9 Clinical Applications of Fiberoptic Laser Systems

9.1 INTRODUCTION

Previous chapters did not detail the usefulness of the integrated laser–fiber system in the various medical disciplines. This chapter explains the laser and fiberoptic methods for each discipline. It demonstrates their potential applications and provides the physician with sufficient background to start reading the latest literature. The various medical disciplines are arranged in alphabetic order. References at the end of the chapter and the bibliography give more details on the specific diagnostic or therapeutic applications. The various diagnostic and therapeutic modalities are summarized and are sometimes illustrated by flowcharts. The clinical applications of lasers are given in Table 8.1.

Each section consists of basic information, followed by the principles of the particular diagnostic and therapeutic methods, and illustrated with clinical results. Emphasis is placed on the systems and methods which have already been put into practice or have been tried in preclinical and clinical experiments. Section 9.2 is somewhat longer, not because cardiology is more important than the other disciplines but primarily because of the technical complexities involved in this field. Also, this is the first section, and many of the technical aspects mentioned in Section 9.2 have relevance to the other sections.

Several medical disciplines such as dermatology and dentistry have not been discussed in detail in the ensuing sections. Although lasers play a major role in dermatology (Andre, 1990), there has been little use of optical fibers. On the other hand, fiberoptic laser systems are potentially useful in dentistry. The interaction between lasers and dental tissue was discussed in the 1960s (Stern and Sognnaes, 1964) and the use of ultrathin endoscopes for viewing root canals was tried in the

1980s (Marshall *et al.*, 1981). In Section 7.4.2 we mentioned that laser–fiber systems may be used to diagnose or treat root caries. However, lasers have just started to penetrate dentistry and oral surgery (Willenberg 1989; Midda and Renton-Harper 1991) and it will be some time before fiberoptic systems are used in dentistry (see Table 9.1).

9.2 FIBEROPTIC LASER SYSTEMS IN CARDIOVASCULAR DISEASE

9.2.1 Introduction

During the past few decades, cardiology has become a prominent specialty in medicine. Cardiovascular disease is one of the principal causes of death worldwide. Major surgery and other invasive modalities are often required to diagnose and treat the disease.

The heart, coronary arteries, and peripheral arteries all constitute a rather complex system of tubes, pumps, and valves which lends itself to the use of fiberoptic investigation and treatment. Fiberoptic imaging can be used to identify a diseased area. Laser–fiber systems can be useful to diagnose and treat cardiovascular disease. Laser angioplasty has already been mentioned. Some of the developments in this area are discussed in recent books (Abela 1990; Litvack 1992; Sanborn, 1989; White and Grundfest 1989) and review articles (Cragg *et al.*, 1989; Isner and Clark, 1984; Isner *et al.*, 1987; Michaels 1990; Waller 1989).

9.2.2 Endoscopic Laser Systems in Cardiology—Fundamentals

9.2.2.1 Fiberoptic Laser Systems

The fiberoptic and laser methods used in cardiology are as follows:

(i) *Guidance*: Optical fibers used for therapeutic or diagnostic purposes are placed near a blockage in an artery with either a catheter or endoscope. The catheter is used by techniques that have been developed for regular angiography. A long, flexible guide wire, inserted into a peripheral artery in the groin or arm, is advanced in the arterial system toward the coronary arteries. The physician twists and bends the guide wire externally. A torque is transmitted to the distal tip of the wire, giving control of the distal tip position. Its position is monitored by x-ray fluoroscopy. When the guide wire is in place, the physician slides a thin catheter over it and into the coronary artery. The guide wire is then pulled out. With the catheter now in position, the physician often injects a radiopaque liquid (also called contrast medium) into the artery. This liquid is opaque in the sense that it highly absorbs x-rays and is clearly seen in fluoroscopic angiography. A thin optical fiber can be inserted into the same catheter and pushed all the way into the artery until its distal tip is brought into contact with the atherosclerotic blockage, as shown in Fig. 9.1.

TABLE 9.1 Clinical Applications of Lasers

Specialty	Laser	Applications
Cardiology	Excimer	Laser angioplasty; endarterectomy
	Ar	
	Dye	
	Nd:YAG	
Dentistry	CO_2	Soft tissue surgery
	Nd:YAG	Caries removal
Dermatology	Ar	Port wine stains and strawberry marks
	Dye	Varicose vein and tattoo excision; spider nevi
Gastroenterology	Ar	Esophageal, gastric, and colorectal polyps and carcinoma; bleeding lesions (ulcer, gastritis)
	Nd:YAG	Esophageal, gastric colorectal, and biliary polyps and carcinoma; bleeding varices, ulcer, gastritis, and angiomata; tumor palliation and cure
	Dye	Biliary stones
General Surgery	CO_2	General cutting tool; welding
	Nd:YAG	Cholecystectomy
Gynecology	Ar	Laparoscopic surgery: endometriosis, tubal surgery, adhesiolysis
	Nd:YAG	
	CO_2	
	Ar	Menorrhagia
	Nd:YAG	
	CO_2	Fallopian tube reconstruction; herpes; infertility cervical conization; valvular carcinoma
Neurosurgery	CO_2	Tumor excision; intracerebral surgery; meningioma and glioma excision
Oncology	Dye	Photodynamic therapy of tumors
	Au	
	CO_2	Tumor debulking
	Nd:YAG	Hyperthermia; thermotherapy of tumors
Otolaryngology	Ar	Bleeding lesions; subglottic hemangioma
	Nd:YAG	Tracheal webs and hemangioma; hemostasis
	CO_2	Polyp excision; tracheal webs and stenosis; papillomas; tracheobronchial carcinoma
Ophthalmology	Excimer	Corneal surgery
	Ar ion	Retinal detachment; iridectomy; proliferative retinopathy; glaucoma; senile macular degradation
	Nd:YAG	Posterior capsulotomy; iridectomy; vitreous bands
Orthopedics	CO_2	Arthroscopic surgery; bone tumor excision
	Ho:YAG	
Urology	Ar ion	Urethral stricture; bladder hemorrhage; bladder tumor excision
	Dye	Laser lithotripsy (kidney stones)
	Nd:YAG	
	Nd:YAG	Bladder bleeding; bladder tumor therapy
	CO_2	Renal resection; penile carcinoma; circumcision: urethral stricture

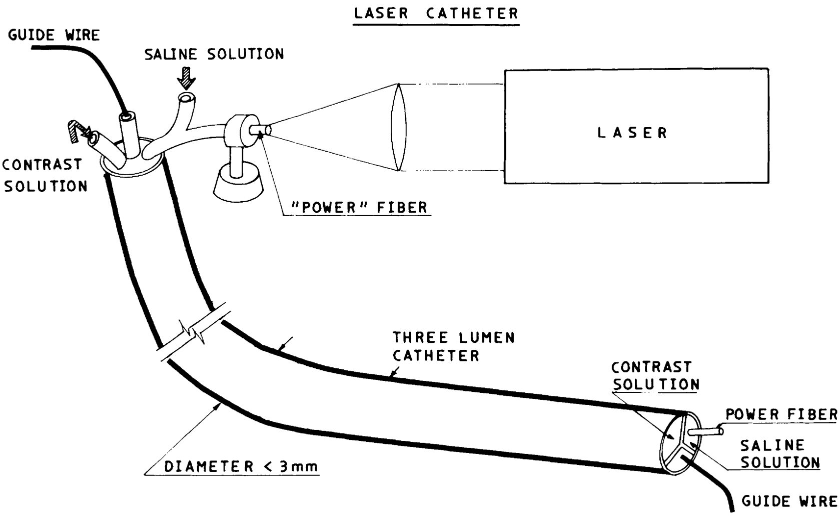

FIGURE 9.1 Laser catheter for cardiology.

(ii) *Imaging*: The development of thin and ultrathin endoscopes paved the way for fiberoptic imaging inside blood vessels. These endoscopes, however, are not as rigid as the guide wire. A torque cannot be applied to the proximal end of the endoscope and transmitted to the distal tip. At present, thin endoscopes can be guided through blood vessels by two methods:

- Guide catheter: The method mentioned in (i) is the simplest for inserting a guiding catheter into a desired artery. The ultrathin endoscope is inserted through this catheter, which is then pulled out, leaving the endoscope in place.
- Guide wire: The wire is inserted first and the endoscope slides over it.

The fiberoptic imaging is performed with regular white light. Image enhancement techniques or fluorescent imaging (see Section 6.5.1) can also be used. In the near future, this imaging method will probably be used to complement the more widely used imaging methods, such as x-ray fluoroscopic angiography or magnetic resonance imaging (MRI). In the far future, fiberoptic imaging may be an independent method, serving as one of the important tools of the cardiologist.

(iii) *Diagnosis*: Optical fiber sensors can be inserted into blood vessels or the heart via thin catheters or thin endoscopes. All the diagnostic methods mentioned in Chapter 7 are applicable in cardiology and most of them have already been tried clinically.

(iv) *Therapy*: Laser angioplasty has been performed to recanalize blockages in the coronary or peripheral arteries in thousands of patients. Lasers can also be used for endarterectomy (the removal of plaque) or for tissue welding in the cardiovascular system.

(v) *Other endoscopic techniques*: Thin endoscopes can be used for many of the therapeutic methods mentioned in Section 6.2, such as injection of drugs or dyes into atherosclerotic blockages or insertion of ultrasonic imaging devices to measure the thickness of the blood vessel wall. These are still under investigation. A complete laser endoscopic system is shown in Fig. 9.2.

9.2.2.2 Mechanical Devices

Several mechanical devices were proposed for atherectomy, the excision of atheroma inside blood vessels (Forrester *et al.*, 1991). Each of these devices is based on a atherectomy catheter which has to be guided and positioned.

(i) *Directional atherectomy* devices (Ellis *et al.*, 1991) are based on a probe with a rotary cutter of diameter 1.5–2.5 mm at its end. This atherectomy catheter is introduced through a guiding catheter and its tip is placed near the stenosis. The atheroma is excised using the rotary cutter and collected in a nose cone. It is removed from the artery when the cutter is withdrawn.

(ii) *Rotational atherectomy* devices (Fourrier *et al.*, 1989) are based on a rotating abrasive burr of diameter 1.5–3.5 mm that is advanced over a thin guide wire. The atherectomy catheter is introduced through a guiding catheter and positioned near the stenosis. The abrasive tip is then rotated at about 150,000 rpm while it is being advanced through the atherosclerotic blockage.

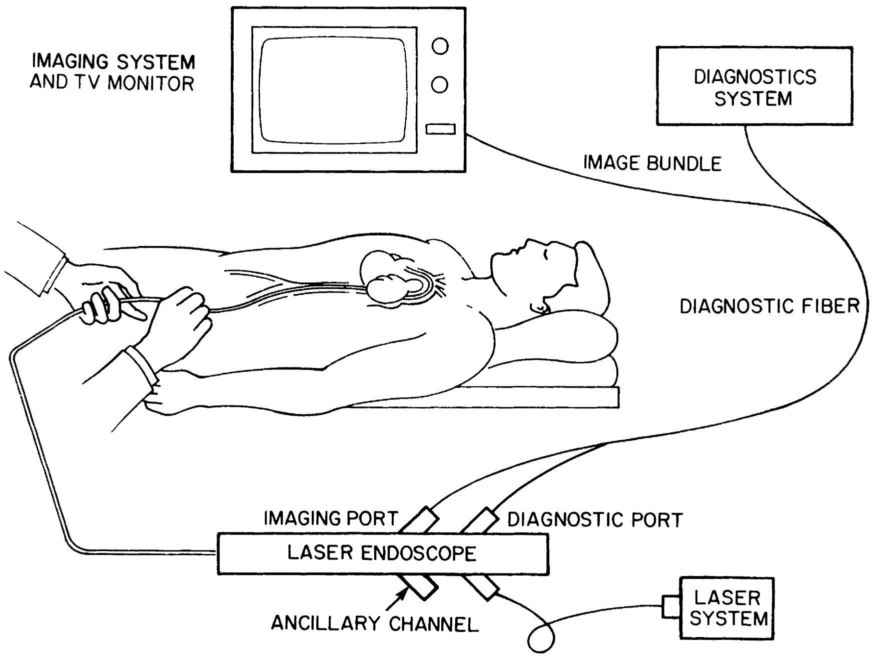

FIGURE 9.2 Laser endoscope system in cardiology.

(iii) *Transluminal extraction* devices (Stack *et al.*, 1991) are based on the excision of small segments of the atheroma and extraction of this atheromatous debris through the atherectomy catheter.

These methods were used successfully to treat blocked peripheral arteries. More than 2000 patients have had coronary atherectomy using mechanical devices, with a high rate of success. Yet all are limited by the catheter diameter, which is larger than that of a laser catheter. Although these devices have been introduced through guiding catheters, in the future it may be possible to insert them through endoscopes.

9.2.3 Endoscopic Imaging—Principles

The cardiologist needs to obtain a good-quality image of the lumen of a blood vessel in order to see the exact shape (and color) of a plaque blockage, which is often asymmetric. Cardiovascular imaging may serve for morphological and pathological diagnosis and will help in various percutaneous interventions. Imaging will enable the physician to direct a laser beam to the exact location of the plaque to be removed, in order to open up a channel in the blockage, while ensuring that the normal blood vessel wall is not affected by the laser beam. Imaging is rather complicated in a thin blood vessel because of the presence of blood that blocks the view and the need to use endoscopes whose diameters are less than 3–4 mm.

9.2.3.1 Angioscopy

The properties of thin and ultrathin fiberoptic endoscopes were discussed in Section 6.3.2. In cardiology there has been interest in carrying out laser angioplasty under angioscopic imaging (Abela *et al.*, 1986). In this section, the particular problems of endoscopic fiberoptic imaging in cardiology are presented.

The system used for guidance and angulation in a thick endoscope is based on mechanical means such as metal wires. Similar methods may be used for thin endoscopes, as shown in Fig. 9.3. In this case the balloon serves to position the thin endoscope at the center of a blood vessel during imaging. It is awkward to

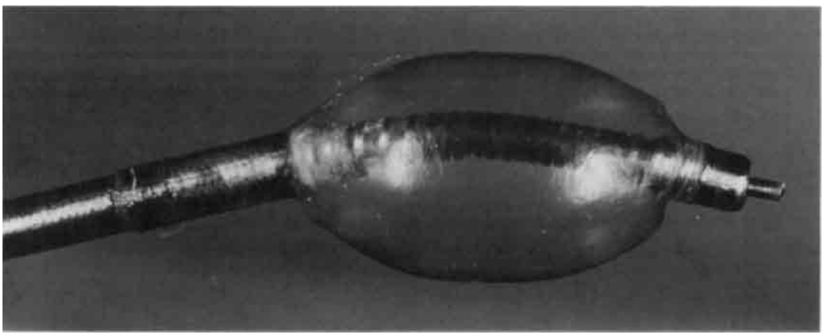

FIGURE 9.3 The tip of a steerable thin angioscope. (Courtesy of Mitsubishi.)

use the same measures for thin endoscopes, and ultrathin endoscopes are currently not steerable. Guidance of the endoscope tip to its exact location was discussed earlier.

The presence of blood makes it difficult to obtain a good image inside a blood vessel. A few methods have been tried to alleviate this problem, such as injecting transparent fluid (e.g., saline or artificial blood) through the endoscope to facilitate viewing. Another method is viewing through a transparent balloon attached to the tip of the endoscope.

During the past few years, there has been progress in angioscopy, especially in the optical quality of the image (Mizuno *et al.*, 1989). Clinical investigations have been performed on the pulmonary artery, cardiac chambers and valves, abdominal and peripheral arteries, coronary arteries, and congenital malformations of the cardiovascular system. Few complications were reported. Coronary angioscopy was used to show features such as narrowing, ruptured atheroma, occluding thrombus, and the lumen surface. Coronary angioscopy was also performed before and after procedures such as percutaneous coronary angioscopy (PTCA) or laser angioplasty (Uchida *et al.*, 1992). The dilatation of the stenotic segments of the arteries was clearly observed, as shown schematically in Fig. 9.4. It depicts a picture taken with the Olympus ultrathin endoscope placed inside the coronary artery, before and after laser angioplasty.

9.2.3.2 Ultrasound Imaging

The most commonly used angiography methods provide two-dimensional images of the lumen. On the other hand, angioscopy provides information about the interior surfaces of blood vessels. Neither method, however, provides information on the thickness of the arterial wall or the thickness and composition of

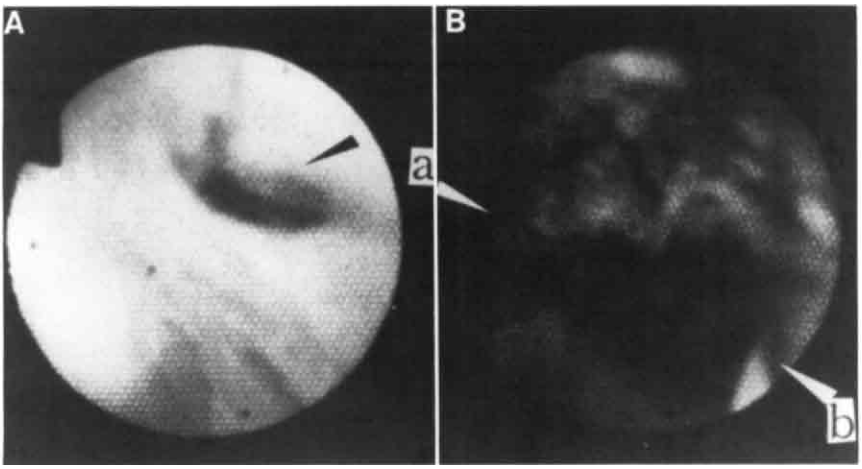

FIGURE 9.4 Images obtained through an ultrathin angioscope: (A) before and (B) after laser angioplasty. (Courtesy of Dr. Y. Uchida.)

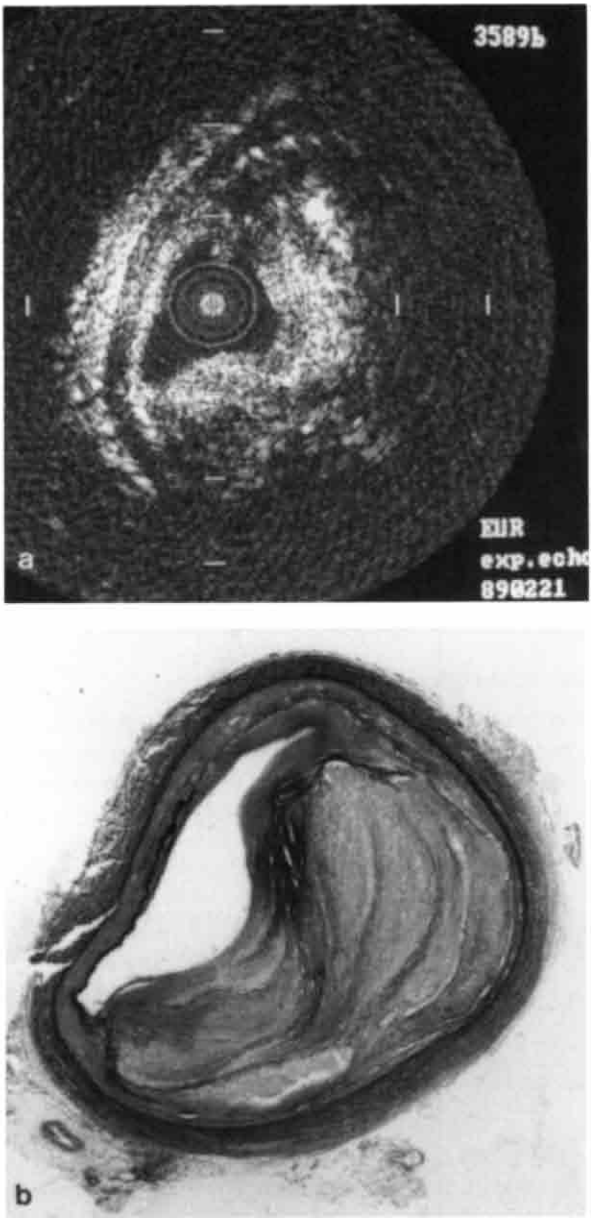

FIGURE 9.5 (a) Ultrasound image and (b) histologic cross section of a femoral artery, following laser angioplasty. (Courtesy of Dr. E. Gussenhoven.)

the atherosclerotic plaque, which is important for laser angioplasty. This knowledge may be provided by miniature ultrasound imaging devices which are attached to the tip of a catheter or an endoscope (Tobis *et al.*, 1989). Such devices have already been tested *in vitro* and *in vivo*. Ultrasound images were obtained from diseased arteries and the luminal cross section, wall thickness, and plaque structure were measured. The results were compared to those obtained by histology. Good correspondence was found between the two methods, indicating that the information obtained by ultrasound imaging may be used in the future for monitoring and control during a laser angioplasty procedure (Bom and Roelandt, 1989).

Figure 9.5 shows the ultrasound (also called echographic) image and the corresponding histologic cross sections of a superficial femoral artery following laser angioplasty. Figure 9.6 shows ultrasound images obtained *in vivo* from a patient

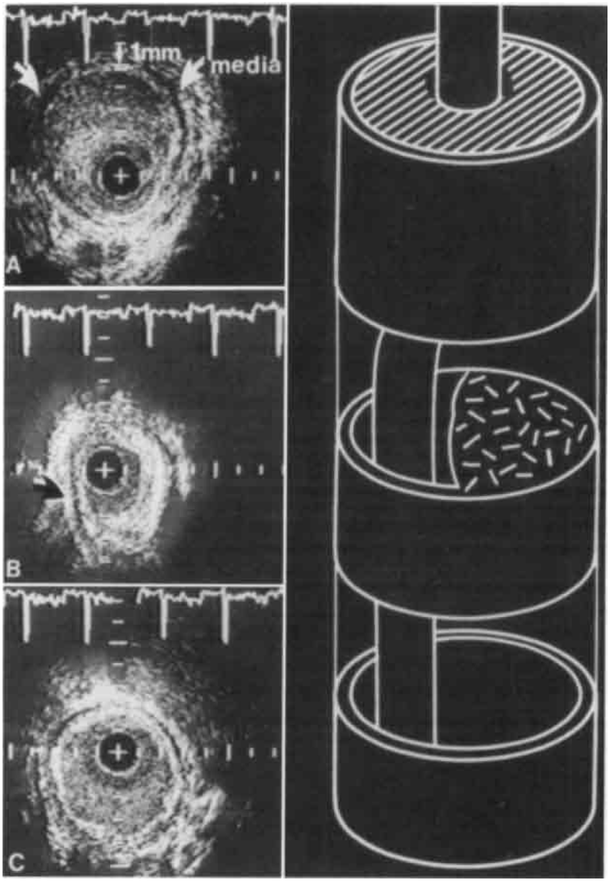

FIGURE 9.6 Ultrasound images obtained *in vivo* from a femoral artery, following laser angioplasty. (Courtesy of Dr. E. Gussenhoven.)

with obstructive disease of the superficial femoral artery after laser angioplasty. The diagram helps illustrate the ultrasonic cross sections.

9.2.4 Diagnosis—Principles

9.2.4.1 Fiberoptic Diagnostics

Chapter 7 discussed a few of the fiberoptic methods used for diagnosis. It was mentioned that a laser beam sent through an optical fiber interacts with blood or with tissue. A returned optical signal sent through the same fiber serves for diagnosis. The optical fiber can be inserted into the body either through a catheter or through a thin endoscope; these methods are well suited for cardiology. They can be used, as mentioned earlier, to monitor blood pressure, blood flow, pH, glucose content in the blood, and so forth. This can be performed either during a regular checkup of a patient or during a laser (or nonlaser) surgical procedure. Several systems have been developed especially for cardiology and are being tested in preclinical and clinical studies.

9.2.4.2 Guidance by "Smart" Systems

Laser-induced fluorescence spectroscopy may be used to distinguish between plaque and normal tissue. Such measurements may be taken through a laser catheter and used to determine the presence (and type) of atherosclerotic plaque. This is the basis of monitoring and control in "smart" laser angioplasty systems.

Scientists (Douek *et al.*, 1991; Garrand *et al.*, 1991) have proposed sending a low-power laser beam (e.g., HeCd UV laser) through a fiber to induce endogenous fluorescence. This fluorescence is collected through the same fiber or through a bundle of fibers. Spectral analysis of the emission functions to identify the tissue in front of the fiber. If this tissue is identified as atherosclerotic plaque, a pulse of a high-power laser beam (e.g., Ho:YAG or dye laser) is sent through the same fiber, or through a special power fiber, to ablate the plaque. The same procedure continues until the tissue in front of the fiber is identified as normal tissue; the ablation process is then terminated. Others (Papazoglou *et al.*, 1990) used UV lasers (e.g., XeCl excimer laser) for ablation and measured the tissue fluorescence through the same fiber. It was found that the fluorescence differs for atherosclerotic plaque and for normal tissue. The laser-induced fluorescence may therefore, once again, serve as a feedback signal which controls the ablation process. The proposed smart system can, in principle, ablate atherosclerotic plaque efficiently without damaging the arterial wall.

A few systems have been tried (Abela, 1990) *in vitro* and *in vivo* and several difficulties were encountered. It was found that repetitive high-power laser pulses induce changes in the tissue surface which give rise to changes in the induced fluorescence. Difficulties have also been found in identifying plaque *in vivo*, because of the presence of blood. In clinical studies, these difficulties led to various complications. Most important, the smart system could not distinguish well between plaque and normal tissue and did not prevent perforations. All these problems will have to be solved before the smart systems become practical.

9.2.5 Fiberoptic Laser Therapy: Angioplasty—Principles

Arteries blocked by atherosclerotic plaque are considered, where we may distinguish between peripheral arteries (in the legs) and coronary arteries (in the heart). A laser beam delivered through an optical fiber serves to remove the blockage. Atherosclerotic plaque is a mixture of fibrous tissue, fat, and calcium that varies not only between patients but within the same patient. It can be soft and easily melted by laser energy. It can also be hard, making it difficult to remove. There are three major concepts for the recanalization of the blocked artery to facilitate blood flow: (i) molding of the plaque, (ii) removal of plaque, and (iii) photochemotherapy. In each case, one of the many lasers and fibers which were mentioned in Table 8.4 is used to perform the laser procedure inside the artery.

This section discusses briefly the guidelines for the uses of different laser–fiber methods. Full details of the laser angioplasty techniques, limitations, and complications are given in the books and review articles mentioned in Section 9.1.

9.2.5.1 Plaque Molding

This method is most applicable in cases in which the plaque is not too hard. The following methods have been tried for this purpose:

(i) Hot tip: This tip was mentioned in Section 8.6. A small metal ball is attached to the tip of an optical fiber and inserted into an artery via a thin catheter. X-ray fluoroscopy is used to guide the metal tip to the plaque. An argon or Nd:YAG laser beam sent through the fiber heats up the metal ball to a temperature of about 600°C in a few seconds. The tip is rapidly pushed through the plaque, which melts and leaves a channel. If the cardiologist keeps the metal tip at one place for too long, it will stick to the blood vessel or even perforate the arterial wall. Although the system has been used clinically, perforations and other complications have been reported (Sanborn, 1988).

(ii) Miscellaneous tips: Various types of tips have been tried in clinical and animal experiments, including attached tips such as flat windows, contact probes, and optical shields (see Fig. 8.3). In other cases, the ordinary tip of the fiber was shaped in the form of a lens, ball, or cone (see Fig. 8.1) (Borst, 1987). All these tips have been tried clinically.

(iii) Laser balloon method: This is a combination of two methods (Spears, 1986). A balloon catheter is used, much as in a regular PTCA procedure, to push plaque to the sides and generate a new channel. Inside the catheter, an optical fiber delivers laser energy. Unlike regular optical fibers, which send the beam in the forward direction, this fiber scatters the laser beam evenly and sideways. The beam must be sent through the balloon while the balloon is inflated. The plaque, which has been expanded by the balloon, is heated and the cracks formed in the plaque are welded. Clinical coronary angioplasty trials are under way (Reis *et al.*, 1991).

9.2.5.2 Plaque Removal

The laser beam is used to vaporize the plaque. The beam is delivered through a power fiber that is inserted either through a catheter or through an endoscope. Several alternative methods can be used. This discussion is divided into three sections; the laser, the fiber delivery unit, and the fiber tip.

Laser

In order to remove the plaque, the laser beam must be absorbed by the plaque or by a coloring agent that has been selectively retained in the plaque. A laser beam that is absorbed in the coloring agent heats up the plaque, causing it to vaporize.

The first laser used for laser angioplasty was the Ar laser. The blue–green light of the Ar laser is highly absorbed by blood and tissue which contains blood. The radiation of this laser, however, is not absorbed well in white or yellowish plaque tissue. The Ar laser beam therefore does not cut plaque faster than it cuts the arterial wall. In addition, this is a continuous-wave (CW) laser that causes thermal damage. Another laser that has been tried is the excimer laser, which has two advantages: the UV is highly absorbed in plaque, and the laser beam is pulsed. As explained in Section 3.8, the pulsed mode leads to tissue removal with little thermal damage. Other pulsed lasers that are highly absorbed in plaque, such as Er:YAG lasers or CO_2 lasers, may also cut tissue with little thermal damage. When the plaque has been colored by dye, a laser with an emission wavelength tuned to the absorption peak of the dye must be used. Tunable dye lasers are the most suited for this purpose.

Fibers

Section 4.8 discussed the various power fibers. With angioplasty, fused silica fibers can be used for near infrared, visible, and the longer-wavelength excimer lasers ($\lambda > 300$ nm). Infrared-transmitting fibers must be used both for the Er:YAG and the CO_2 laser.

Fiber Tips

In some of the experiments reported to date, the distal tip of the power fiber was bare and well polished, but this is likely to cause mechanical perforations. The sapphire tip mentioned in Section 8.3.2, with its rounded form, appears to be much safer.

Blood

The presence of blood presents a special problem in laser angioplasty. The fiber tip can be positioned a few millimeters from the atherosclerotic plaque. There is a layer of several millimeters of blood between the fiber tip and the blockage. Whether an excimer or CO_2 laser is used, this blood layer absorbs nearly 100% of the laser radiation. Several methods have been proposed to solve this problem. Blood can be pushed away with a saline solution. Although this is helpful with visible laser beams (e.g., dye), it does not work with excimer, Er: YAG, or CO_2 lasers, whose radiation is highly absorbed in water. Alternatively, the blood flow can be stopped for 10–20 sec with pressurized gas (e.g., CO_2 gas), as shown schematically in Fig 9.7. The laser beam passes through the gas, vaporizing the plaque. After the 10- to 20-sec period, the blood flow resumes and the procedure is repeated until the blockage is recanalized. The last method may not be safe enough for practical use. When contact tips are used, the tip actually touches the plaque and the blood is displaced.

9.2.5.3 Photochemotherapy

The idea behind this method is identical to the one used for cancer treatment (see Section 3.7.2). A drug is injected into the body and selectively retained by the atherosclerotic plaque. This drug can be injected into the blood stream or directly injected into the diseased area with a catheter or an ultrathin endoscope. The drug is then triggered using a suitable laser wavelength and destroys the host plaque. Preliminary experiments have been conducted using hematoporphyrin derivative (HPD) (Spears, 1986).

9.2.6 Advances in Clinical Testing of Laser Angioplasty Systems

In trying to assess the efficacy of their systems, various research groups chose different laser–fiber systems for their studies. Ultrathin endoscopes are still not widely used. This section discusses the laser catheter systems which have already been tried clinically.

Balloon angioplasty cannot be performed in totally occluded arteries. In principle, the laser procedure is sufficient to generate a new and large lumen in a totally blocked artery. In practice, laser beams were sent through small-diameter optical fibers and generated a "pilot channel." A balloon catheter was then inserted through the narrow lumen and used to enlarge it. This laser-assisted balloon angioplasty procedure, however, suffers from the same high restenosis rate as regular balloon angioplasty.

9.2.6.1 Ar (Argon) Laser Catheter

The Ar ion laser was the first laser tested for angioplasty in animal experiments and preclinical experiments in the early 1980s (Abela *et al.*, 1982; Choy *et al.*, 1984; Lee *et al.*, 1983; Geschwind *et al.*, 1984; Macruz *et al.*, 1980). The lasers were CW Ar lasers emitting visible (blue or green) radiation with power levels of several watts. The fibers used were either regular glass or fused silica fibers. In all the experiments, the distal end of the fiber was bare. Ginsburg *et al.*

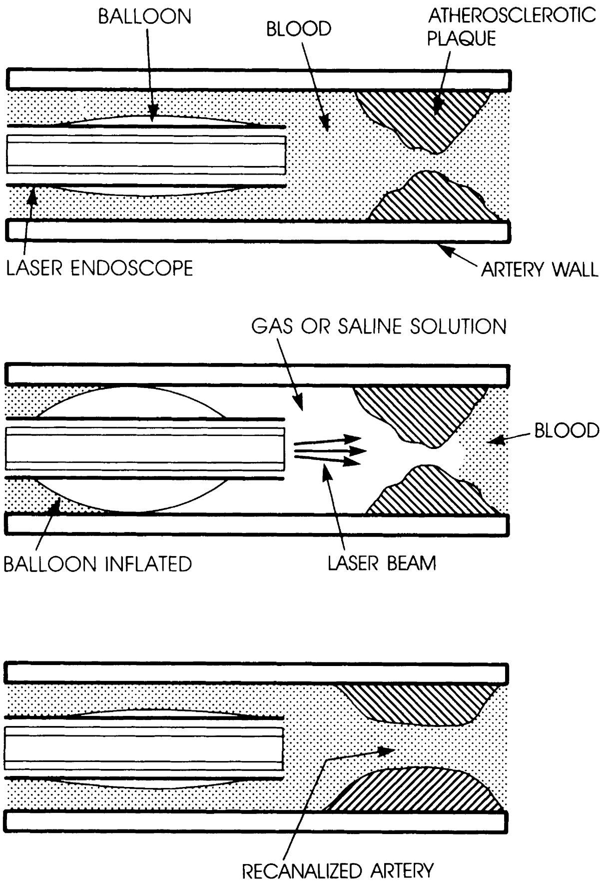

FIGURE 9.7 Laser angioplasty system: (a) schematic drawing and (b) artist's view. (Courtesy of Advanced Interventional Systems.) (*Figure continues.*)

(1985) used the system for clearing blocked peripheral arteries, and Choy *et al.* (1984) experimented with coronary arteries. Severe complications mentioned in these two studies limited their clinical importance.

9.2.6.2 Nd : YAG Laser Catheter

The radiation of the Nd:YAG laser is not highly absorbed in tissue and is therefore not efficient in vaporizing plaque. Yet, a laser catheter based on CW Nd : YAG lasers and "bare" silica fibers was readily available in the early 1980s. This system was thus among the first used clinically for peripheral laser angioplasty. The method was unsatisfactory both because of its inefficiency in removing

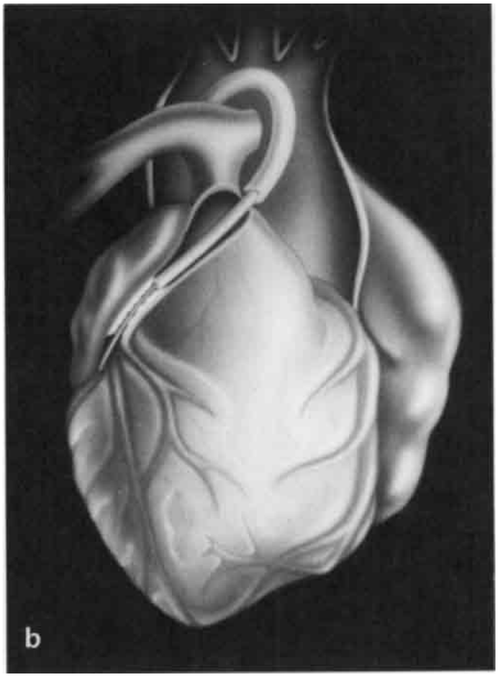

FIGURE 9.7 (*Continued*)

plaque and because of the risk of complications such as perforations. Addition of a sapphire contact tip improved the tissue removal efficiency, and the laser catheter based on CW or pulsed Nd:YAG lasers has been used clinically for laser angioplasty (Linnemeier and Cumberland, 1989).

9.2.6.3 Excimer Laser Catheter

Excimer laser radiation, which is highly absorbed in tissue, can be used to vaporize plaque (including calcified plaque). As mentioned in Section 8.6.3, there were severe problems with the transmission of this laser energy through silica fibers. The early systems, based on thick silica fibers, were too stiff and had to be replaced by a bundle of thinner fibers. A "ring" catheter consisting of 200–300 individual 10-μm fibers in a concentric array with an outer diameter of less than 2 mm (6 Fr) is often used. Many of the technical problems involved in operating XeCl excimer lasers and in using the laser catheter have been solved, making it possible to use this system clinically (Wollenek *et al.*, 1988). Clinical work was limited first to the peripheral blood vessels. More recently, improved catheters have been used either in coronary laser angioplasty or in laser-assisted balloon angioplasty. X-ray fluoroscopic images of a blocked artery before and after laser angioplasty are shown in Fig. 9.8. Thousands of coronary plaques have been re-

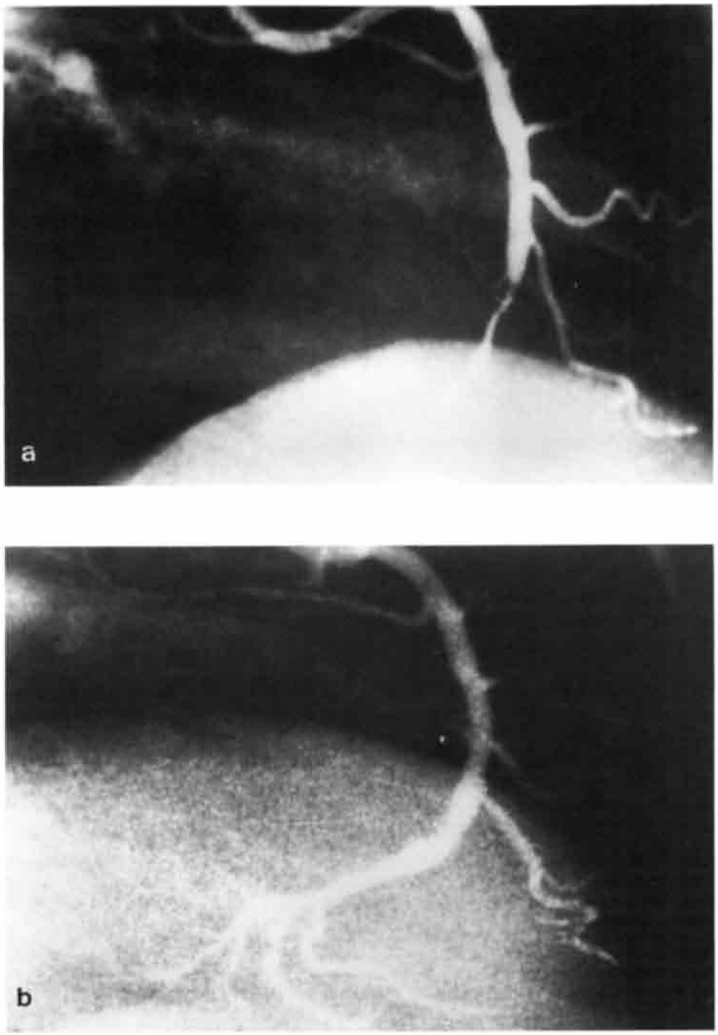

FIGURE 9.8 X-ray fluoroscopy images of (a) a blocked artery and (b) the artery after laser angioplasty. (Courtesy of Advanced Interventional Systems.)

canalized with this method, with a relatively small percentage of complications. Excimer laser angioplasty was found most useful in stenoses which cannot be crossed or dilated with a balloon, in long segments of diseased arteries, and in calcified lesions (Cook *et al.*, 1991).

Some of the procedures depicted in this section may be described with the help of a flowchart, as mentioned in Section 9.12.

9.3 FIBEROPTIC LASER SYSTEMS IN GASTROENTEROLOGY

9.3.1 Introduction

In the mid-1960s, it was realized that laser energy, when absorbed in blood, causes coagulation. In 1970, Goodale used, for the first time, a laser endoscope to control gastric hemorrhage. Goodale generated bleeding ulcers in the stomachs of dogs, introduced rigid endoscopes into their stomachs, transmitted a CO_2 laser beam through the endoscopes (without a waveguide), and stopped the bleeding. In 1971, the same laser was used in an open operation to stop bleeding in the stomach. In 1973, Nath *et al.* transmitted several watts of Ar laser power through thin (150 μm) fused silica fibers which were inserted in the ancillary channel of a fiberoptic gastroscope. They used this laser endoscope to coagulate intestinal bleeding in a dog. Several groups in Germany and the United States followed these experiments with Ar laser endoscopy (Fruhmorgen *et al.*, 1976), and in 1974, accomplished coagulation of actively bleeding lesions in patients. In 1976 Kiefhaber performed the first experiments using Nd:YAG laser gastroscopes for treating gastrointestinal tract bleeding. He found that the hemostatic properties of this laser were excellent, because of the large penetration depth into tissue (Kiefhaber *et al.*, 1977). Other researchers, notably Brunetaud in France, Bown in England and Dwyer and Fleischer in the United States, used the Nd:YAG laser for similar purposes (Dwyer, 1986).

Laser endoscopy in gastroenterology emerged as one of the most important uses of lasers in medicine (Fleischer, 1987; Hunter, 1989, 1991). It has been used to control bleeding, for the palliation of obstructing esophageal and rectal carcinomas, and for the treatment of gastrointestinal tumors. The following sections discuss some of the diagnostic and therapeutic applications of laser endoscopes.

9.3.2 Gastroscopic Imaging and Diagnosis

Various fiberoptic endoscopes are used in gastroenterology, such as the gastroscope and colonoscope. These endoscopes are among the best developed and have high resolution and excellent color rendition. Special endoscopic techniques (see also Secion 6.5) have also been developed (Sivak, 1987) to facilitate diagnostic imaging:

- Magnifying endoscopes with magnification of 30–150× have been developed to observe the gastric mucosa or colonic mucosa *in situ*. They could, in the future, replace histologic examinations.
- Chromoscopy is based on coloring agents which are applied to tissue through the endoscope and accentuate diseased areas.
- Endoscopic ultrasonography is based on miniature ultrasound transducers which are attached to the endoscope and used for ultrasonic imaging. The images obtained may be used to diagnose the mucosa, the submucosa and the layers of the gastric wall, hepatopancreatobiliary diseases, early evi-

dence of gastrointestinal tract tumors, and the depth of cancer invasion into healthy tissue.

9.3.3 Endoscopic Laser Photocoagulation

Gastrointestinal bleeding is a common cause of emergency hospitalization, with a mortality rate of about 10%. This high mortality rate may be, in part, due to the complications of emergency surgery and may be reduced by less invasive methods. Laser endoscopic photocoagulation offers a less invasive method which is controllable and potentially useful for the management of acute hemorrhage and reduction of recurrent hemorrhage. Laser photocoagulation has been used to treat bleeding from peptic ulcers, esophagogastric varices, benign mucosal lesions, and gastric polyps (Fleischer, 1987).

To treat such bleeding, a laser endoscope is introduced and brought to the vicinity of the bleeding site. One of the most severe problems involves the ability to identify the exact site and nature of the bleeding. Blood must therefore be removed around the distal tip of the endoscope. This is often accomplished by sending pressurized CO_2 gas through the ancillary channel in which the power fiber is located. The excess gas in vented through a second ancillary channel, to prevent discomfort to the patient and gastric overdistention. The gas flow also serves to cool the tip of the power fiber during power transmission and clears secretions from the tip.

Both Ar and Nd:YAG lasers have been used for coagulative laser therapy. The Ar laser emission at 488 and 514 nm is highly absorbed in blood. Its advocates claim that it immediately generates a layer of coagulum that will stop the bleeding. To do this, one needs power levels of less than 10 W and a total of less than 100 exposures, each of duration 1 sec. The lower power is believed to reduce the risk of perforation. The Nd:YAG emission at 1064 nm is not so highly absorbed in hemoglobin. It is transmitted through blood, penetrating deeper into the tissue around the bleeding site, and its advocates claim that it results in better coagulation. One needs power levels of up to 100 W and a total of about 50 exposures of 1 sec duration to stop bleeding. The higher power may also be advantageous when there is a need to control bleeding from large vessels. Sapphire tips have also been used for "contact" application of the laser to the bleeding site.

Many groups have conducted series of controlled and uncontrolled trials with different laser endoscopes under a wide range of operating conditions. There is no question that laser endoscopy can control active hemorrhage, with a high rate of success. It has not been shown conclusively, however, that recurrence of hemorrhage is decreased or that the mortality rate is reduced. More work is needed in this area.

9.3.4 Endoscopic Nd:YAG Laser Therapy

Nd:YAG laser endoscopes have been used to treat malignant tumors (Fleischer, 1987) such as esophageal carcinoma which blocks the esophagus and has a poor prognosis. This disease is accompanied with great suffering to the patient due to dysphagia (inability to swallow) and even palliative treatment would be valuable (Fleischer, 1987). A laser endoscope may be inserted into the esophagus and advanced to the outer margin of the tumor, as shown in Fig. 9.9. Laser energy of several kilojoules (100 W peak power) is transmitted through the power fiber, causing vaporization and thermal damage to the central area of the tumor. After 2 days, the treatment is resumed. The laser-treated tissue is necrotic and is removed through the endoscope. Laser energy is reapplied to a deeper region of

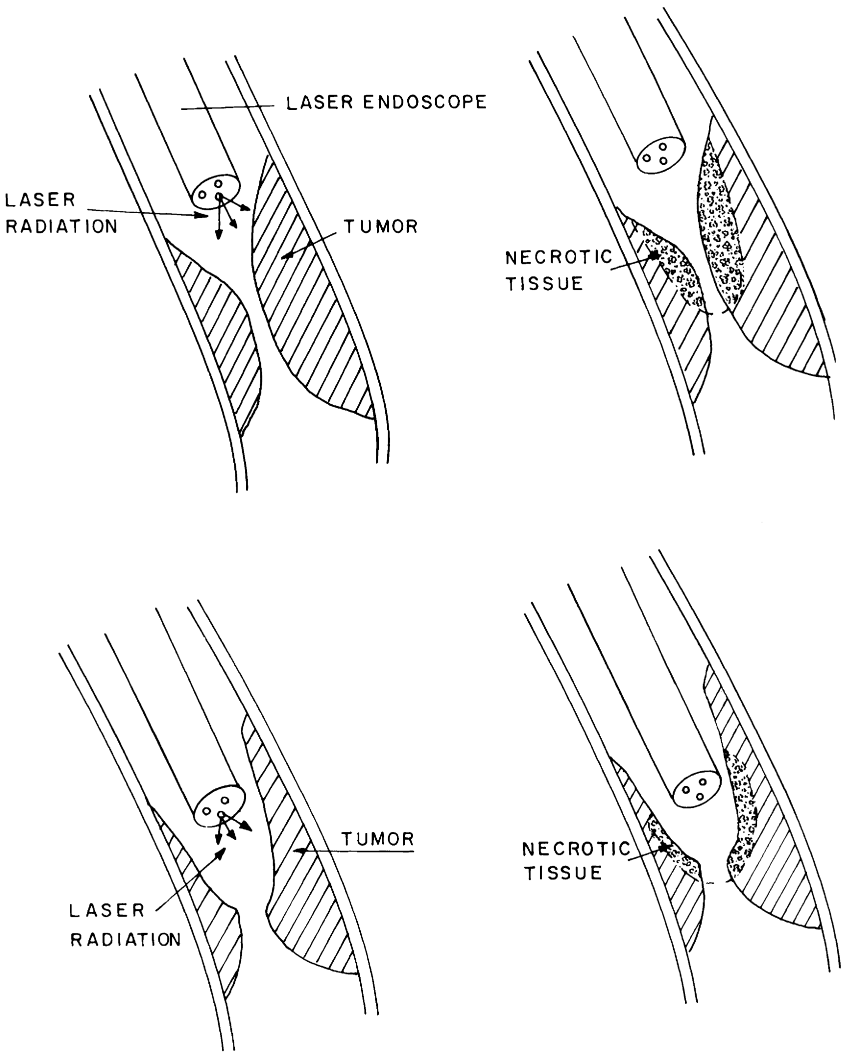

FIGURE 9.9 Laser endoscopy for treatment of gastrointestinal tumor.

the tissue. It again necroses in 2 days and is removed. After several treatments, one may open a new lumen through the tumor, improving swallowing and the quality of life for the patient. It is then possible to insert a stent to hold the lumen patent (i.e., open). Laser recanalization of obstructing tumors is a safe and effective method and is particularly important in cases unsuitable for surgery or radiotherapy.

This method has also been applied to inoperable rectal tumors. The Nd:YAG laser energy opens a channel while coagulating blood vessels. This offers a treatment for the two main symptoms associated with rectal tumors—obstruction and bleeding. The same method has also been applied for colonic tumors.

9.3.5 Diagnosis and Photodynamic Therapy

Photodynamic therapy (e.g., HPD–PDT) is well suited for the treatment of gastrointestinal cancer (Marcus, 1992). In the case of superficial esophageal cancer, early diagnosis and HPD–PDT have been used clinically. HPD–PDT has also been used for palliation of dysphagia that is caused by a malignant tumor. In both cases a cylindrical diffuser tip may be inserted into the esophagus and used for intraluminal treatment. In the case of colon cancer, endoscopic laser surgery or therapy may cause perforations. HPD–PDT is potentially safer. In early clinical studies fiberoptic tips were inserted in colorectal cancer tumors and interstitial treatment was used. In these studies the HPD–PDT was found promising. In principle, the same method will also be useful in the future for early detection and treatment of gastric cancer. But the problems of uniform illumination and of dosimetry are more difficult because of the shape of the stomach, the effects of gastric folds, and the peristaltic motion.

9.4 FIBEROPTIC LASER SYSTEMS IN GENERAL AND THORACIC SURGERY

9.4.1 Introduction

Endoscopic laser surgery, possible to perform for 30 years now, has not been used by many general surgeons (Joffe, 1989). This changed when surgeons started using laser laparoscopic techniques, which had actually been developed for gynecology. The first successful case was laser cholecystectomy, described in the next section. Preliminary work on laparoscopic bowel resection, adhesiolysis, and welding is promising. It is expected that laser surgery of the appendix (i.e., appendectomy) or the liver will follow. As am example, the use of a laser catheter for thoracic surgery is shown schematically in Fig. 9.10.

9.4.2 Laparoscopic Laser Cholecystectomy

The gallbladder, situated on the underside of the liver, contains bile. Stones form in the gallbladder when the bile is oversaturated with cholesterol or bilirubin.

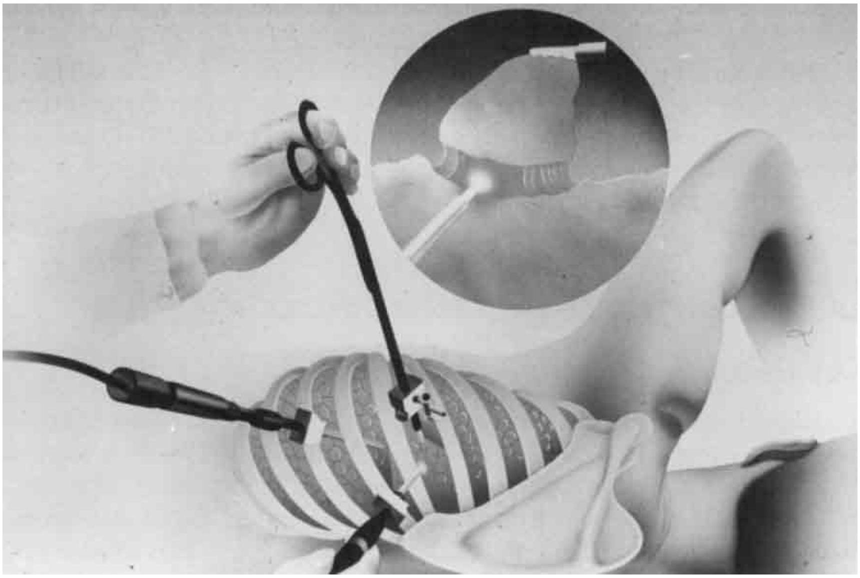

FIGURE 9.10 Endoscopic laser procedure in thoracic surgery. (Courtesy of LaserSonics.)

These stones may block the bile duct that leads from the gallbladder to the small intestine, causing cholecystitis—inflammation of the gallbladder. These stones may be shattered by shock wave lithotripsy or even by laser lithotripsy (Lux *et al.*, 1986). Unfortunately, the stones re-form within a few years and must be removed again. The treatment of choice is often surgical removal of the gallbladder. This cholecystectomy procedure is a major operation which involves a large abdominal scar, a stay of a few days in the hospital, and an extensive recovery period at home.

An alternative solution involves the use of a less invasive laparoscopic cholecystectomy. Typically, four small incisions are needed for this procedure. Through one incision, a rigid laparoscope is inserted, through which the physician obtains a clear image of the gallbladder. Surgical instruments are introduced through two trocar sheaths that are inserted into incisions to hold the gallbladder and other tissues in place. A dissection tool is threaded through the fourth incision and is used to dissect the gallbladder from the liver bed. The first clinical studies used either electrocautery (i.e., coagulating scissors) (Dubois *et al.*, 1990) or a laser catheter (Reddick and Olsen, 1989). The gallbladder can then be removed from the abdominal cavity through one of the trocar sheaths. Electrocautery is a well-established technique that facilitates hemostasis. Yet there have been complications, especially those related to intestinal burns or perforations due to current leakage. The laser beam is easier to control, but the procedure may take longer. It has not yet been established which of the dissection techniques is better (Smith *et al.*, 1990).

Laser cholecystectomy studies have been made with the Nd : YAG laser catheter, using a fused silica fiber and an attached sapphire contact tip. Alternatively, the distal tip of the fused silica fiber itself is specially treated, so it could also be used in contact with tissue during the cutting procedure.

Preliminary studies of laparoscopic cholecystectomy were successful and have generated wide interest (*American Journal of Surgery*, vol. 161, March 1991). This method has been applied successfully on more than 20,000 patients, within 2 years of its introduction. It leads to shorter hospitalization, more rapid recovery, and much better cosmetic results.

9.5 FIBEROPTIC LASER SYSTEMS IN GYNECOLOGY

9.5.1 Introduction

Lasers were introduced into gynecology in the mid-1970s and the first laser operations were carried out by Bellina and French using a CO_2 laser (Bellina 1974; Bellina *et al.*, 1985; Baggish, 1985). They were found to be useful in treating diseases of the lower genital tract such as vulvar, cervical, and vaginal lesions. Internal imaging was first carried out with rigid endoscopes, such as colposcopes, laparoscopes, or hysteroscopes. Laser beams were focused directly on tissue, through rigid endoscopes, and used for endoscopic surgery. Ar and Nd:YAG laser beams were then delivered through power fibers in laparoscopes. Fiberoptic endoscopes have also been widely used in gynecology. One of the most important uses of the CO_2 laser endoscope is in the treatment of cervical intraepithelial neoplasia (CIN), a premalignant lesion of the uterus cervix. Laser endoscopes have also been employed for the management of endometriosis and for intra-abdominal and intrauterine surgery. Because of the early success of laser and fiberoptic systems, gynecology is the medical specialty in which the greatest number of laser procedures are performed in the United States. Some of these endoscopic applications of lasers in gynecology are discussed below. Photodynamic therapy (e.g., HPD–PDT) has also been used clinically in gynecology. Developments related to lasers in gynecology are discussed in several books (Bellina and Bandieramonte, 1986; Keye 1990; McLaughlin, 1987, 1991).

9.5.2 Lower Genital Tract

9.5.2.1 Cervical Intraepithelial Neoplasia

This is a pathological process that results in the formation of neoplasm in the cervix and, in severe cases, may develop to carcinoma *in situ* (CIS). The disease is diagnosed by a cervical smear test that is now routinely used in conjunction with two endoscopic methods: magnification and coloring. The special vaginal endoscopes, called colposcopes, have magnification of 5–25× and are used for examining the cervical epithelium. After the application of an acetic acid solution, irregular epithelial areas become accentuated, making it easier to distinguish the CIN lesion, but this examination is not always definitive. When the results of colposcopy are definitive, however, the lesion is treated effectively by local destruction of the lesion to a depth of a few millimeters.

Several techniques are available for destruction of CIN of the cervix, such as local electrical heating (diathermy) or local freezing (cryosurgery). Effective electrical heating must be performed under anesthesia. Thermal damage to the neighboring tissue may cause complications. The cryosurgery procedure is hard to control and also causes postoperative complications. Vaporization of CIN by highly absorbed laser beams, such as the CO_2 beam, is ideally suited for this problem. The laser beam may be coupled into the rigid colposcope via a long focal length lens and focused to a small spot. The tissue is vaporized with minimal blood loss and pain and with a low complication rate. This laser procedure may therefore be performed without general or local anesthesia on an outpatient basis. Laser endoscopic diagnosis and therapy of CIN has been performed on thousands of patients with a success rate greater than 80%.

9.5.2.2 Vaginal and Vulvar Lesions

Vaginal and vulvar interepithelial neoplasia are much less common than CIN. The traditional surgical procedures in both cases are difficult and may result in complications. Both cases may preferably be treated by the CO_2 laser vaporization through a magnifying colposcope. General anesthesia is recommended. The same method is used now for perineal and vulvar condylomatous lesions, which are benign and bulky tumors caused by viral infection and are contagious.

9.5.2.3 Laparoscopic Laser Surgery

The laparoscope, introduced surgically into the abdomen, is used for examining the pelvic organs. In gynecology, rigid and flexible endoscopes have been used for intra-abdominal laser surgery, as illustrated in Fig. 9.11. A trocar with an outer sleeve (cannula) is introduced into the abdomen; the inner part of the trocar is removed and the endoscope is inserted through the cannula. This endoscope may be a laser endoscope that serves for laser power transmission (via an optical fiber) as well as for irrigation or suction. There are gynecologists who prefer to insert an imaging laparoscope through one puncture, the power fiber through a second puncture and the irrigation/suction tube through a third puncture. In the late 1970s and 1980s, mostly rigid laparoscopes were utilized, but more recently (Cook and Rock, 1991) fiberoptic flexible ones have also been used.

- Endometriosis: Ectopic nests of endometrium may be found in different locations in the abdominal cavity. This often results in the formation of cysts which contain blood and cause chronic, recurrent abdominal pain. These were treated first by an Ar laser beam which was transmitted through a silica fiber (Keye and Dixon, 1983). CO_2 is much more suitable for this purpose because it is highly absorbed by water and is not selectively absorbed by colored tissue. It therefore vaporizes only a thin superficial layer. The CO_2 laser may be operated in the pulsed mode so that the damage to neighboring tissue is minimal. Baggish performed two clinical stud-

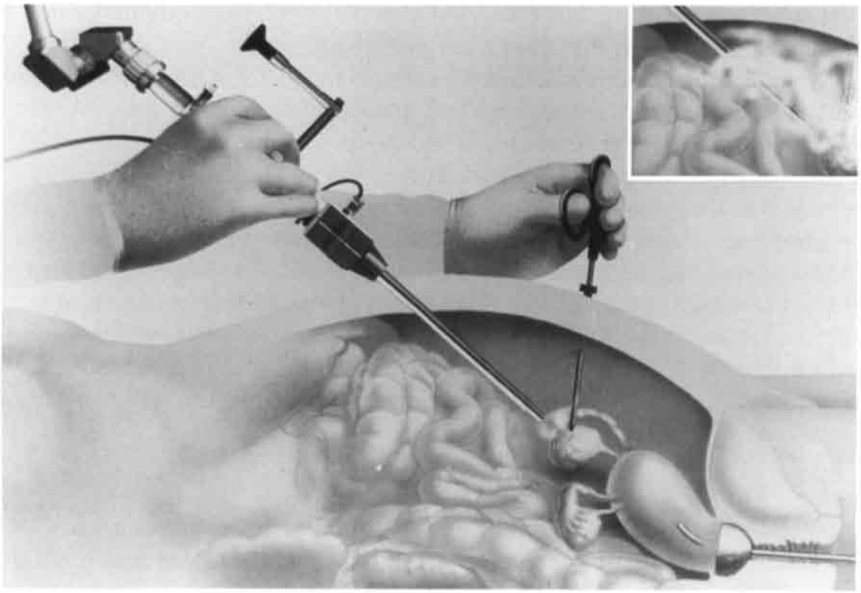

FIGURE 9.11 Laser catheter procedure in gynecology. (Courtesy of LaserSonics.)

ies of laparoscopic treatment of endometriosis, using both rigid and flexible hollow waveguides (Baggish, 1988). The results of the two studies are encouraging.

- Microsurgery for infertility: Laser microsurgery of the fallopian tubes may be performed if disfunction is diagnosed in laparoscopy. Again, this procedure has the advantages of precise tissue removal, bloodless operation, and minimal thermal damage to neighboring tissue. The microsurgical laser operations which have been performed clinically include removal of adhesions (adhesiolysis) and the reanastomosis of the fallopian tubes. The preliminary results of these procedures are also encouraging.
- Intrauterine surgery: The hysteroscope is a special endoscope which has been developed for procedures involving the uterus. It may be introduced into the uterus much like a laparoscope. Laser surgical operations, such as vaporization of the endometrium, have been performed with this endoscope using an Nd:YAG laser and fused silica fibers. An intriguing possibility is the performance of fetal surgery using the same system (Hallock and Rice, 1989).

9.5.3 Diagnosis and Photodynamic Therapy

It is interesting to note that HPD was already used in 1964 for the endoscopic diagnosis of cancer in the cervix (Lipson *et al.*, 1964). PDT is ideally suited for early diagnosis and for the treatment of cancer of the vagina or of the cervix, because they are easily accessible via catheters or endoscopes. Clinical studies have demonstrated that various types of gynecological malignancies can be efficiently eradicated using photodynamic therapy (Marcus, 1992).

9.6 FIBEROPTIC LASER SYSTEMS IN NEUROSURGERY

9.6.1 Introduction

Chapter 2 discussed the general advantages of lasers for surgery and therapy. With the introduction of the operating microscope and its laser adapters and micromanipulator in the late 1970s, lasers made inroads into neurosurgery. For neurosurgery, lasers have the following advantages: (i) the laser beam may be focused to a small area, which is viewed under the magnification of an operating microscope; (ii) the focal spot is easily moved with a mirror system; (iii) the laser beam vaporizes or coagulates tissue in the target area (e.g., a nodule) without mechanical contact and damage to adjacent areas (e.g., neighboring nerves).

Most of the applications of lasers during the past two decades have been intraoperative. CO_2 laser radiation has been used to vaporize tumors in sensitive locations in the brain, pituitary tumors, and meningiomas. Once the exact location of such tumors is determined by computed tomographic (CT) scan, even deeply rooted tumors can be treated in this manner. Spinal cord tumors have also been removed by CO_2 laser radiation, without causing trauma to the spinal cord. Nd: YAG lasers have been used to treat highly vascular and intraventricular tumors, in addition to microvascular repair and vascular anastomosis. These applications paved the way for the use of laser–fiber systems in neurosurgery (Cerullo, 1984; Jain, 1983, 1984; Robertson and Clark, 1988).

9.6.2 Endoscopic Techniques

A few of the endoscopic techniques used in neurosurgery are discussed next.

9.6.2.1 Fiberoptic and Ultrasound Imaging

In the 1920s, endoscopic imaging was already being used in neurosurgery; rigid endoscopes (neuroendoscopes) were used to observe the ventricular cavities or deep-seated tumors in the brain. These have not made a significant impact on neurosurgery.

With the development of CT scanning and magnetic resonance imaging (MRI), it is now possible to determine the location of tumors with great accuracy. A burr hole of diameter 0.5–1 cm is drilled in the skull through which a thin and rigid tube is inserted. A rigid endoscope is inserted through the tube, so that its distal end is brought to the vicinity of the tumor. The endoscope includes irrigation and suction channels and an ancillary channel for auxiliary instruments (e.g., resection or biopsy) or a laser power fiber.

An ultrasound imaging system may also be attached to the tip of the endoscope to allow better positioning of the endoscope. Alternatively, the burr hole is enlarged and a suitable holder attached. A special ultrasound imaging probe is inserted through the burr hole and is positioned in the required position. This probe is then replaced by a rigid plastic tube which, in turn, serves to guide the distal tip of the endoscope to the same position (Otsuki *et al.*, 1992).

9.6.2.2 Endoscopic Surgery

A power fiber is inserted through the ancillary channel of the endoscope. Laser power is transmitted through the fiber and used to treat tumors or other structures. Nd:YAG laser energy transmitted through fibers has been used (Auer *et al.*, 1986) to treat ventricular tumors and cystic tumors in the brain. For cystic tumors, laser energy is utilized to open the cyst and its content are drained through the endoscope. For solid tumors, the procedure involves denaturation of the tissue proteins due to the Nd:YAG laser heating, leading to coagulation necrosis (destruction of tumor tissue).

9.6.2.3 Photoradiation Therapy

Photoradiation therapy is potentially a powerful technique for brain tumors such as gliomas. Because of its selectivity, this treatment may be used to remove tumors in the brain and the central nervous system with minimal disturbance. HPD–PDT was tried clinically on brain tumors in the 1980s. It has been established that HPD accumulates in brain tumors and can be activated with a laser catheter. The power fiber was sometimes introduced into the center of the tumor through a small hole in the skull. In other cases, ordinary surgical methods were used to remove the bulk of the tumor. HPD–PDT was used only on the base of the tumor, in order to eradicate it and prevent tumors from recurring (Marcus and Dugan, 1992). Further studies are in progress.

9.6.3 Lumbar Diskectomy

A common form of lower back pain is sciatic pain, which is often caused by a spinal disk pressing against a nerve root. This condition has been traditionally treated by open surgery. Recently, laser-assisted percutaneous lumbar diskectomy has been used instead. This method is discussed fully in Section 9.9.3.

9.7 FIBEROPTIC LASER SYSTEMS IN ONCOLOGY

9.7.1 Introduction

In previous sections, three distinct ways in which lasers have been used for cancer therapy were mentioned: (i) laser vaporization of malignant tumors, (ii) laser heating for hyperthermia or for coagulation necrosis, and (iii) photoradiation therapy. All three modalities are termed cancer phototherapy and are discussed in review papers (Bown, 1983; Gomer *et al.*, 1989; Dougherty *et al.*, 1990;

Marcus, 1992) and books (Doiron and Gomer 1984; Dougherty, 1989, 1990, 1992; Henderson and Dougherty, 1992; Kessel, 1990; Morstyn and Kayo, 1990).

In this section we discuss briefly the general use of fiber–laser systems for cancer diagnosis and phototherapy. In addition, each section that addresses a specific medical discipline also includes a section on HPD–PDT, the photodynamic therapy based on hematoporphyrin derivative.

9.7.2 Laser Vaporization of Malignant Tumors

Laser energy transmitted through optical fibers in laser catheters or laser endoscopes is able to vaporize or cut malignant tissue. The most suitable lasers for this procedure are the pulsed CO_2, excimer, and Er:YAG lasers, which remove tissue efficiently. Although tumors may also be cut with mechanical tools which are inserted endoscopically, laser vaporization causes much less damage to the surrounding tissues. Laser methods cause less spreading of the malignant cells to healthy regions than mechanical tools. Laser vaporization is a useful technique for the treatment of early malignant disease or for palliative removal of large tumors.

Laser vaporization has been used in gynecology and in laryngology for treatment of early malignant diseases. The main limitation of this method is that the pulsed laser treatment does not coagulate the blood. If bleeding occurs, one must use CW lasers, such as Nd:YAG laser or CO_2 lasers, to stop the bleeding.

9.7.3 Photodynamic Therapy

The use of HPD in photodynamic therapy was studied in the early 1960s (Lipson *et al.*, 1961). HPD–PDT is a viable therapeutic modality for the treatment of cancer (see Section 3.7.2). Malignant tumors respond to this modality even after failure of other modalities such as radiation therapy or chemotherapy. In a worldwide series of clinical trials involving thousands of patients, a variety of tumors were successfully treated. Some of the tumors were in advanced stages of malignancy, and others were in earlier stages. These studies involve many disciplines, which are mentioned in other sections of this chapter. The trials have demonstrated that laser photochemotherapy of tumors may have a fundamental impact on cancer therapy (Dougherty *et al.*, 1990). This section reviews laser–fiber aspects.

- Sensitizer: HPD is given to patients intravenously in a minimum dose of about 3 mg/kg body weight. After 48–72 hr, the sensitizer is localized in malignant tumors. Other sensitizers are also being investigated.
- Diagnosis: HPD may be injected intravenously. After 24–48 hr, the compound is concentrated in malignant tumors. A whole area may now be illuminated by a UV laser beam. The physician may look at the whole area through glass filters that transmit only red light (600–700 nm). A region emitting red light involves a malignant tissue. In dermatology, there is a need to identify basal cell carcinoma. HPD is injected into the body and, after a few days, the face of the patient is illuminated with UV laser light.

The malignant cells are clearly seen by their red emission. In practice, the emission can be recorded using an imaging system with an image intensifier (Andersson-Engels *et al.*, 1990).

- Therapy: When the tumor is exposed to red laser light, the HPD is photoactivated; it converts triplet oxygen to singlet oxygen, which is cytotoxic and kills the tumor cells. The minimum threshold for photoactivation is about 15 mW/cm^2 and a typical fluence is 100 J/cm^2. The exact site of action of the photodynamic therapy is under intensive study. There seem to be effects on both the cellular level and the vascular level. When a malignant tumor has been detected using the laser endoscope, the tip of the power fiber is placed next to or inserted inside the tumor. Red light from an argon pumped dye laser or Au laser is transmitted through the power fiber. This red light photoactivates the sensitizer, which in turn causes a

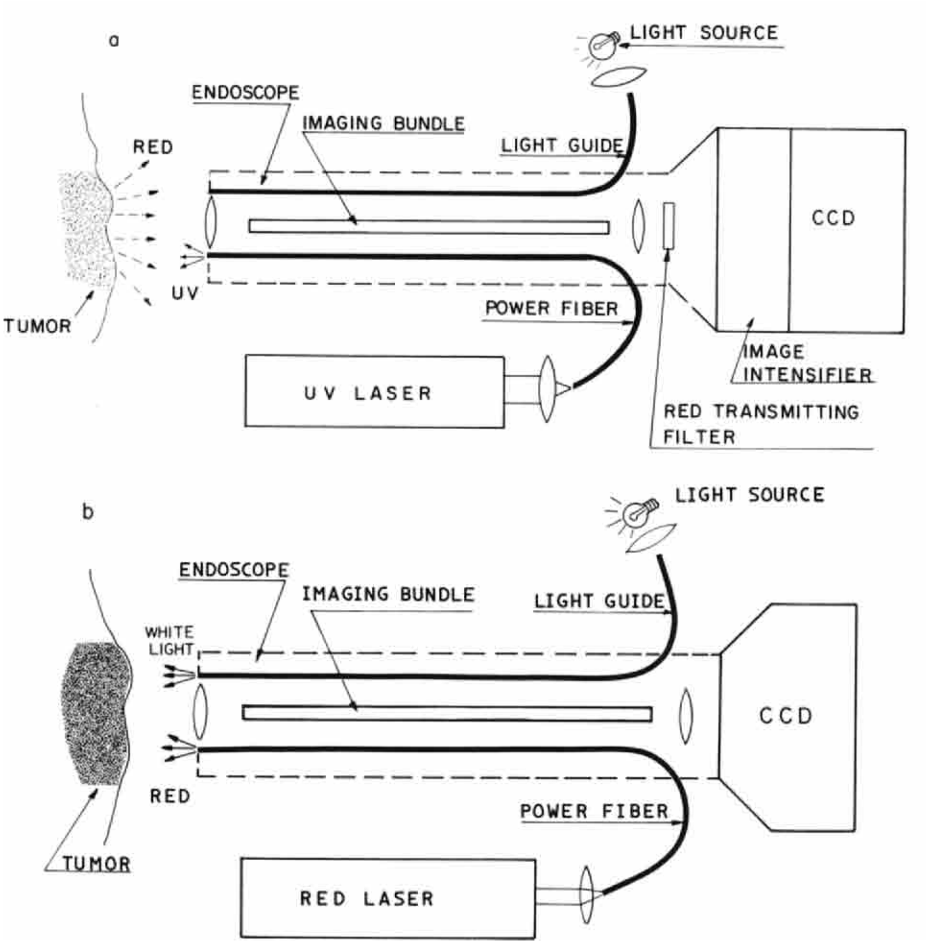

FIGURE 9.12 Endoscopic photodynamic therapy: (a) diagnosis and (b) (HPD–PDT) treatment.

controlled lysis (gradual destruction) of the tumor cells. Figure 9.12 illustrates endoscopic diagnosis and therapy with HPD–PDT.

Figure 9.13 shows endoscopic photographs obtained from a patient with squamous cell carcinoma obstructing the mainstem bronchus.
The general procedures for diagnosis and therapy using HPD–PDT may be described by a flowchart, as discussed in Section 9.12.

9.7.4 Laser Photocoagulation

Laser energy, absorbed in malignant tissue, causes death of tumor cells with delayed sloughing and has been used for cancer treatment. The Nd:YAG laser is

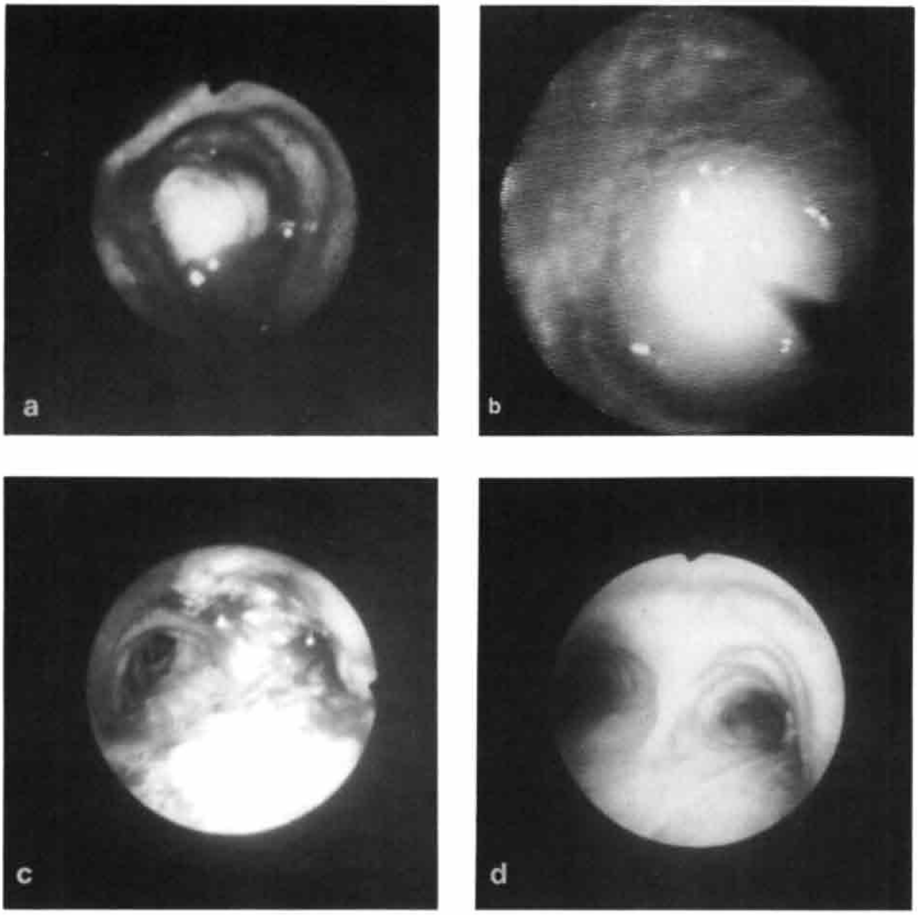

FIGURE 9.13 Endoscopic photodynamic therapy (HPD–PDT) photographs: (a) before treatment (tumor is seen); (b) during laser therapy; (c) "cleanup" after treatment; (d) 3 months after treatment (tumor disappeared). (Courtesy of Dr. S. Lam.)

most suitable for this application because its light is easily transmitted through fused silica fibers and it deeply penetrates tissue. This is particularly important in cases which are unsuitable for conventional surgery or radiotherapy. Nd:YAG laser endoscopes have been used for the palliative recanalization of large malignant tumors which obstruct the upper and lower gastrointestinal tract (Bown *et al.*, 1986) or the main airways (see Section 9.3.4). In regular laser endoscopy procedures, the distal tip of the laser endoscope is brought to the vicinity of the tumor and the distal tip of the power fiber is kept a few millimeters from the tumor. The tip of the power fiber may be inserted inside the tumor and the laser energy is then applied interstitially. This method has also been proved to be effective for the destruction of metastasis in the liver.

9.7.5 Laser Hyperthermia

Sections 3.7.1 and 7.5.1.2 described hyperthermia cancer treatment that is based on heating tissue to temperatures between 42.5 and 43.5°C for tens of minutes. Under these conditions malignant tissue is destroyed while normal tissue is not affected. In laser hyperthermia, the heating is performed by laser energy—normally using an Nd:YAG laser beam which penetrates deep into tissue. The laser energy is delivered through a power fiber which is incorporated in a laser catheter or laser endoscope (Daikuzono *et al.*, 1988). As in laser photocoagulation, the distal tip of the power fiber is placed a few millimeters from the tumor. Alternatively, a diffusing fiber tip is inserted into the tissue for interstitial treatment. Several fibers may be inserted into the tumor with their tips placed (endoscopically) at various depths, facilitating a more even temperature distribution inside the tumor. As an example, cancer of the liver may be considered. Using improved diagnostic methods such as ultrasound or CT, it is now possible to obtain images of hepatic tumors with good resolution. The only treatment that can currently cure such tumors is surgery. Interstitial laser hyperthermia offers an alternative, and by using ultrasound imaging it is even possible to follow the dynamic changes in the tumor during heating and the ensuing necrosis. This method has been tried clinically for cancer of the liver and of the pancreas (Steger, 1991) and it is potentially useful for a variety of other tumors such as those of the adrenal or prostate glands.

9.8 FIBEROPTIC LASER SYSTEMS IN OPHTHALMOLOGY

9.8.1 Introduction

Because the eye is transparent to visible, near-UV, and near-IR light, its inner parts are easily accessible to laser light (see Section 2.4.1). Lasers have thus been used in ophthalmology for therapy and diagnosis for almost three decades. Some of the important laser applications in ophthalmology are briefly discussed.

It has been known for millennia that sunlight can cause damage to the eye. In the 1940s Meyer Schwickerath tried to use concentrated sunlight to produce burn scars inside the eye and found that scars that were produced near holes in the retina prevented retinal detachment (Meyer Schwickerath, 1949). In the 1950s he collaborated with researchers in the Zeiss company in Germany to produce a high-pressure xenon lamp that was used as an intense source of light for retinal "welding." The major problem of this instrument was that this was an ordinary light source. Therefore the light was focused by the eye on a relatively large spot. The irradiance (power density) at that spot was not high and it took a long time (e.g., 1 sec) to produce a burn. During this time heat diffused to other parts of the eye, causing pain and unavoidable eye movement (with a change of position of the spot). Another problem was that the spectral emission of the xenon lamp (at 800–900 nm) was not well matched to the absorption of the retina or the underlying choroid.

With the development of the first ruby laser in the early 1960s, ophthalmologists immediately tried to use it for the same purpose (Ross and Zeidler, 1966). The collimated and monochromatic laser light was focused by the eye to a small spot (<0.1 mm) and lesions were obtained using short pulses (<1 msec), without pain to the patient and without eye movement. The successful use of the ruby laser for intraocular applications paved the way for the use of other lasers for therapy and diagnosis (L'Esperance, 1983).

In ophthalmology therapy, the heating effects of laser beams (e.g., Ar, Kr, or dye lasers) inside the eye may cause photocoagulation. This has been extremely useful for the management of treatment of retinal detachment. A hole or a tear that develops in the retina may lead to separation of the retina from the underlying choroid. The focused laser beam is used to generate around the hole a circle of burn scars that unite the retina to the choroid and prevents detachment. The focused laser beam can also cause heat shrinkage that seals blood vessels inside the eye. This has been used for the treatment of proliferative diabetic retinopathy, a degenerative disease of the retina. Tumors inside the eye are accessible to photochemotherapy treatment, similar to that described in Section 9.7.3, where a suitable red laser (e.g., Au vapor laser) is used. Photodisruption appears when high peak power laser pulses (e.g., Nd:YAG) are focused inside the eye. This has been used for intraocular incision in the posterior capsule of the lens or for incision of vitreous structures inside the eye. More recently, excimer laser beams have been used to reshape the cornea by ablating material from the outer surface of the cornea. Short pulses of highly absorbed laser wavelengths can potentially remove corneal tissue with practically no thermal damage. This refractive keratotomy is potentially an extremely useful method for correcting refractive defects of the eye.

In diagnostics, a laser (e.g., HeNe) beam illuminates the retina and either the scattered light or the electroretinographic response is measured. If the laser beam is scanned across the retina, the physician may detect visual defects or obtain localized functional abnormalities. Visible lasers may also be used for laser Doppler velocimetry (see Section 7.7.1) of the blood in the retinal blood vessels.

These applications of laser do not normally make use of fiberoptic techniques. Some of the special cases in which optical fibers are needed are discussed next (Thompson *et al.*, 1992).

9.8.2 Ophthalmological Applications of Laser—Fiber Systems

In the late 1970s and early 1980s, there were several attempts to perform CO_2 laser surgery or photocautery inside the eye (Bridges *et al.*, 1984; Meyers *et al.*, 1983; Miller *et al.*, 1981). The waveguide used in most of these cases was a rigid metallic or dielectric tube of diameter 1 – 1.5 mm and length 20–30 mm. A ZnSe window was attached to its distal end. The proximal end of the rigid waveguide was attached to the tip of an articulating arm system (see Section 2.3.4). The distal end was inserted into the eye and placed in the immediate vicinity of a diseased tissue. More recently, other lasers have been used. Some of these applications are discussed:

Photocautery

Miller *et al.* (1981) performed photocautery experiments on rabbits to demonstrate that CO_2 laser energy could be used to close blood vessels and seal retinal tears. They found that, at moderate laser powers, the laser probe performed rather well when the power output was 0.5 W for a duration of 2–5 sec. They then performed several successful clinical trials for closing retinal vessels and sealing retinal tears in the case of severe diabetic retinopathy.

Transection of Vitreal Membranes

Vitreous membranes in the eye may be cut (i.e., vitrectomy) by mechanical tools which are inserted via hypodermic needles. The membranes may then be pulled out through the same ducts. Intraoperative complications may arise if the membranes are too close to the retina, particularly, if the membranes are vascular and bleed into the eye. It may thus be advantageous to insert a probe into the eye and bring it to the vicinity of the membrane. CO_2 laser energy is then delivered and microsurgery is performed for the membrane removal. Laser energy is highly absorbed by the membrane and the surgical procedure may be performed without causing damage to the retina.

Such vitrectomy experiments were performed using CO_2 lasers and rigid (Miller *et al.*, 1981) or flexible (Meyers *et al.*, 1983) probes. More recently, Margolis *et al.* (1989) used a pulsed Er:YAG laser (2.94 μm) and IR-transmitting ZrF fibers of diameter 0.3 mm to cut dense membranes which are adjacent to the retina. The Er:YAG laser radiation, which is also highly absorbed in tissue, offers the same advantages as the CO_2 laser. No retinal lesions were produced if the retina was more than 2 mm from the tip of the fiber. Yet the fiberoptic delivery systems used require further improvements.

All these experiments proved the potential of highly absorbed laser beams for practical use in cutting avascular and vascular vitreous membranes. Further experimentation is needed before they are used clinically.

Cataract Surgery

In cataract formation the lens of the eye becomes opaque, leading to blindness. In cataract surgery the lens is removed through a small incision, leaving the capsule that surrounds the lens. The empty capsule is then filled with a polymer that has optical and mechanical properties similar to those of the lens. Instead of surgery, a laser catheter may be inserted through the cornea into the lens. A laser beam sent through the catheter will be used to vaporize the lens material and the vapors could be pumped out through the catheter. This procedure is likely to be less traumatic than regular surgery. Highly absorbed UV or IR lasers may be most suited for this application and experiments are under way (Thompson *et al.*, 1992).

Glaucoma Surgery

Glaucoma is a disease that is manifested by high pressure inside the eye and may lead to blindness. This pressure may be reduced by generating a small hole in the peripheral iris and facilitating better fluid flow. Traditionally, this hole has been generated by a noninvasive procedure: Ar or Kr laser beams have been focused onto the iris. These beams are highly absorbed by the melanin in the iris, and this leads to ablation of a hole. It may be advantageous in some cases to use a laser catheter for this applications (Thompson *et al.*, 1992).

9.9 FIBEROPTIC LASER SYSTEMS IN ORTHOPEDICS

9.9.1 Introduction

A large variety of tissues are encountered in orthopedics, such as bone, cartilage, ligament, fibrocartilage, muscle, synovia, and tendon. These tissues widely differ in their functions, density, and consistency. There is also a diversity of disorders which orthopedists must address. For centuries, orthopedic surgeons have been using mechanical tools such as saws, drills, chisels, and scissors for cutting and other mechanical devices such as screws, pins, rods, and staples for fixation of tissue.

The efficacy of the mechanical instruments is very high for most surgical procedures. Yet there are cases in which improvements are needed. With all cutting devices, force is applied on tissue (normally by a sharp edge of the instrument), giving rise to tissue separation. There is no real monitoring of the applied force and its control depends on the surgeon's experience. In delicate situations, errors are unavoidable and may lead to complications. In addition, the diseased area is frequently situated inside the body and access to it requires surgical exposure, which is undesirable. In principle, the surgeon may use special mechanical tools which are inserted through a rigid endoscope (arthroscope). In practice, however, it is rather difficult to cut dense tissue with such miniature instruments.

The less invasive methods offered by lasers and optical fibers are likely to change the situation. Highly absorbed laser beams, such as excimer, CO_2, or Er:YAG beams, can ablate tissue with great precision. Tissue ablation is carried out without introducing vibrations or mechanical pressure and with little damage to adjacent tissues. This applies to cartilage, tendon, and even bone. Nd : YAG or CO_2 laser energy may also be used for tissue welding. The laser energy may be transmitted to intracorporeal structures via optical fibers or other waveguides, and visualization may be provided through fiberoptic endoscopes. Some of the developments in this area have been discussed in books and review articles (Sherk, 1990; Whipple, 1987).

9.9.2 Arthroscopic Surgery

In the past, the common methods for treating disorders of the knee or the shoulder involved open surgery of the joint (i.e., arthrotomy), a major surgical procedure. Methods were sought for reaching the confined spaces between the articular surfaces of the joints in the knee or the shoulder with less extensive dissection. Endoscopic (i.e., arthroscopic) techniques make it possible to carry out least invasive interarticular surgery. Mechanical devices are introduced through the arthroscope and used in surgical procedures such as meniscectomy or synovectomy. The diameter of these mechanical devices was normally limited to 3–4 mm, and with such thin instruments it was not easy to perform resection of dense tissue. Manipulation of the mechanical instruments may also cause damage to the contiguous tissue. It was natural to try to replace the mechanical tools with lasers, as illustrated in Fig. 9.14.

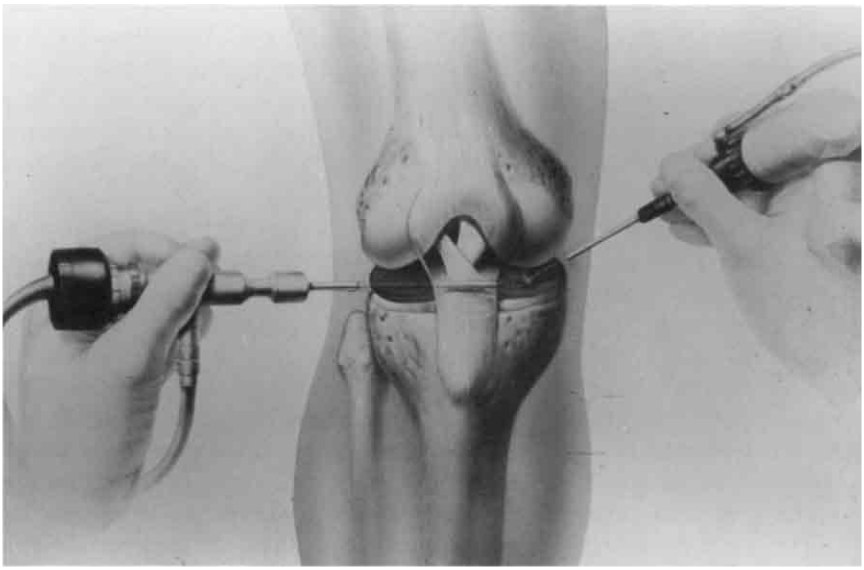

FIGURE 9.14 Arthroscopic laser surgery inside a knee. (Courtesy of LaserSonics.)

The CO_2 laser beam is highly absorbed in human tissue, including meniscus tissue or cartilage. The CO_2 beam, and in particular a pulsed beam, is therefore most suitable for the resection of human meniscus. Preliminary meniscectomy experiments were carried out clinically using a CO_2 laser beam with a special articulated arm. A cannula was attached to the tip of the articulated arm and a tiny mirror was attached to the tip of this cannula. The mirror was used to steer the laser beam. The cannula was inserted into the arthroscope and gaseous nitrogen was introduced through the same cannula in order to obtain distention of the joint space and to flush away the debris. These experiments proved that the meniscus tissue can be removed efficiently without significant thermal damage to neighboring areas, and the remaining peripheral rim of the meniscus heals well. On the other hand, the procedure was limited due to the use of a rigid cannula in a rigid arthroscope. Clinical experiments were also performed (Sherk, 1990) using a CO_2 laser and hollow dielectric waveguides. These procedures offer an attractive alternative to conventional arthroscopy, but they are still somewhat limited by the inflexibility of the waveguide. This situation may improve with the development of flexible IR fibers for the transmission of CO_2 laser beams.

Other lasers such as the excimer, the Nd:YAG, and the Ho:YAG have also been tried clinically for arthroscopic applications. As an example, the Ho:YAG laser energy was delivered through a fused silica fiber; this laser's wavelength is highly absorbed in tissue and cuts the meniscus tissue efficiently. The beam can easily vaporize synovium tissue or loose bodies in the joint. At the same time, the laser beam has hemostatic properties which help prevent postoperative bleeding. In preliminary series of clinical experiments, the fiberoptic-assisted laser arthroscopy was compared to conventional arthroscopic procedures (which make use of mechanical tools). The laser procedure showed significant advantages, in terms of both interoperative effects such as scuffing or trauma and postoperative bleeding or joint inflammation.

9.9.3 Laser Diskectomy

A common orthopedic disorder which affects almost 5% of the population is lower back pain resulting from a herniated intervertebral disk. A ruptured or distorted disk extends into the spinal canal and presses against the spinal cord. This disorder was previously treated by open back surgery such as laminectomy, removal of the lamina, or diskectomy, removal of the disk to reduce the pressure and the pain (cord decompression). Other techniques have been developed in order to reduce the trauma and postoperative effects of intervertebral disk surgery. Some methods involve percutaneous diskectomy using mechanical devices and other methods involve injection of chemicals (e.g., chymopapain) which cause enzymatic removal of the disk. Many of these methods cause complications, including recurrence, and their efficacy is also limited (Sherk, 1990).

During the last decade there have been attempts to use laser–fiber systems for diskectomy. In some early clinical studies (Choy *et al.*, 1987), a fused silica fiber

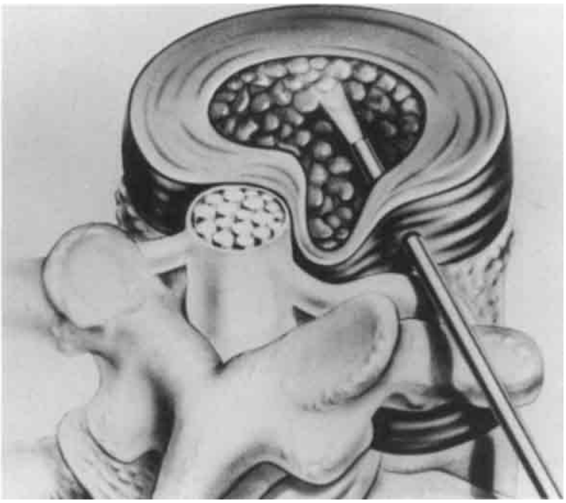

FIGURE 9.15 Laser diskectomy. (Courtesy of Coherent.)

was introduced into the disk space and an Nd:YAG laser beam was transmitted to vaporize tissue and decompress the cord. More recently, a silica fiber was introduced into the nucleus of the disk and Ho:YAG laser energy, which was sent through this fiber, vaporized a portion of the disk tissue (Sherk, 1990). This procedure is illustrated schematically in Fig. 9.15.

The same procedure has also been done using an Ho:YAG laser endoscope system which provided both visualization and guidance during the percutaneous diskectomy procedure. This endoscopic system may afford precise laser ablation and control the volume of nucleus to be removed. In other experiments (Buchelt *et al.*, 1992), an excimer laser beam sent through fused silica fibers ablated diskal tissue *in vitro*. In principle, laser-induced fluorescence (LIF) may be added as a diagnostic tool to distinguish between the two parts of the disk: the annulus fibrosus and the nucleus pulposus. Such a system may be used as another "smart" system that is guided by fluorescence and may prevent penetration of the annulus and injury to the nervous system.

The laser diskectomy procedures are performed percutaneously with local anesthesia. They offer a number of advantages, such as reduced surgical risk, reduced trauma and pain, shorter hospital stay, and faster recovery. When fully developed, laser diskectomy is likely to replace the other procedures described above.

9.9.4 Tissue Welding

While treating the spinal column or the extremities, the orthopedic surgeon is often required to treat disorders of neurological or vascular tissue. When necessary, fixation of these tissues is performed with the assistance of foreign materials such as sutures or glues. Laser welding of tissue has been discussed in detail in Section 3.7.1.3. In particular, laser anastomosis of blood vessels and repair of nerves have been tried using different lasers and various irradiation conditions. Laser anastomosis of blood vessels is potentially useful in orthopedic surgery. It may assist in the transfer of skin or muscle flaps or in the replantation of severed digits or extremities. Nerve repair or grafting is critical to the success of many orthopedic surgical procedures. The laser offers great advantages over conventional suturing techniques. Laser welding is in principle faster, easier to perform, and more reliable. Much more research is needed, however, before this technique is used clinically.

9.10 FIBEROPTIC LASER SYSTEMS IN OTOLARYNGOLOGY (ENT)

9.10.1 Introduction

Natural openings provide easy access into the ear, nose, and throat (ENT). Simple optical systems which have been used for generations made it possible to illuminate and obtain clear images of internal parts. Mechanical tools such as grasping or cutting tools could also be easily introduced into these natural openings, as could electrosurgical and cryosurgical tools. The electrical and cryogenic surgical tools result in uncontrollable thermal damage to neighboring tissue, which is often unacceptable in otolaryngology. For example, in laryngeal surgery, cryosurgery may result in excessive slough and even obstruction of the larynx. Lasers, such as the CO_2 or excimer lasers, are preferable because they remove tissue in a controlled way and with little thermal damage. Laser beams, which are simply reflected by a mirror and focused inside the ear or the oral cavity, have been used for surgical applications.

With the development of rigid endoscopes, it was possible to obtain excellent images of deeper zones in the larynx or the bronchus. Laser beams sent through these endoscopes have been used for surgery and therapy. The introduction of fiberoptic laser endoscopes has changed the situation again. It is hoped that these will make a great impact on endoscopic laser surgery and therapy in otolaryngology and chest medicine. Section 9.10 discusses the topics which are related to fiberoptic laser systems. (Carruth, 1983; Carruth and Simpson, 1988; Davis, 1990)

9.10.2 Endoscopic Laser Surgery—Larynx, Pharynx, and Oral Cavity

In the mid 1970s, lenses were used to focus CO_2 laser beams at a typical distance of 20–30 cm from the lens. Focused laser beams, transmitted in air, were coaxially aligned with rigid laryngoscopes and used for endoscopic surgery (Strong *et al.*, 1973). Many groups used similar laser endoscopes clinically in laryngeal operations such as the treatment of vocal cord nodules (e.g., "singer's nodules"), laryngeal polyps, or other benign tumors such as respiratory papillomas (Shapshay, 1987). The CO_2 laser beam was sometimes used to excise these lesions, which were then extracted with endoscopic forceps. In other instances, the lesions were vaporized until healthy tissue was reached; the rate of success in all these procedures was high. Laser endoscopy was also tried for the management of laryngeal stenoses by endoscopic resection. With benign stenoses, the laser can vaporize or excise the lesions; however, the recurrence rate is not improved in comparison to nonlaser techniques. For malignant tumors, such as carcinoma of the larynx or vocal cord carcinoma, the laser can also serve to excise the tumor. The cure rate is comparable to that of the more traditional surgical procedures or radiotherapy, with less morbidity.

CO_2 laser endoscopy has been also used for the management of benign or malignant tumors in the oral cavity or pharynx and for nasal surgery. This method is useful for the management of both benign and malignant tumors. The benefits of the treatment, in the ease of operation, are the bloodless field and better healing compared to standard surgery.

9.10.3 Endoscopic Laser Surgery—Tracheobronchial Tree

The development of thin, flexible fiberoptic endoscopes has changed bronchoscopy. It is now possible to obtain clear images inside the tracheobronchial tree, perform diagnosis, and use the fiberoptic bronchoscope as a laser endoscope (Shapshay, 1987). Few of the tumors in the trachea and the bronchus are benign, and management of these tumors (as well as stenoses) is similar to that explained in the previous section. The major requirement is early diagnosis of malignant disease and its treatment.

Early diagnosis of carcinoma of the bronchus is carried out by sputum cytology, which shows the presence of malignant cells in the sputum. This method, however, does not provide information regarding the location of the tumors. When the tumors are small, they cannot be easily observed in regular (white light) bronchoscopy and cannot be detected by chest x-ray study. Such early tumors can be detected by the fluorescence techniques described in Section 9.7.3.

Carcinoma of the bronchus may be treated by radiotherapy or by surgery. One of the severe problems is that a significant fraction of the patients suffocate due to blockage of the bronchus. Because of the accumulation of eschar layers, repetitive surgical resection cannot alleviate this problem. Various groups tried to solve the problem with laser endoscopes. The CO_2 laser was used in conjunction with rigid bronchoscopes for laser surgery. Ar or Nd : YAG laser beams were transmitted by fused silica fibers and used in both rigid and flexible bronchoscopes for endoscopic laser coagulation (see Section 9.3.3). Endoscopic laser surgery and therapy are effective as a palliative treatments, improving the life quality of the patients.

9.10.4 Diagnosis and Photodynamic Therapy

The combined use of drugs and laser excitation for diagnosis and therapy, such as HPD–PDT, was discussed in full in Section 3.7.2. This is particularly important in the diagnosis and treatment of carcinoma of the bronchi. As mentioned, early detection of malignant tumors in the bronchi is important and sputum cytology does not provide information about the location of the tumors. Advances in fluorescent diagnosis and endoscopy may provide the necessary answer. Two or three days after HPD injection, a laser catheter is inserted into the bronchial tree and delivers Kr laser light (410 nm). The fluorescence emitted by bronchial tissue is sent back through an optical fiber and passes through a red filter that transmits a narrow band of wavelengths at approximately 630 nm. Red luminescence will be observed only if there is a malignant tumor which was exposed to the Kr laser light. The laser catheter provides a preliminary warning of the presence of tumors, but their exact location can be determined only with fluorescent endoscopy. A laser endoscope may be inserted into the bronchial tree and Kr laser light delivered through the power fiber. Under this illumination, the malignant tumors fluoresce in a characteristic red light which may be observed when a red-transmitting filter is used. The red emission is rather low and an image intensifier is often used to obtain a better picture. Several groups (e.g., Balchun and Doiron, 1982) performed clinical studies and showed that this technique can provide an accurate and quick method for the early diagnosis of carcinoma in the tracheobronchial tree.

When malignant tumors have been detected, the same laser endoscope can be used for photodynamic therapy. A red (630 nm) laser beam is sent through the power fiber to illuminate the malignant tumors. The tip of the fiber may be a cylindrical diffuser tip that is placed inside the lumen. It illuminates the inner surface and is used for intraluminal treatment. Alternatively, the tip may be inserted into the tumor to provide interstitial treatment. Endoscopic photographs of HPD–PDT in otolaryngology were shown in Fig. 9.13. Clinical studies (Dougherty *et al.*, 1990; Marcus, 1992) show the enormous potential of photodynamic therapy in the management of endobronchial lung cancer.

9.10.5 Thin and Ultrathin Laser Catheters and Endoscopes for Diagnosis, Surgery, and Therapy

In Chapter 6 we discussed the development of thin and ultrathin fiberoptic endoscopes, some of which have a flexible distal tip. With these one can perform atraumatic endoscopy of the nasal cavity, the paranasal sinuses, the middle ear, and the eustachian tube.

The passages in the upper airways (e.g., the nose) the paranasal sinuses and the nasopharynx are narrow and not easily accessible. The thin laser catheters and laser endoscopes made it possible to carry out diagnosis, therapy, and surgery inside these passages. Figure 9.16 illustrates the use of a laser catheter for laser surgery inside the nose.

Laser pulses sent through suitable fibers can be used to shatter urinary stones, as mentioned in Chapter 3 and discussed in Section 9.11.4. This technique may also be used to shatter stones in the salivary glands (i.e., sialolithiasis). This is another example of a least invasive procedure that will replace a surgical operation

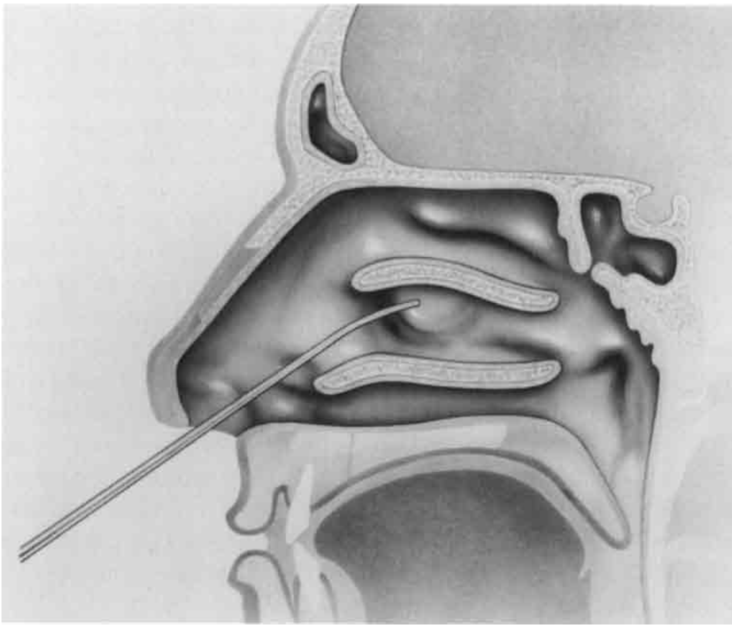

FIGURE 9.16 Endoscopic laser surgery in otolaryngology. (Courtesy of Coherent.)

(Tschepe *et al.*, 1992). Laser lithotripsy in otolaryngology is illustrated schematically in Fig. 9.17.

9.11 FIBEROPTIC LASER SYSTEMS IN UROLOGY

9.11.1 Introduction

For decades, rigid endoscopes have been used in urology and, in particular, for imaging the urethra, the interior of the bladder, and the ureter. Mechanical and electrosurgical systems introduced through these endoscopes have been used successfully for tumor removal, as in the treatment of transitional cell carcinoma of the bladder. Electrohydraulic and ultrasonic devices have also been used for endoscopic therapy of ureteral stones. Laser–fiber integrated systems have shown great promise in the diagnosis and treatment of urological disorders (Staehler *et al.*, 1976).

Lasers have been used for local surgery on the external genitalia, such as the excision of condylomatous lesions of the penis with the aid of the CO_2 laser. In comparison to regular surgery, the proper choice of wavelength and operating conditions gives rise to cosmetically superior results. Lasers have also replaced

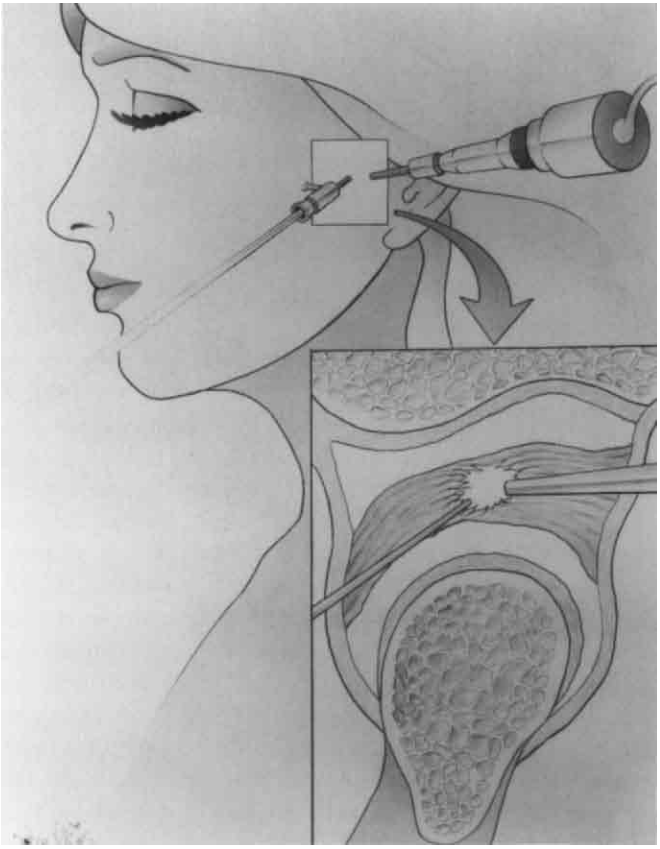

FIGURE 9.17 Endoscopic laser lithotripsy of salivary gland stones. (Courtesy of Coherent.)

surgical knives in open urological surgery. In this section, applications which make use of lasers and optical fibers are considered. Some of the developments in this area are discussed in several books (Hofstetter and Frank 1980; McNicholas 1990; Smith *et al.*, 1990; Steiner, 1988) and review articles (Hofstetter, 1986).

9.11.2 Fiberoptic Laser Surgery in Urology

9.11.2.1 Urethral Stricture

Urethral strictures are usually managed by regular dilatation, by cold knife resection, or by electrocautery resection. The recurrence rate in these methods is rather high because of scarring. Further resection of the tissue may cause further scarring. Stents have also been found useful for the treatment of strictures. Alternatively, a thin laser catheter may be inserted into the urethra; a laser beam delivered through the power fiber in the catheter can, in principle, remove the urethral strictures with no subsequent stricture. Nd: YAG laser radiation was first used for this application, and the deep penetration of the laser energy guaranteed coagulation necrosis throughout the stricture. Later work made use of Ar laser energy, which did not penetrate deeply into the tissue. Although both resulted in a short-term improvement, the strictures recurred. It is possible that pulsed CO_2 laser or excimer laser beams will remove the stricture tissue without damage to adjacent tissue and will result in no scar formation and recurrence.

9.11.2.2 Bladder Tumors

There is a great need for transurethral treatment of carcinoma of the bladder. The goal is to remove completely and destroy the tumor in the bladder wall without perforating the wall and without damage to adjacent structures (e.g., the intestines). Endoscopic resection of the tumors with electrocautery is not satisfactory because of unpredictable thermal necrosis effects and the risk of perforating the bladder wall. These problems can be solved if the tumors are destroyed by Nd: YAG laser energy. The Nd: YAG laser beam was delivered into the bladder via laser catheters, rigid endoscopes (cystoscopes), or fiberoptic endoscopes. Several groups (Hofstetter and Frank 1980; Smith, 1986) have shown that Nd: YAG laser energy, which penetrates through the tumor, causes coagulation necrosis throughout the full thickness of the bladder wall without perforation or damage to adjacent organs. In the case of very large tumors, electrocautery resection is performed first; the base of the tumor is then treated with Nd: YAG laser energy to ensure coagulation necrosis. Thousands of patients have been treated by this method with satisfactory results. The same methods are applicable for small tumors of the ureter. One of the disadvantages of the method is the lack of material for histological examination after the procedure.

HPD–PDT has also been used clinically for therapy of superficial bladder tumors (Marcus, 1992) that do not extend deep into the muscular layers of the bladder. The red laser light penetrates several millimeters into these tumors and efficiently triggers the HPD. The bladder may be distended using transparent fluid or a transparent balloon that is inflated with a fluid. Illumination of the whole bladder is provided by an optical fiber with a spherical diffuser tip (see Section 8.3.2). The preliminary results are encouraging.

9.11.3 Laser Prostatectomy

Endoscopic laser therapy has been tried to for the relief of urethral obstructions due to enlargement of the prostate gland. One of the systems used is transurethral ultrasound-guided laser-induced prostatectomy (TULIP) (Roth and Aretz, 1991). It is based on a rigid stainless steel probe which consists of three parts: ultrasound (US) transducer, Nd: YAG laser catheter, and inflatable balloon. Using ultrasonic guidance, the balloon is placed within the lumen of the prostate and inflated with water. The balloon compresses the prostatic tissue and facilitates the transmission of both US waves and the Nd: YAG laser beam into the tissue. During the procedure the laser beam is used to heat the prostate tissue and to cause coagulation necrosis. The tissue sloughs slowly and creates a larger lumen, relieving the obstruction of the outflow.

9.11.4 Lithotripsy

9.11.4.1 Introduction

Until the 1970s, open surgery was a common way of removing stones from the ureter and the kidneys. A noninvasive technique, called extracorporeal shock wave lithotripsy (ESWL), was introduced for the fragmentation of stones. This method is based on placing a patient in a bathtub and using a spark gap to generate shock waves in the water, which are focused on the stone. The stone fragments may discharge spontaneously. This technique gradually replaced major surgery in cases in which the stones were situated in the upper part of the ureters. Yet, in a significant number of cases the position of the stones or their size makes it impractical to use extracorporeal shock wave lithotripsy. It would be beneficial to fragment the stones endoscopically by a device introduced through the urethra or percutaneously.

9.11.4.2 Endoscopic Lithotripsy

Electrohydraulic Lithotripsy

Shock waves may be generated in water by a miniature spark plug. The electrohydraulic generator contains a special probe which is inserted through a thin urethroscope. It generates shock waves which are used to shatter ureter or bladder stones endoscopically. A major problem of this method is that the instrument shatters large stones into several pieces that have to be crushed mechanically before they are spontaneously discharged. Another problem is the size of the probe. Also, if the electric discharge takes place too close to the ureter wall, it may cause damage.

Ultrasonic Lithotripsy

An ultrasound generator, attached to the tip of a probe, generates waves at a frequency of 20–40 kHz. This probe may be inserted through a urethroscope and placed near a stone. When the tip is placed near a stone immersed in water, it acts like a drill and slowly reduces the stone to small particles. The ultrasonic waves, however, do not affect soft tissue because the impedances of soft tissue and water are almost the same. Some of the problems associated with this method are the relatively large size of the probe and the need to have a fairly high irrigation flow in order to prevent overheating. Although this method is not so effective for bladder stones, it was found to be useful for kidney and ureter stones.

9.11.4.3 Laser Lithotripsy

The two methods described above have several shortcomings; they may cause damage to healthy tissue and both rely on probes that are rather thick and require large endoscopes (10 Fr to 13 Fr). It was therefore suggested in the 1970s that very thin laser endoscopes or laser catheters be used for fragmentation of urethral and bladder stones. Thin endoscopes reduce the risk to the ureter and facilitate improved irrigation flow, while the laser lithotripsy itself causes less damage to tissue. Extensive *in vivo* studies (Dretler, 1988; Steiner, 1988) indicated that the short-pulse Nd : YAG laser and flashlamp-pumped dye laser (see Section 8.6.5) are suitable for this application. Alexandrite lasers have also been used successfully for laser lithotripsy.

Short laser pulses of extremely high peak power are transmitted through

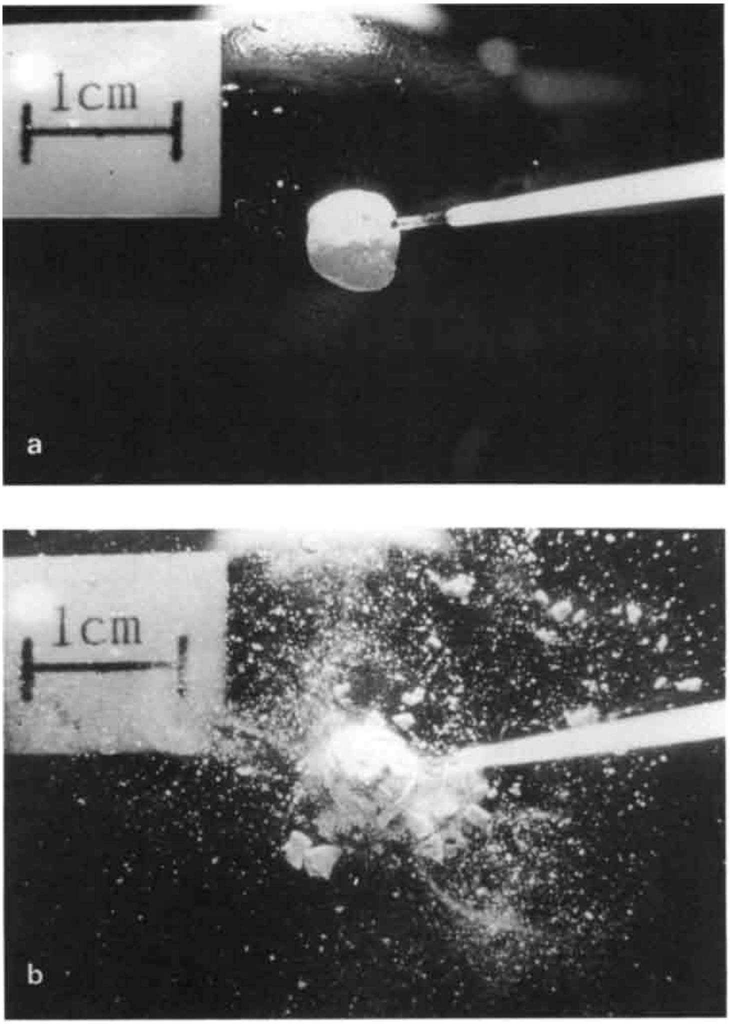

FIGURE 9.18 Laser lithotripsy of stone immersed in water: (a) initial stage; (b)–(d) consecutive stages in the stone fragmentation. (Courtesy of Storz.) (*Figure continues.*)

power fibers and impinge on stones that are immersed in liquids. The pulsed energy generates plasma (accompanied by intense light emission). The plasma, constrained by the surrounding water, generates shock waves that fragment the stones (see Section 3.7.3.2). It was found that the dye lasers generate plasma at lower peak power levels. Nevertheless, many groups prefer the Nd:YAG laser system for lithotripsy.

Figure 9.18 shows the shattering of a stone immersed in water using a pulsed dye laser beam delivered through a fused silica fiber.

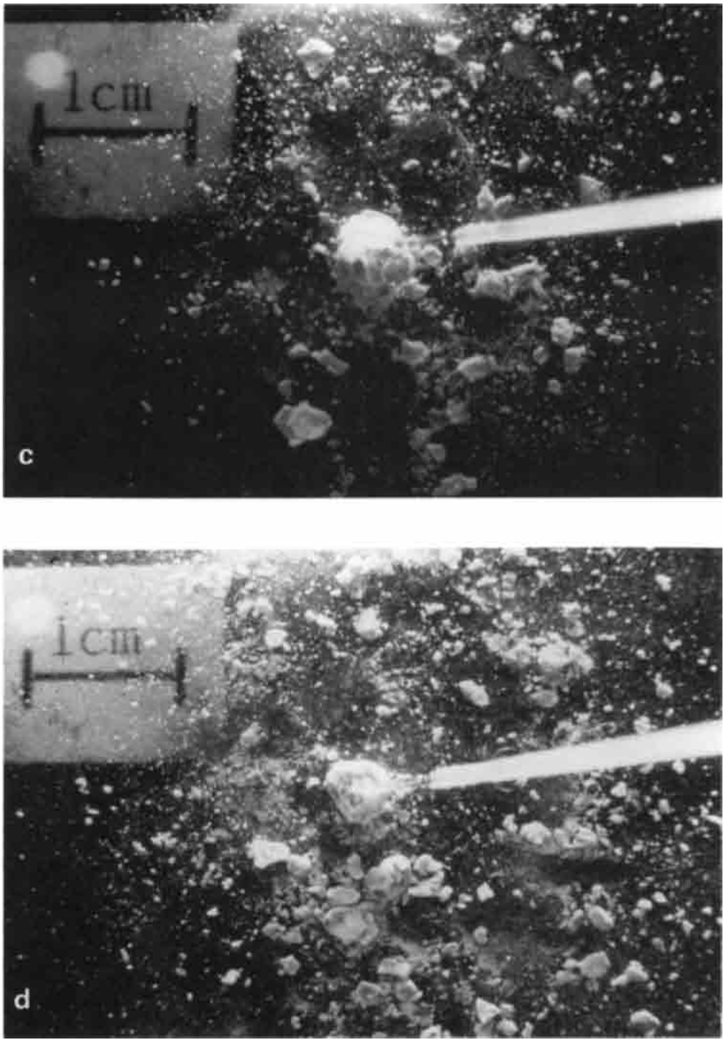

FIGURE 9.18 (*Continued*)

It should be mentioned that there are several types of stones with different compositions. Those made of calcium oxalate dihydrate or uric acid are fragile and easy to fragment, whereas those made of calcium oxalate monohydrate,or cystine calculi are not.

Laser Lithotripsy Using Laser Catheters

A thin (e.g., 6 Fr) laser catheter is inserted through the ureter and guided under x-ray control to the immediate vicinity of the stone. The distal tip of the fiber must be placed very close to the stones in order to fragment them in the ureter, bladder, or kidney. If it is placed too far from the tip, the power density will be insufficient to generate shock waves. Some of the methods used to keep the stone close to the tip are shown in Fig. 9.19. In one method, a special basket made of thin, strong metal wires, together with the power fiber, is inserted through the catheter. The basket is used to pull the stone against the fiber tip. Another method involves a balloon catheter; when inflated, the balloon keeps the catheter in position and the fiber is pushed against the stone.

There are several methods for ascertaining that the distal tip of the fiber touches the stone:

(i) Acoustic signals: When shock waves are generated, there are accompanying acoustic signals. By using a stethoscope placed on the abdominal wall of

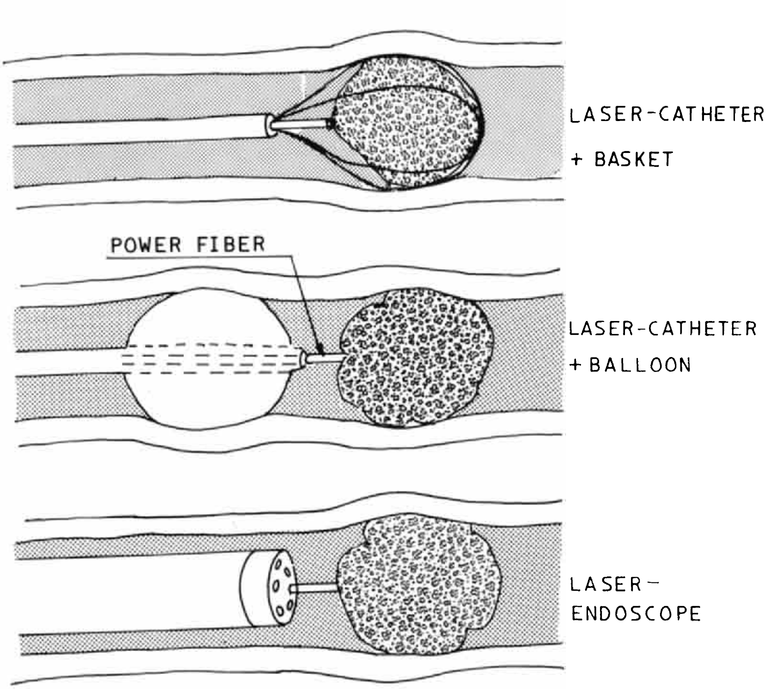

FIGURE 9.19 Laser and fiberoptic systems for laser lithotripsy.

the patient, it is possible to listen to these waves. Alternatively, the acoustic signals generated near the distal tip of the fiber are transmitted back through the power fiber and are detectable at the proximal end of the fiber. These acoustic signals are used for accurate positioning of the fiber.

(ii) Light: The plasma flash consists of a superposition of two emission spectra: a broad spectrum due to the electron transitions in the plasma and a line spectrum due to the emission lines of excited atoms (i.e., calcium). The light emission, transmitted back through the fiber, may easily be measured at the proximal tip of the fiber. The presence of a strong light signal is evidence that the fiber tip is sufficiently close to the stone. It should also be mentioned that the emission spectrum is, in principle, directly correlated to the composition of the stone (calcium oxalate, uric acid, etc.). In practice, while performing stone analysis, it is not easy to find a one-to-one correlation between the emission spectra and the stone composition.

Bhatta *et al.* (1989) studied the possibility of using the acoustic and light signals for "blind" guidance of the laser catheter. They concluded that strong acoustic and strong light signals are produced by calculi. A strong acoustic signal and no light signal suggest that the laser beam is hitting a blood clot. No acoustic and no light signals indicate that the laser is impinging on normal ureter wall or inside the lumen.

During laser lithotripsy, stone particles which are ejected must be washed away; otherwise they will absorb the laser energy and reduce the efficiency of the procedure. Good drainage of the irrigation fluid (i.e., saline solution) is mandatory.

Laser Lithotripsy Using Laser Endoscopes

The first clinical trials involved CW laser beams which were sent through optical fibers. They vaporized the urinary calculi, rather than fragmenting them. This method is likely to cause severe thermal damage and is potentially unsafe. The first experiments with short-pulse Q-switched Nd:YAG lasers were done in the mid-1980s in Germany (Schmidt-Kloiber *et al.*, 1985). They observed the plasma formation when nanosecond pulses of high peak power were focused on stones under water. Later (Hofmann *et al.*, 1988) these researchers reported on the use of this technique for fragmenting urinary calculi.

The first experiments using flashlamp-pumped dye lasers were performed by Watson, Dretler and others (Dretler *et al.*, 1987) Clinical trials were conducted using a 9–11 Fr rigid endoscope (urethroscope) and quartz fibers of diameter 0.2–0.3 mm. The success rate in these trials was high with practically no complications. Later, flexible ureteroscopes were also successfully used. This paved the way for wider clinical use of laser lithotripsy.

Methods identical to those described above may also apply to the fragmentation of kidney (i.e., renal) stones. In this case, the kidney pelvis may be punctured and a rigid endoscope (nephroscope) may be inserted and advanced to the vicinity of the stones. A power fiber is then inserted into the endoscope and used to transmit Nd: YAG or dye laser energy.

9.12 FLOWCHART DIAGRAMS FOR CLINICAL APPLICATIONS OF LASER–FIBER SYSTEMS—ADVANCES

Flowchart diagrams were mentioned in Section 8.7. Here we present a few examples of such diagrams defining clinical procedures. At present there are only few cases in which all the options of laser–fiber system have been applied in a clinical setting. We therefore demonstrate the usefulness of the flowchart diagrams with two *hypothetical* examples. Each procedure which was reported in the literature or which is planned for the future may be presented by a similar diagram.

9.12.1 Flow Diagram for Laser Angioplasty

The flow diagram for a hypothetical laser angioplasty procedure is shown schematically in Fig. 9.20 and the various steps and their implications are described here.

The first step is Start. The next step is imaging, which is normally performed by Angiography. The next step involves decision making; if no blockage is found one goes to Stop; if blockage has been found, one goes on. The next step is again decision making; can one use PTCA for recanalization? If the answer is positive, one goes on to perform PTCA, and if it is successful, the process ends. If the answer is negative, one goes on. The next step is fiberoptic endoscopy accompanied with fiberoptic diagnosis. The following step is decision making regarding whether laser angioplasty could be used for recanalization. If the answer is negative, the process ends. If the answer is positive, one goes on. The next step is choosing the integrated laser–fiber system and the recanalization parameters. The next step is the actual laser angioplasty. Endoscopy and diagnosis are used again to asses the blood flow. The final step involves decision making regarding whether the blood flow is sufficient. If the answer is negative, one has to go back to an earlier step of laser angioplasty. If the answer is positive, the whole process ends.

9.12.2 Flowchart Diagram for Photodynamic Therapy (HPD–PDT)

The diagnosis and therapy steps are shown schematically in Fig. 9.21. Using white light illumination, one starts with regular endoscopy. The next step is decision making. If no tumor is revealed, the process stops. If a tumor is revealed, HPD is injected. The next step usually occurs after 2 days. This step may be fluorescence endoscopy—imaging of the tumor using UV light illumination and imaging through a red filter (alternatively, only the intensity of the red emission is

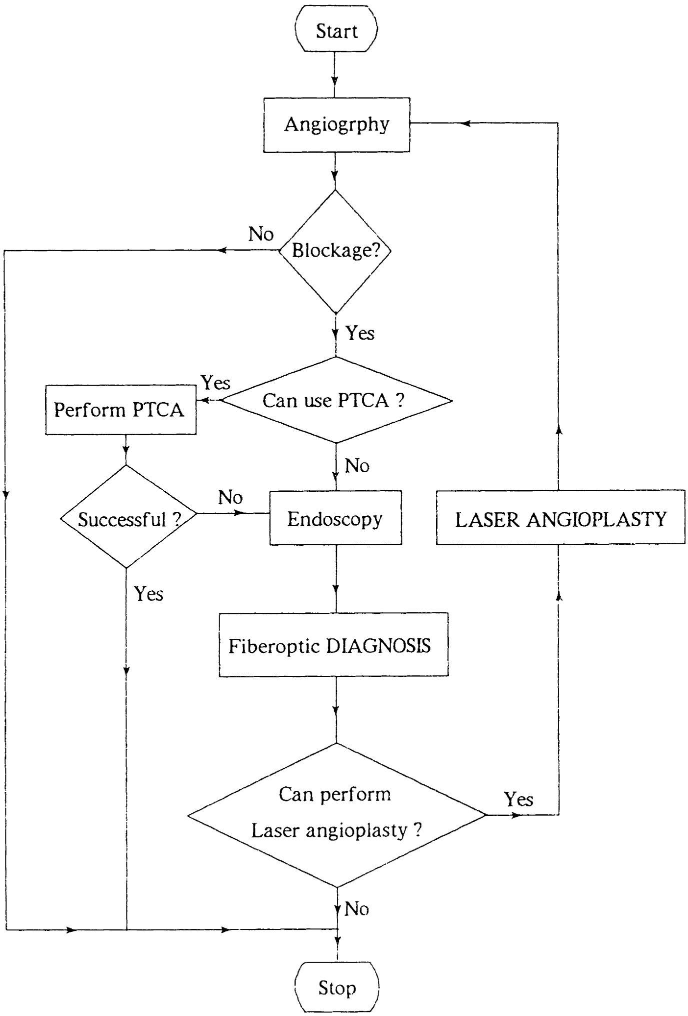

FIGURE 9.20 Flow diagram for laser angioplasty.

measured). The next step is again decision making. If no red emission has been detected, the tumor is benign and the process stops. If red emission has been detected, the tumor is carcinogenic. The area is then illuminated by a red laser. The next step is decision making. Fluorescence endoscopy (or simple detection of the red emission) is used again. If there is no more red emission, the tumor has been eradicated and the process stops. If not, one has to continue with the treatment as shown.

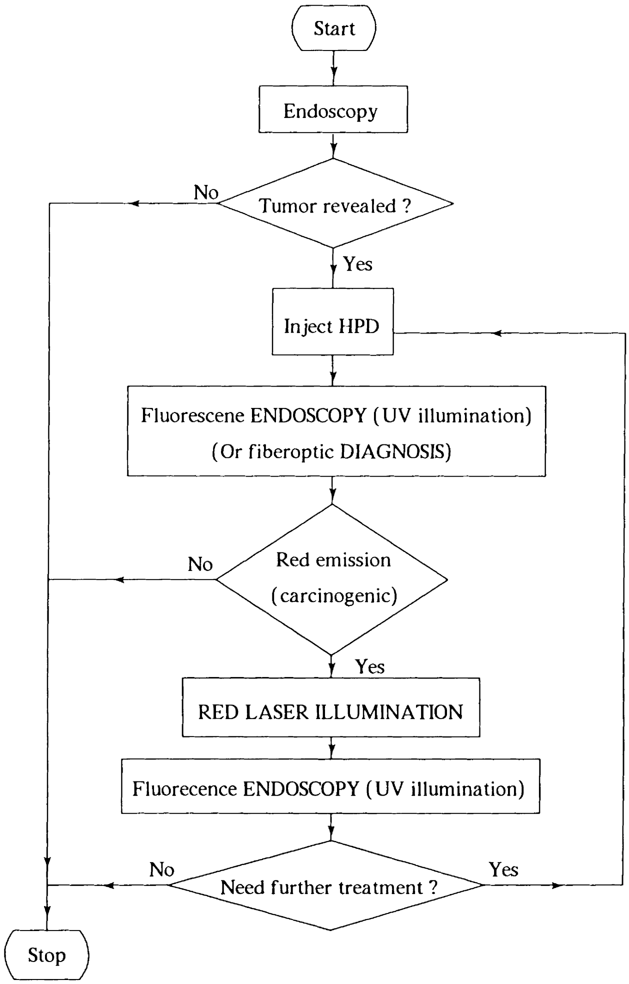

FIGURE 9.21 Flowchart diagram for HPD-PDT.

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Appendix

A.1 PHYSICS CONSTANTS

Speed of light $c = 3 \times 10^8$ m/sec

Electron charge $e = 1.6 \times 10^{-10}$ coulombs

Planck's constant $h = 6.6 \times 10^{-34}$ joule sec

1 eV $= 1.6 \times 10^{-19}$ joule

A.2 PROPERTIES OF LIGHT

A.2.1 Division of the Optical Spectrum

The optical spectrum may be divided as follows (see Fig. A.1):

Extreme UV:	10–100 nm
Far UV:	100–300 nm
Near UV:	300–390 nm
Visible:	390–780 nm
Near IR:	780 nm–1.5 μm
Middle IR:	1.5–10 μm
Far IR:	10–100 μm

Comment: This division serves just as a guideline. There are authors who use a slightly different division.

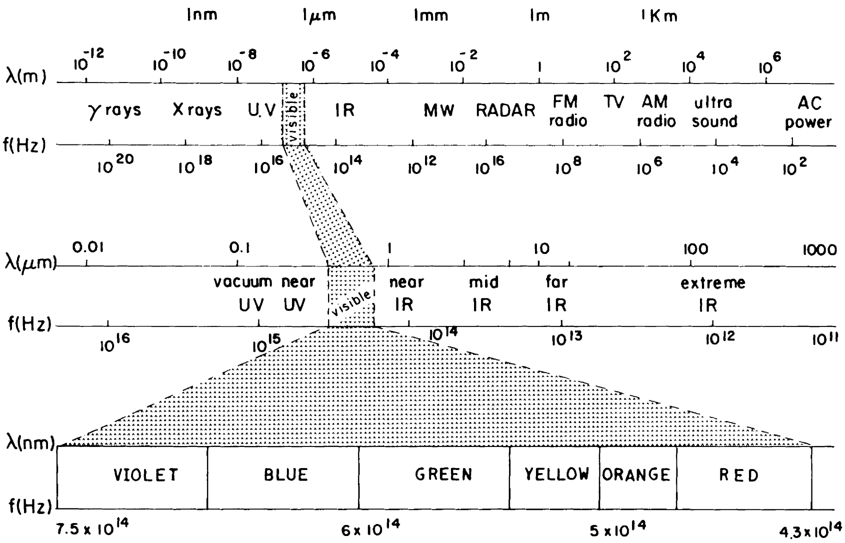

FIGURE A.1 The electromagnetic spectrum.

The wavelengths of the various visible colors are as follows:

Violet: 390–455 nm
Blue: 455–492 nm
Green: 492–577 nm
Yellow: 577–597 nm
Orange: 597–622 nm
Red: 622–780 nm

A.2.2 Light and Radiometry—Terms and Units

From the classical point of view, light consists of electromagnetic radiation; the scientific measurement related to this radiation is called radiometry. Radiometric terms and units are discussed below. Prior to this discussion is a description of the physical quantities and units of energy and power which are commonly used.

Energy Terms

Energy: Measures the amount of work a system is capable of performing. The units which are commonly used are calories or joules. A calorie (cal) is the amount of energy needed to raise the temperature of a gram of water by 1 degree centigrade, and 1 joule (J) is 0.24 calories. Another unit which is commonly used is the electron volt (eV), where 1 eV $= 1.6 \times 10^{-19}$ J.

Power: A measure of the rate at which energy is used. The commonly used units are watts; 1 watt = 1 joule/second.

Radiometric Terms

Radiant energy: The energy E carried by a beam of light is described as radiant energy and is measured in joules (J).

Radiant power (flux): The power P is the energy carried by the beam in 1 second and is measured in watts (W), that is, J/sec. It is also defined as radiant flux.

Power density: The power p incident on a unit area. It is measured in W/ cm^2. If power P is incident on an area A, then $p = P/A$. This quantity is also defined as *irradiance* and is particularly important when a beam of light is incident on a surface.

Fluence: The total energy incident on a unit area; it is measured in joules.

Radiant intensity: This the power I emitted by a point source into a unit solid angle; it is measured in W/steradian. This radiant intensity is particularly important in describing light sources such as incandescent lamps.

Comment: In older literature, irradiance was called *intensity*; the term is used loosely in the laser literature. It may be used when there is no danger of confusing it with irradiance.

A few examples will illustrate the various quantities and units:

EXAMPLE I: If a laser beam of energy 75 calories is totally absorbed in 1 g of water at room temperature ($T = 25°C$), its temperature will increase from 25°C to 100°C. Clearly, the same amount of energy will raise the temperature of 75 g of water by 1°C to 26°C.

EXAMPLE II: In a 100-W laser, 100 joules are emitted each second. If the laser operates for 6 sec, the total energy emitted is

$$E = 100 \times 6 = 600 \text{ j} = 144 \text{ cal.}$$

This energy can bring roughly 2 grams of water from room temperature to boiling point.

EXAMPLE III: A beam of power P is incident on an area A for time t.

The irradiance (or power density) is P/A.

The total energy delivered to the area is $E = Pt$.

The fluence is $F = E/A = Pt/A$.

Light and Photons

From the point of view of quantum theory, light consists of a stream of particles called photons. For monochromatic light, the *energy* e of each photon is related to the frequency ν by the famous formula $e = h\nu$, where h is Planck's constant ($h = 6.6 \times 10^{-34}$ J/sec). Alternatively, one could write $e = hc/\lambda$ where c is the light velocity ($c = 3 \times 10^8$ m/sec) and λ is the wavelength. The photon energy is inversely proportional to wavelength. Therefore a photon of UV light is more energetic than a photon of visible light, and the latter is more energetic than a photon of IR light.

The *energy E* in a beam of light is the sum total of the energies of the photons; that is, it is the energy e multiplied by the total number of photons N, $E = eN$.

The *power P* in the monochromatic beam is determined by the total energy $E = eN$ that passes through an area in a unit time, $P = eN/t$. If the beam is incident on a surface area A, the power density on the surface is again given by P/A.

EXAMPLE I. *CW Lasers*: For an HeNe laser the wavelength is $\lambda = 633$ nm with emission in the red; the frequency is $\nu = 4.8 \times 10^{14}$ Hz and the energy per photon is $e_r = 3 \times 10^{-19}$ J = 1.9 eV. For a 1-mW HeNe laser an energy of 10^{-3} J is emitted per second. If we denote by N_r the number of photons that are emitted per second, then $N_r \times e_r = 1$ mW, that is, $N_r = 3.3 \times 10^{15}$ photons per second.

For an HeCd laser the wavelength is $\lambda = 325$ nm with emission in the UV; the frequency is $\nu = 9.35 \times 10^{14}$ Hz and the energy per photon is $e_{uv} = 5.9 \times 10^{-19}$ J = 3.7 eV. For a 1-mW HeCd laser an energy of 10^{-3} J is emitted per second. In this case $N_{uv} = 1.7 \times 10^{15}$ photons per second.

In the red beam, the individual photons have lower energies e_r than the photon energy e_{uv} in a UV beam. On the other hand the total number of red photons emitted per second is larger than the corresponding number of UV photons, so that $N_r e_r = N_{uv} e_{uv}$.

An infrared laser (i.e., CO_2) beam may consist of a very large number of photons, each of which has a low energy (e.g., 0.2 eV). The total energy or power density of such a beam may be high and should not be confused with the individual photon energy in this beam!

EXAMPLE II. *Pulse Lasers*: For an XeCl excimer laser the wavelength is $\lambda = 308$ nm; the frequency is $\nu = 9.7 \times 10^{14}$ Hz and the energy per photon is 6.4×10^{-19} J = 4 eV. If the laser emits 10 mJ per pulse, there are 1.5×10^{16} photons in that pulse.

A.3 REFLECTION AND ABSORPTION OF LIGHT IN A SAMPLE

Let us consider a beam of intensity I_0 that is normally incident on a slab of thickness t, shown in Fig. 3.1, and define $K = \alpha\lambda/4\pi$. In the noncoherent case, the reflectance is

$$r = I_r/I_0 = [(n - 1)^2 + K^2] \;/\; [(n + 1)^2 + K^2]$$

and the transmittance is

$$\tau = I_t/I_0 = [(1 - r)^2 \exp(-\alpha t)] \;/\; [1 - r^2 \exp(-2\alpha t)].$$

When there is no absorption, $\alpha = 0$, one obtains the formulas used in Section 3.3.1

Glossary

Ablation Removal of tissue.

Absorbance (or absorptance) Ratio of the absorbed light intensity I_a to the incident intensity I_i. It is a dimensionless quantity.

Absorption The transformation of light (radiant) energy to some other form of energy—usually heat—as the light traverses matter.

Absorption coefficient In a nonscattering sample, the reciprocal of the distance l over which light of intensity I is attenuated (due to absorption) to $I/e \approx I/3$. The units are typically cm^{-1}.

Acceptance angle Maximum incident angle at which an optical fiber will transmit light by total internal reflection.

Anastomosis Connection of two tubes. In particular, laser heat facilitates anastomosis of blood vessels.

Angiography Use of x-ray imaging to reveal disease in arteries. A radiopaque contrast medium (angiographic dye) injected into arteries absorbs the x-rays. The dye is seen as dark lines on the x-ray fluorescence screen.

Angioplasty The "reshaping" of blood vessels.

Angioscopy Endoscopic imaging inside the blood vessels in the cardiovascular system.

Ar (argon) ion laser A laser with a lasing medium composed of ionized argon gas; the emission is in the visible (0.5–0.6 μm).

Articulated arm An assembly consisting of several mirrors that are mounted on hinges. The assembly is used to direct a beam from the laser head to the target tissue.

Atheroma Fatty degeneration of the inner walls (intima) of the arteries in arteriosclerosis.

Atherectomy Excision of atheroma.

Atherosclerotic plaque A fibrous tissue that also contains fat and sometimes calcium. It accumulates in arteries and produces occlusion.

Attenuation Decrease in the intensity of light passing through matter. Attenuation is caused by reflection, scattering, and absorption.

Attenuation coefficient Reciprocal of the distance l over which light of intensity I is attenuated to $I/e \approx I/3$. The units are typically cm^{-1}.

Autofluorescence Natural tissue fluorescence.

Beam A slender stream of light.

Balloon catheter A catheter that includes an inflatable balloon at its end.

Bifurcated bundle of fibers A bundle of fibers that is divided into two branches on one end.

Biliary Pertaining to the bile.

Biliary calculus Gallbladder stone.

Biocompatible Something that does not cause harm to biological tissue.

"Bypass" operation See CABG

CABG (coronary artery bypass grafting) An open heart operation in which a section of a vein or an artery is used to bypass a blocked coronary artery.

Calorie A unit of energy. One calorie is the amount of work needed to raise the temperature of 1 gram of water at 15°C by 1 degree centigrade. 1 calorie = 4.2 joules.

Cannula A tube which is inserted into the body. It is often fitted with a pointed rod for ease of insertion.

Cataract A condition in which the lens of the eye becomes opaque, causing partial blindness.

Catheter A flexible hollow tube normally employed to inject liquids or drain fluids from body cavities.

CCD (charged-coupled device) camera A solid-state electronic device that serves as an imaging chip and is used in miniature video cameras.

Chemical F/O sensors Fiberoptic sensors that detect chemical parameters (e.g., pH).

Cholecystectomy Surgical removal of the gallbladder (*chole*—gall; *cystectomy*—excision of a bladder).

Chromophore Any coloring agent in tissue which absorbs light. The main chromophore in skin is melanin.

Cladding Outer part of an optical fiber. It has a lower refractive index than the core.

CO (carbon monoxide) laser A laser where the lasing medium is CO gas with IR emission at 5 μm.

CO_2 (carbon dioxide) laser A laser where the lasing medium is CO_2 gas with IR emission at 10.6 μm.

Coagulation Change of state of a fluid (e.g., blood) from liquid to semisolid. In the case of exposure to laser beams, coagulation results from overheating.

Collimated beam Beam of light in which all the rays are parallel to each other.

CW (continuous wave) Continuous operation, with no interruptions (e.g., of a laser).

Core Inner part of an optical fiber through which light propagates. It has a higher refractive index than the cladding.

Cornea A transparent watchglass-like tissue that covers the front of the eye.

Coronary artery One of the major arteries that supply blood to the heart.

Coupler An optical device that interconnects optical components.

Critical angle Minimum incidence angle in a medium where light is totally internally reflected.

CT (computed tomography) A noninvasive x-ray imaging method that is particularly useful for the detection and for obtaining three-dimensional images of tumors inside the body.

Cyst A saclike structure or a pocket in the body; it is often filled with a fluid.

Cytotoxic Having toxic effects on cells (and tissue).

dB (decibel) Engineering unit for the ratio of the input power P_{in} in a given device to the output power P_o. It is convenient to measure the logarithm of the ratio $\log(P_o/P_{in})$, and the dB is a standard unit that is equal to 10 times that log; $1\text{ dB} = 10 \log(P_o/P_{in})$.

Depth of field The correct term is depth of focus (see below).

Depth of focus Axial distance over which a beam is clearly focused. In endoscopy, the axial distance over which the image is still clearly focused.

Dichroic A surface that reflects different colors when viewed in different directions.

Direct F/O sensor A fiberoptic sensor without an optode attached to the distal tip of the fiber.

Divergence The "spreading" of a light beam in general, and in particular of a laser beam as it moves away from the laser.

Dye laser A laser where the laser medium is a liquid dye. Dye lasers emit in a broad spectral range (e.g., in the visible) and are tunable.

Diskectomy Removal of a disk that causes pressure and pain in the spine.

Efficiency The overall efficiency of a laser is the ratio of the input electrical energy to the output energy in the laser beam.

EM (electromagnetic) radiation Flow of energy that is related to the vibration of electric and magnetic waves.

EM (electromagnetic) spectrum The entirety of the electromagnetic waves that differ from each other in frequency and wavelength.

Emission spectrum The emission obtained from a luminescent material at different wavelengths, when excited by a narrow range of shorter wavelengths.

Endarterectomy Removal of diseased endothelium from within a blood vessel.

Endoscope Optical instrument used for viewing internal organs.

Energy The product of power (watts) and time (sec). Energy is measured in joules (J).

Er:YAG (erbium:yttrium aluminum garnet) laser A solid-state laser whose lasing medium is the crystal Er:YAG with emission in the mid-IR at 2.94 μm.

Excimer laser A laser whose lasing medium is an excited molecular complex (e.g., KrF or ArF); the emission is in the UV ($\lambda < 400$ nm).

Excitation spectrum The emission spectrum at one wavelength is monitored and the intensity at this wavelength is measured as a function of the exciting wavelength.

Extinction length Distance over which light is attenuated in an absorbing material by a factor of 100.

F number (*f*#) Ratio of the focal length f of a lens to its diameter D; $f\# = f/D$.

FEL (free-electron laser) A laser that is based on the emission from accelerated electrons. The laser is tunable over a wide spectral range.

Fiberscope A viewing instrument that incorporates an ordered bundle for imaging and a light guide for illumination.

Field of view The extent of an object that can be imaged or seen through an optical system.

Fluence The total energy that is incident on a unit area. It is a product of the power density of the laser beam and the irradiation time.

Fluorescence Luminescence that essentially occurs simultaneously with the excitation of a sample.

F/O Fiberoptic.

Focal spot The spot obtained at the focus of a lens. The size of the spot depends on the lens and on the wavelength, but its diameter is never smaller than the wavelength of light.

Fr (French) Measure of the diameter of a medical catheter; 1 Fr = 1/3 mm.

Fresnel reflection (or Fresnel loss) When light travels from one medium to a second medium with a different index of refraction, part of the light is transmitted into the second medium and part is reflected. The reflection is referred to as Fresnel reflection or Fresnel loss.

GaAs laser A laser based on the semiconductor material GaAs. The emission is in the near IR, at about 1 μm.

Gaussian beam If the intensity at the center of the beam is I_0, then the formula for a Gaussian beam is $I = I_0 \exp(-2r^2/w^2)$ where r is the radial distance from the axis and w is the beam "waist." The intensity profile of such a beam is said to be bell shaped.

Glaucoma A disease of the eye characterized by abnormal interocular pressure that may lead to loss of sight.

Glioma Neoplasm derived from cells in the brain, spinal chord, and pituitary gland.

Guide wire A flexible wire that is inserted into the body and threaded through the vascular system. The wire may then be used to guide a catheter or an endoscope to a desired location.

HeNe (helium neon) laser A gas laser whose laser medium is a mixture of the gases He and Ne; the emission is in the red (0.628 μm).

Hertz (Hz) A unit of frequency that is equal to 1 cycle per second. It is often used to indicate the pulse repetition rate of a laser (e.g., a 10-Hz laser emits 10 pulses per second).

HF (hydrogen fluoride) laser A gas laser whose laser medium is the gas HF and whose emission is in the IR (with several lines between 2.7 and 2.9 μm).

HPD (hematoporphyrin derivative) A compound used in cancer diagnostics and therapy.

Hyperplasia Increase in the size of tissue or organ.

Image guide An ordered bundle of fibers that is used for image transmission.

Index of refraction Ratio of the velocity of light in a vacuum to the velocity of light in a given material.

Indirect sensor A fiberoptic sensor whose optode is attached to the end of the fiber.

Infrared (IR) The part of the electromagnetic spectrum that is invisible and extends between 0.7 and 1000 μm.

Intensity (i.e., radiant intensity) Power emitted into a unit solid angle (watts/steradian W/sr).

Intima The inner wall of a vessel.

Intraluminal Within the lumen of a cylindrical organ.

In vitro Inanimate matter (in medicine, pertaining to experiments on dead tissue).

In vivo Of living matter (in medicine, pertaining to experiments on animals or humans).

Irradiance Ratio of the power incident on a sample to the illuminated area.

Joule A unit of energy that is equal to 0.24 calorie.

Laparoscope An instrument that is introduced into the abdomen; it is normally used for imaging the pelvic organs.

Laser Acronym for light amplification by the stimulated emission of radiation. A device that generates a beam of light that is collimated, monochromatic, and coherent.

Laser angioplasty Use of laser beams sent through power fibers for the removal of blockages in arteries.

Laser catheter A catheter that incorporates an optical fiber for the transmission of a laser beam.

Laser endoscope An endoscope that incorporates an optical fiber for the transmission of a laser beam.

Laser power Rate of radiation emission from a laser, normally expressed in watts (W).

LDV (laser Doppler velocimeter) A laser technique for measuring the velocity of a moving body. It may be used for measuring the velocity distribution of the blood cells (and thus the blood flow).

Lesion An injury or an alteration of an organ or tissue.

Light guide Assembly of optical fibers that are bundled but not ordered (noncoherent) and are used for illumination.

Lithotripsy Shattering of stones in the body. Laser lithotripsy refers to shattering by the application of an intense laser beam.

Lumen The passage contained within the walls of a tube (in particular, the opening inside a blood vessel or the opening inside a catheter).

Luminal A property which applies to the lumen.

Luminescence Light emitted from a sample which is irradiated (excited) by energetic photons.

Lysis Gradual and successful destruction of cells (or ending of a disease).

Micrometer (i.e., micron or μm) A unit of length that is equal to a thousandth of a millimeter.

Microsecond (μsec) One-millionth of a second.

Microwave Electromagnetic waves in the frequency range 10^9-10^{11} Hz.

Millijoule (mJ) One-thousandth of a joule.

Millisecond (msec) One-thousandth of a second.

Monochromatic Of one color only (e.g., a laser beam of one color); in practice, a beam containing a very narrow range of wavelengths.

MRI (magnetic resonance imaging) A noninvasive imaging technique that is based on magnetic resonance methods. It provides a wealth of information about inner structures in the body and in particular about tumors.

Multifiber A small bundle of fibers.

MW (megawatt) One million watts (10^6 watts).

mW (milliwatt) One-thousandth of a watt (10^{-3} watt).

Myocardium Heart muscle tissue.

nm (nanometer) A unit of length equal to one-billionth of a meter (10^{-9} m), or one-millionth of a millimeter.

nsec (nanosecond) One billionth of a second (10^{-9} second).

Nd:YAG (neodymium:yttrium aluminum garnet) laser A solid-state laser whose lasing medium is the crystal Nd:YAG with emission in the near IR, at 1.06 μm.

Necrosis Death or decay of tissue.

Normal incidence Incidence of a light beam on a plane at an angle of 90° to the plane.

Numerical aperture (NA) Light-gathering power of an optical fiber. It is proportional to the sine of the acceptance angle.

Optical detector A device that converts optical energy to an electrical signal.

Optical fiber Thin and transparent thread through which light can be transmitted by total internal reflection.

Optical filter A device that transmits only part of the spectrum incident on it.

Optode A transducer that is attached to the distal tip of a fiberoptic sensor. The interaction between the optode and the body is monitored by the fiberoptic sensor.

Ordered (coherent) bundle Assembly of optical fibers that are ordered in exactly the same way at both ends of the bundle.

Palliate Alleviate pain or disease.

Photon The fundamental unit of light energy.

Phosphorescence Luminescence which is delayed with respect to the excitation of a sample.

Photosensitizer A substance that increases the absorption of another substance at a particular wavelength band.

Physical F/O sensors Sensors that measure "physical" quantities such as pressure or temperature.

Plaque See atherosclerotic plaque.

Plasma (physics) Ionized gas, at high temperature.

Plasma (medicine) The fluid part of the blood.

Power The rate of delivery of energy. It is normally measured in watts, that is joules per second.

Power density The power (e.g., of an incident laser beam) divided by the area on which it is incident. The units are watts/cm^2.

Power fiber Optical fiber that can transmit a laser beam of relatively high intensity.

PTCA (percutaneous transluminal coronary angioplasty) A procedure based on a balloon catheter that is inserted into a blocked coronary artery. The lumen is enlarged by inflating the balloon.

Recanalization See laser angioplasty.

Reflectance (or reflection coefficient) The ratio of the intensity I_r reflected from a surface to the incident intensity I_i. It is a dimensionless quantity.

Renal Pertaining to the kidney.

Repetition rate Number of pulses (e.g., laser pulses) per second. The repetition rate is measured in hertz.

Resolution Measure of the ability of an optical imaging system to reveal details of an imagel, i.e., to resolve adjacent elements.

RF (radio frequency) The part of the EM spectrum between about 10^6 and 10^8 hertz.

RT (room temperature) A temperature of about 27°C or 300 K.

Saline solution A salt solution that is used for medical treatment. This solution is designed to have the same osmotic pressure as blood.

Spectrum Range of frequencies or wavelengths.

Stenosis Narrowing.

Stent A device used to maintain some body orifice open.

TEA (transversely excited atmospheric) CO_2 laser A special CO_2 gas laser that operates at atmospheric pressure. It emits very short pulses of very high peak power.

Total internal reflection Reflection of light at the interface between media of different refractive indices, when the angle of incidence is larger than a critical angle (determined by the media).

Transmittance Ratio of the intensity transmitted through a sample I_t to the incident intensity I_i. It is a dimensionless quantity.

Trocar A surgical tool that consists of a sharp-ended rod which is enclosed in a wider tube (cannula). The trocar is inserted through the skin into a body cavity and the rod is withdrawn, leaving the tube in place.

Tunable laser Most lasers emit at a particular wavelength. In tunable lasers, one can vary the wavelength over some limited spectral range.

Ultrasound Mechanical vibrations with frequencies in the range $2 \times 10^4 - 10^7$ Hz.

UV (ultraviolet) The part of the optical spectrum that extends between about 10 and 390 nm.

Vacuolation Creation of spaces or holes in tissue.

Visible The part of the optical spectrum, roughly in the range 0.4 to 0.7 μm, that can be sensed by the human eye.

Vitreous humor A transparent jellylike substance that fills the chamber between the lens and the back of the eye.

Watt Unit of power. One watt is equal to 1 joule per second.

Wavelength Distance between two adjacent peaks in a wave (e.g., in an EM wave).

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