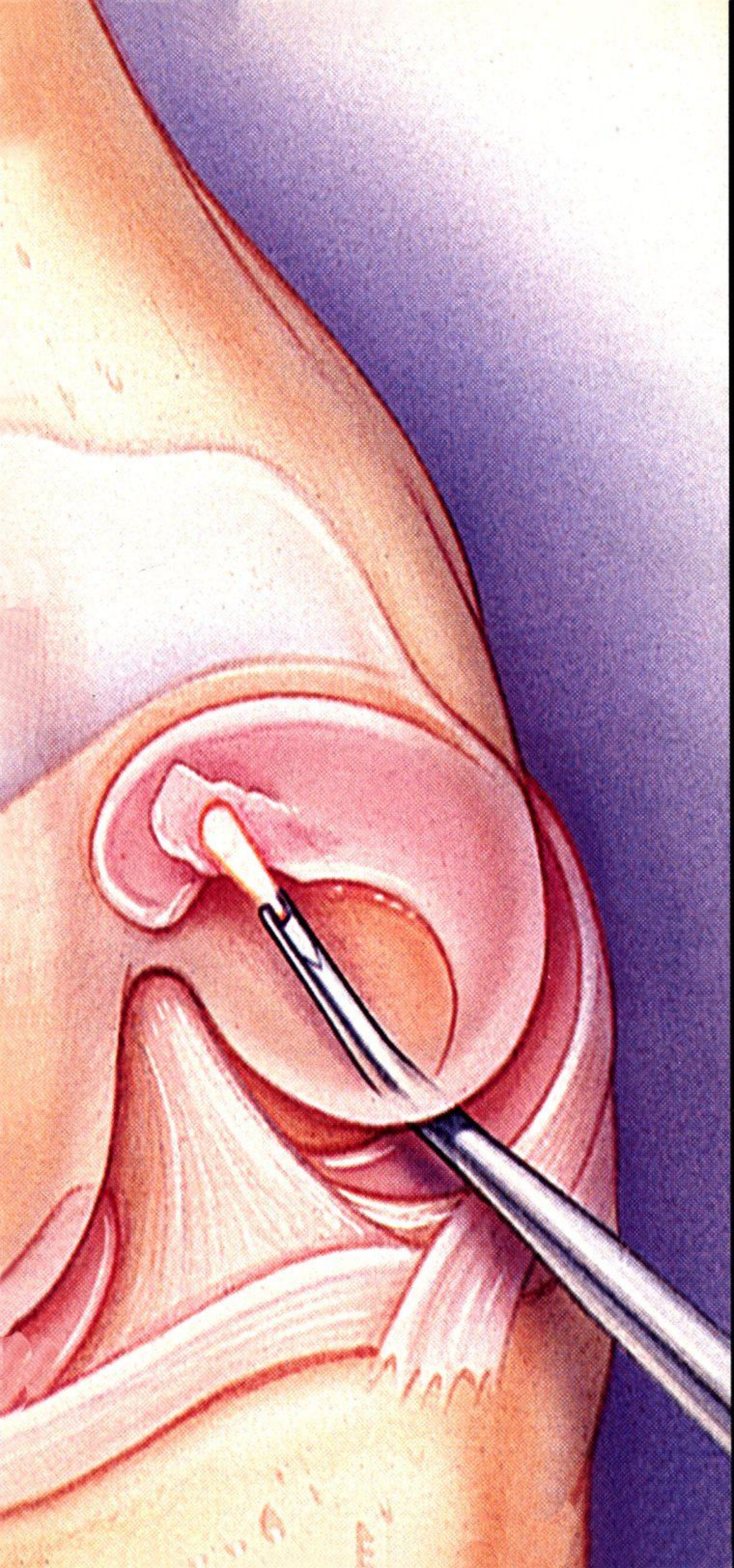

HIGH POWERED DELIVERY: FIBEROPTIC LASER SURGERY

By Jeffrey G. Manni

Snapshot: Fiberoptic delivery of laser energy for surgery and therapeutic applications offers the medical community a new way of viewing and manipulating human tissue. Manni explores this potential and provides insight on the technical challenges facing this field.

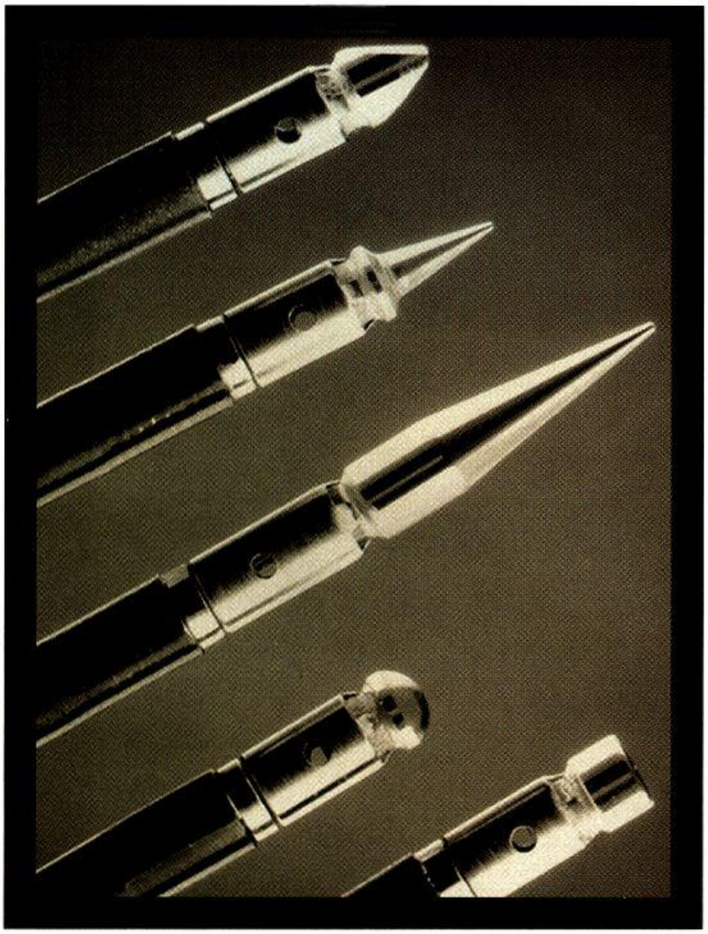

Photo courtesy of Surgical Laser Technologies.

Figure 1. Sapphire contact tips.

Fiberoptic delivery of laser energy has greatly expanded the role that lasers play in surgical and other therapeutic medical applications. Even if fiberoptic laser delivery is not an absolute technical requirement, it can, and often does, make the difference between having a practical laser procedure that achieves widespread clinical acceptance, and one that does not.

This article describes the role that fiber delivery plays in laser surgery and medicine. A brief history of surgical lasers and fibers is provided, followed by a discussion, in general terms, of how fiber-delivered lasers are used to provide therapy. Trends and technical challenges that face surgical laser developers are discussed. The article concludes with a discussion of new developments that will increase growth in the medical laser marketplace.

Brief history of fiberoptic laser surgery

The appearance of high-power continuous-wave (cw) Nd:YAG lasers, and the concomitant development of low-loss quartz optical fibers (developed for telecommunications applications), set the stage for the introduction in the early 1980s of the first fiber-delivered, high-power lasers appropriate for surgical applications. The first surgical Nd:YAG lasers operated at 1064 nm, provided tens of watts of output power, and were used with flat-ended quartz fibers (cleaved or polished). Fibers were clearly much more convenient to use than articulated arms, and seemed to offer the potential for scalpel-like use. Surgeons discovered quickly, however, that the cw Nd:YAG laser used with a flat-ended quartz fiber was of limited use.

When used in a "free-beam" or non-contact mode (fiber tip held off the tissue surface), 1064-nm laser energy cuts or vaporizes soft biological tissue with very crude surgical precision; that is, with "collateral" thermal injury of several millimeters or more at the edges of tissue cuts. This occurs because 1064-nm laser energy is absorbed relatively weakly and penetrates deeply into soft biological tissue.

Relatively few surgical applications can tolerate such crude surgical precision. Thus, the free-beam cw Nd:YAG laser was relegated primarily to applications that require photocoagulation of soft tissue (use of laser energy to cook tissue, much like an egg is coagulated in

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boiling water) or to cauterize and close bleeding vessels. Cutting precision could be improved by using the quartz fiber tip in contact with tissue, but the tip tended to melt rather quickly and contact use was not considered practical. Cutting and vaporization were generally not attempted with this laser-fiber combination.

About 1984, Surgical Laser Technologies (Oaks, Pa.) invented and commercialized the "contact-tipped" fiber delivery accessory as a means to greatly improve the surgical precision of the cw Nd:YAG laser. Contact-tipped fibers are terminated with a shaped sapphire tip that can be used reliably in direct contact with tissue, without melting. The tips are also designed ("coated") to partially absorb 1064 nm so that they become very hot; tissue is cut or vaporized as a result of being in contact with the hot fiber tip. Soft tissue can be cut or vaporized with only 0.5 to 1 mm of collateral thermal injury in most cases, which means that "contact Nd:YAG lasers" can be used for most surgical applications. Just as importantly, tactile feedback similar to that achieved with a scalpel is now possible with sapphire tips. Contact surgery with cw Nd:YAG lasers gained popularity throughout the 1980s and is still in use today (See Fig. 1).

Partially in response to the success of the contact Nd:YAG laser, other fiber-delivered surgical lasers were developed and commercialized in the late 1980s and early 1990s. The frequency-doubled Nd:YAG (532 nm) laser, high-power argon laser (488/514 nm), and pulsed holmium laser (2100 nm) can all be used with flat-ended fibers in a contact or non-contact mode; contact-tipped fibers are generally not required to achieve good surgical precision with these lasers. The high-power diode laser (800-980 nm) is similar to the Nd:YAG in that contact-mode, hot-tip fibers are needed to achieve precise cutting. Practical infrared fiber delivery accessories have been developed recently, at least for lower average power applications, that should allow pulsed erbium lasers (2.8-2.94 μm) to be added to the list of fiber-delivered surgical lasers.

General uses of fiber-delivered lasers

In addition to contact-mode surgery, fiberoptic laser delivery enables access of internal tissue through very small skin incisions, or natural body openings, for minimally invasive surgery (MIS). While many procedures involve only routine cutting or vaporization, other surgical tasks and MIS laser treatments rely heavily on fiberoptic delivery instrumentation.

Photocoagulation necrosis

This is a form of bloodless surgery that does not involve cutting or vaporization. Instead, laser energy with a deeply penetrating wavelength is used to thoroughly coagulate the soft tissue mass to be removed. Dead tissue is broken down and removed by the body's "resorption" mechanism, or is sloughed away, over a period of several days or weeks. Applications include removal of obstructive tumors in the gastrointestinal tract and debulking of enlarged prostates to improve urinary outflow. So-called "interstitial" fibers, which can be inserted into tissue as a needle would, are being used increasingly to aid the process of thoroughly coagulating large tissue masses.

Lithotripsy

Pulsed laser energy delivered through an optical fiber can fragment calculus (stones) into small pieces that can be removed without major surgery, or passed naturally by the patient. Fiberoptic delivery enables clinicians to access and pulverize stones in virtually any part of the body, including the gallbladder, urinary tract, and salivary glands. Researchers are also experimenting with pulsed laser energy to clear blocked tear ducts. The size of the fiber tip and how it is held in relation to the stone is thought to play an important role in launching laser-generated acoustic energy so as to fragment the stone efficiently (see Fig. 2).

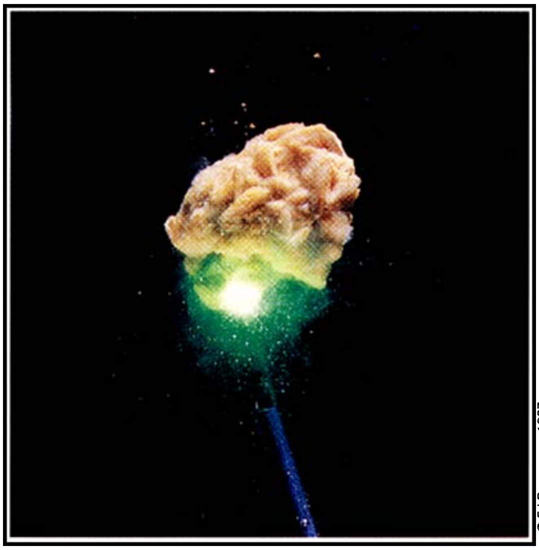

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Figure 2. Pulsed dye laser fragments a urinary stone

Hard-tissue ablation

Some types of pulsed laser energy can be used to precisely cut or ablate hard, calcified tissue such as bone and teeth. Er:YAG lasers are being considered as a "patient friendly" alternative to the high-speed drill for tooth restoration procedures. Fiberoptic laser delivery is highly desirable for easily accessing all tooth surfaces of interest, and is required for potential laser applications in root-canal surgery (alternative to mechanical reamers). Prospective bone ablation applications of erbium and other lasers will also benefit from the use of a fiber to easily access bony structures in joints, the paranasal sinuses, the middle ear, and the spine.

Photodynamic therapy

Photodynamic therapy, or PDT, combines light with photosensitizer drugs to selectively destroy pathological tissue. (PDT is described in more detail in another article in this issue; see page 16). Fiberoptic delivery is important not only for accessing internal tissue structures in a minimally-invasive fashion, but for controlling the uniformity of light exposure during PDT. Specialized fiberoptic tips, including interstitial PDT fibers, have been developed for uniformly illuminating tissue in a variety of internal and external PDT treatment situations. Real-time fiberoptic monitoring of light energy dosage may also become an important part of PDT technology, since it has been shown that real-time monitoring can improve the consistency of PDT results.

Surgery in fluid media

It is sometimes desirable to cut or vaporize tissue in a wet or completely flooded surgical field using laser energy that is strongly absorbed (greatly attenuated) by the fluid. Perhaps the best example is arthroscopic knee surgery with a 2-μm holmium laser. The arthroscopic surgeon prefers to work in a knee joint that has been "distended" by filling it with a sterile saline solution, so that the arthroscope and surgical instruments can be manipulated in the joint more easily. The holmium laser's success in arthroscopic surgery is due, in part, to the fact that its energy can be delivered through robust (quartz) optical fibers that can be used reliably in a wet surgical field. By using the fiber tip in direct contact or near-contact with tissue (one or a few millimeters off the tissue surface), the intervening fluid layer is made thin enough that holmium laser energy can reach the tissue surface essentially unattenuated, in spite of the fact that holmium energy is very strongly absorbed by saline. (It is thought that the first portion of each laser pulse literally vaporizes fluid out of the way, or "parts the waters," so that the remaining pulse energy can reach tissue unattenuated. [See Fig. 3.])

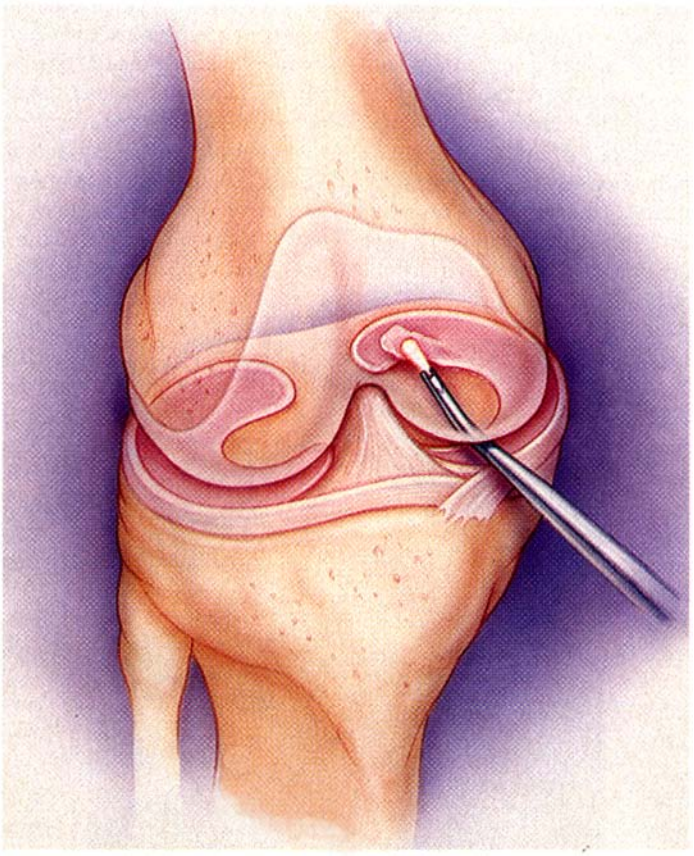
Illustration courtesy of Coherent Medical.

Figure 3. Arthroscopic knee surgery with a laser.

Tissue welding

Laser energy of an appropriate wavelength can be used to bond or "weld" tissue together. Tissue is gently heated with laser energy so that the tissue edges to be joined become "sticky," but without heating tissue so much as to kill it. Fiberoptic delivery is usually a practical necessity from an ease-of-use standpoint. For example, when welding vessel or duct ends together, some fiberoptic devices being developed can clamp or hold the duct ends while simultaneously applying laser energy to the entire 360° of the repair. Laser tissue welding during laparoscopic surgery and other MIS procedures will require fiberoptic delivery if such welding applications are to gain clinical acceptance.

Technical trends in laser surgery and medicine

The trends discussed below will help shape the future of laser surgery and medicine. They will also have important design implications for future laser products and the fiber delivery accessories that will be used with them.

Laser output versatility

As more is learned about how to best provide therapy with lasers, practitioners are demanding more versatility from laser products so that treatments can be "tailored" to the needs of specific applications and clinical situations. Products with wavelength- and/or temporal-mode versatility, which allow the practitioner to select among two or three different wavelengths, or between continuous-wave and high-peak-power pulsed emission modes, are becoming increasingly popular in numerous market segments.

Microendoscopic surgery

Extremely thin endoscopes with shaft diameters of 0.4 to 2 mm are being developed or used clinically for applications in intraocular surgery, middle ear surgery, spine surgery, and possibly intravascular surgery (within blood vessels). More so than any other surgical modality, lasers used with very thin optical fibers (100- to 300-μm core diameters) may be particularly well-suited to microendoscopy.

Combined diagnostics and therapeutics

Because laser energy can be delivered through thin optical fibers, it is possible to combine diagnostic and surgical capabilities in the same thin catheter. For example, a laser surgery fiber might be combined with one or more fiberoptic sensors, or an ultrasonic imaging transducer, in a catheter or endoscope with an outer diameter of only 2 to 3 mm.

Feedback-controlled laser surgery
Interest continues to build in the use of feedback control methods to actively control laser output parameters as needed to improve clinical results or patient safety. Depending on the application, an optical, thermal, or acoustic sensor is used to provide an electronic feedback signal which controls the laser parameter of interest in real time. Examples include control of pulsed laser energy during lithotripsy procedures to reduce risks of duct wall perforation, active control of laser power during panretinal photocoagulation to improve treatment uniformity, and real-time control of laser power to maintain a constant tissue temperature during tissue welding. This improves the strength of the welded joint.

Photocoagulation therapy
Coagulation necrosis of tissue with subsequent sloughing or resorption of necrotic tissue is a relatively benign way to remove tissue and is being considered for an increasing array of surgical applications. Tonsillectomy via photocoagulation necrosis is being investigated as a way to perform tonsillectomy in an outpatient, or potentially, an office setting.

Technical challenges

Although optical fibers have enabled lasers to be used in many applications that would otherwise have been impossible or impractical, the potential of fiber-delivered surgical lasers remains largely untapped. This section describes some of the technical challenges that must be overcome if lasers are to be used in a substantial portion of the roughly 20 million surgeries performed annually in the U.S., rather than the present 2% of surgeries.

Cost remains the major impediment to a wider acceptance of lasers. Laser equipment cost, and in some cases, per-use fiber accessory cost, must be reduced substantially if lasers are to become cost effective for most applications in which they provide tangible benefits. Equipment cost reduction by a factor of two is needed in most market segments, and in some segments a factor of three to five is needed. Low-cost production methods for making contact fiber accessories, and other specialized fibers, are needed to reduce per-use fiber costs.

The substantial training often needed to learn a new laser-based surgical procedure is another important obstacle to laser acceptance. Lasers, delivery accessories, and ancillary instrumentation must be optimized to make laser procedures easier to learn and perform.

The trend toward laser products which provide wavelength and/or temporal mode selectability will continue. Medical laser system designers have come to realize that proper selection of laser wavelength, emission mode, and delivery accessories not only determines surgical performance, but can also greatly improve ease-of-use and reduce the amount of training needed to learn a new procedure. One of the major challenges of medical laser system design is to increase output versatility while maintaining reliability and reducing system cost. Development of fiberoptic delivery accessories that can be used reliably and cost-effectively with various wavelengths and emission modes is also a key R&D task.

Optical fibers with improved transmission, mechanical, and/or biocompatibility properties, and reduced cost, are needed for use with lasers operating in the 2.5- to 3-μm range, and in the 5- to 10-μm range. Fibers with improved transmission and reduced "color-centering" tendencies are needed for transmission of UV laser wavelengths; an optical fiber that can efficiently transmit 193-nm energy would be of great interest. Fibers that can transmit infrared, visible, and UV wavelengths (through the same fiber) may eventually be needed for multi-wavelength clinical applications.

The trend toward "least-invasive" surgical procedures will, in general, require higher and higher average laser powers through smaller and smaller-core fibers. Laser designs that improve output "brightness" will continue to a be an important challenge in the foreseeable future. Laser-fiber system designs that can reliably deliver high peak laser powers are also needed.

Future growth areas

Significant growth will occur in the therapeutic laser marketplace as a result of lower-cost and more versatile diode-based laser products, the development of new minimally-invasive alternatives to conventional surgical procedures, and the development of new laser-based therapies. Diagnostic and imaging applications of (lower power) lasers will likely provide many new growth directions for the medical laser industry in the next decade.

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New therapies

In the future, photodynamic therapy (PDT) will go beyond cancer treatment. Potential applications include treatment of severe psoriasis and rheumatoid arthritis. The role of laser and non-laser light sources will increase as new PDT applications are developed, achieve regulatory approval (a slow and arduous process because the procedure involves a pharmaceutical), and gain clinical acceptance.

Possible "low-level light therapy" or 'biostimulation" applications include non-surgical treatment of carpal tunnel syndrome, pain management, and accelerated wound healing. Such applications could greatly increase the use of fiber-delivered lasers (and non-laser light sources) if such methods should gain acceptance. For most of these applications, which tend to be non-invasive using externally applied energy, fiberoptic laser delivery would be desirable primarily from a convenience standpoint.

Diagnostics

The use of applied spectroscopic methods to characterize the structural, biochemical, and physiological status of living tissue, in real time, has enormous commercial potential that probably dwarfs the therapeutic laser marketplace in comparison. Lasers (diode-based lasers in most cases) and fiberoptics will play an integral role, but the downward pressures on equipment and per-use cost are even more severe than in the therapeutic marketplace.

The ability of light to make non-invasive measurements on external and internal tissue is of critical importance for such applications. Optical biopsy, or the use of laser spectroscopy methods to identify malignant or precancerous tissue, is one of the hotter areas of R&D activity at the moment. Other potential applications include non-invasive monitoring of blood glucose levels in diabetic patients, and real-time optical monitoring of brain oxygenation and function in neurosurgical patients.

Imaging

Light-based alternatives to magnetic resonance imaging (MRI), positron-emission tomography (PET), and x-ray computed axial tomography (CAT) are being developed to noninvasively image internal tissue structures in three dimensions. Optical tomography systems have the potential to be much more compact and affordable than competitive modalities, which would render tomographic imaging capability available to a broader range of health care providers, but are unlikely to supplant MRI, PET, or CAT scans. Some optical tomography methods under development use multimode fibers, some employ partial-coherence interferometric techniques using single-mode fibers, and others do not employ fibers at all.

In summary, fiberoptic delivery of laser energy has enabled new surgical laser procedures and provides an important mechanism by which laser treatments can be optimized in terms of clinical performance and ease-of-use. This will also be true for new diagnostic and imaging applications that will come to the fore in years to come. The combination of diode-based lasers with new fiberoptic techniques will enable laser methods to penetrate not only the traditional health care marketplace, but will allow lasers to play an important role in the emerging home health care market as well.

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The role of diode-based lasers

Semiconductor diode laser-based systems, including diode lasers and diode-pumped solid-state lasers, are expected to have a dramatic impact on the surgical laser industry. They should significantly reduce equipment and fiber per-use costs, and improve ease-of-use, for many existing and prospective laser procedures.

Dropping prices for high-power diode laser components will eventually enable medical laser systems that are much more affordable. Advances in high-power diode laser technology, resulting in reduced cost-per-watt of output power, and increased competition among diode laser component manufacturers, will bring down the cost of high-power diode laser components substantially (factor of 2 or more), in the near term (1 to 3 years), and without "postulating" the theoretical existence of some very-high-volume market which exploits manufacturing economies of scale. Such cost reductions will allow diode-based lasers to play a much larger role in medical laser system design.

Diode-based designs will eventually enable multiple wavelengths and temporal emission modes to be obtained easily from the same compact device, or alternatively, will enable more affordable products such that practitioners can own multiple lasers and choose among them as needed. The ability to select wavelength and emission mode will, in many instances, enable inexpensive fiberoptic accessories (in terms of per-use cost) to be used where more expensive fiberoptics would otherwise be required. Increased flexibility to match laser output parameters and fiber delivery hardware to the surgical task at hand will make it easier to learn and use lasers (See Fig. 4).

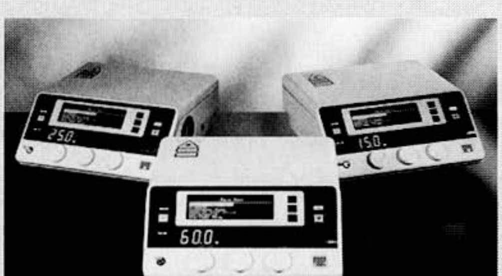

Photo courtesy of Diomed Ltd.

Figure 4. Compact 15-, 25-, and 60-W surgical diode laser.