LASERS IN UROLOGIC SURGERY

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Preface

APPLICATION OF LASER ENERGY is finding an increasing role in a number of medical and surgical specialties. The keen interest in urologic laser surgery is a natural evolution considering the endoscopic expertise of urologists and the sophisticated instrumentation that allows endoscopic access to virtually the entire urinary tract. However, these factors have somewhat impeded the progress of laser urologic surgery, because effective alternative therapy exists in many of the areas in urology in which lasers are being used. Nevertheless, interest in laser surgery is increasing at an astounding rate among urologists, and there seems little doubt that lasers will become an important tool in the armamentarium of the clinical urologist.

At first glance, it may seem somewhat premature to publish a book dedicated to urologic laser surgery considering the relative novelty of the field and the lack of widespread familiarity with the instruments. However, these very factors have prompted the efforts to establish a comprehensive review of the information necessary for the physician interested in urologic applications of laser energy. Reports of clinical experience with lasers in urology are scattered throughout the world's literature in multiple languages. Various books in print have single chapters or sections devoted to urology, but none provides a comprehensive review of the material most interesting to a clinical urologist.

This text is intended to serve as a basic reference for individuals interested in urologic applications of lasers and provides in a single volume material otherwise available only from multiple sources. In addition, updated information is provided from a number of outstanding investigators in North America and in Europe. The initial chapters provide basic information regarding laser physics and tissue effects that is essential for safe and effective application of the instruments. Subsequent chapters cover various aspects of urology in which lasers have shown promise, and review the pertinent clinical experience. Finally, Dr. Dixon in his chapter provides an important perspective regarding urologic surgery as a component of a functional laser surgical unit in which many of the instruments are used by various medical and surgical specialties.

The purpose of this book is not to convince the reader of the advantages of lasers or to promote their use. Rather, it is hoped that presentation of basic information will allow further investigation and clinical experience that will help define the ultimate role of lasers in urologic surgery.

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THE MEDICAL APPLICATIONS of nonionizing radiation have historically been limited to its effects on the eye and skin. The major source of this radiation has been the sun. Since the invention of the laser, new applications of nonionizing radiation have been developed. Lasers are now being used in both diagnostic and therapeutic aspects of medical treatment.

This chapter is an introduction to the physical and biophysical principles of laser. The intent is to provide the information necessary to predict the effect that various laser devices will have when used therapeutically. The word laser is an acronym for Light Amplification by Stimulated Emission of Radiation (see Common Laser Terminology at the end of the chapter). A laser is capable of generating an intense, almost parallel beam of electromagnetic energy of a given wavelength or color. These characteristics make the laser a unique device for many medical and surgical applications.

History of Lasers

The principles necessary for the formation of the concept of the laser were firmly established as early as the 19th century with the advent of Bohr's theory and optical resonators. In 1917, Einstein[1] proposed the concept of *stimulated emission,* thus laying the foundation for Schwalow and Townes (1958) and Prokhorov Vasov to independently describe the physical principles of maser (Microwave Amplification by Stimulated Emission of Radiation) several decades later. The first successful application of stimulated emission of microwaves was made by Gordon and colleagues[2] in 1955. In 1960, Maiman[3] first observed stimulated emission in the visible portion of the spectrum by exciting a ruby rod with intense pulses of light from a flash lamp, generating the first laser beam.

In 1961, Javan and associates[4] developed the first gas laser and demonstrated the first continuously operating laser using a mixture of helium and neon. Also that year, using a neodymium-doped yttrium-aluminum-garnet (Nd:YAG) rod, Johnson[5] developed a laser that emitted energy in the near infrared (IR) portion of the spectrum. The argon laser, emitting energy in the blue-green portion of the spectrum, was developed by Bennett and coworkers[6] in 1962. The CO_2 laser, emitting spectral energy in the far IR portion, was developed in 1964 by Patel and colleagues.[7]

Physical Principles

Currently many materials (solid, liquid, and gas) are used as the active medium in lasers. Laser wavelengths cover the entire visible portion of the electromagnetic spectrum as well as wavelengths in the ultraviolet (UV) and IR portions. An atom, molecule, or ion in its normal energy state, or *ground state,* is capable of becoming excited to a higher energy state by the absorption of thermal, electric, or optical energy. The word *atom* will be used to represent the generic term for an atom, molecule, or ion. After energy is absorbed, an atom will spontaneously return to its ground state and thereby liberate the absorbed energy. This process is referred to as *spontaneous emission of radiation* (Fig 1–1). Stimulated emission of radiation is a process whereby an atom in an excited state returns to the ground state after an interac-

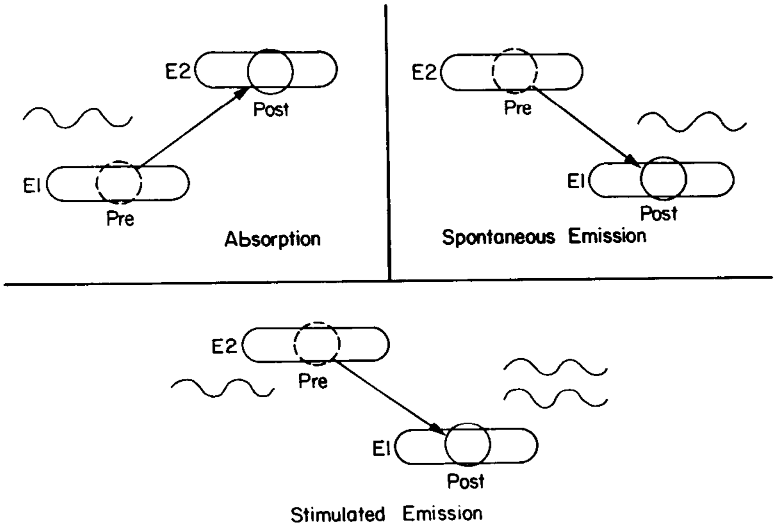

Fig 1–1.—Energy diagram illustrating the process of absorption, spontaneous emission, and stimulated emission. For explanation see text. *E* = emission. (From Dixon J.A.: *Surgical Application of Lasers.* Chicago, Year Book Medical Publishers, 1983. Used by permission.)

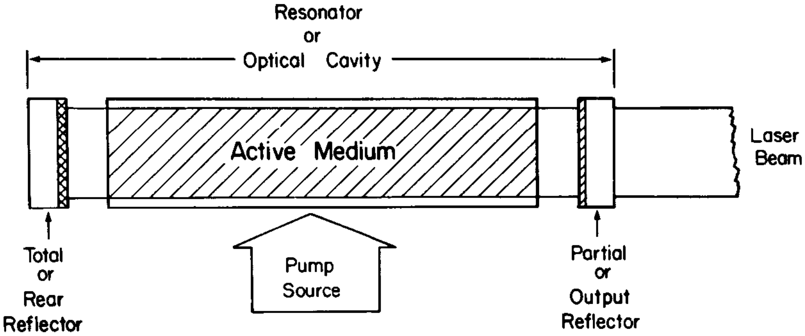

Fig 1–2.—Basic components of a laser. The active medium is a collection of atoms or molecules. (From Dixon J.A.: *Surgical Application of Lasers*. Chicago, Year Book Medical Publishers, 1983. Used by permission.)

tion with an incident wave of wavelength corresponding to the absorption energy wavelength. The net result of such interaction will be two waves of the same wavelength traveling in the same direction and in phase with one another. When a collection of atoms is excited and more atoms are at the upper energy states than at the ground state, such a system is said to contain a *population inversion*. A population inversion is necessary for lasing action to take place.

Figure 1–2 illustrates the basic components of a laser. The *active medium* is a collection of atoms capable of undergoing stimulated emission. Materials such as carbon dioxide, argon, and neodymium serve as active media for certain laser types. At each end of the active medium are two parallel mirrors that make up the *optical cavity* or *resonator* of the laser. The front mirror has been designed to reflect only a portion of the light impingent upon it, thereby transmitting some fraction of the total energy. The rear mirror, or total reflector, reflects 100% of the impingent energy. The last major component of the laser system is an energizing source or pump. The pump may be a source of thermal, electric, or optical energy that provides the energy for absorption by the active medium. If the material is pumped with sufficient energy, a population inversion will occur. Photons of light created from the spontaneous emission will radiate in all directions. Much of this spontaneous radiation will be eventually dissipated in the form of heat. A small percentage of the spontaneous radiation (photons) will travel along the axis of the laser cavity. These photons will collide with atoms in the excited state, thereby stimulating the emission of radiation. As further collisions of photons and excited atoms occur, more intracavity energy develops. The intensity of the intracavity energy is amplified by reflections between the parallel mirrors. At the partial reflector (front), a portion of the energy is permitted to escape out of the cavity. This energy is in the form of an intense beam of coherent light.

Lasers and Their Characteristics

Table 1–1 lists the most commonly used medical and surgical lasers and their corresponding characteristics. Other laser wavelengths are being investigated. Some lasers (dye lasers) are capable of generating a band of wavelengths. These devices permit the continuous selection of any wavelength within the band. Currently, continuous wave dye lasers are limited to relatively low-power applications. A highly experimental, free electron laser is theoretically capable of producing electromagnetic radiation of great intensity throughout most of the electromagnetic spectrum. Such a device would be of great experimental value. Improvements in these lasers hold great promise for the future.

Lasers are capable of generating light either in the form of a continuous delivery of energy referred to as *continuous wave* (CW) lasers or in the form of discrete or multiple pulses referred to as *pulsed* lasers. Most CW medical lasers can be operated in a *gated* manner. This permits the relatively low-power CW energy to be delivered for a short duration. This "pulse" of energy is quite different from a "pulsed"

TABLE 1–1.—CHARACTERISTICS OF MEDICAL LASERS*

LASER TYPE	WAVELENGTH (NM)	POWER RANGE W(JOULES)	MODE†	DELIVERY SYSTEM
CO_2	10,600	0.1–100	CW and pulsed	Direct couple to microscope Articulated arms Experimental fiberoptics
Nd:YAG	1,060	5–120	CW and Q-switched	Fiberoptics
Ruby	694	(>30 J)	Pulsed	Direct couple to microscope
Doubled ND glass	503	(>3 J)	Pulsed	Direct couple to microscope
Argon	458–515	0.001–25	CW and pulsed	Fiberoptics (hand-held and microscope)
Dye	400–700	0.001–6	CW	Fiberoptics

*From Dixon JA.: *Surgical Application of Lasers*. Chicago, Year Book Medical Publishers, 1983, p. 14. Used by permission.
†CW = continuous wave.

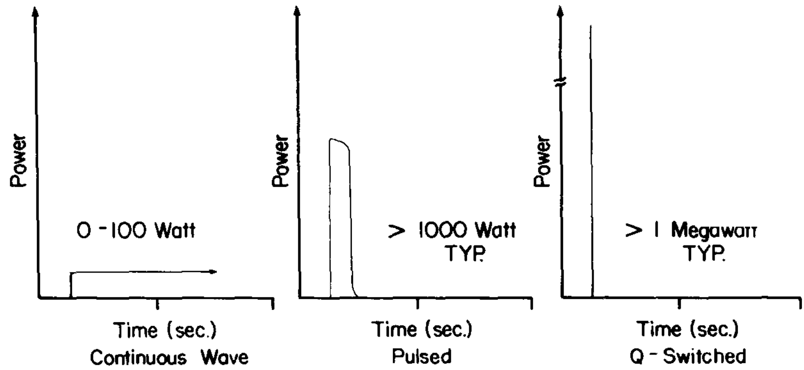

Fig 1–3.—The power-time diagrams illustrate the differences between continuous wave, pulsed, and Q-switched laser operation. (From Dixon J.A.: *Surgical Application of Lasers*. Chicago, Year Book Medical Publishers, 1983. Used by permission.)

laser. The intensity of a pulsed laser is much higher than typically achievable from a CW device. The duration of a pulsed laser is typically less than 1 msec, although longer pulsed lasers are common. Both CW and pulsed lasers can be forced into a pulsed mode of operation known as *Q-switched*. Typically, Q-switching is accomplished by inserting a fast shutter between the active medium and one of the mirrors. With the shutter closed, the energy contained in the active medium will be far above the lasing threshold levels with the shutter open. The buildup of energy is very rapid. The excess excitation can be discharged in an extremely short period when the shutter is opened. The result is a pulse of energy of exceedingly short duration with an intensity several orders of magnitude higher than without Q-switching (Fig 1–3). Owing to this extremely high-powered pulse, the flash is also referred to as the *giant pulse*.

Frequently, the diameter of the laser beam is too large and has insufficient power to be used for most medical applications. For these reasons, a focusing lens is inserted in the laser beam path to reduce the beam diameter to a size suitable to the task. This decrease in beam diameter increases the *power density* (PD) and, thus, the effect on tissue. The PD (watts per square centimeter or W/sq cm) is an expression of the laser power as a function of the surface area in contact with the tissue. Table 1–2 gives the relationship between PD, power, and beam diameter.

TABLE 1–2.—POWER DENSITY CHART

SPOT SIZE (mm)	POWER (W)								
	2	5	10	15	20	25	30	40	50
0.2	5.5 K†	14 K	28 K	42 K	55 K	71 K	84 K	110 K	139 K
0.4	1.3 K	3.3 K	6.6 K	10 K	13 K	17 K	20 K	26 K	33 K
0.6	610	1.5 K	3.1 K	4.6 K	6.1 K	7.9 K	9.3 K	12 K	15 K
1	215	544	1.1 K	1.6 K	2.1 K	2.8 K	3.3 K	4.3 K	5.4 K
1.5	94	239	478	722	944	1.2 K	1.4 K	1.9 K	2.4 K
2	55	139	277	419	645	710	839	1.1 K	1.4 K
2.5	35	88	176	265	347	449	531	694	878
3	24	61	121	183	239	310	366	479	606

Power density (PD) for a TEM_{00}‡ gaussian laser beam. For proper use of chart:

1. Measure beam diameter (mm) on phosphor plate or use a wooden tongue blade with the laser on for ≈ 0.2–0.4 sec (PD >500 W/sq cm).
2. Measure power (W) delivered to tissue.
3. Enter chart using diameter (mm) and power (W) to obtain power density in (W/sq cm).

*From Dixon J.A.: *Surgical Application of Lasers*. Chicago, Year Book Medical Publishers, 1983, p. 16. Used by permission.
†K = ×1,000.
‡TEM = transmission electromagnetic mode.

Biophysics

The effect that optical radiation may have on tissue can be separated into categories depending on the portion of the spectrum that is incident on the tissue. The UV portion of the spectrum, particularly ultraviolet B (280–315 nm) and ultraviolet C (100–280 nm) regions, can produce marked erythema (sunburn), increased pigmentation, photokeratitis, and skin cancer. High levels of exposure of optical radiation in the ultraviolet A region (315–400 nm) can result in cataract formation. One of the beneficial effects of UV radiation is the formation of vitamin D. The UV region of the electromagnetic spectrum has an effect on tissue, principally by a photochemical rather than thermal reaction. Skin erythema produced in the ultraviolet A region, however, may also be thermal.[8]

The visible region of the spectrum ranges from about 380 nm to 700 nm. There are many effects of visible light on the body. Optical radiation can be absorbed by the pigment granules in the pigment epithelium and choroid of the eye to stimulate the photoreceptors (rods and cones) for vision. If the intensity of the radiation is too great, the absorbed energy is converted into excess heat and can cause thermal damage.[9]

The absorption and scattering of visible light through skin is dependent on many characteristics of the tissue. Owing to the optically inhomogeneous structure of tissue, the modeling or predicting of the absorption and scattering of light is less than perfect. The amount of light absorbed by tissue will differ with the amount of an absorbing chromogen or pigment present. Naturally occurring pigments include, among others, melanin and hemoglobin. The thermal effect that light will have on tissue will be a function of the wavelength of the incident beam and the absorption characteristic of the tissue and chromogen.

Visible light can have effects other than thermal. Mester and colleagues[10–12] suggest a stimulating effect of low levels of red light on the phagocytotic index, wound healing, and hair growth. These results have not been widely duplicated.

Light in conjunction with *photosensitizers* can be used to produce a variety of tissue effects. A photosensitizer is a light-absorbing molecule capable of transferring the absorbed energy to other molecules that are not capable of absorbing light themselves. The photosensitizers can be either endogenous or exogenous.

Some well-studied photosensitizers are the porphyrins. When porphyrins are not associated with iron, they act as potent photosensitizers. In porphyria, large quantities of porphyrin are produced in the bone or liver tissue. The porphyrin localizing in the skin and underlying tissue can cause changes ranging from simple hyperpigmentation to tissue destruction.[13] One exogenous photosensitizer, a hematoporphyrin derivative (HPD), is capable of localizing in malignant tissue.[14] The tissue containing HPD will fluoresce when illuminated with short wavelength visible and UV light.[15] This is being used to aid in the diagnosis and localization of certain cancers.[16] When illuminated with longer wavelengths ($\simeq$630 nm, red), the HPD in the presence of oxygen creates a singlet oxygen ($_10^2$), the latter having a pronounced cytotoxic effect.[17] Clinical trials are underway[18] to study the efficacy of such photobiologic applications of light.

Electromagnetic energy in the near IR portion of the spectrum (780 nm to 3 μ) can cause skin and retinal burns and cataract formation with excessive exposure. At longer wavelengths, the mid-to-far IR portion of the spectrum (3–1,000 μ), tissue effects are limited to the superficial layers of tissue. This is particularly true at 10.6 μ, the wavelength of emission of the CO_2 laser. This radiation is heavily absorbed by the water in the cells.

Excessive optical radiation throughout the spectrum can cause thermal damage, resulting in tissue coagulation necrosis. The extent of thermal damage is a function of the following parameters (Fig 1–4).

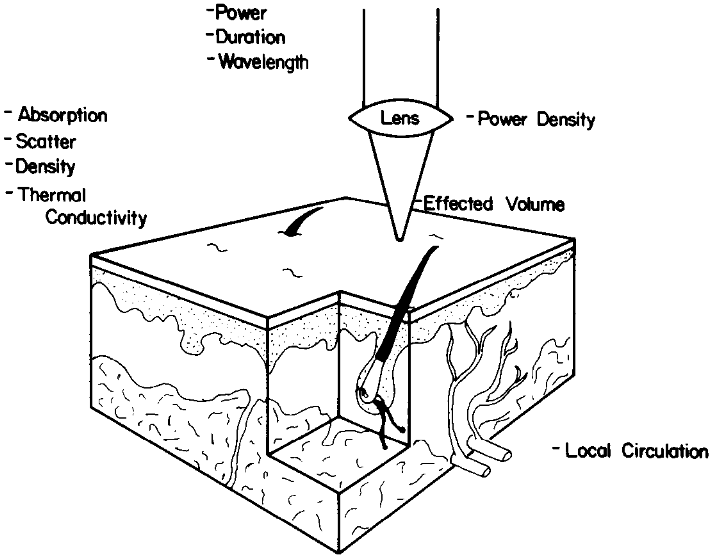

Fig 1–4.—Diagram illustrating parameters that determine the effect of a laser on tissue. (From Dixon J.A.: *Surgical Application of Lasers.* Chicago, Year Book Medical Publishers, 1983. Used by permission.)

1. Absorption and scattering coefficients at particular wavelength.
2. Power density of optical radiation on tissue.
3. Duration of exposure.
4. Size of radiated area.
5. Cooling component, i.e., blood flow.

As a consequence of the process of stimulated emission and amplification, the resulting laser emission is *monochromatic,* i.e., a very narrow spectral color. The monochromatic property of laser light can be appreciated by comparing the bandwidth of various laser beams with the bandwidth of an ordinary tungsten lamp (Fig 1–5).

The energy deposited by the laser to the tissue is the product of the power of the laser and length of time (duration) that the beam is in contact with the tissue. The duration of exposure of the energy is an important variable in control of both the desired and unwanted effects on tissue. The desired effect may be vaporization of tissue or a controlled thermocoagulation. In contrast, the undesirable effect may be coagulation necrosis and edema. The relationship between area of thermal effect as a function of power and duration is illustrated in Figure 1–6,A. Illustrated in this plot is the relationship between depth