caprioglio et al. [66])

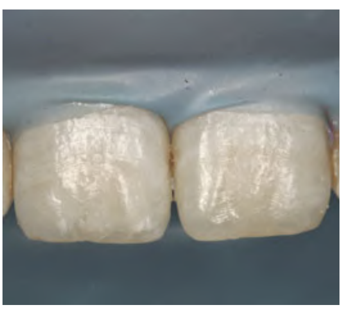

Fig. 7.161 Buccal view after the bonding and smoothening procedures are completed (Reprinted with permission from Caprioglio et al. [66])

Fig. 7.162 Palatal view of the same case (Reprinted with permission from Caprioglio et al. [66]

In case of a fragment which is not completely congruent for the surface of the element, it is advisable, once the fragment is reattached, to prepare a chamfer along the fracture line, using a fine grit, round-shaped bur (40 µm, ISO 12–14) (technique of the differentiated or secondary bevel) in order to reduce the visibility of the fracture line and proceed with adhesive technique and an anatomical stratification with the suitable masses of dentin and enamel.

Sometimes the fragment is not completely broken down and removed from the tooth (Figs. 7.163 and 7.164); erbium laser in this case is used to clean and decontaminate the detached surfaces, before their re-bonding using adhesive procedures and flowable composite to be pushed in depth in the fissure between the fragment and tooth (Figs. 7.165 and 7.166).

The intervention is completed by checking the occlusion and by finishing with rubber tips, fine grit discs and a goat's hair toothbrush for final polishing.

7.8.4.4 Composite Restoration

The preparation of class 4 caries is easily performed with erbium lasers with a procedure similar to the one before. Cavity preparation is simply limited to dentin decontamination, the regularisation of the margins and the creation of a rounded or chamfer finishing line. Preparation of the dentin must be conservative, limited only to the decontamination and conditioning of the surface using energy ranging from 50 to 75 mJ at 10 Hz, sufficient to reach the proposed goal. Clinical evaluation of the quantity of exposed dentin is important, as well as the proximity of the pulp tissue; intraoral x-ray images and the positive response to heating and cooling pulp vitality tests advise whether or not to perform a superficial laser melting of the dentin, which includes the closure of dentin tubules in the area next to the

Fig. 7.163 Fracture of the angle of upper right central incisor with fragment lost; another part of the fractured fragment remained attached to the tooth through the periodontal fibres

Fig. 7.164 The crack line goes vertically under the gum: palatal view shows the complete fracture and separation of the two parts

Fig. 7.165 The fragments were bonded while kept in position with the fingers and light cured

Fig. 7.166 Final palatal view after checking the occlusion and by finishing with silicone tips

pulp in order to prevent postoperative sensitivity; this procedure is an operator-sensitive one and suggested for advanced dentists (erbium laser: 25 mJ, 10 Hz, defocused, with low or no water spray). In case of laser dentin sealing (melting), the acid etching of that area must be avoided, but must be considered in that dentin sealing produces a limitation of the adhesive potential of restoration. The apposition of a liner (calcium hydroxide or bioactive dentin substitute or glass ionomeric cement) in these deep dentin areas is facultative and only recommended in case of pulp exposure.

Preparation, finishing, and conditioning of the enamel margins require a very low amount of energy, from 35–50 mJ to 75–80 mJ, emitted at a low frequency of 10–15 Hz, for better operative control, or at 25–30 Hz when expert operators require a more efficient smoothening of the margins. The use of low energy and high water spray limits both overpreparation and pain perception of the patient and ultrastructural thermal damage to dental structures (Figs. 7.157, 7.158, 7.159, 7.160, 7.161, 7.162, 7.163, 7.164, 7.165, 7.166, 7.167, 7.168, 7.169, 7.170, 7.171, 7.172, 7.173, 7.174, 7.175, 7.176, 7.177, 7.178 and 7.179; Table 7.5).

Alternatively to laser conditioning of the margins (Fig. 7.180), it is possible to obtain smooth margins using round-shaped burs on the buccal side, while at the palatal side the finishing line depends on localisation of the contact surface of maximal intercuspation of centric; if the contact is close to the margin, it is opportune to move the finishing line cervically performing a more apical chamfer. If the line of fracture is more incisal, a straight preparation with Sof-Lex Pop-On discs offers a wider surface for adhesion and support for composite materials, and it is more conservative. Finishing involves, as usual, hand scalpels, fine grit round-shaped bur, or ultrasound tip and brown silicone tip (Figs. 7.181 and 7.182).

Taking into consideration the high necessity for adhesion, the procedure with adhesives must always follow the etching with 37 % orthophosphoric acid for 20 s of the edges of the enamel and of the dentin surface, respecting the deep para-pulpal areas (Figs. 7.183, 7.184, 7.185 and 7.186).

7.8.4.5 Complicated Crown Fracture

In case of crown fracture of a tooth with vital pulp and minimal pulp exposure (less than 1 mm^2), laser-assisted pulp capping is recommended within the first 24 h; a Nd:YAG, diode, erbium, or CO laser can be used for this purpose. For a complicated crown fracture that involves a larger pulp exposure (1–2 mm^2), or even a small exposure but after 48 h, a conservative pulpotomy can be also performed using laser (see Sect. 8.4 and Figs. 8.39, 8.40, 8.41, 8.42, 8.43 and 8.44).

7.8.5 Class 5 Cavity Preparation

Class 5 cavities refer to lesions localised in the cervical one-third of the tooth (neck), on the buccal side or, more rarely, lingual side of all the teeth. The cervical lesions can be carious or non-carious.

7.8.5.1 Cervical Carious Lesions (NCCL)

They can be primary carious lesions, in the case of enamel that is slightly mineralised due to poor hygiene, or secondary to non-carious lesions or previous restorations, in the case of insufficient oral hygiene (Figs. 7.187 and 7.188).

Cervical carious lesions are usually associated with the presence of inflamed and hypertrophic marginal gingival tissue, which partially covers the lesion (Figs. 7.187, 7.188 and 7.189). These conditions require making the margin of the cavity become over-gingival (for 1 mm), to allow

Fig. 7.167 Uncomplicated enamel-dentin fracture of the angle of upper right central incisor (Reprinted with permission from Olivi et al. [85])

Fig. 7.168 Enamel-dentin are irradiated with Er,Cr:YSGG laser

Fig. 7.169 Image at the mirror shows the incisal laser preparation on buccal and palatal site; small dentin exposure surrounded by enamel (Reprinted with permission from Olivi et al. [85])

Fig. 7.170 Orthophosphoric acid is used to uniform the macro-roughened laser surface and to improve the adhesive superficial properties of the prepared tooth

Fig. 7.171 The restoration shows the colour and morphology achieved by the anatomical layering technique, using micro-hybrid composite

Fig. 7.172 Follow-up one year later (Reprinted with permission from Olivi et al. [85])

Fig. 7.173 Follow-up after 10 years shows the long-life quality of the margins of restoration and high aesthetic result in time

Fig. 7.174 Adhesive-cohesive failure of previous composite filling in uncomplicated horizontal enamel-dentin fracture (Reprinted with permission from Olivi et al. [87])

Fig. 7.175 Immediate post-op image (Reprinted with permission from Olivi et al. [87])

Fig. 7.176 Image at the mirror shows the incisal Er:YAG laser preparation on buccal and palatal site; large dentin exposure surrounded by enamel. Note few burnishing spot on dentin, probably due to pre-focused irradiation (Reprinted with permission from Olivi et al. [87])

Fig. 7.177 Blue Sof-Lex Pop-On disc (3 M-Espe) is used to smooth the flat incisal margins (Reprinted with permission from Olivi et al. [87])

Fig. 7.178 Orthophosphoric acid is used to uniform the macro-roughened laser surface and to improve the adhesive superficial properties of the prepared tooth (Reprinted with permission from Olivi et al. [87])

Fig. 7.179 The final restoration shows the colour and morphology achieved by the anatomical layering technique, using micro-hybrid composite (Reprinted with permission from Olivi et al. [87])

Fig. 7.180 Margin fracture and wear

Fig. 7.181 Margin conditioning using Er,Cr:YSGG laser and thin 400 μm conical tip at low energy

Fig. 7.182 Hand excavators or scalpels are used to finish the surface and margins, removing the unsupported prisms and dentin flakes, produced if high power laser irradiation is used to prepare the tooth

Fig. 7.183 Silicon tips are also used to finish the surface and margins

Fig. 7.184 Pellets soaked with sodium hypochlorite is used to scrub the surface, for removing both unsupported prisms and the denatured collagen resulted from laser irradiation

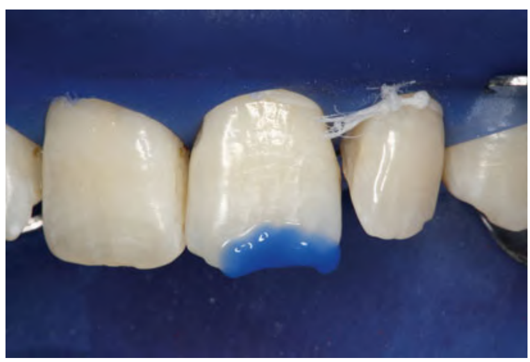

Fig. 7.185 Orthophosphoric acid is used to uniform the macro-roughened laser surface and to improve the adhesive superficial properties of the prepared tooth

Fig. 7.186 Tooth restoration completed using micro-hybrid composite (dentin mass) covered by nano-filled composite (enamel mass)

positioning of the rubber dam and finishing of the cavity and restoration (Figs. 7.189, 7.190 and 7.191). Sometimes, the lack of adherent gingiva, sufficient to protect the dento-gingival attachment from traction of the alveolar mucosa, can suggest a muco-gingival surgery with an apically positioned flap as an alternative to laser gingivectomy. For thorough evaluation of the advantages and disadvantages of these interventions, anatomical and aesthetic parameters should be considered.

7.8.5.2 Non-carious Cervical Lesions (NCCL)

Among the non-carious cervical lesions (NCCL), we distinguish *abrasions*, usually multiple and provoked by mechanical action (incorrect brushing and/or abrasive toothpastes), and erosions, also multiple and provoked by the chemical action of acidic substances consumed (e.g. coke, lemon, yogurt, citric acid-based drinks, candies) or associated with pathological complications (e.g. gastroesophageal reflux) (Figs. 7.192 and 7.193). Other buccal lesions, called *abfractions*, are provoked by compressive-disclusive forces (centric-eccentric) exercised on the teeth during function and are considered to be idiopathic lesions [69] (Fig. 7.194). The term *abfraction* means “to break away” [70] and is derived from the Latin words “ab” or “away” and “fractio” or “breaking” [71, 72]. Pathogenesis of this lesion is related to an uncorrect occlusion and/or function (parafunction such as bruxism or grinding). Compressive forces and lateral forces cause the teeth to bend, creating tensile stresses that disrupt the chemical bonds of the crystalline structures of the enamel and dentin. As a result, the disrupted tooth structure is more susceptible to

Fig. 7.187 Cervical carious lesion extending also under the gingiva; as result there is a marginal inflammation of the gum

Fig. 7.188 Secondary cervical carious lesion: after detachment of the filling, the caries extension under the gum is visible as blackish-brownish softened tissue

Fig. 7.189 Cervical carious lesion extending also under the gingiva; a gingivectomy is necessary to expose the healthy dental margin (Reprinted with permission from Olivi G., Olivi M., Sorrenti E., Genovese M.D. Laser a Diodi 810 nm: applicazioni cliniche in odontoiatria Laser Tribune Settembre 2012- anno VIII N.9 pag 16–18)

Fig. 7.190 Laser gingivectomy performed with 810 nm diode laser in continuous wave at 1.4 W, 300 μm tip (Reprinted with permission from Olivi G., Olivi M., Sorrenti E., Genovese M.D. Laser a Diodi 810 nm: applicazioni cliniche in odontoiatria Laser Tribune Settembre 2012- anno VIII N.9 pag 16–18)

Fig. 7.191 Immediately after the gingivectomy, a rubber dam is placed on the premolar and cavity preparation is achieved with Er:YAG laser at 120 mJ, 15 Hz, using 600 μm conical tip

chemical dissolution (erosion) and abrasion and results in the development of typically wedge-shaped lesions. Abfractions are usually observed on the buccal surface at the cement-enamel junction (CEJ) of the teeth, because of the presence of thinner thickness of enamel, with prevalence ranging from 27 to 85 % of the population [69, 73]. Often, the causes of the *erosions* and *abfractions* coexist, producing complex lesions that easily relapse with detachment of the restoration due to the low adherent surface of the cavities and to eccentric forces exercised on the restoration during the function or parafunction. Cervical lesions (NCCL) can become carious if ignored and subjected to poor hygienic conditions; as such, restorative treatment is advisable.

A common element of non-carious cervical lesions is the presence of sclerotic dentin as a reaction to the damaging chemical-physical stimuli; sclerotic dentin has low adhesive properties, because the closure of dentin tubules and the lack of collagen fibres (see Sect. 1.3.4) negatively affect the adhesion of the restoration to the tooth. Another common element, which negatively influences adhesion, is the difficult isolation of teeth with these lesions. Effectively, the cervical border between the lesion and the root is often unclear and plane, and it is difficult to identify its limit and to firmly position the clamp for the rubber dam. The presence of a thin marginal periodontium, associated with a thick adherent gingiva, is often found in patients with abrasions or abfractions (see Fig. 7.192). It also makes the positioning of the retractive cord difficult, which can sometimes provoke minimal periodontal damage with possible bleeding.

Erbium lasers can be considered the "gold standard" for the treatment of class 5 lesions, both for its ability to expose the cervical margin

Fig. 7.192 Evident non-carious lesion (abrasion and abfraction) of the upper molar: note the thin free marginal gingiva and the thick adherent gingiva

Fig. 7.193 Typical aspect of acid erosion on central incisors (gastroesophageal reflux)

Fig. 7.194 Patient with evident wears of the occlusal surface due to bruxism shows also abfraction of the neck of the lower bicuspids; note the orange-brown colour of the tertiary dentin

of the lesion with good control of the bleeding (gingivectomy of about 1 mm) and for the minimal preparation of the dentin surface.

Generally class 5 cervical lesions do not require anaesthesia. They are easily approachable with an analgesic laser technique. The laser beam easily penetrates the dentin exposed to the pulp tissue, quickly inducing membrane hyperpolarisation that results in loss/decrease of impulse conduction with a short refractory period towards nociceptive stimulus. Energy is then progressively increased to ablative levels. *Cervical carious lesions* have softened dentin exposed, so that can be directly irradiated with erbium lasers, which selectively vaporise the carious tissue. The required energy is inferior compared to more mineralised non-carious cervical lesions. A minimal quantity of initial energy of 120 > 100 mJ is necessary for the ablation of carious tissue, to be reduced to 40–50 mJ for conditioning of the cavity; the cavity design follows the carious process that selectively absorbs erbium laser irradiation (Figs. 7.195, 7.196, 7.197 and 7.198, 7.199, 7.200, 7.201, 7.202, 7.203 and 7.204).

Non-carious cervical lesions present more mineralised dentin as result of a defensive mechanism of the tooth to external chemical-physical damage. The typical wedge loss of dental substances of the abfractions is directly irradiated to expose “fresh” dentin, removing the superficial layer of sclerotic dentin.

Erbium lasers are very efficient because of its minimal invasive action on the sclerotic dentin, which is easily removed using just higher energy for carious dentin (150 > 100 mJ), until fresh den-

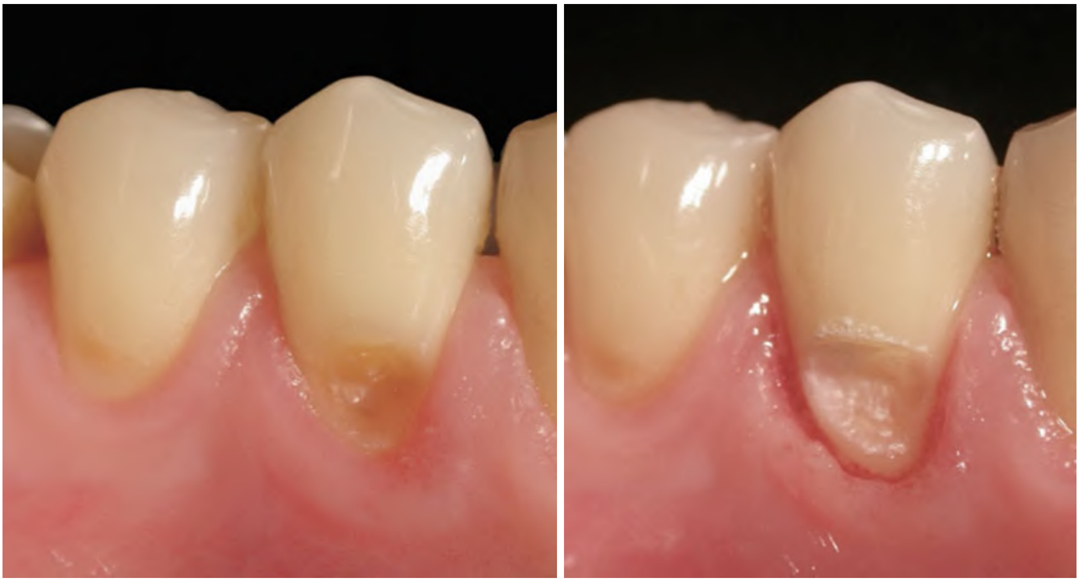

Fig. 7.195 Lower bicuspid presenting cervical carious lesion (*left*); after Er,Cr:YSGG laser gingivectomy, the same device is used for cavity preparation (*right*) (Reprinted with permission from Olivi et al. [87])

Fig. 7.196 Laser preparation completed (*left*); different times of acid etching are used for enamel (30s) and dentin (20s) acid etching (in the *middle* and *right*)

tin is not visible. A change of irradiation angle is advisable, from distal to mesial and from incisal to gingival. The axial wall of the tooth represents the bottom of the cavity, and laser preparation follows the abraded-eroded surface without extending itself to searching for a plane or equally convex bottom that could affect the pulp in the deepest cavities. The produced surface is finely roughened, thanks to the final conditioning at low energy (40–50 mJ). The incorrect use of higher energy parameters could create deeper overlapped microcavitations with differences in depth that can create sites of minor adhesion for adhesion itself.

Fig. 7.197 Cavity prepared and conditioned (*left*); primer and bonding are applied in different steps (in the *middle*); cavity bonded ready for restoration

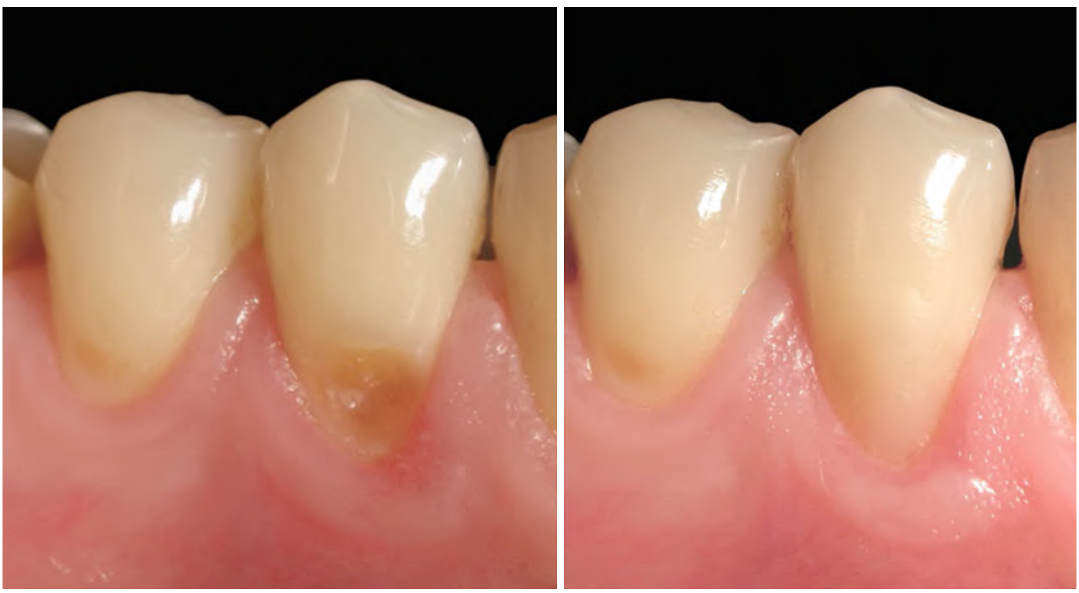

Fig. 7.198 Before (*left*) and one week after (*right*) restoration, performed with micro-hybrid composite; note the fast and complete healing of the gum after gingivectomy and the good matching of the colour (Reprinted with permission from Olivi et al. [87])

In both carious and non-carious lesions, the enamel margins must be finished. The enamel margin of the coronal one-third of the tooth must be outlined with a straight horizontal finishing line to satisfy aesthetic request. The margin preparation is completed with accurate chamfer finishing, performed with the same round, fine grit bur and brown silicone rubber (see Figs. 7.35, 7.36, 7.37, 7.38 and 7.39).

Fig. 7.199 Demineralisation of the cervical area (see also Figs. 9.2, 9.3 and 9.4)

Fig. 7.200 Minimal irradiation performed at 120 mJ is sufficient to remove the superficial altered layer of the tooth

Fig. 7.201 Smoothening of the margins is followed by acid etching

Fig. 7.202 Macro-roughened-micro-etched surface ready for the bonding and restoration

Fig. 7.203 Restoration completed with micro-hybrid composite

Fig. 7.204 One-year follow-up image shows the integrity of the margins

Fig. 7.205 Same clinical case of Fig. 7.194: abfraction of lower premolars

Fig. 7.206 Er,Cr:YSGG laser irradiation in focus mode for dentin ablation at 150 mJ

Fig. 7.207 Er,Cr:YSGG laser irradiation in defocused mode for dentin conditioning at 50 mJ

Fig. 7.208 Enamel margin finishing using fine grit, round-shaped bur

Fig. 7.209 One-week follow-up of micro-hybrid composite restoration

Fig. 7.210 Ten-year follow-up: despite concomitant abrasion and abfraction, the margins of the restoration are sufficiently intact

The enamel of the cervical one-third, if present, tends to get progressively thinner until the complete disappearance at the level of the amelo-cementum junction. At this point it is difficult to obtain a good seal, and a mechanical margin finishing at the cementum or dentin level, at the neck of the tooth, is fundamental, together with efficient etching to improve adaptation and seal of composite restoration; the finishing line is generally parallel to the gingival arch without necessarily reaching the border line, and it is performed with a round, fine grit bur and a brown silicone rubber (Figs. 7.205, 7.206, 7.207, 7.208, 7.209 and 7.210).

7.9 Cracked Tooth Syndrome

Cracked tooth syndrome typically depends on very small fractures which cannot be seen through x-ray examination. Sometimes the fracture is visible on the proximal enamel ridge or on a cuspid, or not visible because it is below the gumline or under an amalgam filling, making diagnosis very difficult to perform [74, 75]. The term "cracked tooth syndrome" (CTS) was first introduced by Cameron in 1964 [76].

Cracked tooth syndrome more often occurs in molars which absorb most of the force of

Fig. 7.211 Patient with severe pain referred to a caries-free lower molar; the image shows the presence of a longitudinal fracture starting from the occlusal fissure up to the distal enamel ridge

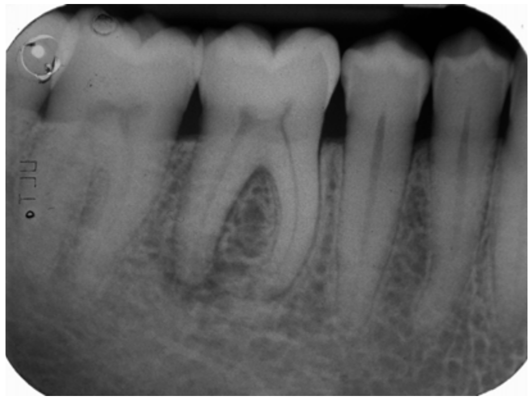

Fig. 7.212 The x-ray examination shows apical lesion on the distal root

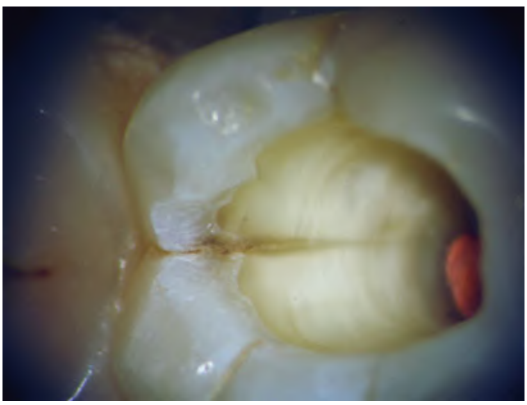

Fig. 7.213 The intraoperative image shows the longitudinal path of the cracks that affect the distal root; the tooth required a root canal therapy

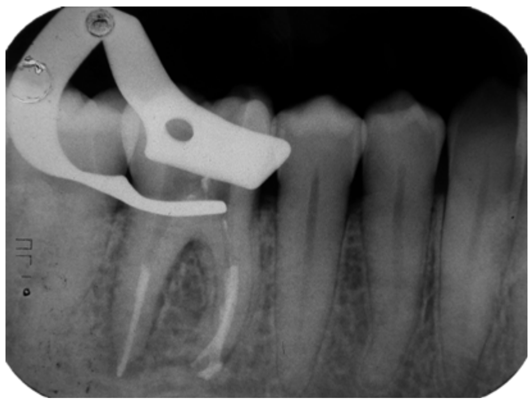

Fig. 7.214 The x-ray examination shows the root canal filling

chewing. Teeth with large or even small amalgam fillings are more susceptible to cracks due to possible expansion of the filling material, which can even happen many years after restoration. The fillings of cavities with fewer walls (1 and 2 class) are more susceptible to cracks (Fig. 7.211). Furthermore, patients who grind or clench may be more susceptible to cracked tooth syndrome.

Treatments for cracked tooth syndrome do not always completely relieve the symptoms. Deep cracks can affect the pulp and root canal therapy is needed (Figs. 7.212, 7.213 and 7.214). The problem is double: the weakness of the dental structure that can suddenly fracture and the consequent bacteria contamination throughout the fracture, which affects the pulp or, more rarely, the periodontal tissues. In consequence, sometime extraction is necessary for continuous pain to pressure after root canal treatment.

Successful treatment depends on the location, direction and extent of the crack and deep bacterial contamination. Often cracks have a mesiodistal direction, crossing or not the floor of the tooth, and vary from superficial in the outer dental layers to deep splits in the root affecting the pulp or/and the root walls (see Fig. 7.215, 7.216, 7.217, 7.218, 7.219, and 7.220).

Fig. 7.215 Patient with hypersensitivity of a lower molar with class 1 cavity restored with amalgam; the image shows several microcracks on the enamel mesial and distal ridges as well as on buccal and lingual fissures; *white arrows* show the presence of microcracks on the enamel

Fig. 7.216 Preoperative x-ray of lower molar

Fig. 7.217 After the amalgam removal, several microcracks are evident on the floor of the tooth

Fig. 7.218 Erbium, chromium:YSGG laser was used for the decontamination and cleaning of the bottom of the cavity; the longitudinal crack from the distal ridge appeared deep and full of debris

Fig. 7.219 A total etch procedure was performed and adhesive was applied and cured

Fig. 7.220 After 2 years a root canal therapy was required for sub-acute pulpitis

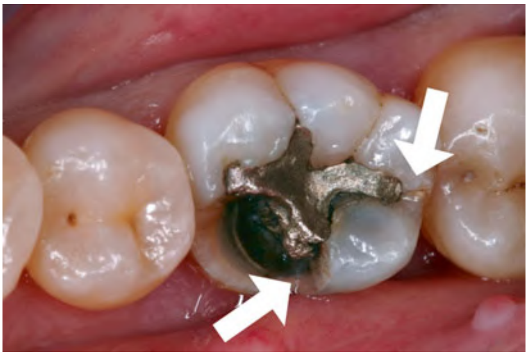

Fig. 7.221 Lower molar with old cracked and infiltrated amalgam filling; *white arrows* show the presence of microcracks on the surrounding enamel

Fig. 7.222 The amalgam filling was removed with high-speed drill; caries was removed via erbium laser; *white arrows* show the presence of microcracks on the enamel

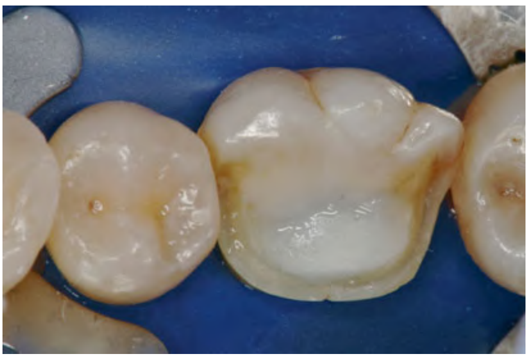

Fig. 7.223 The cavity was immediately sealed with adhesive and a build-up with micro-hybrid composite was performed; proper preparation for inlay and finishing was performed with high-speed drill

Fig. 7.224 Indirect ceramic inlay bonded

In the case of proximal location (mesial or distal) and superficial extent of the crack, removal of the old restoration and ablation of the dentin in the proximal area can resolve the symptomatology (Figs. 7.221, 7.222, 7.223 and 7.224). When the crack extends under the gingiva and the enamel-cementum junction, it must be decided where to stop the ablation of the dental tissue. It is advisable to keep the margins of the restoration out of the gingiva, bonded on the enamel; it is therefore not advisable to remove all the enamel affected by the crack. In these cases, if the symptomatology disappears, a complete reconstruction with a metal-ceramic crown is advisable, with the metal-gold margin of the crown exercising a "ferula effect" on the prepared sub-gingival tooth, in order to reinforce the residual dental structure and to prevent a possible complete radicular fracture. When the crack extends towards the bottom of the tooth (pulp chamber roof), often the early pulp contamination is not clinically valuable, until an x-ray shows a peri-apical pathology appears (see Fig. 7.220).

Dental laser preparation involves the removal of the old restoration with rotative instruments. In the literature there are no

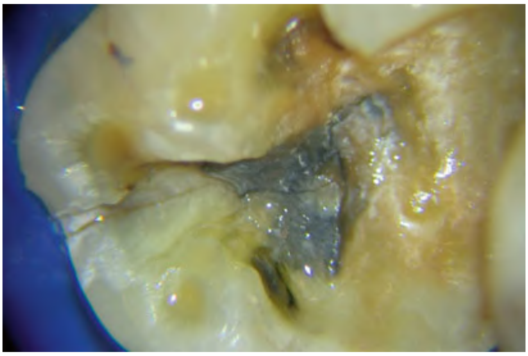

Fig. 7.225 Lower molar presenting a mix of amalgam and composite fillings to be removed; after filling removal, a microcrack running from distal to the centre of the tooth was visible

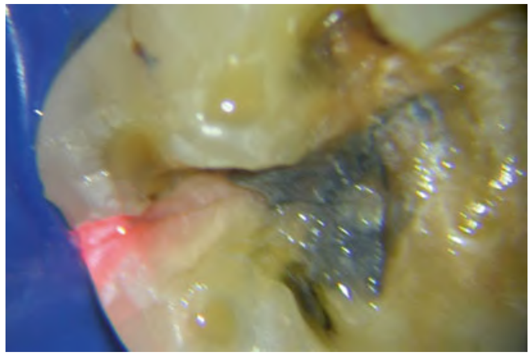

Fig. 7.226 Tipless hand-piece of erbium:YAG laser was used to remove the caries and to decontaminate and clean the microcrack

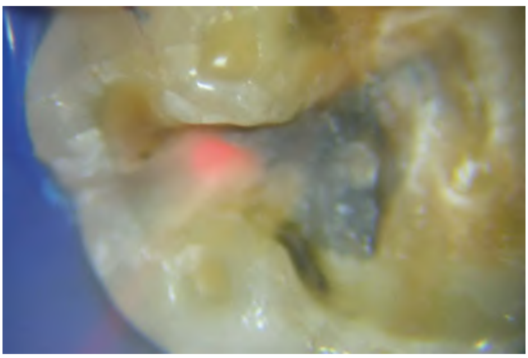

Fig. 7.227 Tipless hand-piece of erbium:YAG laser during the decontamination and cleaning of the microcrack: spot size 0.9 mm in defocused mode

studies on laser treatment of the CTS, so what is reported here is based on the clinical experience of the author in applying the laser concepts in dentistry. The removal of carious dentin (if there is any) is performed with erbium laser at low energy (150 mJ or less), and as always, decontamination and conditioning are executed on the bottom of the cavity and on the crack (75 mJ > 50 mJ) (Figs. 7.225, 7.226 and 7.227). Erbium laser permits decontamination to the depth of 300–400 μm with l'Er:YAG [49] and to a dentin thickness of 500 μm with laser Er,Cr:YSGG [51]. The surface is well cleansed, without debris or smear layer, with the dental tubules opened and ready for adhesion. If you do not have an erbium laser, you can use a near-infrared laser, whose irradiation should be limited along the area of the crack, permitting a deeper decontamination [50] (Figs. 7.228 and 7.229). The dentin surface resulting from laser irradiation with laser Nd:YAG (1,064 nm) at 1 W, 15 Hz, with a fibre of 300 μm or with diode laser at 0.4–0.5 W in continuous waves, with a fibre of 300–400 μm, presents mainly thermal interaction. The microscopical aspect shows superficial melting with closure of the dental tubules, very effective in case of pre-existing sensitivity but negatively affecting the bonding procedures (Fig. 7.230). Alternatively, for those who have both wavelengths, double irradiation can be used, using the near infrared, for deeper decontamination, and medium infrared successively to leave a clean surface with the dental tubules opened, which is surely more adequate to this clinical situation (Figs. 7.231, 7.232 and 7.233). If contamination is very deep, a conservative therapy can evolve in the necrosis of the pulp; in this case a root canal therapy is necessary (see Figs. 7.212, 7.214, and 7.220).

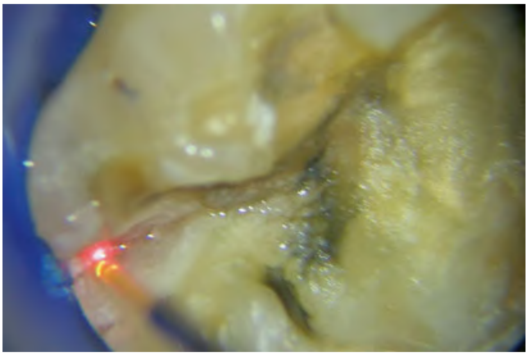

Fig. 7.228 If available, the near-infrared Nd:YAG irradiation limited to the affected area allows a deeper decontamination of the microcrack (1 W, 15 Hz, 100 µs pulse, 300 µm fibre) but also a loss of adhesion on the treated area; close contact mode (1 mm) allows a more precise irradiation

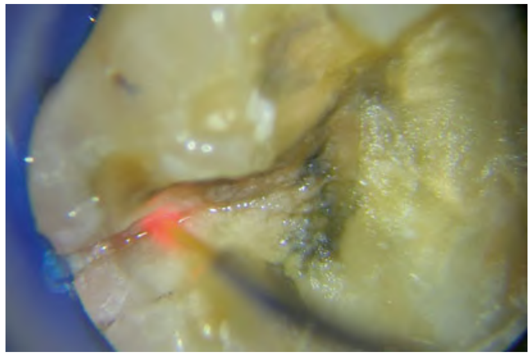

Fig. 7.229 Nd:YAG in focus mode irradiating the microcrack area only

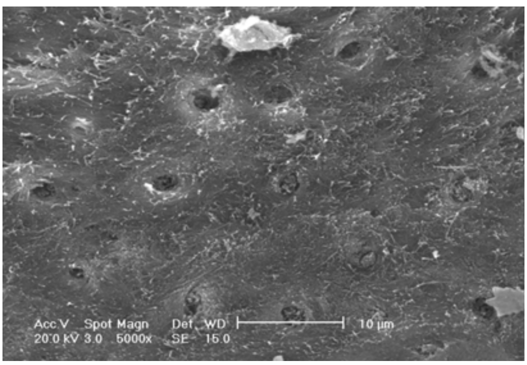

Fig. 7.230 SEM image of Nd:YAG irradiation on dentin at 1 W, 15 Hz, 100 µs pulse, 300 µm fibre; partial closure of the dentin tubules is not suitable for adhesion

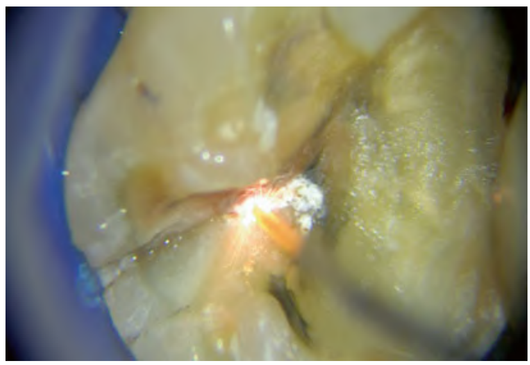

Fig. 7.231 Intraoperative image showing the thermal interaction of Nd:YAG laser on amalgam-pigmented dentin (absorption superficially in pigment despite diffusion in deep depth); this interaction must be avoided

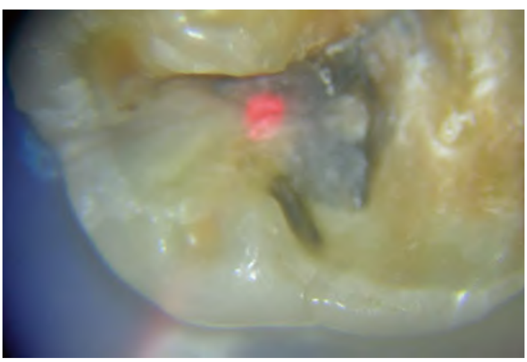

Fig. 7.232 When the two wavelengths are available, after near-infrared decontamination of the microcrack area, the use of erbium lasers allows an optimal cleaning of the already decontaminated surface, leaving a substrate more suitable for adhesion

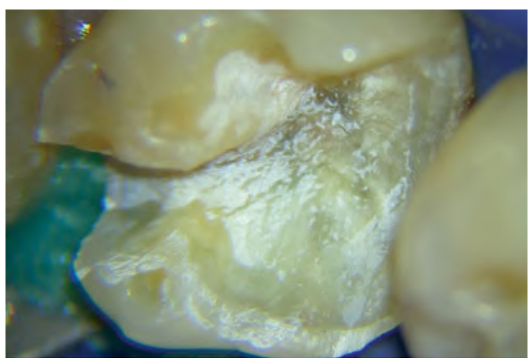

Fig. 7.233 The surface of the molar after laser irradiation shows the typical whitish area, an expression of microexplosion with presence of loosely adherent flakes; chemical conditioning is required for a better adhesion

7.10 Erbium Laser (Carious Removal) Preparation for Indirect Restorations

The choice between direct or indirect restoration depends on many elements, among them the shape and complexity of the cavity, the presence or absence of enamel at the level of the cervical step, the number of other restorations already present in the same arcade, the relationship with the proximal and antagonist tooth, age of the patient and the risk of caries, high aesthetic expectation and economical factors.

Generally the dimension of the carious process represents the most important element of choice, and usually indirect restoration (inlay) can be more invasive than direct restoration (filling).

Indirect restoration of big cavities allows simple management of the contact point with the antagonist and proximal tooth, thanks to laboratory phases or digital planning and execution of restoration. Indirect restoration, both in composite and in ceramic, also shows superior mechanical characteristics compared to composite stratified restoration in cavities; for this reason they are more appropriate for wide cavities where cusps and proximal marginal crests must be reconstructed [77, 78]. Moreover, the characteristics of the surface of indirect restoration are superior compared to those of direct restoration.

The laser removal of caries in wide and complex cavities is well conjugated with cavity preparation of indirect restoration, allowing a mini-invasive approach. The selective removal of carious tissue follows the carious process, limiting the ablation of same healthy residual substance (Figs. 7.234, 7.235 and 7.236); subsequent build-up in composite permits the filling of undercuts using a composite

Fig. 7.234 Preoperative image showing dental caries extending on all the distal surfaces, including the contact point

Fig. 7.235 Er:YAG laser was used at different settings for caries removal and gingivectomy

Fig. 7.236 After isolation with rubber dam, the surface has been conditioned for immediate sealing and build-up

Fig. 7.237 Orthophosphoric acid etching

Fig. 7.238 Immediate sealing and composite build-up

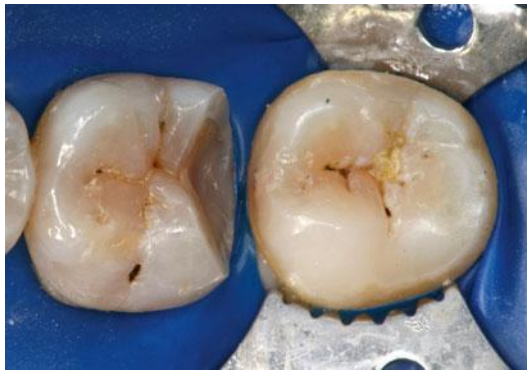

Fig. 7.239 The high-speed drill with a specific-shaped bur has been used to define the outline form before digital impression

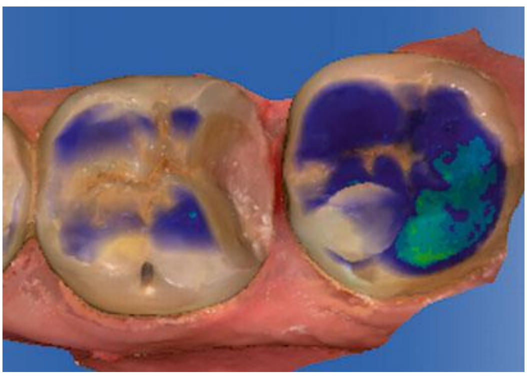

Fig. 7.240 Digital model after scanning (CEREC system, Sirona, Germany)

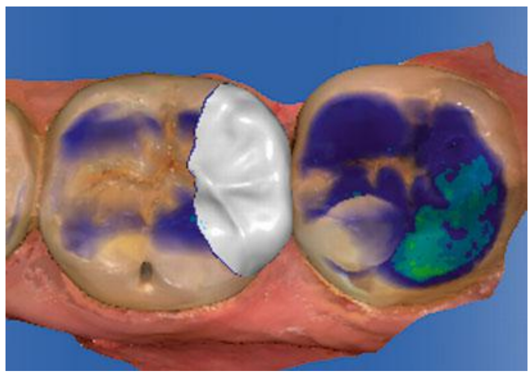

Fig. 7.241 Digital project of the ceramic inlay

Fig. 7.242 Feldspathic ceramic inlay bonded with the same composite used for the build-up

highly filled with biomechanical characteristics of hardness and elasticity similar to dentin, so it permits better maintenance of the residual dental substance (Figs. 7.237, 7.238 and 7.239). As a result, there is a correctly prepared and shaped cavity for the impression (conventional or digital) (Fig. 7.240) and a wide surface suitable for the bonding in indirect restoration (Figs. 7.241 and 7.242). Laser preparation, composite build-up and subsequent indirect restoration are also indicated in the case of enamel-dentin cracks for restoration of complex cavities (see Figs. 7.221, 7.222, 7.223 and 7.224).

Fig. 7.243 Preoperative image shows an old amalgam restoration and microcracks on mesial and distal enamel ridge, as well on the lingual cusp/wall

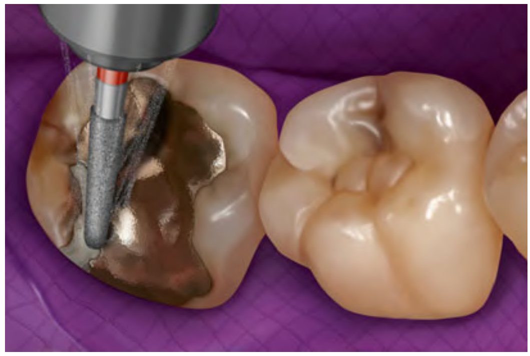

Fig. 7.244 High-speed drill is used to remove the amalgam restoration

Fig. 7.245 Once the amalgam has been removed, the dentin surface appeared discoloured for amalgam pigmentation and decayed; also the microcracks are better visible, on mesial, distal and lingual side

Fig. 7.246 Erbium lasers are used to remove the caries on the bottom of the cavity and to cleanse, decontaminate and condition the dentin surface

Fig. 7.247 Dental surface cleaned after Er:YAG irradiation

In case of indirect restoration, erbium laser preparation must be limited to the removal of carious tissue, and it follows mechanical removal with rotative instruments of pre-existing old restorations (Figs. 7.243, 7.244 and 7.245). The same phases of management of the bottom of the cavity follow (Figs. 7.246, 7.247, 7.248 and 7.249) (see Sects. 7.7.1, 7.7.2 and 7.7.3). Once the build-up in composite is completed, the preparation of the cavity is simply and quickly finished with specific burs while the smoothening of the margins is performed with fine grit chamfer bur or with ultrasonic tips or hand scalpels (see Sect. 7.7.4) (Figs. 7.250 and 7.251). It should be

Fig. 7.248 Chemical conditioning of the surface improve the adhesive properties of dentin: 37 % orthophosphoric acid etching for 20 s

Fig. 7.249 After laser-chemical conditioning the two-step adhesive (primer and bonding separately) were applied; note the microcracks on distal ridge, and multiple on the enamel buccal cervical margin without macroscopically invade the dentin

Fig. 7.250 Laser preparation for removing an old infiltrated filling on the neighbour molar. Micro-hybrid composite has been used for both filling of the first molar and build-up of the second molar; finally high-speed drilling was performed for shaping the outline form before the impression

Fig. 7.251 Micro-hybrid composite inlay has been bonded on the prepared surface, using the same composite of the build-up and of the restoration, so that a unique block has been used to restore the tooth

noted that at the moment of sealing, the bottom of the cavity and most of the walls have already been treated with composite and adhesive systems and that the dental tissue exposed remains only on the peripheral margins. The immediate adhesive treatment of the cavity bottom and walls before conventional or digital impression (immediate dentin sealing, IDS), in addition to performing immediate protection of the exposed dental substance, also allows, according to Magne (2005), subsequent, major adhesion to the restoration [79].

The preparation of indirect cavity restorations with a sub-gingival proximal extension also involves the exposure and positioning of the margins of the cavity at extra- or juxta-gingival level (see Sect. 7.11 and Fig. 7.235).

Laser can be also used for the preparation of veneer in the case of an already highly weared surface, with exposed dentin, which will only be smoothened and conditioned using laser and finished on the enamel margins with round-shaped or chamfer red grit burs, before impression (Figs. 7.252, 7.253, 7.254 and 7.255).

Fig. 7.252 Er:YAG laser preparation of a weared cuspid; the high-speed drill was used with a chamfer bur to define the shape for indirect veneer

Fig. 7.253 After scanning impression, a digital tooth model was prepared by CEREC software (Sirona, Germany)

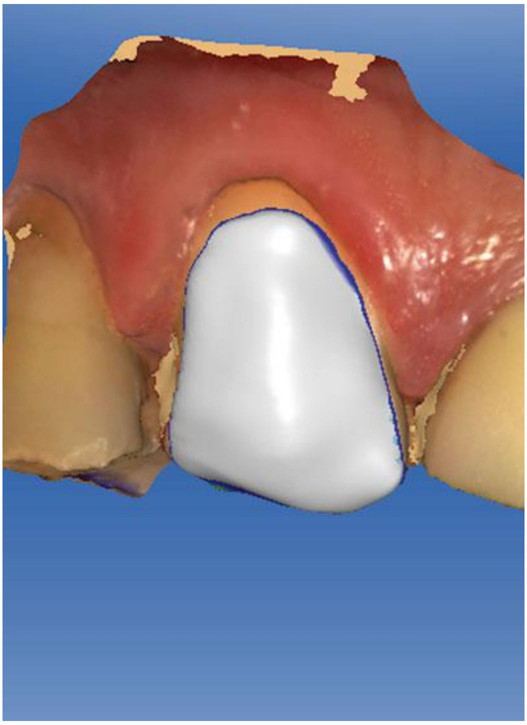

Fig. 7.254 Digital project completed

Fig. 7.255 Disilicate ceramic veneer has been bonded to the cuspid surface

Fig. 7.256 A 21-year-old patient with agenesis of central incisors still maintains the weared primary teeth; orthodontic therapy permitted preparation of the correct space for final teeth restoration

Laser can also be useful for preparing and finishing veneers in particular cases, for example, to condition the aprismatic enamel of deciduous teeth, in case of teeth agenesis and indirect restoration (Figs. 7.256, 7.257 and 7.258). Moreover, dentin laser conditioning of teeth prepared for veneer, on people with aged highly sclerotic dentin, is useful to increase adhesion, following all the passages described in Sects. 7.7 and 7.8 (Figs. 7.259 and 7.260).

Fig. 7.257 A minimal preparation was performed just to allow to fit two ceramic veneers. The aprismatic primary enamel was laser conditioned at 75 mJ with Er:YAG laser in order to create a microsurface more suitable for adhesive bonding; also a laser gingivectomy allows a minimal lengthening of the teeth

Fig. 7.258 Final ceramic veneers bonded

Fig. 7.259 An 84-year-old patient required aesthetic restoration of the frontal aged and weared teeth; Er:YAG laser was used to improve the adhesive property of an aged sclerotic dentin that has low adhesive property; note the different aspect colours of irradiated dentin and composite (upper right central incisor)

Fig. 7.260 Disilicate ceramic veneer bonded after laser conditioning

Table 7.6 Clinical parameters for gingivectomy, gingival troughing and crown lengthening

	Gingivectomy and gingival troughing					Osseous crown lengthening			
	Power	Energy	Pulses(s)	Pulse duration	Tip	Energy	Pulses(s)	Pulse duration	Tip
Er,Cr:YSGG	–	50–75 mJ	>20 pps	140 µs or 700 µs	400 µm	200 > 150 mJ	20 > 15 pps	140 µs	600 µm
Er:YAG	–	100–120 mJ	>20 pps	300 µs or 700 µs	600 µm	250 > 180 mJ	20 > 15 pps	50–100 µs	800 µm
Diode	0.8–1.5 W cw 1.5–2.5 gated	–	– toff 10–20 ms	– ton 10–20 ms	400 µm	n.a.	n.a.	n.a.	n.a.
Nd:YAG	2–3 W	100 mJ	20–30 pps	300 µs	300 µm	n.a.	n.a.	n.a.	n.a.

Table shows the range of clinical parameters suggested for Er,Cr:YSGG, Er:YAG, diode and Nd;YAG lasers for gingivectomy, gingival troughing and osseous crown lengthening
n.a. not applicable

7.11 Laser Gingivectomy for Sub-gingival Carious Removal and Impression

One of the advantages of using erbium laser in conservative procedures is the possibility to use the laser for soft tissue applications. In case of sub-gingival localisation of the cervical (class 5) or proximal (class 2 and 3 and inlay-onlay) margins of carious cavity, a gingivectomy is recommended in order to expose the cavity margins and to permit correct positioning of the dental dam and the margin preparation, finishing and filling. The use of laser allows a quick operation, and depending on the wavelength, it can effectively control bleeding, with minimal or no symptoms; after laser gingivectomy an immediate restoration and/or impression is possible, and sometimes if necessary, the impression can be deferred to a successive moment, even only two to three days later. Different wavelengths are available for this application [80, 81].

Erbium lasers efficiently vaporise the gingival tissue due to their affinity with water, but they do not allow efficient haemostasis like the near-infrared lasers [80]. Erbium lasers and erbium-chromium lasers work similarly, because of their thermal effect on the water content of gingiva. The lower absorption of the 2,780 nm wavelength (erbium-chromium laser) in water allows slightly higher penetration of this laser and a superior thermal and coagulating effect. Interaction with erbium-chromium laser is also quicker and requires less energy (50–75 mJ) [81, 82]. Both wavelengths can be also used in setting the laser at longer pulse duration for this purpose and reducing air-water spray ratio (see Table 7.6). Using such a setting increases the thermal effect of the interaction and bleeding control. The use of lower energy and higher pulse frequency (>20–50 pps) allows the execution of clear-cut with notable continuity of action (Figs. 7.261, 7.262, 7.263, 7.264, 7.265, 7.266 and 7.267). It must also be remembered that increasing the frequency of pulse repetition, reducing the time of thermal release of the tissue, increases the thermal effect but, consequently, also the patient's sensitivity. Interventions without anaesthesia are more easily achievable with low pulse frequency, but they have less control on bleeding. The thermal effect on the target can also be reduced through mild cooling with a spray, which permits better control of sensitivity, to the detriment of coagulation [81]. Erbium lasers however never generate carbonisation of the tissues, and thermal rise on the tissue always remains superficial and localised (maximum absorption and absence of diffusion). Vaporisation or incision of the soft tissue occurs at temperatures of 100 °C in the irradiated tissue; the coagulation of the tissue is performed at

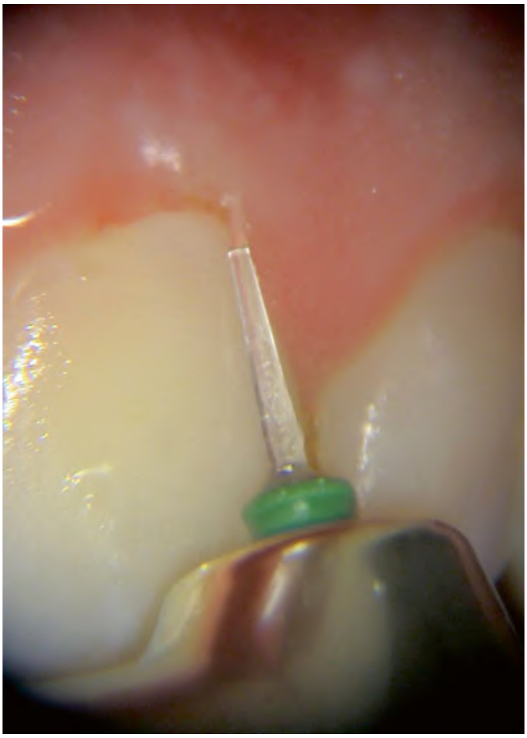

Fig. 7.261 Er,Cr:YSGG laser starting the gingiva vaporisation at 50 mJ, 50 Hz, 700 μs pulse and a 400 μm-tip and a few water spray to control the heating of the interaction

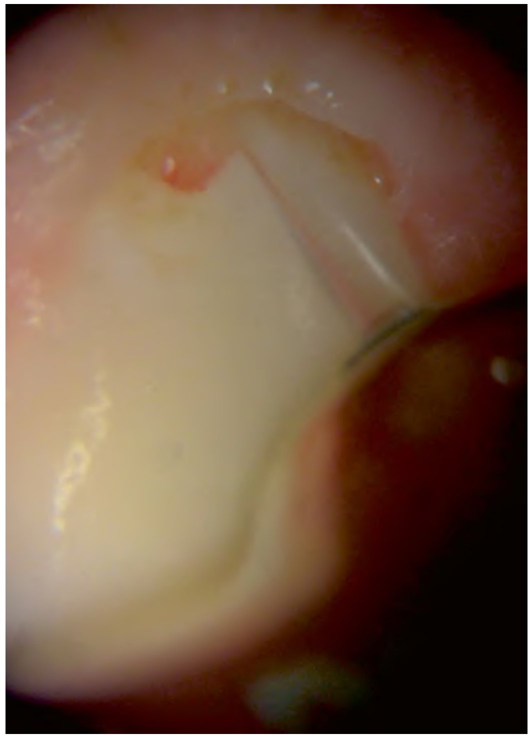

Fig. 7.262 Er,Cr:YSGG laser approaching to vaporise gingival tissue on the zenith of gingival arch

around 55–60 °C, reducing the energy, defocusing and setting off the water spray [80, 81]. Conical tips from 400 to 600 μm are available for incision.

During preparation of class 5 cavities, the angle of buccal irradiation must be parallel to the long axis of the tooth, making efforts to avoid unwanted irradiation of the enamel and radicular cement (Fig. 7.268).

In the case of preparation of class 2 cavities (mesial or distal), the laser tip can be positioned in the proximal area, parallel to the long axis of the tooth, perpendicular to the gingiva with the lateral side of the tip laying on the cervical step, which will act as a guide (Figs. 7.269, 7.270, 7.271, 7.272, 7.273, 7.274 and 7.275). Wider gingivectomy can be achieved through a buccal or palatal approach of the tip, perpendicularly to the gingival papilla (Fig. 7.276).

The surgical approach to the soft tissue must take into consideration the maintenance of the biological width of periodontium (3.0–3.5 mm), and

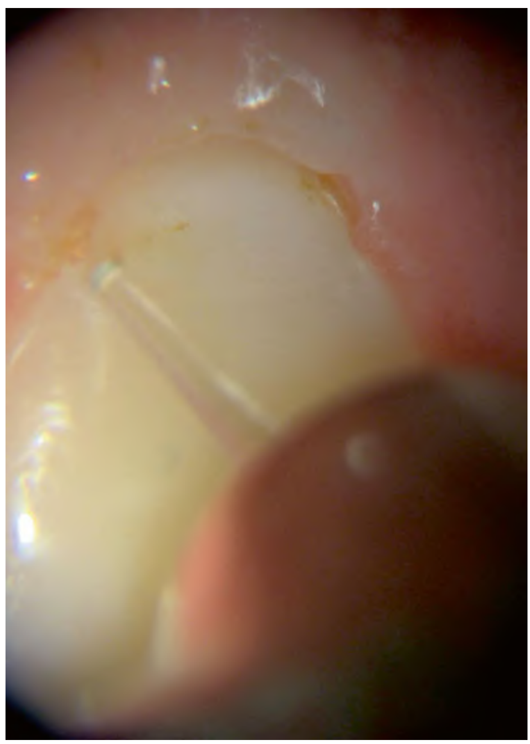

Fig. 7.263 Er,Cr:YSGG laser gingivectomy; note the absence of bleeding during the intervention

Fig. 7.264 A 22-year-old patient with recurrent marginal gingivitis; note a class 5 carious lesion below the gingival margin on upper left central incisor

Fig. 7.265 Er,Cr:YSGG laser gingivectomy completed. The cervical lesion is exposed; because of the correct laser setting and procedure, any bleeding is visible

very deep cavities can involve a partial crown lengthening of both the bone and gingival tissue. Erbium lasers are very effective for this procedure because of the possibility of safe operation on both tissues [83]. Parameters must be changed (shorter pulse duration, higher energy and air-water spray on the bone) in order to have more efficient interaction on one tissue or on the other (Table 7.6).

The lasers in the visible or in the near-infrared spectrum cannot be used for osseous crown lengthening.

As stated, erbium lasers do not allow perfect control of bleeding, and in the case of impression for indirect restoration, they are more suitable with a two-session technique (Figs. 7.277, 7.278, 7.279 and 7.280). In the case of consistent gingival remodelling, the two-session technique with erbium lasers is very reliable, simple and predictable, producing efficient vaporisation on the tissues and quick remodelling of the gingival parabolas with a good response from the tissue in just 5–6 days. In the following session, a decision can be taken about possible reallocation of the margins with additional finishing before the impression. Erbium, chromium:YSGG laser and erbium:YAG lasers are used at 50–75 mJ and 100–120 mJ, respectively, with laser tips of 400 and 600 µm. Erbium lasers can be also used simply for gingival reshaping as a

Fig. 7.266 After gingivectomy Er,Cr:YSGG laser was also used to prepare the class 5 cavity in the same session; immediately after the restoration, the soft tissue shows no sign of thermal damage

Fig. 7.267 One-week follow-up image shows good healing of gingiva

Fig. 7.268 A 35-year-old patient presenting a very complex case, with multiple and deep caries on the posterior upper right quadrant

Fig. 7.269 During the first session the old restorations and caries were removed from the first molar and two premolars

Fig. 7.270 Laser gingivectomy was performed between the two premolars to expose the cavity margins

Fig. 7.271 Gingivectomy permitted placement of the rubber dam, allowing isolation of the premolars and deep caries removal, decontamination and conditioning; note how close is the roof of the pulp chamber of the first premolar (darker area)

Fig. 7.272 The decontamination of deep dentin was followed by placing a liner of calcium hydroxide in the proximity of the dental pulp; an immediate dentin sealing and composite build-up completed the first session

Fig. 7.273 In the following session, the first molar was laser prepared and filled with a direct class composite restoration; the premolars were prepared with high-speed drill for indirect inlay and onlay

Fig. 7.274 Graphic rendering depicts laser gingivectomy to expose the cavity margins of premolars before the impression for indirect restorations. The laser tip is parallel to the long axis of the tooth, working perpendicularly to the gingiva; the lateral side of the laser tip is placed in contact with the enamel of the cervical step of the cavity distal box, which acts as a guide for the laser

Fig. 7.275 Graphic rendering depicts a different approach of gingivectomy from the buccal side and different angulations; working from the buccal or lingual side, it is easy to establish the depth of gingival removal

Fig. 7.276 Immediately post-operative image shows the limited bleeding of the procedure

Fig. 7.277 An immediate impression was taken; note the absence of any blood remaining in the impression

Fig. 7.278 Third session one week later shows the high quality of the gum with improved healing; the teeth are ready for the bonding of indirect restorations

Fig. 7.279 Case completed with direct and indirect micro-hybrid composite restorations

Fig. 7.280 A 23-year-old patient with upper left conoid lateral incisor required an aesthetic treatment of the frontal teeth. The treatment plan involved direct restorations on central incisors and indirect ceramic veneers on lateral; also a laser gingival recontouring of left central incisor was planned (Reprinted with permission from Olivi and Genovese [85])

Fig. 7.282 One-week follow-up shows the good healing of the gum (Reprinted with permission from Olivi and Genovese [85])

Fig. 7.281 After direct restoration a laser gingivectomy was performed with Er:YAG laser. Note on one side (gingiva) the almost complete absence of bleeding and on the other side (tooth) the unwanted interaction of laser beam on the cervical enamel, due to uncorrect angulation of the laser beam at 45–60° towards the gum. A correct angulation involves an inclination almost parallel to the tooth long axe, avoiding any interaction of laser beam with the hard tissue (Reprinted with permission from Olivi and Genovese [85])

completion of restoration in an aesthetic area (Figs. 7.281, 7.282, 7.283 and 7.284).

In contrast, near-infrared and the KTP lasers, in the green spectrum of light, interact selectively with haemoglobin and melanin, the soft tissue target chromophores. A gingivectomy performed with these lasers in continuous wave allows a very precise incision and a perfect control of bleeding. The use of superpulsed parameters at higher power also makes good haemostasis possible. Near-infrared lasers perform a quick and effective troughing of the gingiva, allowing an immediate precise impression in the absence of gingival fluid or bleeding [84]. For this reason, the use of diode lasers in continuous waves at 0.8–1.5 W or in gated mode at 2–2.5 W (ton 10 ms-100 > 1,000 Hz) with fibres of 300–400 µm is advisable for this procedure (Table 7.6).

Fig. 7.283 Three-week follow-up permitted verification of the perfect healing of the gum (mesial and distal area) and the re-mineralisation of the enamel after using fluoride application for 1 week (Reprinted with permission from Olivi and Genovese [85])

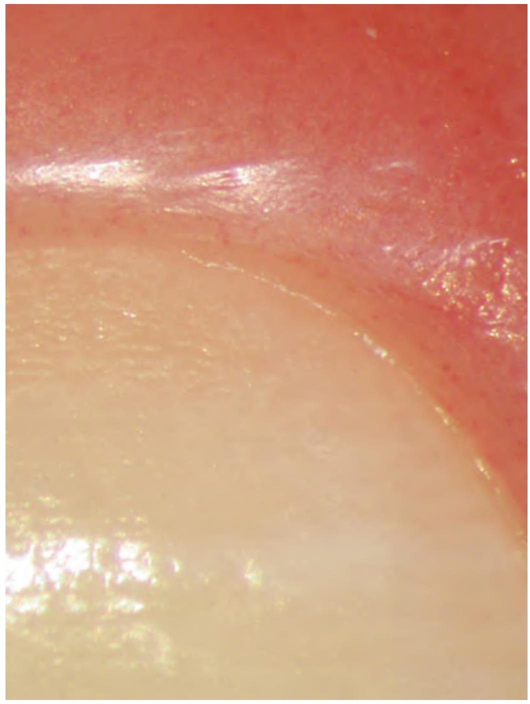

Fig. 7.284 Three-week follow-up permitted verification of the perfect healing of the gum (mesial and distal area) and the re-mineralisation of the enamel after using fluoride application for 1 week (Reprinted with permission from Olivi and Genovese [85])

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8 Laser Applications for Vital Pulp Therapy

Giovanni Olivi and Maria Daniela Genovese

Abstract

The conservation of pulp vitality is one of the objectives of restorative dentistry.

The maintenance of pulp vitality depends on a correct diagnosis of normal pulp or reversible pulpitis and on a correct therapeutic approach. The therapy varies depending on the degree of contamination of the pulp tissue. The interventions include the therapy of dentin hypersensitivity, the treatment of deep dentin caries, the direct pulp capping, the partial pulpotomy, and the apexogenesis (root formation). The erbium lasers greatly improve the decontamination of deep caries and are very useful for dental excavation due to the selectivity of action on carious tissue. Also all the laser wavelengths are used for coagulation of the exposed pulp, so creating the biological bases for the formation of tertiary dentin. Studies from literature are shown and operative protocols are presented by the author.

The conservation of pulp vitality greatly improves the dental prognosis, from both a biomechanical and esthetic point of view [1]; its preservation is one of the objectives in restorative dentistry and can be viewed as the borderline between restorative dentistry and endodontics [1, 2].

The maintenance of pulp vitality depends on the diagnosis of normal pulp or reversible pulpitis versus infected pulp or irreversible pulpitis and a correct therapeutic approach. The therapy varies depending on the patient's symptoms and degree of contamination of the pulp tissue. The diagnosis and procedural decision path is clinical and so mainly subjective.

The interventions include the therapy of dentin hypersensitivity, the treatment of deep dentin caries, the direct pulp capping, the partial pulpotomy, and the apexogenesis (root formation) [3, 4].

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8.1 Dentin Hypersensitivity

Dentin hypersensitivity is a common clinical condition in dentistry. It can affect young and adult patients and more commonly affects the canines and premolars of both the arches. The hypersensitivity is usually characterized by short, sharp pain, starting from the neck of the tooth, in response to different stimuli: thermal (hot and cold drinks and foods), evaporative, tactile (eating, toothbrushing), osmotic (hypertonic solutions such as sugars), and chemical (acid beverage or fruits). The most common trigger is the cold [5] with higher percentage of people with hypersensitivity reporting pain upon application of a cold stimulus or drinking cold beverages [6]. Dentin hypersensitivity can be related or can depend on different types of dental (carious and non-carious cervical lesions) or periodontal defects (gingival recession) associated with exposed dentinal surfaces [7].

The sensitive stimulus is transmitted to the pulp across the dentin through a hydrodynamic mechanism (dentin fluid moving across the tubules, creating a pressure on peripheral nerve endings) [8, 9]. Based on this hydrodynamic theory, it would be possible to hypothesize that teeth exhibiting dentin hypersensitivity should have dentinal tubules open at the root surface and patent to the pulp.

A study from Absi et al., on caries-free teeth with exposed cervical root areas scheduled for extraction, examined by scanning electron microscopy the numbers of tubules per unit area. Hypersensitive teeth showed significantly highly increased numbers of tubules per unit area (approximately 8×) with significantly wider dentin tubule diameters (approximately 2×), when compared to nonsensitive teeth [9].

Over the years, the pulp tissue responds to external biological and chemo-physical stimuli transmitted along the dentinal tubules to the dental pulp, with the production of tertiary dentin and sclerotic dentin, so lessening the symptoms of hypersensitivity (see Chap. 1) [10–13].

According to the hydrodynamic theory and to the patency of dentinal tubules at the cervical site, the treatment of dentin hypersensitivity is based on the closure of the dentin orifices.

Different substances can occlude the entrance of the dentin orifices through several professional applications of different fluoride varnishes or bonding agents.

The use of laser devices has been also proposed to modify the superficial layer of the exposed dentin, occluding the dentin orifices through an organic–inorganic melting of the dentin surface; this thermal effect differs using different wavelength (see Sects. 4.1, 4.9.1 and Figs. 4.66, 4.67; see Sect. 7.5.3 and Figs. 7.45, 7.46). The desensitizing therapy can resolve the symptoms, preventing a chronic pulpal stimulation that when associated to some pathologies is uncomfortable and/or painful and can evolve toward pulpitis [14]; many studies have been indeed performed in patients with periodontal disease where the therapy may be associated to a rise in dentin hypersensitivity during the periodontal maintenance [14–18].

8.1.1 Laser Treatment of Dentin Hypersensitivity

Several studies investigated the ability of laser irradiation to reduce or resolve the dentin hypersensitivity. Cunha–Cruz J (2011) reviewed several articles on laser applications for dentin hypersensitivity, from MEDLINE, Embase, and Cochrane Central Database as well as Cochrane Oral Health Group's Trials Register and National Research Register, and also included studies from specific laser journals. Because of heterogeneity of the studies, a meta-analysis was not performed, and only qualitative synthesis was presented. Eight trials (of 234 participants) met the inclusion criteria; half of the included studies compared diode laser with topical desensitizing agents, but the findings were conflicting. The remaining studies involving Nd:YAG laser, Er:YAG laser, and CO_2 laser all showed the three types of lasers that were superior to topical desensitizing agents, but the superiority was slight. He et al. in the same year (2011) performed another systematic review and the result published was similar.

However, some study seems to be clinically significant to explain the superior ability of lasers for this application.

8.1.2 Diode Laser

Diode laser has been proposed for periodontal treatment for pocket and root surface decontamination and soft tissue vaporization and also to resolve the uncomfortable post scaling dentin hypersensitivity or tooth hypersensitivity. A study reported the complete absence of pain achieved in 86.6 % of patients treated with laser and only in 26.6 % of patients treated with fluoride after the third visit [15]. The association of 2 % sodium fluoride solution (NaF) and diode laser showed a significant reduction of discomfort compared to baseline values immediately posttreatment (82.6 %), after 1 month (69.5 %) and after 6 months (60.8 %). Inferior results were obtained with laser or NaF alone or a solution of hydroxyl-ethyl-methacrylate and glutaraldehyde (HEMA-G: Gluma desensitizer) [16]. Also a significantly greater immediate response was observed when a diode laser was associated to 10 % potassium nitrate gel (NK) after the periodontal therapy [17, 18].

8.1.3 Nd:YAG and Erbium Lasers

Schwarz et al. compared the effect of Er:YAG laser and chemical agents, concluding that desensitizing of hypersensitive dentin with an Er:YAG laser (80 mJ/pulse, 3 Hz) was effective and the maintenance of the positive result was more prolonged than with polyurethane-isocyanate (22.5 %) and methylene chloride (77.5 %) (Dentin Protector, Vivadent, Germany) [19].

Two in vitro studies compared the Er:YAG and the Nd:YAG laser; the lower energy (60 mJ, 2 Hz) of Er:YAG laser reported higher decrease of dentin permeability than Nd:YAG laser (1.5 W, 15 Hz), also if with no statistical difference between them (26.05 % versus 19.03 % of cases) [20]. In vivo, the Nd:YAG laser (1 W, 15 Hz, 60 s, two times) resulted in a significant reduction of VAS score at each follow-up examination when compared to Er:YAG laser (100 mJ, 3 Hz, 60 s, two times) [21]. This study concluded that Nd:YAG laser was more effective than Er:YAG laser in reduction of patients' pain.

Here we have to highlight the higher energy of the Er:YAG laser and the lower energy of the Nd:YAG used in vivo, compared to the parameters used in the in vitro study, and the related results: whatever the wavelength used, higher success rate was associated to the lower energy used.

However, some study reported equal improvements comparing the status before and 6 months after treatment using the Er:YAG laser and a glutaraldehyde-based desensitizing system (Gluma) [22] or the Nd:YAG laser and fluoride varnish [23], but in this case, a significant improvement of discomfort relief immediately after treatment and after 1 week was found.

8.1.4 Operative Procedure

The use of near-infrared lasers (diode and Nd:YAG) for periodontal applications is very common. Beside the antibacterial and coagulating action, these lasers are very helpful at the end of the procedure to prevent dentin hypersensitivity.

If it is not performed immediately after the periodontal session, but in a following one, the procedure is preceded by teeth polishing in order to have a clean surface to be treated. The dental arches are first isolated with a mouth opener; a NK or NaF gel/varnish is applied on the teeth surfaces, and laser irradiation is performed with very low energy, in defocused mode (1 cm far from the surface) and scanner modality in 30 s for each tooth. After the irradiation, the fluoride gel remains on the teeth for 5 min and after that the gel is sucked and the patient is advised not to rinse the mouth for 1 h. The procedure can be repeated after 15 days if needed (Figs. 8.1 and 8.2).

Chronic hypersensitivity requires a follow-up visit after 6 months, possibly including another desensitizing laser session at time, due to the transient period of desensitizing action. Laser settings suggested from the author are commonly very low and safe and enable a gentle heating of the irradiated surface, the precipitation of the K and F ions, and a minimal thermal interaction of the wavelength with the dentin; as a result, dentin

Fig. 8.1 After a periodontal session, a topic fluoride gel is applied on the teeth surface

Fig. 8.2 Defocused and scanning mode

tubule orifices are closed through an organic–inorganic melting including the K and F ions.

Diode laser setting is 0.4 W in continuous wave with a non-activated 400-μm fiber.

Nd:YAG laser setting is 0.75 W, 15 Hz, always with a non-activated 400-μm fiber.

Er:YAG and Er,Cr:YSGG are used at 25 mJ, 10 Hz, with a 600-μm tip and with water spray off and air spray on.

8.2 Deep Dentinal Caries

As previously discussed (see Sects. 7.5.1, 7.5.2, and 7.5.3), treatment of the deep dentin at the completion of cavity preparation is an important step for maintaining the pulp vitality.

The identification and removal of the deeper layers of caries are clinically subjective to perform, and concern about the survival of microorganisms in deep carious lesions may often lead to unnecessary over-excavation in healthy dentin, with exposure of the pulp during complete caries excavation [24].

To minimize this risk, conservative caries removal techniques have been proposed, including indirect pulp capping, partial removal, and stepwise excavation [25, 26]. The differences and borders among these techniques are minimal.

Indirect pulp capping is defined by Ingle as a procedure where a small amount of carious dentin is retained in deep cavity to avoid exposure of pulp, followed by the application of calcium hydroxide on the deep carious dentin in proximity to the pulp in order to stimulate the formation of reparative dentin [27].

Lately, also new technologies, including among the other, chemomechanical preparation and laser, have been investigated for this purpose [4, 28].

8.2.1 Carious Removal Rationale

Different caries removal techniques have been proposed to challenge the doctrine of complete caries removal. The rationale of these techniques considers the composition and changes of carious dentin, the decrease of bacteria load during excavation, and the formation of the tertiary dentin.

Carious dentin consists of two main distinct layers:

- An outside layer that is irreversibly denatured and infected; it is not remineralizable and should be removed.
- An inside layer that is reversibly denatured, not infected, and remineralizable and should be preserved.

Deep dentin treatment is focused on changing an active lesion into a less active or arrested lesion, even without performing an excavation close to the pulp [29], thus promoting the pulpodentinal complex to form tertiary dentin [30].

However, it must be emphasized that the final excavation step of the less softened dentin closer to the chamber roof is critical.

8.2.2 Indication

When a patient has negative history for pain, a tooth has no clinical symptoms, if not a transient pain shortly before treatment, and the intraoral radiograph reveals carious lesions to such a depth that a complete removal of caries would probably cause a pulp exposure, a stepwise excavation or an indirect pulp capping may be suggested.

In a clinical–microbiological study, the stepwise excavation technique was carried out on several patients with deep caries and negative history for pain; the outer layer of carious dentin was found typically orange colored; 6 months after excavation, a calcium hydroxide-based medication, and ZOE temporary filling, the dentin color changed to dark brown in the central inner layer when starting the second session, to finally resemble the color of the completely excavated peripheral dentin at the end of the excavation [24, 31]. Also the consistency of dentin changed, with enhanced hardness of the dentin, associated with a marked reduction in bacterial growth after the final excavation; the study suggested that the initial removal of the cariogenic biomass appears to be essential for control of caries progression [24]. At the second excavation, both stepwise excavation and partial carious tissue removal presented lower pulp exposure rates and higher success rates than complete carious removal [24, 32–34].

Several clinical trials have demonstrated the benefits of incomplete caries removal, in particular in the treatment of deep caries, and based on the reviewed studies, incomplete caries removal seems advantageous compared with complete excavation, when in proximity to the pulp, also leading to a reduced need for the direct pulp capping [32–36]. However, there is no consensus in the literature about which is the better technique [37], being the main difficulty, to understand when the excavation must be stop.

8.2.3 Laser Treatment of Deep Dentin

All the laser wavelengths allow for deep decontamination in the outer and inner dentin layers [38], but it is the full cavity preparation performed with the erbium family lasers that offers several advantages [4, 39, 40] that can play a fundamental role in the treatment of deep dentin caries, as specifically reported in Table 8.1.

Using the erbium lasers, whether the choice is an indirect pulp capping or stepwise excavation or complete caries excavation, the laser-assisted technique makes the procedure much more predictable, as the erbium lasers are more selective for carious tissue (see Sect. 7.5), thus allowing complete caries vaporization while preventing possible unwanted pulp exposure and detoxifying the surface up to 300–500 μm [41, 42] (see Sects. 7.5.1 and 7.5.3), so ensuring a deeper decontamination in dentin (Figs. 8.3 and 8.4).

During laser cavity preparation, the complete caries removal is performed at 150 mJ or less, at 15–20 Hz, with short pulse duration (100–300 μ) and air/water spray on; the final decontamination of the dentin surface must be performed carefully to avoid damage to the pulp and performed at lower energies of 70–80 mJ at 10 Hz (100-μ pulse duration), in focused mode and with water spray. The seal of the deep dentin area close to the pulp, called also dentin melting, allows the prevention of postoperative sensitivity and is executed in a defocused mode at 25 mJ, 10 Hz,

Table 8.1 Erbium laser advantages in deep dentin treatment

Advantages	Hazards
Selective carious dentin removal, saving more healthy dentin to be ablated	Operative hazard
Deep decontamination of the irradiated surface	Microbiological hazard
Clean surface and reduced possibility of dislodging infected dentin chips into the pulp	Microbiological hazard
Reduced heating of the pulp during laser cavity preparation	Physical hazard

Fig. 8.3 Fracture of buccal cuspid of an upper premolar with deep decay underlying an old, fractured composite filling (Reprinted with permission from Olivi et al. [3])

Fig. 8.4 Before placing the rubber dam, the old filling is removed and the gross dentin decay is removed by Er:YAG laser; also a minimal marginal gingivectomy is performed in order to place the proximal margin above the gum (Reprinted with permission from Olivi et al. [3])

Fig. 8.5 Decontamination and final melting of the deep dentin surface is performed by Er:YAG laser at 25 mJ, 10 Hz (Reprinted with permission from Olivi et al. [3])

Fig. 8.6 A first layer of calcium hydroxide is applied as capping material (Reprinted with permission from Olivi et al. [3])

Fig. 8.7 A second layer of calcium hydroxide is applied after the hardening of the first one and then is burnished on the dentin to allow a better sealing (Reprinted with permission from Olivi et al. [3])

Fig. 8.8 Dentin immediate sealing and composite buildup guarantee an hermetic seal (Reprinted with permission from Olivi et al. [3])

short pulse duration (100–300 μs), with air on to cool the operative field (no water or low air–water spray), for 5 to 10 s (Fig. 8.5); the application of a bioactive liner (calcium hydroxide, MTA, or Biodentine) and an immediate composite filling complete the procedure, allowing for an hermetic seal of the cavity (Figs. 8.6, 8.7, 8.8, 8.9, and 8.10).

The final decontamination procedure, but not the caries vaporization, is also possible with all the other laser wavelengths used in dentistry (see Chap. 4).

Fig. 8.9 Indirect composite restoration is bonded (Reprinted with permission from Olivi et al. [3])

Fig. 8.10 The 1-year intraoral x-ray shows a good sealing and the absence of apical translucency (Reprinted with permission from Olivi et al. [3])

If during the procedure a pulp exposure occurs, a laser direct pulp capping can be performed: if the diagnosis has been correct, the exposure is minimal, the surrounding area is clean and decontaminated, and the erbium laser makes also this procedure more predictable (Figs. 8.11, 8.12, 8.13, and 8.14).

If the choice is a stepwise technique, the operator, after an initial removal of the gross carious dentin mass using both a hand excavator

Fig. 8.11 Carious infiltration around old amalgam filling

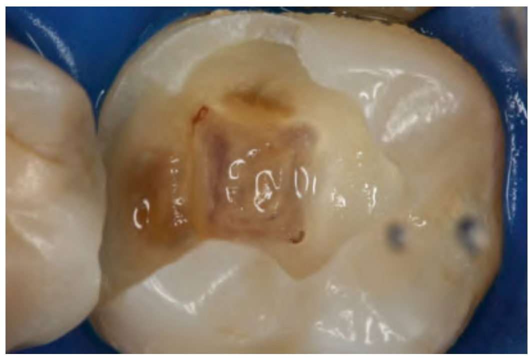

Fig. 8.12 Filling and carious removal performed with high speed drill: after cleaning the bottom of the cavity with sodium hypochlorite, multiple micro pulp exposures occur; also visible is the roof of the chamber

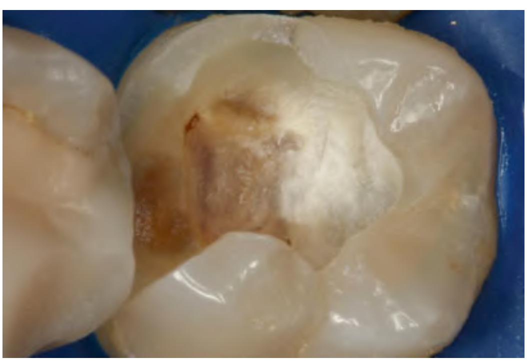

Fig. 8.13 Er:YAG laser decontamination and conditioning; also partial melting is performed on deep dentin surface

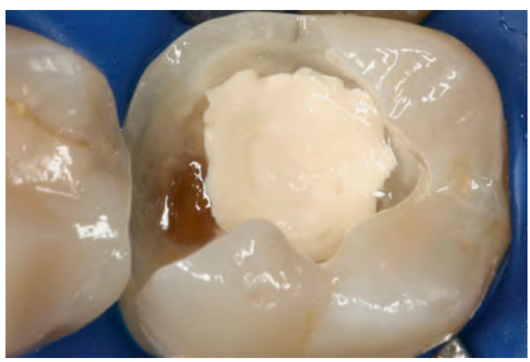

Fig. 8.14 Pulp capping is performed with two layer of self hardening calcium hydroxide

and a laser, has to partially remove the inner caries layer, avoiding to dig deep the dentin surface, thus avoiding the pulp exposure; lower energy is required for carious tissue, and the operator has to check the better energy to use in a range of 150 mJ up to 100 mJ. After a final laser decontamination at 75 mJ, 10 Hz on the inner dentin layer, the application of a calcium hydroxide medication and an hermetic temporary sealing (glass ionomer cement or Biodentine) in order to stimulate the formation of reparative dentin complete the first session. After 4–6 months during the second session, the liner material must be carefully removed, and the underlying dentin must be checked with a probe and an excavator; then a final laser decontamination is performed before the final restoration. If at this stage a pulp exposure occurs, a root canal therapy has to be considered.

8.3 Direct Pulp Capping

Traditional definition of S. Cohen and R. C. Burns [43] described pulp capping as “the application of a medicament or dressing to the exposed pulp in an attempt to preserve vitality.”

Ingle’s [27] defined the direct pulp capping as “the protection of a pulp exposed for trauma to the anterior teeth, accidental mechanical exposure during tooth cavity preparation or deep dentinal decay.”

These definitions identify the indications for this therapy that are schematized in Table 8.2.

A review of the international literature shows how the different success rates of the pulp-capping procedures are related to various clinical situations that led to the exposure. High success rate was found in the treatments performed for trauma to the anterior teeth [44–46] or accidently during mechanical preparation [47], all conditions with lower bacterial component than the posterior teeth treated for deep caries [2, 45].

Historically, direct pulp capping after exposure during caries excavation has been considered controversial, and instead, conventional endodontic therapy has been recommended in this case [47–49]; indeed, when bacterial by-products induce pulpal inflammation, compromise immune responses, and impede cellular differentiation and recruitment, normal pulpal repair mechanisms may not function properly.

The success of pulp capping basically depends on the proper diagnosis of reversible pulpitis before treatment [4, 50]; however, a definitive pulpal diagnosis is often difficult to establish [51].

8.3.1 Indication, Diagnosis, and Prognosis

Matsuo et al. analyzed the relationships between the success rates of pulp capping to carious exposed pulp and some clinical findings and found that the age of the patients, type of teeth, responses to thermal stimuli and percussion, and diameter of pulpal exposure had no influence on the success rate, while the degree of bleeding was indicative of the prognosis of this treatment. He found that the success rate of the study was 81.8 % and also estimated the length of time necessary for adequate postoperative follow-up to be 20–24 months [52].

Table 8.2 Indication for direct pulp capping

Pathology	Time	Exposure size	Exposure site	Degree of bleeding
Recent dental trauma	24 h	~ 1 mm		Limited, red
Mechanical exposure during cavity preparation	Immediate filling	~ 1 mm	Occlusal	Limited, red
Exposure during deep caries excavation[a]	Immediate filling	~1 mm	Occlusal	Limited, red

[a]In this case, a partial pulpotomy can be considered
~ means about

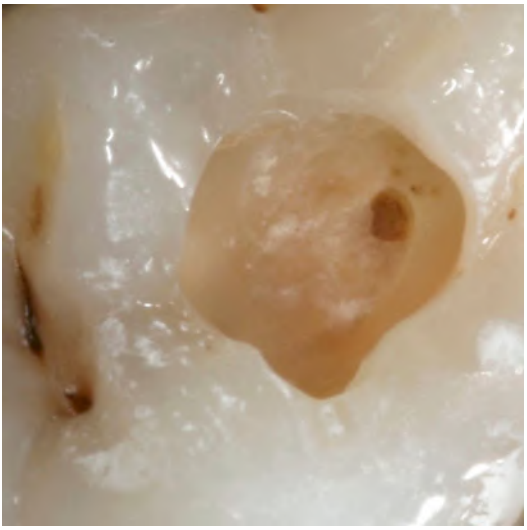

Fig. 8.15 Upper molar shows minimal occlusal pulp exposure; the pulp is not visible, probably pulled back for a chronic inflammation process. Pulp capping is not advisable

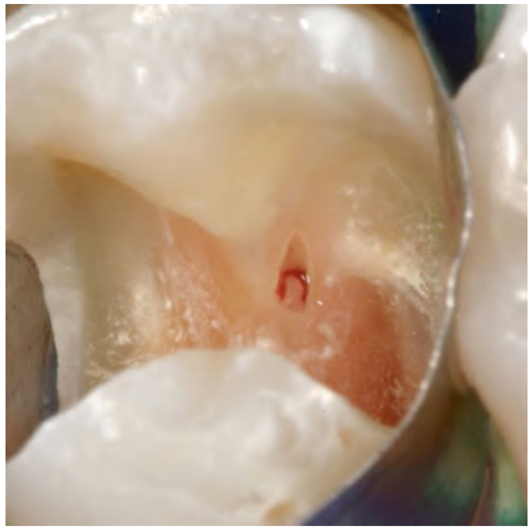

Fig. 8.16 Upper premolar shows occlusal pulp exposure; the appearance of the pulp tissue is vital, no bleeding

Barthel et al. [11] determined other factors that might have an influence on the success rate of the therapy, such as the type of capping agent, type of restoration, and site of exposure.

They found that the placement of a definitive restoration within the first 2 days after pulp exposure is a factor of influence to contribute significantly to the survival rate. Results showed 44.5 % failures after 5 years and 79.7 % failing after 10 years [11].

Also Al-Hiyasat et al. determined that the success was associated more with mechanical exposure than with carious exposure (92.2 % versus 33.3 %). Permanent restoration had a better outcome than temporary restoration (80.8 % versus 47.3 %) and more with class 1 occlusal restoration (83.8 %) than with proximal multiple surface restorations (class 2, 56.1 %; class 3, 58.8 %; mesial-occlusal-distal restoration, 28.6 %) [49].

It is possible to summarize the contraindications for pulp capping in carious teeth, when the following preoperatory symptoms and intraoperatory signs are present:

- Preoperatory symptoms
  - Decay associated to a recent or past history of spontaneous or recurrent or nocturnal pain
  - Thickening of the periodontal ligament at the level of the apex observed radiographically
- Intraoperatory signs
  - Extensive pulp exposure (>1 mm diameter)
  - Inflamed or necrotic appearance of pulp tissue at microscopic observation (Figs. 8.15, 8.16, 8.17, and 8.18)
  - Abundant bleeding after exposure which does not resolve after 1–2 min that confirms the inflamed status of irreversible pulpitis
  - Site of the exposure on the axial wall of proximal decay that may be a concern because of the large extent of pulp tissue involved in the inflammation

In these instances, even partial pulpotomy must be carefully considered.

Table 8.3 reports clinical contraindications for pulp-capping procedures in permanent carious teeth.

Fig. 8.17 Accidental pulp exposure during inlay cavity preparation with mechanical instruments in an upper molar; the pulp appears vital, with no bleeding

Fig. 8.18 Upper molar with occlusal pulp exposure: note the clear color of predentin around the pulp exposure. The pulp appears vital with no bleeding

Diagnostic tests and examinations to establish a correct diagnosis and outcome are:

- Objective examination; intraoral examination (color, tumor), evidence of lack of mobility, and pain at percussion are also important diagnostic elements.
- Intraoral radiographic examination to assess the degree of the pulp exposure and verify the absence of a thickened periodontal ligament at the apex.
- Electrical and thermal tests (cold and hot).

Also a laser Doppler flowmeter (LDF) has been studied in recent years and found very effective in detecting the revascularization of damaged pulps following traumatic injury or dental caries, compared to other procedures such as electric pulp testing [53–55].

In case of dental trauma, beside the other diagnostic data, the decision path on the treatment plan to be followed includes the time between trauma and therapy, the size of pulpal exposure, the type of bleeding, and the appearance of the pulp to a microscopic examination (Figs. 8.19, 8.20, 8.21, and 8.22). Table 8.4 reports the indications for pulp therapy in case of complicated dental trauma.

Table 8.3 Contraindication for pulp capping in carious teeth

Preoperatory symptoms	Decay associated to pain
	Thickening of the periodontal ligament at the level of the apex at x-ray
Intraoperatory signs	Extensive pulp exposure (>1 mm diameter)
	Inflamed or necrotic appearance of pulp tissue
	Abundant bleeding after exposure which does not resolve after 1–2 min
	Site of the exposure on the axial wall of proximal decay

8.3.2 Laser for Operative Field Control

Among the innovative techniques proposed to halt the carious process and promote the repair of potentially damaged tissue, the use of laser has proved to be highly effective, thus improving the survival rates when compared to the conventional techniques [1, 2, 56–64].

If a correct diagnosis is performed and the pulp is affected by a hyperemia or a reversible pulpitis, the positive effects of the laser irradiation can create the biological base for the

Fig. 8.19 Diagram of small pulp exposure (1 mm) in upper incisors for complicated dental trauma

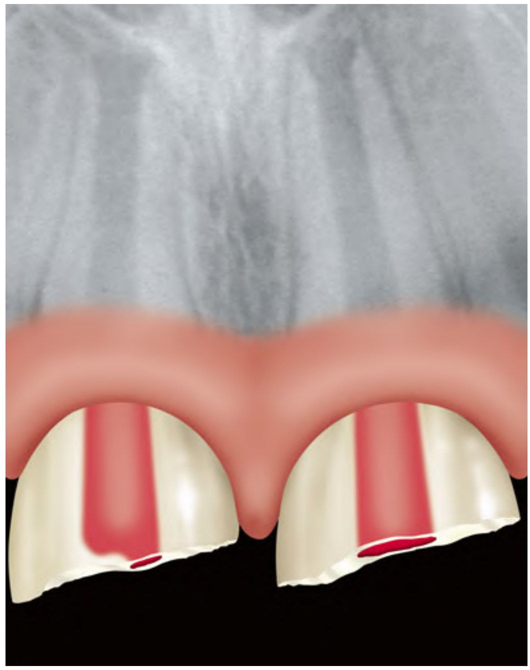

Fig. 8.20 Diagram of larger pulp exposure (1 > 2 mm) in upper incisors for complicated dental trauma

Fig. 8.21 Diagram of pulp capping in upper incisors for complicated dental trauma

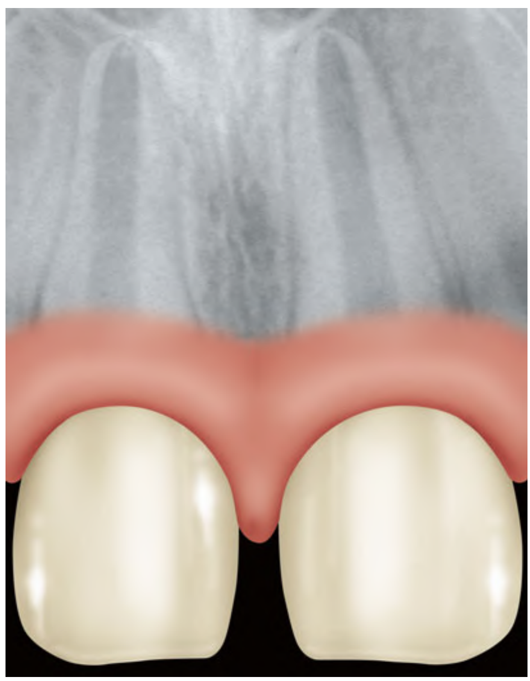

Fig. 8.22 Diagram showing root maturation after pulp therapy for complicated dental trauma (Reprinted with permission from Olivi et al. [4])

Table 8.4 Pulp therapy in complicated dental trauma

	Pulp capping	Pulpotomy		Pulpectomy
Exposure size	Smaller <1 mm	Smaller <1 mm	Larger >1 mm	Small or large
Time between trauma and therapy	Within 24 h	Within 48–72 h		>72 h
Quality of bleeding Pulp appearance	Serum, bloody, red color Pink color	Bloody, red color Red color		Bloody, dark red color, pus Gray color
Symptoms	None	None		Painful (pulpitis) None (necrosis) Tumor (abscess)

development of the healing process, conditioning the operatory field through a deep decontamination and an effective coagulation; finally, a pulp-capping material can promote the formation of a dentinal bridge. An immediate filling is a mandatory condition to maintain these conditions.

Laser-assisted pulp capping (LAPC) decontaminates the exposed area, superficially or more in depth, depending on the wavelength used and coagulates the pulp, leaving a dry site very suitable for a capping material; according to Matsuo et al., a good hemostasis increases the success rate of the procedure [52] (Figs. 8.23, 8.24, 8.25, and 8.26).

Moreover, the irradiated and coagulated pulp presents an amorphous necrotic superficial layer that avoids any direct contact of whatever capping material with underlying vital pulp, making the choice for the liner wider.

When erbium chromium or erbium lasers are used for the complete procedure including the cavity preparation, the other advantages of the erbium laser [4, 39, 40] are the reduced heating in the pulp during the cavity preparation [65, 66] and the reduced intra-chamber pressure during the vaporization of deep carious dentin layers that leads to a reduced possibility of accidental misplacement of infected chips in the pulp chamber [2, 27].

When erbium lasers are not available and only the near-infrared (diode and Nd:YAG) and infrared (CO_2) lasers can be used, the cavity is prepared with conventional mechanical technique, and these lasers allow only decontamination of the cavity and coagulation of the exposed pulp.

According to other studies [11, 49], an hermetic seal of the pulp exposure and an immediate permanent filling after the pulp capping allow for a superior success rate; an hermetic pulp–dentin interface seal ensures the maintenance of the decontamination and, at the same time, stimulates the formation of tertiary dentin which will enhance the healing of the treated tooth.

Clinicians have used many materials for direct pulp capping, including calcium hydroxide, hydrophilic resins, resin-modified glass ionomer cements, and, more recently, mineral trioxide aggregate (MTA) and tricalcium silicates (Biodentine™).

8.3.3 Pulp-Capping Agents

8.3.3.1 Calcium Hydroxide

Calcium hydroxide (CH) has been used for many years for pulp-capping procedures [67]. Long-term studies on the use of calcium hydroxide-based preparations (nonhardening suspensions and hardening cements) have shown variable results that are somewhat unpredictable [11, 46, 51, 68]. The fact that the material does not provide close adaptation to dentin can result in limited odontoblast differentiation and reparative dentin formation within dentin bridges, characterized by tunnel defects [69–71]; tunnel defects may provide a pathway for the penetration of microorganisms that induce pulpal irritation and produce subsequent dystrophic calcification [70]. Although calcium hydroxide does not have the ability to properly seal the pulpal site, it has been used in one-visit tooth restoration when used in

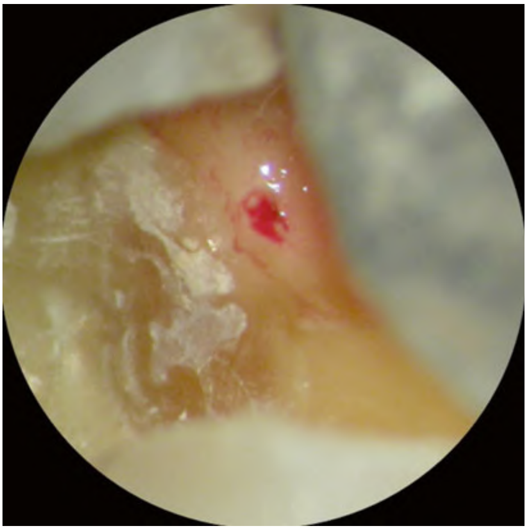

Fig. 8.23 Pulp exposure for deep decay after cavity preparation (Reprinted with permission from Olivi et al. [4])

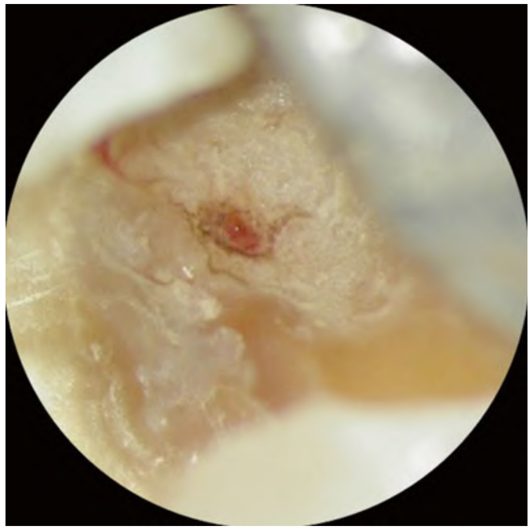

Fig. 8.24 Er:YAG laser coagulation with a 600-μm tip for 5–6 s at 30 mJ and 3 Hz in defocused mode with air cooling but no water (original magnification ×40)

Fig. 8.25 Upper molar shows a pulp exposure for deep decay at the end of cavity preparation

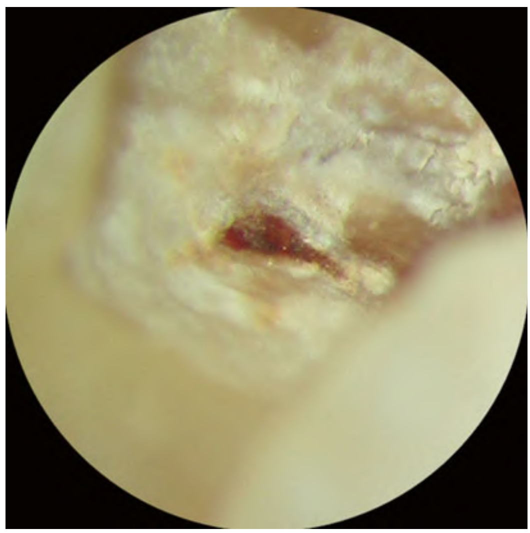

Fig. 8.26 Er,Cr:YSGG laser coagulation with a 600-μm tip, at 25 mJ, 10 Hz, water off

combination with amalgam or adhesive composite materials for an immediate sealing [4]. On the other hand, a scanning electron microscopic ultrastructural study by Goracci and Mori evaluated the resin–dentin and calcium hydroxide–dentin interface with resin composite restorations and indicated that polymerization shrinkage of the resin composite caused the separation of the calcium hydroxide from the dentinal surface, forming 8- up to 15-μm-wide interfacial gaps in 100 % of the areas studied. This finding confirmed that pulpal inflammation after calcium hydroxide use may be associated to the microleakage of restorations and to the subsequent transit of bacteria [72]. Accordingly, the research has been directed toward materials which are much more adherent to dentin and stable over time.

8.3.3.2 Adhesive Systems and Glass Ionomer Cement

The use of dentinal adhesives [73–75] and even of glass ionomer bases [76, 77] in direct contact with the pulp tissue has been evaluated in numerous studies, and results were inconsistent.

8.3.3.3 Mineral Trioxide Aggregate

Mineral trioxide aggregate (MTA) is a bioactive silicate cement that has been shown to be an effective pulp-capping material in nonhuman models and human in vivo studies [78–80]. The small particle size, the sealing ability, the alkaline pH when set, and the slow release of calcium ions are all favorable factors for pulp capping [81]. Numerous studies demonstrated the absence of cytotoxicity of the MTA when in contact with fibroblast and osteoblast cultures [82] as well as

Fig. 8.27 Panorex showing a left lower molar of young patient with immature apex. The molar presents a decay underlying an old filling

Fig. 8.28 Nine months intraoral radiograph shows the maturation of the apices in progress and maintenance of pulp vitality after pulp capping performed with Er:YAG laser, using Biodentine™ as capping material and composite as filling

the stimulation of dentin bridge formation when used for direct pulp capping [81, 83].

If compared to the use of CH, the application of MTA ensures a more hermetic and lasting seal and therefore the formation of a more compact and thicker dentin bridge that do not include fibrotic tissue. Negative factor is that MTA requires a longer time to harden and the completion of the restoration requires a second session after 48–72 h that can be a problem in case of esthetic restorations in anterior teeth.

8.3.3.4 Biodentine

A new tricalcium silicate-based cement (Biodentine™), composed mainly of a tri- and dicalcium silicate powder and an aqueous calcium chloride solution, has been recently introduced, and several studies demonstrated its tissue compatibility [84, 85]; Biodentine allows the formation of mineralized dentin bridge after pulpotomy that has similar morphology and integrity to those formed with the use of MTA [86].

Tricalcium silicate is also the main component of MTA and Portland cement; in addition to their biocompatibility, all these types of material are known to be biologically active (bio-active) [87].

During the setting phase of Biodentine, calcium hydroxide ions are released from the cement, resulting in a pH of about 12–12.5 and a basification of the surrounding area. This high pH inhibits the growth of microorganisms and can disinfect the dentin. Biodentine is not soluble, not moisture sensitive, not absorbable, and safe and has good radiopacity. The setting time is only 12 min that allows a restoration to be completed in one visit. On the opposite of dark MTA, it does not stain, and there is no need of surface preparation due to the micro-mechanical anchorage; it also showed higher shear bond scores compared to MTA when used with composite [88].

The physical properties of Biodentine™, the elasticity modulus, and the pressure resistance are comparable with dentin and are higher than those of MTA and calcium hydroxide (Dycal, Dentsply or Life, Kerr) [89]; however, Biodentine™ is not suitable for a permanent enamel replacement (Figs. 8.27 and 8.28). Table 8.5 summarizes the different properties and characteristic of the capping agents.

Table 8.5 Pulp-capping materials: $Ca(OH)_2$, MTA, and Biodentine

	Calcium hydroxide	Mineral trioxide aggregate	Biodentine
Biocompatibility	Biocompatible	Biocompatible	Biocompatible
Seal	Suboptimal seal	Optimal seal	Optimal seal
Solubility	Soluble and resorbable	Non-soluble and non-resorbable	Non-soluble and non-resorbable
Action over time	Time-limited effect	Prolonged effect over time leads to formation of a more apical dentin bridge	Prolonged effect over time
pH	10.5–12.5	12.5	12–12.5
Bacteriostasis	Bacteriostatic	Bacteriostatic	Bacteriostatic
Tertiary dentin	Promotes the formation of tertiary dentin	Promotes the formation of tertiary dentin	Promotes the formation of tertiary dentin
Operative field	Needs a dry field	Needs a wet field	Needs a dry field
Restoration	Allows immediate restoration	Needs time to harden, the restoration is differed	Allows immediate restoration Setting time 12 min
Mechanical properties	Soft, needs a double layer and a covering layer prior the filling material	Hard, needs a filling material in a second session 48–72 h later	Hard, similar to dentin; can be used as a base or temporary filling
Removability	Easy to remove	Difficult to remove	Easy to remove
Price	Economical	Expensive	Intermediate
Color	Does not pigment the tooth	Dark gray material can pigment the tooth	Dentin color
Reliability	Predictable, tried and tested for many years	Predictable, tried and tested in the last years	Relatively new material

Fig. 8.29 Minimal pulp exposure during deep class 1 cavity preparation (original magnification ×40) (Reprinted with permission from Olivi et al. [4])

Fig. 8.30 Pulp capping is performed with a 810-nm diode laser in defocused mode, for 5 s at 0.6 W in CW: note the layer of superficial charring (original magnification ×40) (Reprinted with permission from Olivi et al. [4])

8.3.4 Laser-Assisted Pulp Capping

8.3.4.1 Neodymium:YAG Laser

In 1999, a retrospective study by Santucci on 94 permanent teeth, treated with Nd:YAG laser-assisted pulp capping also using a glass ionomer base (Vitrebond, 3M), showed a success rate of 90.3 % at 54 months against the 43.5 % of the group treated with self-hardening calcium hydroxide alone (Dycal, Dentsply or Life, Kerr) [58].

Neodymium:YAG (1,064 nm) laser is well absorbed by hemoglobin and scarcely by water so that the interaction with dentin is purely thermal and ineffective for carious removal; thus, cavity preparation must be performed with mechanical rotative instruments, and the laser can only be used for the final decontamination and coagulation of the exposed pulp.

Due to its deep tissue interaction, it is advisable to reduce the emitted energy during cavity decontamination (75 > 50 mJ, 10 Hz, 100 µs) and coagulation of tissue which may otherwise cause necrosis of the pulp (100 mJ, 10 Hz, 300 µs). Irradiation must be carefully performed in a defocused mode, with a 400-µm fiber and under magnification; the microscopic examination allows for better observation of the laser–tissue interaction.

8.3.4.2 Diode Laser

Lately, few studies have been published on peer-reviewed journal about the use of diode laser in pulp-capping therapy. Cannon et al. compared, in an animal study, the antibacterial hemostatic effects of three different therapies and reported significantly less inflammation using a 810-nm diode laser compared to chemical coagulating agents (ferric sulfate, chlorhexidine, and diluted formocresol solution) [63].

Also a pilot clinical study from Yazdanfar et al. has proved the 810-nm diode laser-assisted procedure to be more effective than the conventional technique in enhancing the outcomes of pulp-capping therapy for carious exposures [64].

The diode lasers (from 810 nm up to 980 nm) are well absorbed by hemoglobin and are well suited for cavity decontamination and coagulation of the exposed pulp.

After preparing the cavity with mechanical rotative instruments, the author proposes the use of laser to decontaminate in defocused mode the exposed surface using a 400-µm non-activated fiber at 1 W, pulsed emission ($10ms_{ton}$ $10ms_{toff}$); the exposed pulp is then irradiated and coagulated (after fiber activation) for 5–10 s (or less, stopping the irradiation when the area appears coagulated) at 0.4–0.5 W in continuous wave (cw) and defocused[1] mode, while controlling, through the use of magnification, the optimal distance which will ensure a more superficial tissue interaction (Figs. 8.29 and 8.30).

8.3.4.3 CO_2 Laser

In 1998, Moritz et al. presented two studies using pulsed CO_2 lasers and reported success rates of 93 % and 89 % compared to the control group which used traditional methods with calcium hydroxide [56, 57]. The proposed protocol used the laser at a 1-W power per 0.1 s with 1-s intervals between each application; the protocol was repeated until hemostasis and coagulation of the exposed pulp were achieved.

Suzuki et al., in animal study, also investigated the role of CO_2 laser for direct pulp capping, associated with various experimentally developed adhesive resin systems as capping agents [90, 91]. A power output of 0.5 W was used, in superpulse mode (pulse duration, 200 μs; interval, 5,800 μs; 0.003 J/pulse), with cycle of 10 ms irradiation; 10 ms interval; in defocused mode (approximately 20 mm) for 3 s (total applied energy of 0.75 J), and with air cooling. The use of CO_2 laser irradiation was effective in arresting the pulp hemorrhage but showed a tendency to delay reparative dentin formation compared with the calcium hydroxide group.

Also Nammour et al. used an animal model to investigate the efficacy and effectiveness of CO_2 laser [61]; laser irradiation at 3 W, 0.1 s pulse duration, 1 Hz, 0.3 mm spot size, and energy density of 425 J/cm^2 was used for coagulation and calcium dihydroxide as capping agent.

The CO_2 lasers (from 9,300 nm up to 1,060 nm) are well absorbed by water and hydroxyapatite. The coagulation obtained with a CO_2 laser is very effective and stable in the time, and also the newer wavelength 9,300 nm is proposed today for both hard and soft tissue ablation. However, since today, the use of the CO_2 laser also needs a traditional mechanical cavity preparation with rotating and manual instruments.

8.3.4.4 Erbium Laser

Olivi and Genovese in a clinical study reported a success rate of 80 % after 4 years using an Er,Cr:YSGG laser and calcium hydroxide as capping agent for pulp capping in posterior decayed teeth [1]. Criteria of success were the absence of symptoms and absence of apical translucency at x-ray examination. Olivi et al. in another follow-up study compared also the use of two different erbium lasers (erbium,chromium:YSGG laser and erbium:YAG laser) and calcium hydroxide, with the traditional technique of calcium hydroxide alone [2]. The 4-year follow-up showed no significant difference between the two laser groups (success rate was 80 % for the Er,Cr:YSGG group and 75 % for the Er:YAG); the traditional calcium hydroxide group showed significantly lower success rate (63 %). Also, the two laser groups did not show significant differences between the adult and adolescent groups, suggesting the beneficial use of the laser-assisted technique in adult patients.

The erbium lasers are highly absorbed by water. Erbium laser leave the dentin and pulp surface very, very clean. The decontamination ability of these lasers is inferior to that of the near-infrared laser, but easier and safer to perform. Also the coagulating capacity of erbium lasers is lower than that of other wavelengths but sufficient to guarantee a dry oper-

> The guidelines proposed by the authors also consider the safe use of low erbium laser energy that is emitted in defocused mode, with short time of irradiation (max 10 s, in case repeated). With regard to pulp coagulation, when possible, the preference falls into short pulse duration or intermediate pulse duration, to better control the pulp heating. The authors considers the erbium lasers (2,780 nm and 2,940 nm), the first choice for the vital pulp therapy (including pulp capping and pulpotomy).

[1] Defocus mode is a term that indicates a working distance where the laser spot is not at focus; consequently, the fluence decreases as a function of the distance. For pulp coagulation, the author suggests to use the lowest energy available and to start the irradiation from 1 cm far from the surface, slowly focusing toward the surface and the fiber/tip until the wanted effect is visible; stop when the correct working distance is found.

Table 8.6 Clinical parameters for vital pulp therapy

	Er,Cr:YSGG				Er:YAG			
	Energy	Pulses/s	Pulse duration	Spray	Energy	Pulses/s	Pulse duration	Spray
Partial pulpotomy	120–150 mJ	15 pps	140 µs	On	120–150 mJ	15 pps	300 µs	On
Pulp coagulation	10–15 mJ	10 pps		Water off Air on	5–10 mJ	15 pps	100 µs	Water off Air on
Dentin sealing (melting)	25 mJ	10 pps		Water off Air on	10–25 mJ	15 pps	100–300 µs	Water off Air on

ating field, with no bleeding. The formed coagulated area is more superficial than that which is created with other wavelengths or when a chemical pulp-capping agents are used; this allows the development of a more coronal dentinal bridge. Experimental animal studies conducted by Jayawardena et al. using the erbium:YAG laser showed no bleeding and no dentin chips (debris) at the exposure site immediately after pulp exposure. An area of blood extravasation near the exposure site was also found. The laser group demonstrated more reparative dentin formation (dentin bridges) near the exposure site than the control group, especially at 2 weeks [92].

Hasheminia et al. conducted an animal study evaluating the use of the erbium laser in pulp-capping procedures while using 200 mJ at 3 Hz with a long pulse duration (700 µs), without air or water and covering the surface with MTA or calcium hydroxide. Histological evaluation at 4 months confirmed the formation of a dentinal bridge in both groups [62].

8.3.5 Erbium Laser Pulp-Capping Protocol

What emerges from the presented studies is the lack of uniformity in the laser settings used, mainly the energy and pulse duration. Table 8.6 reports the various laser wavelengths used for vital pulp therapy including the pulp-capping agent used.

Erbium laser cavity preparation allows the operator to take all the advantages derived from the use of laser (see Chap. 7). Once cavity preparation with the erbium lasers is complete, the deep dentinal surface can be decontaminated with 75 mJ, 10 Hz, with high air–water ratio of the spray (the spot used is normally the 600-µm or the 900-µm spot of the tipless handpiece). Finally, the approach to exposed pulp occurs in a clean and decontaminated field, so that the possibility to dislodge infected dentin chips into the pulp is rare; the decontamination of the exposed pulp is performed slightly reducing the energy (50 mJ, 10 Hz) and gently and carefully irradiating for 15–20 s. During the superficial decontamination, the pulp will bleed slightly; this step will be followed by a careful coagulation (in defocused mode) of the pulp tissue without the use of water while maintaining a gentle air cooling from the laser spray. In order to preserve the vital pulp tissue from heat damage, the parameters suggested by the author for these clinical applications are significantly lower than those reported in the literature, not only a short pulse duration is used (100–300 µs), but also the air from the spray helps to cool the area. The thermal effect of erbium laser is so high when interacting with the pulp tissue that a longer pulse duration (600–700 µs) is unuseful if not harmful for the pulp vitality.

The coagulation of the pulp is obtained using very low energy (10–25 mJ, 10 Hz for the Er,Cr:YSGG, and 5–10 mJ, 15 Hz, utilizing the Er:YAG, both using 600-µm tip), delivered in defocused mode (~8–10 mm, usually the tip is out of the cavity margins), thus avoiding superficial necrosis (black-brown color following laser energy absorption); thus, a blanching (white color following laser energy absorption) of the pulp shows the lower thermal interaction indicative of coagulation (see Figs. 8.23, 8.24, 8.25, and 8.26). The use of low rate repetition allows

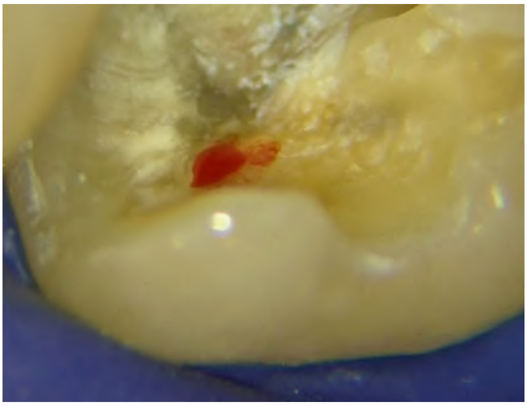

Fig. 8.31 Minimal pulp exposure in lower left molar after deep carious removal: the bleeding is limited and red colored

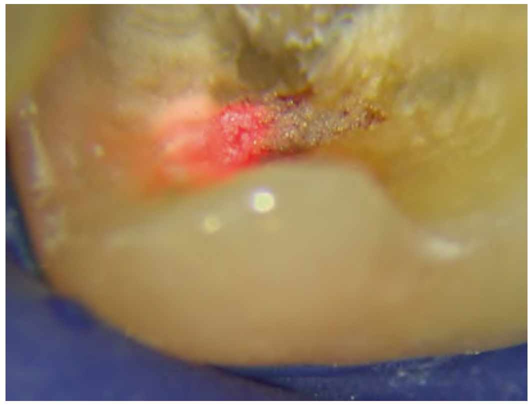

Fig. 8.32 Er:YAG laser is used with a no-contact handpiece in defocused mode at about 20 mm from the surface for pulp coagulation; 10 mJ, 15 Hz, 100 μs, no water air spray cooling

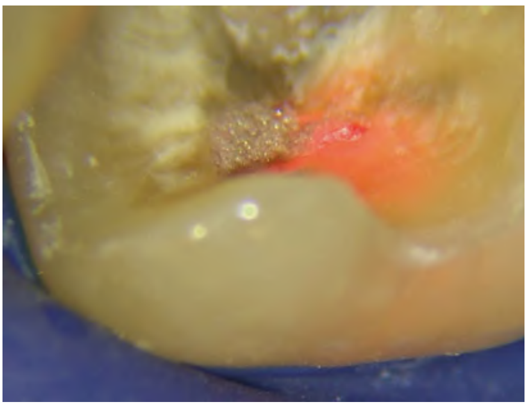

Fig. 8.33 Operative microscope allows close control of the interaction; a precise coagulation is performed in scanning mode with erbium laser

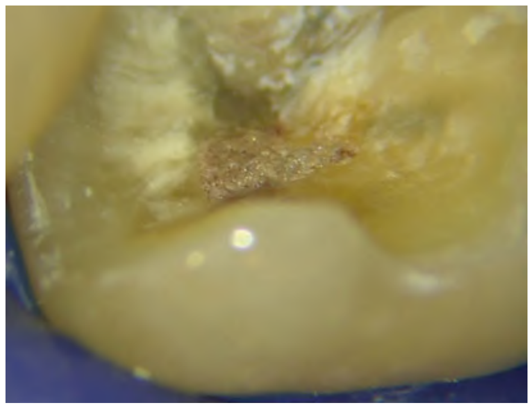

Fig. 8.34 A stable clot is formed after about 10 s of irradiation

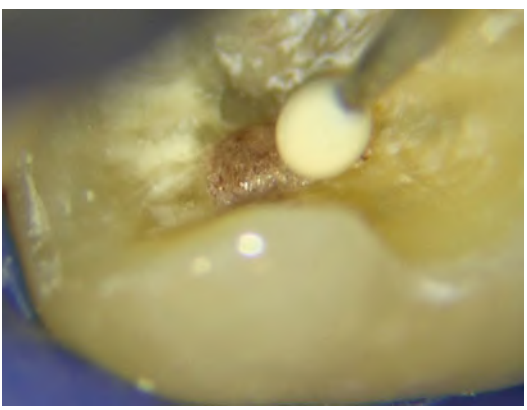

Fig. 8.35 A first layer of calcium hydroxide is applied on the coagulated pulp

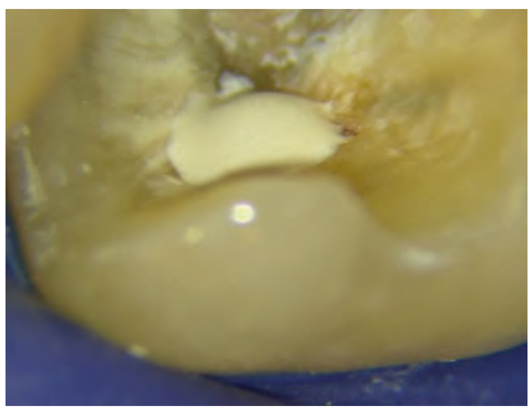

Fig. 8.36 After a second layer of calcium hydroxide is hardened, adhesive procedure allows for an hermetic sealing

Fig. 8.37 Upper molars show deep cavities and pulp exposure (tooth #1.7) irradiated with Er:YAG laser for deep decontamination and dentin melting

Fig. 8.38 Upper molars show calcium hydroxide pulp capping and immediate dentin–composite sealing using flowable composite

for maximum control of the laser–pulp tissue interaction, thus allowing an optimal coagulation; also the use of magnification definitely promotes closer and better monitoring of the procedure and helps in understanding and controlling the interaction (Figs. 8.31, 8.32, 8.33, and 8.34).

8.3.5.1 Pulp Exposure Capping and Hermetic Seal

Once the pulp surface is coagulated, the treated area is covered with a pulp-capping agent. MTA is very adherent, bioactive, and stable material, but it requires a second visit to complete the filling and sometimes (anterior esthetic restoration) cannot be recommended.

Calcium hydroxide presents some limit, especially because of its scarce adhesion to dentin–pulp interface and the polymerization shrinkage at the interface. To prevent the shrinkage, the author proposes to position the material in two different layers, and after its hardening, the second layer is pressed on the dentin margin of the exposure, in order to ensure a greater adhesion of the calcium hydroxide to the dentin surface (Figs. 8.35 and 8.36). The peripheral etching and the application of the adhesive system followed by a first layer of flowable composite complete the sealing (Figs. 8.37 and 8.38).

Biodentine is a very good alternative to the MTA; it is very highly adherent to dentin surface and has similar mechanical property of dentin; the color easily matches the dentin and can be use as both a temporary filling and later as a base, to be covered with composite.

Fig. 8.39 Complicated dental trauma to frontal teeth: pulp exposure on tooth #2.1; note the intrapulpal hemorrhage. See also Figs. 7.53, 7.54, 7.55, and 7.56

8.4 Partial Pulpotomy

This procedure is indicated in young patients with complicated trauma with pulp exposure larger than >1 mm or/and occurred within 48 h from the therapy. There is also indication to a partial pulpotomy in adults with exposure of the pulp for deep dentin caries, especially when the exposures occurred in the axial walls of proximal decays.

The pulpotomy represents the last step of vital pulp therapy, and its rationale is the removal of a

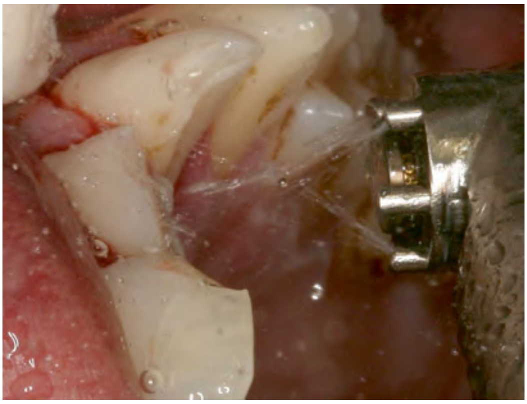

Fig. 8.40 During a complex first session that included also the treatment of the soft tissues for the associated trauma to the periodontal tissues, a pulpectomy is performed using Er:YAG laser

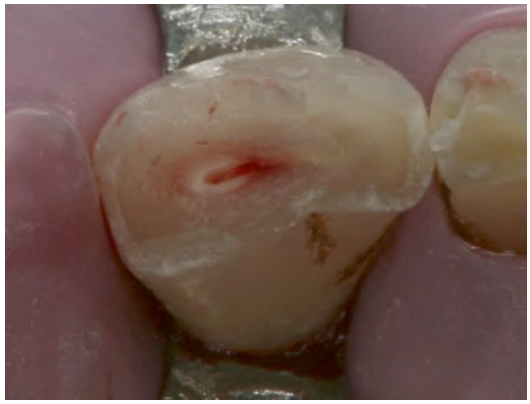

Fig. 8.41 Rubber dam placed: Er:YAG laser pulpotomy is completed using 120 mJ, 10 Hz, 100 µs pulse duration, with water spray. After treatment, the pulp has ceased to bleed alone

Fig. 8.42 MTA is placed on the exposed surface as capping material

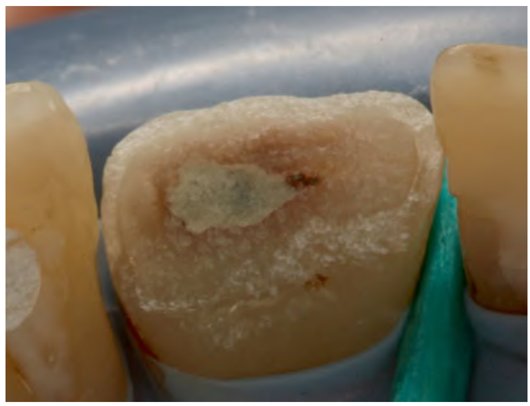

Fig. 8.43 MTA is partially removed using a sharp sterile excavator, and the surface is irradiated again before a final composite restoration is placed

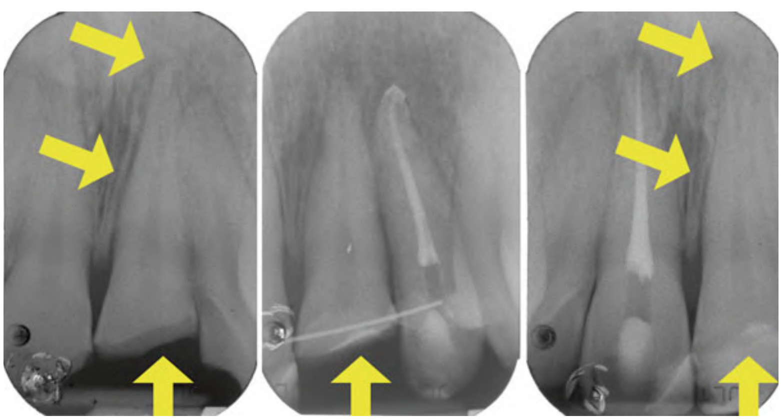

Fig. 8.44 *Left*: preoperative x-ray showing the complicated fracture of tooth #2.1, the thickening of periodontal space of 2.1, and the apical translucency of 2.2. *Middle*: 7-day postoperative x-ray shows the pulp capping on 2.1 and the endodontic therapy performed on 2.2 for acute pulpitis. *Right*: 1-month postoperative x-ray shows a root canal therapy performed on 1.1 for pulpitis; the radiograph also shows healing in progress for the 2.1 with pulp capping

part of pulp that can be, probably, superficially infected due to the initial passage of bacteria through deep caries or to complicated dental trauma with larger pulp exposure occurred within a time (48–72 h) which may be sufficient to create an infection of the pulp tissue.

Conventionally, the exposed pulp tissue is removed using a sterile round shape diamond bur to a depth of 2–4 mm [93]. Bleeding is controlled with sodium hypochlorite or ferric sulfate, and in case of protracted or heavy bleeding, the diagnosis of irreversible pulpitis is made, and the therapy is pulpectomy (root canal therapy).

Laser energy is able to vaporize the pulp tissue, decontaminating and coagulating the residual pulp; laser leads to favorable results using different wavelengths (Nd:YAG, Er,Cr:YSGG or Er:YAG, and CO_2).

The author utilizes the erbium family lasers to vaporize the coronal pulp; the laser is set on appropriate parameters (120–150 mJ, at 12–15 Hz, and 140–300 μs, with air–water spray on), and the procedure is repeated two or three times for 10–15 s, with intervals of 30 s until vaporization of the pulp tissue is obtained at the desired depth. Bleeding control is performed using lower energy (Figs. 8.39, 8.40, and 8.41).

Once the bleeding is controlled, the pulp is dressed with a layer of nonhardening calcium hydroxide, followed by a second layer of self-hardening calcium hydroxide (Dycal, Dentsply or Life, Kerr), or MTA (ProRoot, Dentsply), or Biodentine (Septodont) [94]; a placement of permanent restoration guarantee the hermetic seal of the cavity (Figs. 8.42, 8.43, and 8.44).

Table 8.6 reports the parameters used for the vital pulp therapy including pulpotomy.

8.5 Apexogenesis (Root Formation)

In case of pulp exposure in immature teeth, the preservation of the vital pulp allows the continuous physiological development of radicular walls with gradual closing of the root end.

Laser can be beneficial in this field for two reasons: it contributes to the maintenance of pulp vitality through the coagulation and decontamination of the exposure site or through the laser-assisted pulpotomy, and it can, possibly, biostimulate the maturation process. There are only two animal model studies available in the literature on the effect of low-level laser therapy for accelerating the dentinogenesis after pulpotomy of immature permanent teeth (apexogenesis). Fekrazad et al. studied the biostimulating effects of a diode laser (810 nm, 0.3 W, 4 J/cm^2, for 9 s) to accelerate the rate of dentinogenesis in apexogenesis of immature permanent dog teeth, using MTA as capping agent and reporting positive results [95]. Mathur et al. in a case study reported the successful use of a diode laser for vital pulpotomy in traumatically exposed pulp of an 8-year-old boy, to ensure continued root development and apexogenesis [96].

The tissue biostimulation and revascularization are a promising field of applications of low-level laser therapy that can be considered to improve both the pulp healing and the radicular dentin walls development.

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9 Laser Application for Dental Bleaching/Whitening

Giovanni Olivi and Stefano Benedicenti

Abstract

The esthetics of the smile has nowadays an increased demand in clinical dental practice. The color of teeth depends on the quantity and quality of reflected light, the quantity of the incident light, the thickness of the enamel, and the quantity and quality of dentin reflecting the light. The classification of discolorations includes intrinsic and extrinsic dyschromia; dyschromia can be isolated to one or more elements or generalized, so extended to many elements. While extrinsic dyschromia can be easily treated at home by the patient with toothpaste or by professional polishing techniques, air-flow polishing, the intrinsic dyschromia requires professional bleaching treatments or esthetic dentistry treatments (composite resins, veneers, crowns). Among the side effects of dental bleaching, over-bleaching represents a serious risk that can be easily avoided using laser with proper parameters and time of application. Research demonstrated the presence of damage to the enamel surface when the time of application of the bleaching gel lasts more than 20 min. Different wavelengths and protocols are proposed, all having a safe total time of application within 20 min.

The esthetics of the smile represents an important medium of support in verbal and nonverbal communication, and in consequence, dental cosmetics have seen increasing demand in the clinical dentistry practice over time.

In order to increase the esthetics of the smile, the ancient Egyptians and Phoenicians achieved dental whitening by combining a treatment with potassium carbonate and solar light. The ancient Romans exalted the tradition of candid white teeth using natural composites based on wax [1].

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During the fourteenth century, metal wires and nitric acid were used together, until the eighteenth century when solar light was used again combined with potassium carbonate and acidic milk [1].

At the end of the nineteenth century, thanks to developments in chemistry, a new compound was produced: the hypochlorous acid, which in form of salt represented an efficient industrial bleaching system for over a century [1].

In 1884 for the first time A.W. Halan used a concentration of hydrogen peroxide (H_2O_2) as a bleaching system that worked with electricity, creating pyrozone. This solution, having a low superficial pressure, was able to penetrate the dental tubules, but with notable risks and contraindications (flammability and bad smell) [2].

In 1919 C.H. Abbot created superoxol, a solution with 30 % hydrogen peroxide and distilled water activated by a heat source [3].

In 1924 the use of a solution saturate of sodium perborate and hydrogen peroxide was proposed for (hydrating) teeth before treatment with superoxol and a light source [4]. Other authors also proposed using a light [5, 6] to accelerate the bleaching reaction by activating the bleaching agent.

In 1961 a mixture of sodium perborate in water were used in the devitalized teeth; in 1963 Nuttling and Poe substituted the water in the mixture with superoxol (*walking bleaching technique*) without using light or heating [7].

In 1983 the dissociation of oxygenated water in an alkaline environment was achieved in the presence of a catalyst, generating radical peroxide. In 1989 a home-bleaching technique, based on carbamide peroxide (*Nightguard bleaching*), was proposed and it is still in use [8, 9].

The first modern dental bleaching agent derives from hydrogen peroxide. The last generation is represented by products similar to the predecessors, but with a water base, in order to reduce problems related to the dehydration of hard tissue and of local irritation of the soft tissues.

9.1 Tooth Discoloration: Classification and Causes

The color of teeth depends on the quantity and quality of reflected light, the quantity of the incident light, the thickness of the enamel, and the quantity of dentin reflecting the light. The color of teeth can be altered by substances that provoke dyschromia, which can be classified as intrinsic and extrinsic [10] (Table 9.1).

Dyschromia can be isolated, that is to say localized in one or more elements, or generalized, meaning extended to most of the elements.

The classification of dyschromia is essential to evaluate the predictability of bleaching and the stability of the result.

While extrinsic dyschromia can be easily treated at home by the patient with toothpaste or by professional polishing techniques, air-flow polishing, the intrinsic dyschromia requires professional bleaching treatments or esthetic dentistry treatments (composite resins, veneers, crowns).

9.2 Extrinsic Dyschromia

Extrinsic dyschromia is caused by external compounds incorporated in the acquired film on the enamel surface, which cause coloration as a result of the chemical interaction between pigmenting substances and the surface of the tooth [11]. Among these extrinsic factors there are chromogenic bacteria (actinomyces), food and drink, smoking, drugs, plaque, tartar, products with chlorhexidine, metal salt, etc.

Table 9.1 Intrinsic and extrinsic discoloration of teeth

Extrinsic
Chromogenic bacteria, food and drink, smoking, medicine, plaque, tartar, products with chlorhexidine, metal salt
Intrinsic preeruptive
Fluorosis, tetracycline, traumas, imperfect amelogenesis
Intrinsic posteruptive
Inadequate dental treatments, trauma, tertiary dentin

The clinical classification by Nathoo S.A. is the most frequently used and is based on clinical pigmentation that distinguishes between three kinds of discoloration [12].

9.2.1 Direct Tooth Discoloration Type N1

Colored compounds (chromogens) links to the dental surface provoking pigmentation; the color of the pigmentation is similar to that of the chromogen. Colored food and drinks (carrots, turnips, cherries, liquorice, coffee, tea, wine) directly depose chromogenic substances; the tannins contained in the drinks mentioned interact through mechanisms of ionic exchange.

Fig. 9.1 Concomitant extrinsic and intrinsic posteruptive discoloration of the teeth. The extraoral image shows the presence of plaque; tartar, associated to discoloration due to infiltrated composite fillings (on teeth #1.1, #2.3, #3.4, #4.4, #4.6); decay (on teeth #1.4, #2.1, #2.2); several decalcification; and abrasion with tertiary dentin on tooth #2–4)

Fig. 9.2 Concomitant extrinsic and intrinsic posteruptive discoloration of the teeth. The extraoral image shows decay on tooth #1.2, dyschromia of teeth #1.4, 2.4 and 4.6 for pulp necrosis. Decalcification of tooth #2.1 and deposits of tartar and plaque on the neck surface of the teeth

Metallic ions are also one of the causes of these kinds of discoloration (green pigmentation from copper or black from iron) (Figs. 9.1 and 9.2).

9.2.2 Direct Tooth Discoloration Type N2

Colored compounds change color after linking to the tooth. They are usually present in the interproximal or cervical areas of the aged teeth. This could be caused by modification induced on the proteins of the acquired film.

9.2.3 Direct Tooth Discoloration Type N3

The pre-chromogen is a colorless compound, which, through different chemo-physical reactions, after linking to the enamel leads to chemical reactions which produce pigmentation. The discolorations caused by chlorhexidine, stannous fluoride are included in this group Figs. 9.3, 9.4, and 9.5.

9.3 Intrinsic Dyschromia

They are provoked by different factors that modify the coloration of the tooth linking to the organic and mineral structure of the tooth, during both the development and mineralization period.

They involve the entire tooth and are divided into:

(a) Preeruptive dyschromia: fluorosis, tetracycline, trauma, and amelogenesis imperfecta
(b) Posteruptive dyschromia: inadequate dental treatments, trauma, and tertiary dentin

The most common among preeruptive intrinsic discolorations is *fluorosis*; it is due to a fluoride overexposure, usually for its high concentration in the water of some geographical areas. Its accumulation is extremely harmful not

Fig. 9.3 The extraoral image at 1 year follow-up after scaling and polishing and restorations. Note the Nathoo type N3 dyschromia due to excessive use of chlorhexidine rinse (orange staining)

Fig. 9.4 The extraoral image at 1.5 year follow-up shows better hygiene due to the improved compliance of the patient

Fig. 9.5 Concomitant extrinsic and intrinsic posteruptive discoloration of the teeth. The extrinsic staining is due to continuous use of chlorhexidine rinse (orange staining). The intrinsic posteruptive dyschromia (type N3) of the upper right incisor is due to a reactive tertiary dentin consequent to a previous trauma; the upper right incisor is vital

only for teeth, but also for the liver and for bones. Fluorosis was classified by Dean (1924, 1942) as questionable, very mild, mild, moderate, and severe, and it is important to be able to recognize its seriousness, depending on the intensity of discoloration, because it can represent a strong limit to conventional bleaching systems [13, 14].

Tetracycline discoloration can be preeruptive, when it is caused by consumption of this antibiotic during the second or third months of pregnancy, or posteruptive during the first years (6–8 years), and the entity and quality of the alteration (grey brown/yellow) depends on the ingested dose [1]. These pigmentations are the most difficult to treat (Figs. 9.6 and 9.7).

Amelogenesis imperfecta (malformation of the enamel) can be caused by:

– Hematological disorders (hemolytic disease of the newborn, thalassemia, anemia falciparum)
– Malnutrition, lack of vitamin D, and native hypocalcemia
– Maternal hypo-/hyperthyroidism and maternal diabetes
– Mental delay, cerebral paralysis, and cardiac malformation
– Ectodermal dysplasia

Intrinsic posteruptive discoloration can also depend on other factors:

– Decalcification
– Carious lesions
– Childhood diseases (e.g., measles)
– Endodontic treatments
– Trauma and pulp necrosis (red blood cell hemolysis)

Dental trauma can provoke abnormal discoloration through different pathogenetic mechanisms [1]:

Reactive dentin: The reaction of the pulp-dental organ, after a traumatic damaging event, can provoke a conspicuous deposition of reaction dentin to protect the pulp which usually remains vital. The increase in dentin thickness provokes a loss of transparency of the tooth with relative decoloration (see Sect. 1.4.4.3 and Fig. 9.5).

Fig. 9.6 A 40-year-old female that took tetracycline medication during childhood. The extraoral image shows the typical intrinsic posteruptive dyschromia (*grey brown/yellow*) more evident to the cervical side of the teeth due to the thinner width of enamel

Fig. 9.7 The immediate post-bleaching image shows presence of little damage to the gingiva and good bleaching result, more evident on the crown than on the neck. The bleaching has been performed with 532 nm KTP laser

Fig. 9.8 A 28-year-old male the day after an accident; trauma involved the two central incisors with complicated and not complicated enamel-dentin fractures as well as a not complicated fracture on left lateral incisor. Also many enamel cracks and infraction are visible

Fig. 9.9 The image 1 week post laser pulpotomy and MTA capping shows the characteristic pink coloration after an internal hemorrhage with hemolysis of red blood: the tooth remained vital

Pulp hemorrhage and pulp necrosis: In the case of pulp hyperaemia and/or pulpitis, post-bleeding hemolysis of red blood cells provokes the liberation of hematoidin and hemosiderin, which, combining with sulfuric anhydride derived from the decomposition of pulp proteins, creates iron sulfide. This substance penetrates the dental tubules, and it is responsible for their dark color (Figs. 9.8, 9.9, and 9.10).

In case of necrosis of the pulp, the final products of decomposition (hydrogen sulfide, carbon dioxide, fatty acids, etc.) can also penetrate the dental tubules and cause abnormal pigmentation

Fig. 9.10 The image 2 weeks later shows the spontaneous resolution of the internal hemorrhage on the left central incisor and dyschromia and internal hemorrhage on the right central incisor due to irreversible pulpitis

[15]. If coloration and pathology are irreversible, endodontic treatment is necessary and the sodium hypochlorite irrigation allows cleaning the dental tubules from the products of degradation and from red blood cells. A non-vital bleaching procedure will follow, if needed.

9.4 Dental Bleaching and Bleaching Agents

Dental bleaching causes the breakage of chromophore groups present in the organic and inorganic components of the tooth due to a redox chemical reaction. Oxygen radicals are liberated by the peroxides contained into the bleaching products and diffused through the tooth's hard tissue up to the amelo-dentin (enamel-dentin) junction. This specific redox chemical process degrades the color systems (quinone and aromatic systems) destroying the double links and producing composites with a low molecular weight, mainly carboxylic, colorless, and water-soluble acids, easily removable by washing.

The main bleaching agents in dentistry are the hydrogen peroxide (H_2O_2) and carbamide peroxide, which, in the presence of a catalyst, splits into hydrogen peroxide and urea [16–22], but oxygen radicals are those which determine the whitening process. The chemical reaction, in the presence of activators and photo-activators, can be accelerated through the application of heat and/or by light (both ordinary or laser light) which are able to accelerate and to increase the intensity of the chemical reaction, helping the dissociation of the peroxide and increasing the formation of oxygen and ion peroxide [23] (Figs. 9.11, 9.12, 9.13, and 9.14).

Fig. 9.11 Optical microscope polarized light observation of the enamel surface immediately after placing a gel containing 38 % hydrogen peroxide: no activation (time 0). The image shows the initial formation of oxygen microbubbles on the enamel surface (Courtesy of University of Genova, ©2012)

Fig. 9.12 Optical microscope polarized light observation of the enamel surface after placing a gel containing 38 % hydrogen peroxide: no activation. Note the increased formation of oxygen microbubbles after 30 min (Courtesy of University of Genova, ©2012)

Nowadays the techniques used involve the use of hydrogen peroxide (3–38 %) and carbamide peroxide (10–40 %), both auto- or photo-activated, or a mix of sodium perborate and hydrogen peroxide. These products can be used with different application times and different concentration, home bleaching, in-office bleaching, or power bleaching (Fig. 9.15).

The bleaching technique increases dentin permeability and can also intensify dental sensitivity, especially with longer treatment and a raised temperature (see Sect. 9.5).

In Europe the scientific committee on consumer safety (CSSC) decided to limit the use of bleaching products or dental brightening products to that containing hydrogen peroxide in a range of 0.1 % up to 6 % (20 volumes), present (free) or liberated by other composites or mixes contained in those products; these products can be safely administered only by dentists, once the absence of

Fig. 9.13 Optical microscope polarized light observation of the enamel surface immediately after laser activation of the gel containing 38 % hydrogen peroxide; 980 nm laser activation for 30s, no-contact handpiece. The initial formation of oxygen microbubbles on the enamel surface is more evident than in the case of self-activation (Courtesy of University of Genova, ©2012)

Fig. 9.14 Optical microscope polarized light observation of the enamel surface 30 min after laser activation of the gel containing 38 % hydrogen peroxide; 980 nm laser activation for 30s, no-contact handpiece. The formation of oxygen microbubbles on the enamel surface is much higher than in the case of self-activation (Courtesy of University of Genova, ©2012)

risk factors is guaranteed. Use is permitted only for those who are 18 years old or over [24–26].

9.5 Collateral Unwanted Effects

The side effects caused by tooth whitening agents can be divided into major and minor.

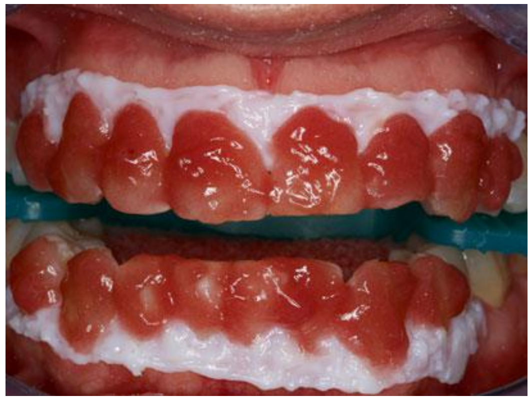

Fig. 9.15 Opalescence Boost PF (Ultradent, UT, USA) is a 40 % hydrogen peroxide chemically activated power whitening gel that doesn't require heating or lighting to work. Time suggested by the manufacturer is 40 min in the dental chair. The gel contains PF (potassium nitrate and fluoride) that has been shown to help reduce sensitivity

Among the minor side effects of tooth whitening are:

- Posttreatment dentin hypersensitivity, usually transitory.
- Temporary reduction of the adhesion of composite resins, for which it is advisable to postpone subsequent restoration for at least a couple of weeks.
- Corrosion of the superficial layer of the amalgam filling with possible release of silver ions and mercury, if the bleaching agent comes in contact with an amalgam filling.
- Gingival irritation due to the infiltration and caustic action of the peroxide under the protective gingival barrier, which can be quickly resolved (2–3 days) and helped by the use of a vitamin E-based cream (Figs. 9.16, 9.17, and 9.18).
- Algic-dysfunctional TMJ syndrome because of long opening of the mouth during the bleaching session.

The major side effects are:

- The possibility of systematic acute toxicity, only in the case of accidental ingestion of a large quantity of hydrogen peroxide. Ingestion

Fig. 9.16 A 48-year-old female required an esthetic whitening treatment. The starting color was previously evaluated

Fig. 9.17 Immediately post-op image shows mild gingival irritation due to contact with the bleaching gel. Laser activation with 532 nm KTP laser, using a specific handpiece; total procedure time 12 min. A vitamin E-based cream was applied for 2 days on the gingiva to reduce the sensitivity and accelerate the healing

Fig. 9.18 One week post-op image shows the healing of the gingival irritation and the very good esthetic result. The bleaching has been performed with 532 nm KTP laser

can provoke abdominal cramps and also sensorial disorientation.
– Possible chronic systematic toxicity has not been clinically proved, even with long use of mouthwashes containing peroxides or perborate (until 3 years).
– Over-bleaching.

Tooth bleaching happens through the chemical process of breaking double carbon-carbon links. If the exposure time of the tooth to bleaching gel is longer more than 20 min, it is possible to overlap the optimal "whitening" to a pathologic condition called over-bleaching, which involves the formation of the final products of oxidation (H_2O and CO_2). At the structural and clinical level, the over-bleaching shows an increased porosity of the enamel, until arrival at the loss of hard substance, increase in dental sensitivity, and the need for devitalization of the tooth [27]. The procedure time must therefore be kept under 20 min (Figs. 9.19, 9.20, 9.21, and 9.22).

9.6 Laser Dental Bleaching

During photo-assisted bleaching, the activation sources of bleaching products can be an ordinary light, emitted by a halogen, xenon, or led lamp, which produces light in the blue visible spectrum with a certain amount of infrared radiation (heating) or a laser light.

Different sources of laser light used today are the KTP laser which emits a green visible light (532 nm) and the diode lasers (from 803 up to 1064 nm), the Nd:YAG laser (1064 nm), and recently the Er:YAG laser (2940 nm), all emitting invisible infrared light.

The first laser light to be used for dental bleaching was a visible blue light (488 nm) of the argon laser, already proposed by Benedicenti et al. for photo-polymerization of the composite, not in use anymore nowadays because of the possibility of using the more versatile and ergonomic diode lasers [28–30].

The Food and Drug Administration (FDA) in the USA approved three kinds of laser that can be used instead of traditional lamps for bleaching:

Fig. 9.19 Image of the healthy intact enamel before the application of the bleaching gel (Courtesy of University of Genova, ©2012)

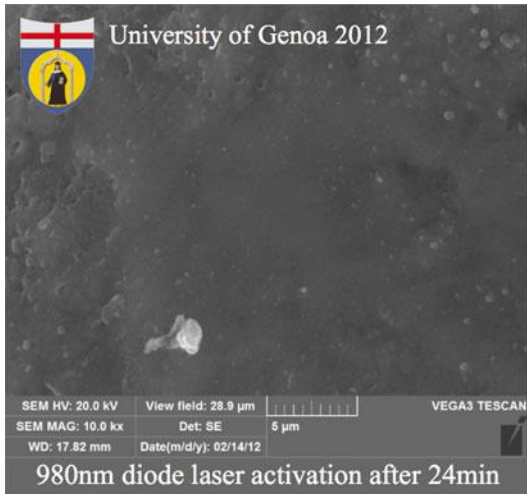

Fig. 9.20 Image of enamel surface washed for 60 s after the application of a 38 % hydrogen peroxide gel, activated by a 980 nm laser for 30 s and remained on the surface for 24 min. Initial reversible alterations of the prismatic enamel structure are visible in the left-top side of the image. The alterations have a diameter of 0.5 µm (Courtesy of University of Genova, ©2012)

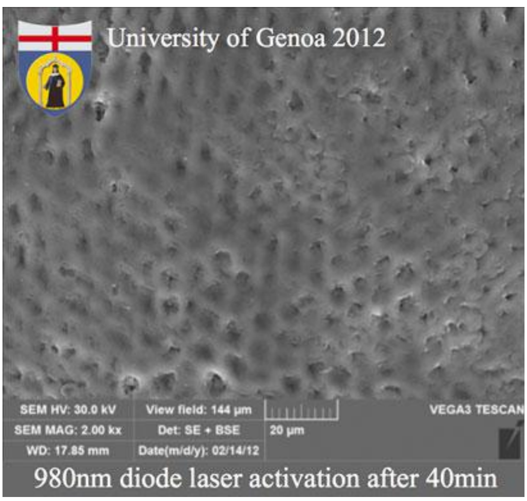

Fig. 9.21 Image of enamel surface washed for 60 s after the application of a 38 % hydrogen peroxide gel, activated by a 980 nm laser for 30 s, and remained on the surface for 40 min. Partially reversible alterations of the prismatic enamel structure are visible on all the area of the image. The alterations have a diameter of 5 µm with a pattern similar to that of the orthophosphoric acid etching, described by Silverstone (Courtesy of University of Genova, ©2012)

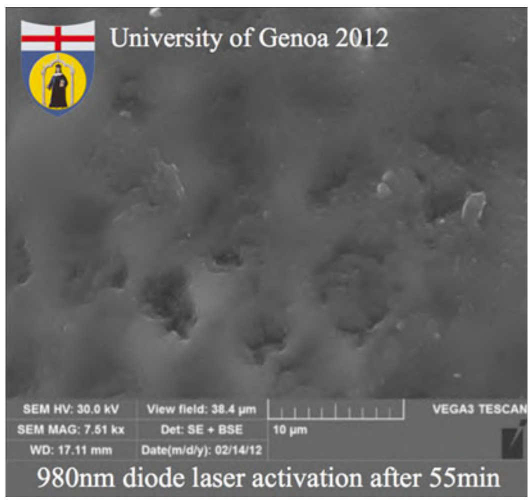

Fig. 9.22 Image of enamel surface washed for 60 s after the application of a 38 % hydrogen peroxide gel, activated by a 980 nm laser for 30 s, and remained on the surface for 55 min. The erosions of the prismatic enamel structure are irreversible and visible on all the area of the image. The erosions have a diameter of 5 µm and are deeper due to the longer time of resting that created a typical etching pattern of the enamel as described by Silverstone for the orthophosphoric acid (Courtesy of University of Genova, ©2012)

the argon laser, CO_2 laser, and the diode lasers. During laser irradiation protective glasses must be worn, specific for the wavelength used, for the patient, the assistant, the operator, and also including anybody in the operatory room.

The American Dental Association (ADA) Council on Scientific Affairs defined tooth bleaching as one of the most conservative cosmetic treatments for a person's smile; however the ADA reaffirmed that the treatment is not risk-free and so professional pretreatment dental examination, diagnosis, and supervision are advisable; it is also mandatory to explain the side effects of tooth bleaching [31].

The use of laser light as a bleaching product activator presents different advantages compared to other professional techniques, home bleaching, or in-office bleaching.

- It reduces the operation time and therefore reduces the risk of over-bleaching and of post-operation sensitivity.
- If used correctly, it determines a minimum increase of intra-pulp temperature, preventing the risk of damage to the pulp (inferior to 5.5 °C) [32].
- It lets the nascent oxygen penetrate deeper into the enamel and dentin, exercising an efficient action even in the deepest dyschromia, such as the tetracycline [33, 34].
- The treatment can be complete and be efficient in just one session.

The introduction of laser light as an induction source has been a great help to reduce the post-operation sensitivity. The use of a matrix gel containing an appropriate colored pigment (specific chromophore for a specific range of wavelengths), to be placed on the tooth and be able to absorb the wavelength, makes possible to concentrate the thermal energy of the laser irradiation only on the thickness of the material applied, avoiding a deep overheating of the pulp.

For example, using an argon or KTP laser (470 and 534 nm, respectively), the complementary colors to their monochromatic lights are yellow orange and red purple, and so such a colored-pigmented material, such as rhodamine, that absorbs within this range would be suitable [1] (Figs. 9.23 and 9.24).

Black or dark particulate material also absorbs across all near infrared wavelengths and would thus also be suitable with diode lasers (810–980 nm) or Nd:YAG lasers (1064 nm) [35–38]. However some other colorless gel (white) contain pigments specific certain types of laser wavelenght Figs. 9.25 and 9.26.

The use of laser with gel which is not specific for the wavelength not only does not bring the advantage of the laser technique, but also brings the disadvantages of the unuseful penetration of light through the gel and the hard dental substance, causing undesirable and potentially painful and/or harmful heating of the tooth and the pulp [39]. Some in vitro studies reported high temperature rises with different light sources, including diode lasers [35, 39, 40].

Fig. 9.23 Specific gel, containing red-purple pigment such as rhodamine, complementary to green light at 532 nm, absorbs the KTP laser light (Deka, Italy)

Fig. 9.24 Specific gel for 940 nm diode laser (Epic, Biolase, CA; USA)

Fig. 9.25 Colorless (*white*) 30 % hydrogen peroxide formula containing pigments specific to certain types of laser (810, 980 and 1064 nm) (Heydent JW – Power Bleaching Gel Laser; Germany)

Fig. 9.26 Red gel 40 % hydrogen peroxide (Opalescence Boost, Ultradent, UT; USA), without any specific chromophore, may be also used with erbium:YAG laser because of its high component in water

Recently, the Er:YAG laser has been described as a safe laser wavelength to be used for office bleaching treatments [39]. The major component (40–55 % by weight) of bleaching gels is water; the Er:YAG laser is highly absorbed in water, and due to the high water content of bleaching gels, there is no need for the presence of additional pigmented absorbing components, so that all the gel products available can be used safely. The high absorption of Er:YAG laser energy in aqueous gel (in the first 10–50 μm of the gel) makes the procedure also safe for the pulp vitality by eliminating the potential risk of overheating the pulp [39].

In addition, considering the Er:YAG laser's ability for hard-tissue ablation, the use of relatively low pulse energy (40 mJ), long pulse duration (1000 μs), and large spot size of the R17 handpiece (5 mm) employed [41] ensure the safety of dental hard tissues because the resulting lower fluence (0.5 J/cm^2) was reported to be below the ablation threshold of enamel and dentin, as well as below the ablation threshold of water [42].

Studies from Gutknecht et al. showed that for 35 J of delivered Er:YAG laser energy during a treatment time of 30 s, the maximal temperature increase in the pulp chamber was below 2.6 °C. Measurements with the diode (810 nm) and the Nd:YAG (1064 nm) laser showed much larger cumulative energies required to achieve the same reduction of the bleaching time, compared to the Er:YAG laser [39].

9.6.1 Preliminary Procedure

Whichever technique is used, the bleaching procedure must follow a standard procedure which includes a preliminary dental visit, involving:

– General and dental medical history: it is useful also to find out some incorrect habits that could compromise the final result and the lasting of bleaching (excess of smoking, coffee, or other pigmenting substances).
– General inspection: it involves the analysis of hard and soft tissue and a complete radiographic examination. Dental bleaching is a treatment to be performed solely in the presence of healthy periodontium. Eventual gingival recession must be protected and the eventual phenomena of preexisting hypersensitivity must be evaluated. This procedure is also not advisable in patients with enamel cracks, primary or secondary caries or dental hypersensitivity.
– Informed consent: the patient must be informed about major and minor risks possibly related to the bleaching. Patients with direct or indirect restorations in the esthetic areas should be informed of the irregular result that will be achieved and the possible need to proceed with the renovation of the restorations after bleaching treatment (Figs. 9.27 and 9.28).
– Excessive expectations (patient should be aware of the treatment's limits) and poor

compliance of the patient in tolerating the time of the treatment can be contraindications. The patient should also be advised not to consume products that can stain teeth up to 48 h after treatment; this would include, but not be limited to, some colored fruits, coffee, red wine, tomato sauces, tea, tobacco, etc.

– Photographic examination and color evaluation complete the informed consent. The series of photos is executed before and after professional treatment, to motivate the patient in the maintenance of the result and control of external dyschromia. Photographs must be taken before and 7 days after the procedure of office bleaching. The color scale VITA is used as a reference.
– Initial preparation: only after adequate periodontal therapy and the resolution of existing pathologies will it be possible to proceed to the treatment. This includes mechanical and/or manual scaling, and root planing if needed, in order to remove tartar deposits, deplaquing, and a selective polish to eliminate extrinsic pigments (see Figs. 9.2, 9.3, and 9.4).

Fig. 9.27 Determination of hue and chroma; the patient must be aware of the presence of the full ceramic crowns on the lateral incisors that once bleached the teeth will become more evident

Fig. 9.28 Image immediately after laser bleaching; note the transitory mild gingival irritation due to the contact of the peroxide with gingiva and the evident difference in color between the ceramic crowns and the whitened teeth

Box 9.1 VITA Shade Scale Listed by Brightness/Value

B1. A1. B2. D2. A2. C1. C2. D4. A3. D3. B3. A3.5. B4. C3. A4. C4

It is helpful to sort the VITA shade scale by brightness (value) instead of color groups, having the rods sample in the sequence reported in Box 9.1; this helps to recognize the improved whitening after the bleaching procedure.

9.6.2 Teeth Bleaching Procedure

The application of bleaching gel is preceded by a series of preparatory steps.

Step 1: The teeth's surfaces that must be treated are washed using a prophylaxis rubber small cup or a toothbrush with synthetic bristles, assembled on a micro-motor at low speed with micronized pumice (2–3 μm) to cleanse the teeth surface and allow a better penetration of the bleaching agents (Figs. 9.29 and 9.30).

Step 2: Vaseline is applied to the lips in order to avoid perilabial dehydration during the session. A silicone mouth-opener is then used to protect lips and checks from bleaching products.

Step 3: Teeth and gingiva are dried with an air spray, and a light-curing liquid dam is applied to the gingival margins of the teeth, for a height of about 3 mm; it is important to ensure that the gingiva is perfectly protected and to avoid the protective dam invading the coronal surface of the teeth, so compromising the success of the treatment (Fig. 9.31).

Step 4: A 35–40 % hydrogen peroxide base whitening gel is prepared and applied to the dental surfaces (usually from second premolar to second premolar) for a thickness of

2–3 mm, depending on the modality of the chosen product (Fig. 9.32). It is also possible to proceed to the technique of the "double arch," acting simultaneous on the two arches or bleaching one arch after the other, with a gap of a week, starting from the superior (superior teeth have thicker enamel and react better to the procedure), so as to make the patient more aware of the obtained result (Figs. 9.33 and 9.34).

Step 5: The active oxygen that is released during whitening reactions is not totally directed towards

Fig. 9.29 Determination of hue and chroma before a treatment

Fig. 9.30 Cleansing of the elements to bleach with micronized pumice and a brush mounted on low speed drill

Fig. 9.31 A silicone mouth-opener is then used to protect lips and checks from whitening products and gingival light-curing barrier is applied to protect the gums

Fig. 9.32 Application of the bleaching gel on the tooth surface for a thickness of 2–3 mm

Fig. 9.33 One arch irradiation using specific no-contact handpiece for 810 nm diode laser

Fig. 9.34 Double arch irradiation

the teeth's surface, but part of it is spread to the external environment. For this reason it is advisable to interject a barrier consisting of a transparent film laying on one side on the light curing, on the other side to the lingual/palatal versant, being careful not to dislocate some gel on the mucosa. In this way the barrier makes possible to address the totality of the reacting oxygen towards the teeth's surface (Figs. 9.35, 9.36, and 9.37).

9.7 Laser Activation Procedure

Depending on the laser wavelength it is necessary to modify the power parameters of the laser. The use of different laser equipments makes a standardization of the power parameters to set difficult; power should be set according to fluence (J/cm^2) and so of the surface of the handpiece. It is therefore good to follow the manufacturer's indications or those of the protocol from specific research for the wavelength used.

During this procedure the operator and the patient must wear specific protective glasses for the laser wavelength used.

If handpieces for multi-tip irradiation are used, it is advisable to irradiate alternate teeth, so that the same element is not subjected to laser light overexposure during the irradiation of adjacent teeth.

After the application of the gel and of a transparent film, there is 15 min in which the gel is allowed to operate on the dental surfaces (see Figs. 9.35 and 9.36).

Fig. 9.35 Application of a transparent film to maintain the oxygen on the teeth surface

Fig. 9.36 Double arch bleaching using the transparent film

Fig. 9.37 One week check of the result using VITA scale color reevaluation

Fig. 9.38 Preoperatory image of a 65-year-old female with complex prosthetic case; the treatment plane involved posterior implant rehabilitation, laser gingival contouring, and porcelain veneering of the upper frontal group. To make the esthetic result uniform laser bleaching has been proposed for the lower incisors to make the teeth color uniform

Longer times of application or very aggressive products can cause irreversible damage on the enamel (over-bleaching).

After this amount of time the film is removed, gel is aspirated, the part under it is gently washed, and the result is checked. The presence of hypersensitivity or of lesions in soft tissues is also evaluated.

The hypersensitivity can be treated with the application of fluoride gel or varnish, laser activated or not. In the case of a lesion of gingiva or mucosa (manifested as a whitish decoloration up to a deep caustic lesion), an immediate hydration of the tissue with a water syringe is performed followed by the application of a vitamin E-based cream.

With the aim to make uniform the obtained result, the patient, in the absence of sensitivity, can continue whitening at home, using an individual thermoplastic tray (or mask or positioner), with a reserve tank for a hydrogen peroxide base gel at 10 % (8 h each day) up to 16 % (4 h each day); the treatment last 4–5 days (a syringe) after which results are evaluated again (Figs. 9.38, 9.39, 9.40, 9.41, 9.42, 9.43, 9.44, 9.45, 9.46, 9.47, and 9.48).

9.7.1 KTP Laser 532 nm

The dose of 1 W for 30 s with fiber 600 μm is suitable for vital elements. Irradiation must be performed at alternating teeth; after a first session of about 10–12 min (30s × 20 teeth) the gel is aspirated and the teeth are thoroughly rinsed and

Fig. 9.39 Preoperatory evaluation of dental hue and shade after the esthetic treatment of upper central incisors: the base color of lower incisor is darker than A3.5; the upper incisor has been completed with A2 shade

Fig. 9.40 One week post-op evaluation confirmed an improved whitening of the teeth of about three steps (brighter than A3). The bleaching has been performed with 940 nm diode laser (Epic, Biolase; USA)

Fig. 9.41 Preoperatory evaluation of dental hue and shade, using VITA scale: the base color is A2 with diffused whitish area

Fig. 9.42 One week post-op evaluation confirmed an improved whitening of more than four steps (from A2 to brighter than B1). The bleaching has been performed with 810 nm diode laser (Picasso AMD, USA)

Fig. 9.43 Preoperatory evaluation of dental hue and shade: the base color is A2 on frontal and A3.5 on cuspids

Fig. 9.44 One week post-op evaluation confirmed an improved whitening of the teeth. The bleaching has been performed with 980 nm diode laser (SiroLaser, Germany). The case has been completed with porcelain veneers on the weared upper incisors

Fig. 9.45 Preoperatory evaluation of dental hue and shade of a 50-year-old female with pronounced abrasions of the cervical part of cuspids and bicuspids: the base color is darker than A4 on the neck of cuspids

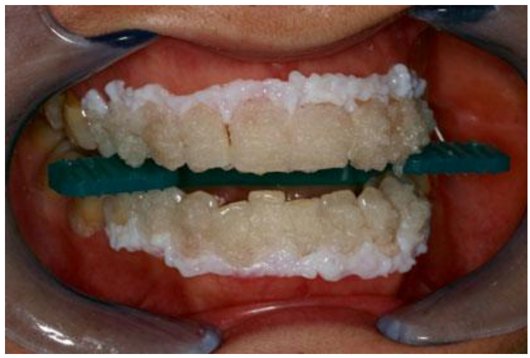

Fig. 9.46 The bleaching has been performed with 980 nm diode laser (SiroLaser, Germany) and white gel with specific absorbent pigment

Fig. 9.47 Immediate post-op application of fluoride gel to reduce the hypersensitivity

Fig. 9.48 Immediate post-op evaluation confirmed an improved whitening of the teeth

rehydrated; it is appropriate that a second or third session is performed as described above [1] (Figs. 9.49 and 9.50).

9.7.2 Diode Laser

Some diode lasers are provided with specific multi-tip handpiece for multiple irradiation on different quadrants. Considering the wider emitting surface, these systems require a high total power in order to guarantee a proper fluence (Figs. 9.51 and 9.52).

9.7.2.1 Diode Laser 810 nm (Picasso, AMD; Dentsply, USA)

Laser settings suggested by the manufacturer are 7 W power, emitted in gated mode (1.5 ms t_{off} for 9.9 ms t_{on}), using a specific multi-tip handpiece (actual power output 2.5–2.8 W) (Figs. 9.53 and 9.54). Each area (four teeth) is irradiated, without making contact with the gel, for 30 s; the total time for the two arches is about 3 min (6 areas × 30 s). After all the teeth have been irradiated with a laser for 30 s, the gel is left on the teeth for further 4 min, for a total cycle/time of 7 min.

Fig. 9.49 Bleaching handpiece for KTP laser (Deka; Italy)

Fig. 9.50 KTP laser green light bleaching, using specific rhodamine base pink-purple gel

Fig. 9.51 Bleaching handpiece for 810 nm diode laser (Garda laser; Italy)

Fig. 9.52 No-contact one-tooth bleaching handpiece irradiating red pigmented gel

Fig. 9.53 Specific multi-tip handpiece for 810 nm diode laser (Picasso, AMD; USA)

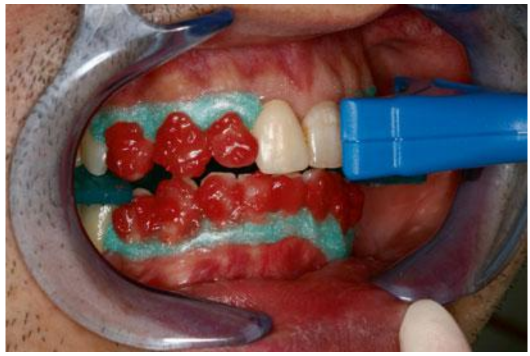

Fig. 9.54 Alternating irradiation in order to not create overheating of the dental surface, using multi-tip handpiece (Picasso, AMD; USA)

Fig. 9.55 Specific multi-tip handpiece for 940 nm diode laser (Epic, Biolase; USA)

Fig. 9.56 Irradiation of lower arch using the multi-tip handpiece for 940 nm diode laser (Epic, Biolase; USA)

All the gel is sucked from the teeth completing the first cycle. The steps are repeated twice; at the end, water from the syringe rinse thoroughly and teeth and gum reevaluation is performed (total procedure time 14 min) [43].

9.7.2.2 Diode Laser 940 nm (Epic 10, Biolase, USA)

Laser settings suggested by the manufacturer are 7 W power, emitted in cw, total energy 200 J, using the handpiece in close proximity (~1 mm) to the teeth surface without making contact with the gel (Figs. 9.55 and 9.56). The laser is activated holding the handpiece in place for the duration of approximately 30 s.

The upper and lower arches are divided into four treatment sites, consisting of 4–5 teeth (4 areas × 30 s); the procedure is repeated for all quadrants two times, so that the total time for the two arches is about 4 min. The gel is allowed to remain on the teeth for 5 min after the second laser cycle, for a total cycle time of about 9 min.

The gel is then removed using high-speed suction, and an air and water spray flushing is used to remove any residual gel. A new brushed applicator tip is used to reapply the whitening gel and to perform a new activation. At the end, a rinsing with water spray thoroughly cleans the teeth.

In one in-surgery visit, it is suggested to perform a maximum of two gel applications for a total of 18 min bleaching [44].

9.7.3 Erbium:YAG Laser 2940 nm (LightWalker, Fotona, Slovenia)

The TouchWhite™ protocol has been proposed for the Er:YAG laser (LightWalker AT, Fotona; Slovenia) using a specific handpiece (R17 handpiece) and commonly used 40 % H_2O_2 water-based bleaching gel (Opalescence Boost, Ultradent, South Jordan, UT; USA) (Figs. 9.57 and 9.58) (see also Fig. 9.15). The irradiation procedure is performed at 40 mJ (delivered fluence per pulse: 0.2 J/cm^2), 10 Hz, VLP mode (pulse duration: 1000 µs), 20 s per tooth, 3 times on each application of bleaching gel (60 s per tooth). Gel application and irradiation cycle are performed three times during the treatment process for a total of 12 min for each arch. After each treatment, the bleaching gel was suctioned and washed away [39, 41].

Fig. 9.57 Specific handpiece (R17 for LightWalker AT, Fotona; Slovenia) for TouchWhite™ protocol (2940 nm)

Fig. 9.58 TouchWhite™ protocol using 2940 nm of the Er:YAG laser is absorbed by any type of bleaching gel, with and without pigment; here the application of red gel with 40 % hydrogen peroxide (Opalescence Boost, Ultradent, UT; USA)

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Appendix: Laser Safety

Introduction

Laser can damage nontarget the oral tissues, skin, and eyes as the result of accidental direct exposure to the laser beam or through the combustion and inhalation of gases, chemicals, and materials used in dentistry.

A requirement for the clinicians which incorporate lasers in their practice is to ensure that they and each member of the dental team are knowledgeable of and practice laser safety. The knowledge of the specific laser(s) being used and laser physics and the compliance to the local rules and regulations are mandatory. These regulations apply to laser use, according to health and safety legislation of each state/country, and a laser safety officer (LSO) has the responsibility to ensure that these measures are adhered to [1–3].

Laser Classification

Lasers used in dentistry are classified with regard to the potential for damage. Table 1 presents an outline of the four basic classes of lasers used in dentistry, their emission parameters, examples of their use in dentistry, potential risks to unprotected tissues, and safety measures.

Laser Hazards

The laser hazards can be summarized as follows:

1. Eye hazards
2. Nontarget oral tissue hazards
3. Skin hazards
4. Chemical and infective hazards
5. Fire hazards
6. Other hazards

The maximum permissible exposure (MPE) is the value of exposure limit above which tissue damage may occur. Each laser has its own nominal hazard zone (NHZ), and the manufacturer has the responsibility of informing the specific NHZ in the operator's manual [1, 2].

Eye Hazards

The laser beam may cause damage to the eye from direct exposure or reflection when the wearing of appropriate eyewear is not adhered to. The wavelengths in the visible to near infrared (400–1400 nm) may result in retinal burns in the area of the optic disk due to the relatively nonabsorption by water [2, 4]. In addition, the visible wavelengths may cause damage to the red or green cones in the retina, which can lead to color blindness. Corneal, aqueous, and lens damage may occur from the mid- to far-infrared wavelengths (1400–10,600 nm) (Fig. 1 and Table 2).

It is imperative and mandatory that the patient, dentist, dental personnel, and anyone within the NHZ use appropriate eye protection during laser procedures. The eyes must be protected when the dental laser is on, prior to the laser being turned on. The lenses of the glasses must be constructed of wavelength-specific material to contain or attenuate the energy of exposure within the MPE values,

G. Olivi, M. Olivi (eds.), *Lasers in Restorative Dentistry: A Practical Guide*,
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Table 1 Laser classification, power output, risk analysis, and safety measures [1, 4]

Laser class	Maximum output	Use in dentistry	Possible hazards	Safety measures
Class I Class IM	40 μW 400 μW	Caries detection Scanner	No implicit risks Possible risk with magnified beam	Blink response Laser safety labels
Class II Class IIM	1 mW	Aiming beam Caries detection	Possible risk with direct viewing Significant risk with magnified beam	Sight aversion response Laser safety labels
Class IIIR Class IIIB	Visible 5 mW Invisible 2 mW 0.5 W	Aiming beam Low-level lasers PDT Chemotherapy Mucosal scanning cytofluorescent devices	Eye damage Eye damage	Safety eyewear Safety personnel Training for Class IIIR and IIIB lasers
Class IV	No upper limit	Surgical lasers	Eye and skin damage Nontarget tissue damage Fire hazards Plume hazards	Safety eyewear Safety personnel Training and local rules Possible registration to comply with national regulations

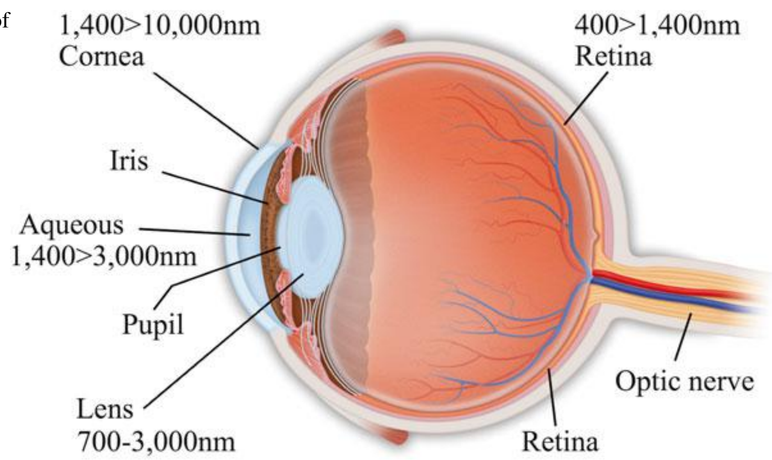

Fig. 1 Graphic representation of eye structure and possible wavelength-related hazards to specific anatomical parts

Table 2 Eye and skin hazards of dental lasers [5, 6]

Laser wavelength	Eye structure	Eye damage	Skin
405 > 532 nm	Retina	Retinal lesions	Photosensitive reactions (400 > 700 nm)
Caries detection 655 nm Oral pathology cytofluorescent devices 630–900 nm	See below[a] Lens (>700 nm)	Retinal lesions Retinal lesions and cataract (>700 nm)	
Diodes 810 > 1064 nm Nd:YAG 1064 nm	Retina Lens	Retinal burns Cataract	Excessive dryness Blisters Burns
Er, Cr:YSGG 2780 nm	Lens	Cataract	
	Aqueous humor	Aqueous flare	
Er:YAG 2940 nm	Cornea	Corneal burn	
CO_2 10,600 nm	Cornea	Corneal burn	

[a]Class I and Class II caries detection lasers may become hazardous to the retina when viewed through optical aids (e.g., loupes and operative microscope), as such magnification devices can make a diverging beam more hazardous [6]

and the specific wavelength is imprinted on the lenses. The entire periorbital region must be covered by glasses, and they must have appropriate side panels to prevent laser beam entry. Practitioners using magnification loupes or a microscope must have the appropriate inserts or filters.

Appropriate care should be taken when cleaning the laser glasses to prevent removing the protective coating on the lenses by caustic disinfecting solutions. The eyewear should be cleaned with an antibacterial soap and dried with a soft cotton cloth.

Nontarget Tissue Hazards (Oral Tissues and Skin)

It is important that the laser operator be aware of accidental damage to nontarget tissues. Care must be taken to avoid accidental ablation of adjacent tissues. Anodized and non-reflective instruments should be used to avoid reflection; stainless steel instruments and rhodium mirrors may be safely used if precautions are taken to minimize reflection. Potential damage to the skin can occur depending on the laser's wavelength and its absorptive potential, power density, duration of exposure, and spot size. Photosensitive skin reactions may happen with visible-wavelength lasers; excessive dryness, blister, or burn may happen with medium- and far-infrared lasers [5] (Table 2).

Chemical and Infective Hazards

The laser beam can produce plume damage. "Plume" is defined as the gaseous by-products and debris from laser-tissue interaction. It can have a smoky appearance or be completely invisible to the naked eye.

The plume may pose a risk due to the aerosol developed by the laser-tissue interaction. Organic and inorganic matters include toxic gases, chemicals, bacteria, viruses, and fungi. The laser-generated airborne contaminants (LGAC) may include human immunodeficiency virus, human papilloma virus, carbon monoxide, hydrogen cyanide, formaldehyde, benzene, bacterial and fungal spore, cancer cells, and, when removing composite resin materials, methyl methacrylate monomer. Therefore, protective surgical clothing and fine-mesh face masks capable of filtering 0.1 μm particles must be worn.

Fire Hazards

Ignition of gases or material can occur due to the high temperatures of Class IV and some Class III B lasers. Nitrous oxide and oxygen are allowed for conscious sedation according to ANSI Z136.3 when used with a nosepiece during laser operation [3]. Also to be avoided within the NHZ are alcohol-soaked gauze, alcohol-based anesthetics, and any products containing oil-based substances such as petroleum jelly, which may be flammable.

The laser should not be used if the patient uses an oxygen tank. When using general anesthesia, the flash point of some anesthetic aromatic hydrocarbons used in general anesthesia may be exceeded. Also it should be considered that materials not normally flammable may ignite in an oxygen-enriched atmosphere.

Other Hazards and Infection Control [7]

Lasers are surgical instruments, and during its use, dental practitioners and their staff must follow the standard precautions that include gloves, masks, protective glasses or face shield, and gowns. The risk of a needlestick injury with a fine quartz tip is possible.

To prevent contamination, reusable fibers and tips must be heat sterilized in addition to the handpieces. To ensure effective sterilization, any debris on the end of the tip must be removed and/or cleaved prior to sterilization. Wipeable or removable barrier should be placed over the operational controls on the laser. A high-level disinfectant can be used on the laser and surrounding operatory surfaces.

Service hazards would include electrical, air, and water supply lines, in addition to connectors and filters. Tripping over wires and cables is a hazard and the lasers should be moved with caution.

Safety Measures for Laser Dentistry

Test firing of the laser should be performed by the clinician or LSO before clinical use in an appropriate environment/medium (water glass for medium- and far-infrared lasers and dark absorbing paper for visible and near-infrared lasers) with low-energy setting, to ensure for proper functioning parameters (repetition mode, pulse duration, emission mode, air/water spray) of laser, appropriate for the procedure. Safety measures also include:

- To cover the foot switch to prevent accidental operation.
- To lock the unit panels to prevent access by unauthorized access.
- A key or password protection to prevent laser from being used by unauthorized persons.
- A remote interlock to shut off the laser if a door should be opened during operation.
- An emergency stop switch or button to shut down the laser immediately.
- A laser software diagnostics can show error messages allowing for shutdown if any component is not functioning correctly.
- Time-lapsed default to standby mode when laser is not used for a set period of time.
- Standby mode will not initiate laser when foot pedal is stepped on.
- Visible signs on the laser such as standby mode light vs. ready mode light.

Multi-chair open dental offices must have the physical dimensions of the controlled area. The surfaces within the controlled area should be non-reflective, and all supply cables for the laser system should be protected from inadvertent damage. A fire extinguisher should be available and easily accessible.

For specific health and safety regulations applied to laser use that follow the legislation of each state/country, the laser user has the responsibility and obligation to adhere to local governmental rules.

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Index

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