CHAPTER **49**

The Use of the ND: YAG Contact Laser In Podiatric Surgery

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INTRODUCTION

Laser surgery is a significant technological development which has affected medicine and surgery during the last decade. Overstated claims of the value of laser surgery are often misleading to the public, and can result in health care being sought solely on the basis of the availability of laser surgery. As physicians, we declare quality of patient care based on our training and experiences, not necessarily on the tools we choose to use. The laser is simply another tool available to the surgeon which, when used properly can be a benefit to the patient.

The reader is encouraged to review the glossary of terms following this article, in order to be familiar with the terminology associated with lasers.

DEFINITION

The word "laser" is an acronym for light amplification by the stimulated emission of radiation. The characteristics of laser light which distinguish it from visible light will be discussed. Laser light is best understood in terms of its wave characteristics, which are characterized primarily by four qualities: wavelength, amplitude, frequency, and velocity (Fig. 1).

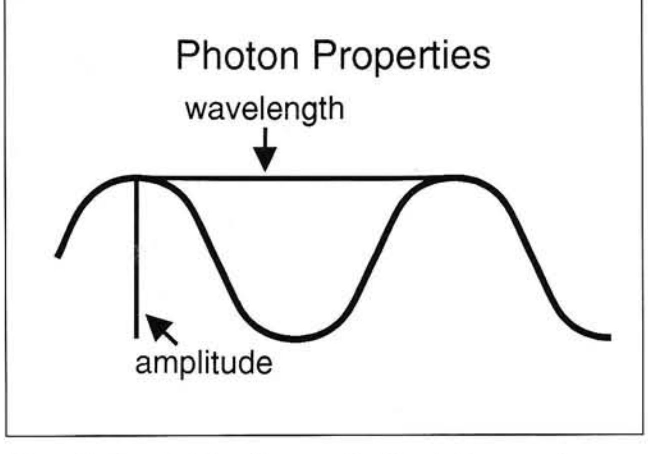

Figure 1: Characteristics of a wave showing photon properties.

LASER BIOPHYSICS

Properties of Light

Light is a bundle of energy with no mass. The smallest measurable unit of light (energy) is known as a photon. Photons are characterized by wavelength, frequency, energy, and have no mass. An understanding of the fundamental properties of light waves is essential in understanding how a laser functions.

Spontaneous Emission of Radiation

Spontaneous emissions result from energized electrons decaying back and forth from their original orbits (Fig. 2). These spontaneous emissions produce a photon of light in which the wavelength and amplitude of the emitted light varies according to the magnitude of the energy change. Note that

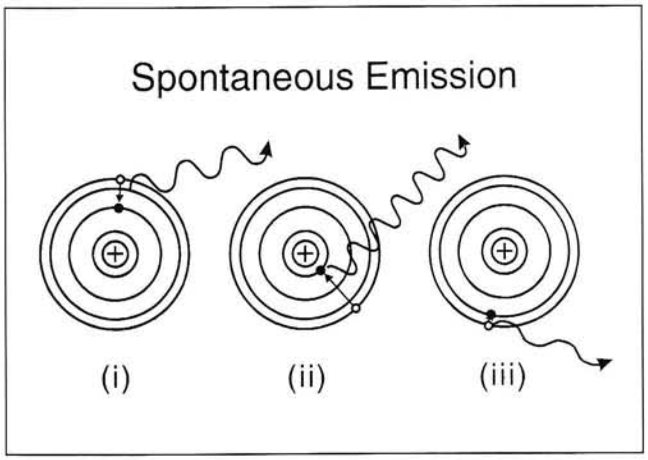

Figure 2: Spontaneous emission.

in spontaneous emissions the distribution of the photon is in random directions, and the overall light output is incoherent. Different energy levels produce multiple colors of light, and all the colors combined produce white light. An example would be the incandescent lamp as a source of non-coherent light emitted in different directions. When a flash light is turned on, a stream of electrons provided by the electrical source of the battery pass through a tungsten filament. The tungsten atoms which originally are in a ground state, are forced to a higher energy level resulting in collisions of electrons and release of photons in random directions. The atomic transitions from a particular energy level to a lower level is the process of spontaneous emission.

Stimulated Emission of Radiation

The process of laser light is a different phenomenon known as stimulated emission of radiation. In stimulated emission, electrons are energized in a substance which has undergone stimulation so that many of the atoms are in an excited state. The first atom (i) undergoes spontaneous decay emitting a photon P1.

This interacts with a second energized atom (ii) stimulating the emission of a second photon P2 with the same light wave characteristics in perfect phase with P1. Each of the identical photons further stimulate energized atoms to produce identical photons such as P3 and so on (Fig. 3). Thus, the basis for the development of laser light is stimulated emission. Each photon stimulates another energized electron to produce a further proton, similar to a chain of dominos falling.

The waves of laser light produced in this fashion are reflected back and forth many times between mirrors in the laser chamber, increasing the amplitude of the wave with each pass. In the laser system, one of the mirrors is partially transmissive which allows the laser beam to exit the laser chamber and pass through a delivery system to the surgical field.

THE ELECTROMAGNETIC SPECTRUM

Light from any source is electromagnetic radiation and can be located on the electromagnetic spectrum, although the different regions of the spectrum are not sharp and distinct. Electromagnetic radiation has a wave nature which consists of the vibrating electric field. The distance between the two peaks of a wave determine its wavelength. Additionally, electromagnetic radiation also has a frequency, which is the number of successful peaks that pass a point per second. This can also be described as the number of oscillations per second, which is expressed in Hertz (Hz). Figure 4 outlines the ultraviolet, visible, and infrared electromagnetic spectrums. Note that the laser, depending on the substance utilized, can be present in the visible or infrared electromagnetic spectrum. The ND:YAG laser is a laser medium which produces 1064nm light in the near infrared light electromagnetic spectrum.

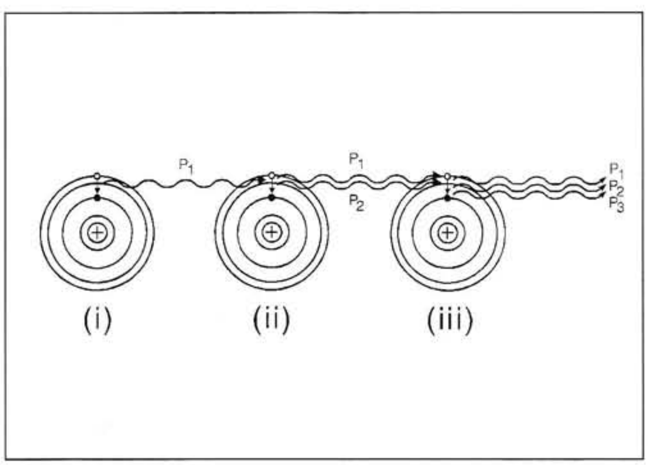

Figure 3: Stimulated emission.

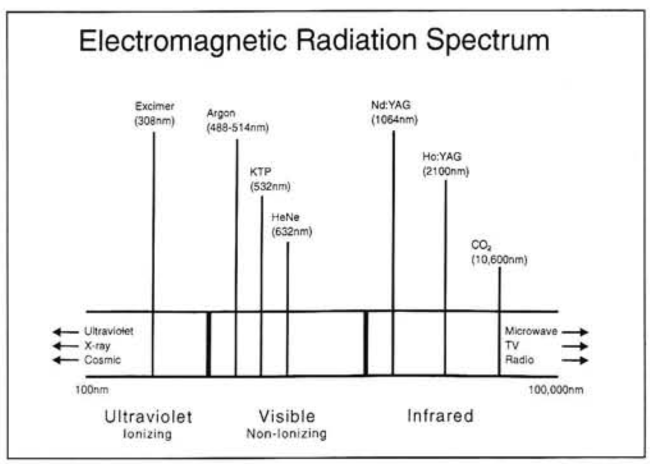

Figure 4: Ultraviolet, visible and infrared electromagnetic spectrums.

BASIC COMPONENTS OF A LASER SYSTEM

A laser system utilizes a power supply which excites the laser medium. This in turn produces the laser light (Fig. 5). Great amounts of heat are generated during this process, and raise the temperature of the laser medium. A cooling system is necessary in order to assure proper operation and safety. The laser medium itself may vary, and usually a laser is named for the medium. For example, the ND:YAG laser has an active medium of a crystal of yttrium, aluminum, and garnet doped with neodymium ions producing a near infrared radiation of 1064nm.

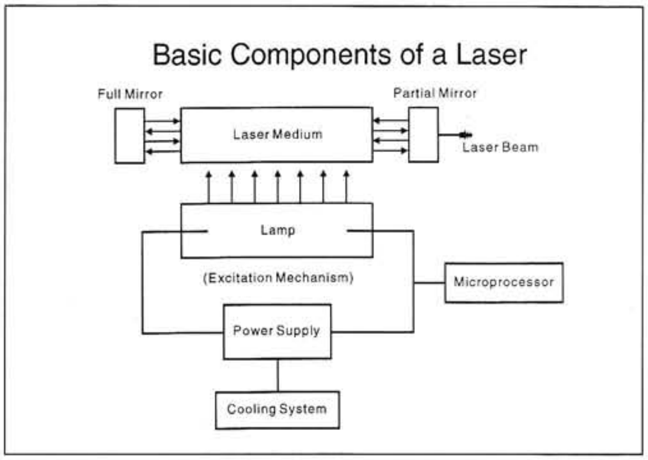

Figure 5: Basic components of a laser system.

High voltage electricity or intense flashes of light is the energy which excites the laser medium. This is known as the excitation mechanism. For the laser light to exit the laser, a system of full and partial mirrors are used to transmit approximately 5% of the light to the delivery system as a laser beam. The entire laser unit is programmed by an operator control panel through the use of a microprocessor located inside the laser. The messages from the control panel are sent to the microprocessor controlling the power supply, laser chamber, and cooling systems in order to produce the desired output of energy.

CHARACTERISTICS OF LASER LIGHT

Laser light is monochromatic (one color) due to the fact that the photon originated during stimulated emission originates from the same energy level. This unique property of having certain wavelengths with specific characteristics is important in laser applications. In contrast, normal light contains all different wavelengths and colors, and is known as white light. As white light passes through a prism the multiple colors of the light are dispersed according to their wavelengths. Since laser light is monochromatic, only one color is visible when it passes through a prism (Fig. 6).

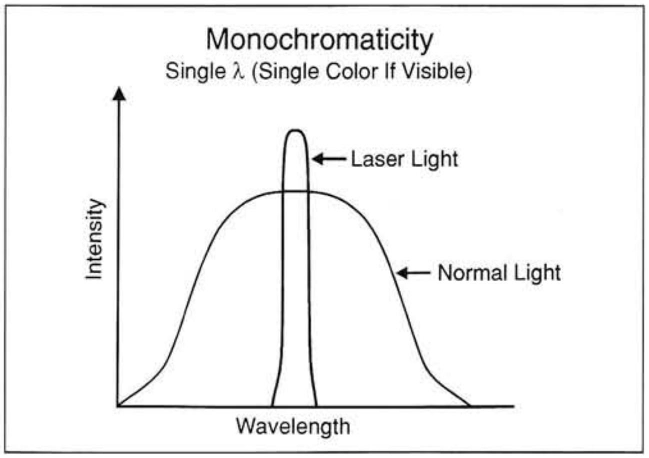

Figure 6: Monochromacity of laser light.

Laser light is colliminated, and emerges parallel with little divergence of the beam. This property of laser light is important in controlling the beam of light while using various optic devices. In contrast, the light from a flashlight is not collimated and diverges as it travels away from the light source (Fig. 7). Laser light is parallel, so that the laser pulse is collimated and the spread between the beam is insignificant. Therefore, there is minimal loss of power along the beam, and its intensity can be focused to achieve the desired effect.

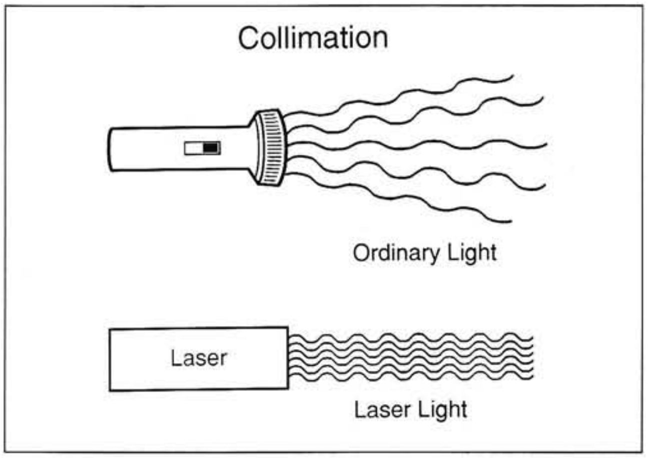

Figure 7: Comparison of collimated light and non-collimated light.

Ordinary light (an incandescent lamp) is incoherent and consists of light waves radiating in all directions, which are out of phase with one another. It is impossible to phase together the waves of ordinary light, since multiple wavelengths (colors) are produced. In contrast, laser light is coherent and is of one wavelength (color) which allows the waves to synchronize when they are phased together. All waves are in phase, and the sum of the amplitude of all the waves of laser light are confined to produce an area that has increased irradiance. Figure 8 compares a non-coherent light source effect on the focal spot passing through a lens, in comparison to a coherent light source such as a laser, as it passes through a lens to a focal spot. The focal spot of non-coherent light is a low-powered density, whereas the focal spot of a coherent light source such as laser, is a high powered density. The laser beam, as it passes through various types of delivery systems, is of benefit to the surgeon at the surgical field as a potentially high powered source.

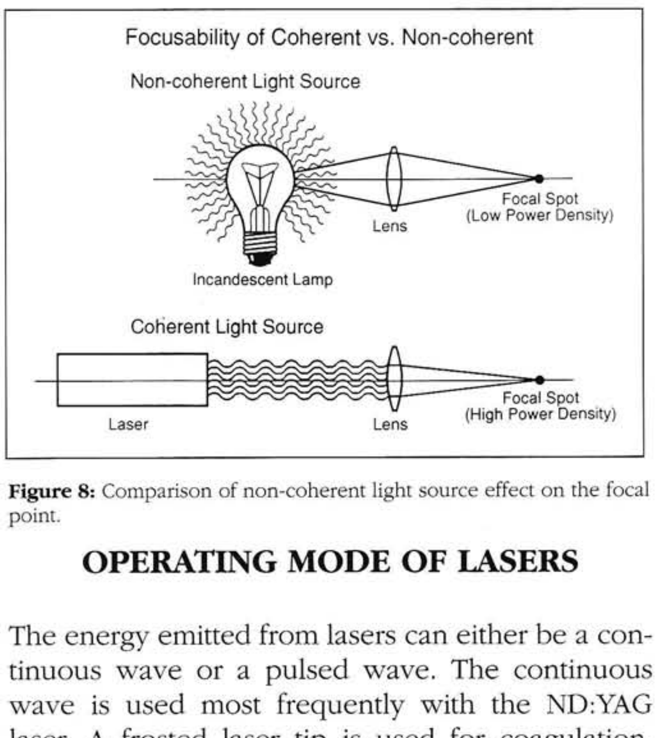

Figure 8: Comparison of non-coherent light source effect on the focal point.

OPERATING MODE OF LASERS

The energy emitted from lasers can either be a continuous wave or a pulsed wave. The continuous wave is used most frequently with the ND:YAG laser. A frosted laser tip is used for coagulation, and a non-frosted tip is used primarily for cutting.

The pulsed wave laser emits extremely short bursts of laser energy over an interrupted period of time. The pulsed mode is used with an open laser beam, rather than a closed laser beam system utilizing the frosted or non-frosted tips.

TISSUE INTERACTION

Laser light, when it strikes any object, can be reflected, transmitted, scattered, absorbed, or any combination of these effects (Fig. 9). In order to create any effect on living tissue, the laser light must be absorbed. Scattered laser light may be absorbed over a large area, and provides different minimal effects on the tissue. Reflected laser light has no effect on tissue.

The laser's effect on tissue depends on the specific wavelength, intensity, and duration of the laser energy exerted on the tissue. The size, color, and composition of the tissues are also variables which may alter the laser's effect.

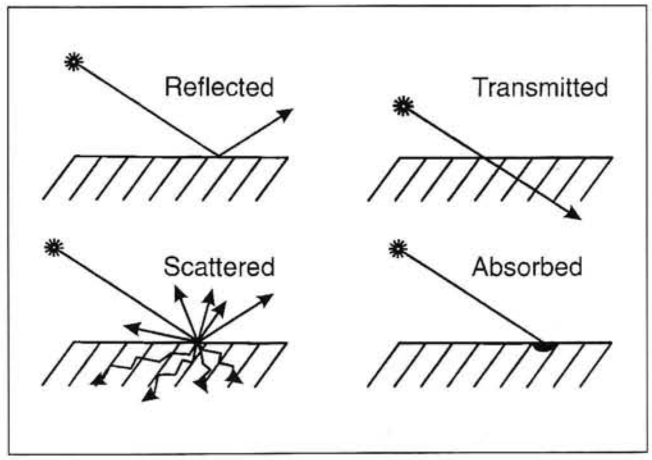

Figure 9: Tissue interaction when a laser beam strikes an object.

The ND:YAG contact laser is very efficient in performing subcutaneous dissection, as well as in providing hemostasis when utilizing a frosted tip on the laser. Greater care must be utilized in performing capsular dissection with the ND:YAG laser, due to the increased density of the tissue and the requirements for increased thermal energy causing potential undesirable thermal effects, burning of tissue, and scarring. The ND:YAG contact laser is used in non-osseous cases, allowing soft tissues to undergo periods of thermal relaxation by removing the laser from the site and using copious amounts of sterile water for irrigation. This minimizes adjacent thermally induced undesirable effects, such as periostitis of osseous structures. In capsular dissection, intense local thermal effects from the laser scalpel can cause avascularity of periosteal arteries particularly at a higher density setting and extreme caution must be utilized. Conventionally, when utilizing the ND:YAG contact laser with a frosted tip, the initial skin incision is made with a steel blade carried to the superficial level of the dermis. The remaining soft tissue dissection is performed with the laser scalpel, utilizing the frosted tip to assure hemostasis.

In podiatric surgery, the ND:YAG laser is utilized as a contact (non divergent) fiber. The desired effect utilizing a contact probe or sapphire tip produces tissue effects only when the probe or tip touches tissue. This is in contrast to an open beam or non-contact laser beam where divergence is characteristic (Fig. 10).

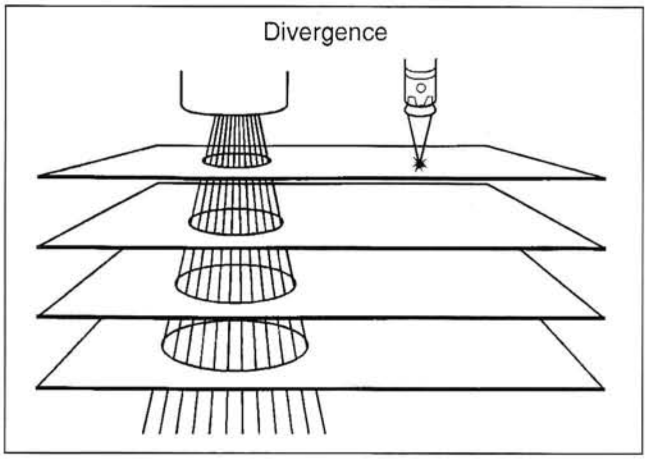

Figure 10: Effect of non-contact vs. contact applications of ND:YAG laser.

Absorption of laser energy in tissue causes different surgical effects to take place at different levels of temperature. The actual thermal injury varies, depending upon the wavelength of the laser material, as well as the amount of power density (watts/cm2). Protein is denatured at 40-70 degrees centigrade. Tissues can be coagulated from 70-85 degrees centigrade. Vascularization occurs at 85-100 degrees centigrade and vaporization of tissues occurs at 100 degrees centigrade or more. Carbonization of tissue occurs at 400 degrees centigrade or more. The ND:YAG laser in an open beam has a thermal injury depth of 2-6mm and great care must be utilized in it surgical use. In contrast the CO_2 laser has a thermal injury depth of 0.5mm. In the contact closed laser beam utilizing a probe or sapphire tip, the laser energy is expressed primarily as heat at the level of the probe or tip, rather than an open beam. Desired effect can be obtained by varying the power density (watts/cm2) (Fig. 11).

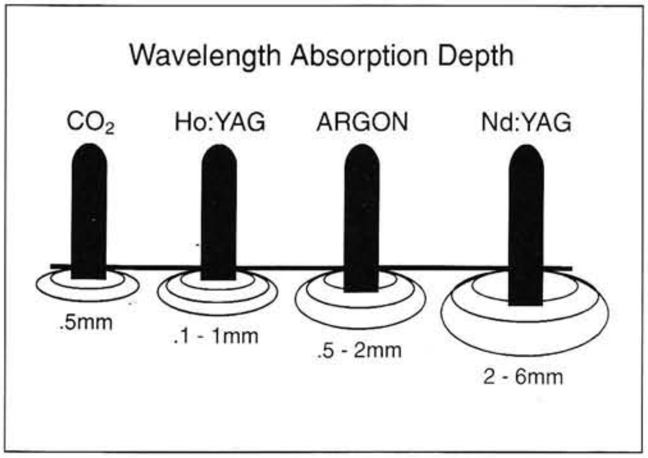

Figure 11: Wavelength absorption depth of various laser mediums utilizing an open beam on tissues.

With the use of the ND:YAG laser, the thermal effect on penetration depth varies with the pigmentation of the tissue (Fig. 12). In pigmented tissue, the depth is approximately 1.0mm, in contrast to unpigmented tissue, where the depth may be 4.0mm of penetration in an open beam laser. These characteristics enable the ND:YAG laser and the open beam condition to be very effective in treating skin lesions such as a Portwine E stain (birthmark), or any skin lesions with a high level of hemoglobin, such as a hemangioma.

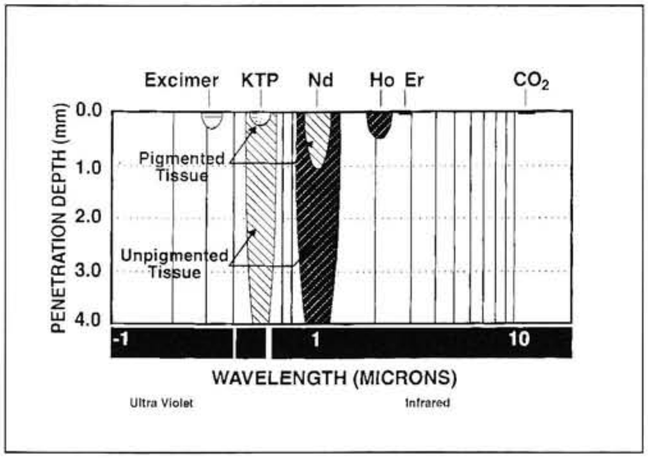

Figure 12: Effect of various laser medias on penetration depth.

The effect of laser light at various power densities on living tissue is demonstrated in Figure 13. Cells which absorb laser light are initially heated to the boiling point, destroying the cell. Additional laser power will cause the cell to explode, throwing off steam and cellular debris. With increased power density the laser beam will cause the steam and debris from the site of impact to be carbonized in the laser beam.

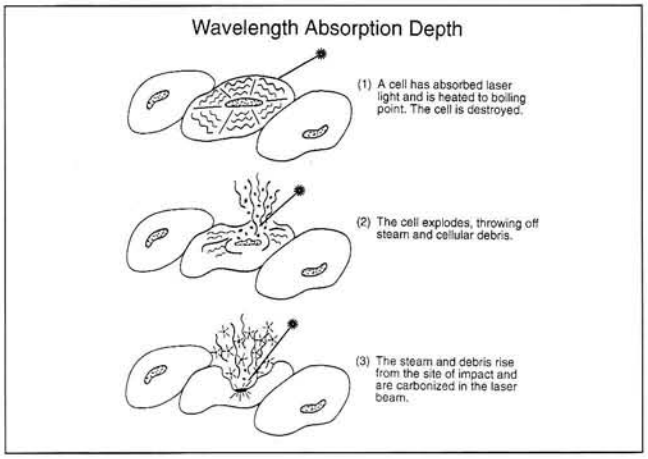

Figure 13: Effect of laser light at various power densities on living tissue.

SAFETY

One of the first steps in the safe use of lasers is to understand their hazard classification. The hazard potential of lasers is categorized by the maximum output power available for each laser. The American National Standard Institute (ANSI) has established a classification which has been approved by the FDA (Table 1).

When incorporating a laser program in a hospital setting, a laser safety committee is usually formed. This committee typically consists of a chairman, operating room director or head nurse, laser nurse, and a laser biomedical technician. This committee should be responsible for insuring that the proper level of physician training is instituted, as well as that the proper equipment is acquired and maintained.

Table 1

CLASSIFICATION OF LASERS

CLASS 1: A laser considered to be incapable of producing damaging radiation level and therefore, exempt from radiation hazard control.

CLASS 2: A low powered visible laser that emits up to one nw of power. This laser requires a CAUTION sign and depends on the eye aversion response to bright light for safety. e.g. HeNe aiming beam.

CLASS 3: A medium power laser that requires controlled measures to prevent viewing of the direct beam. A DANGER sign is required.

CLASS 4: A high powered laser that requires control measures to prevent exposer of direct and reflective beam to eyes and skin. Most medical lasers are classified as class 4. These are the most hazardous and require special labeling.

All operating room personnel, including the patient, must wear eye protection (Fig. 14). The particular type of safety glasses or goggle is dependent upon the type of laser in use. Each laser's wavelength is characterized by different absorption characteristics, and damage depends upon the type of laser beam in use. Visible and near-infrared laser wavelengths pass through the cornea, lens, and vitreous humor of the eye, and are absorbed into the retina. A direct exposure can cause permanent blindness, but even scattered forms of radiation may be focused by the lens up to 100,000 times its power. The damage may be painless at first, but may cause loss of vision over a period of time. Additionally, any windows should be covered with an appropriate laser shield to assure that there is no reflection of the beam through the window.

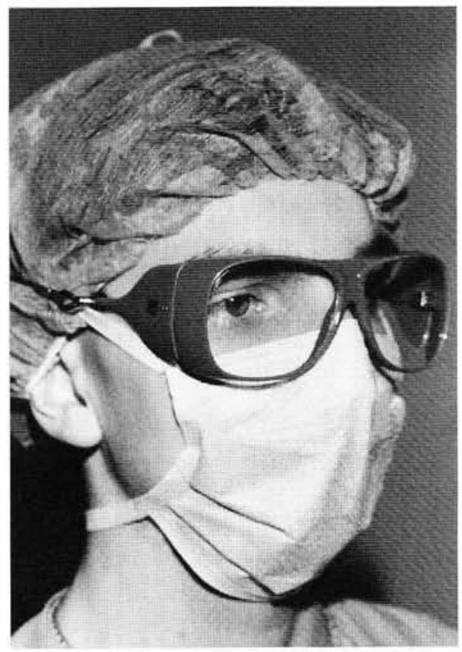

Figure 14: Typical eye protection.

Warning signs must be posted on all entrances to the operating room when the laser is in use (Fig. 15). Additionally, flammable and explosive material including alcohol, solvents, and certain topical anesthetics should not be used in the presence of lasers.

All laser equipment is equipped with a key switch to prevent unauthorized use of the laser. The key should not be stored with the laser, but should be made available only to those who have been appropriately trained in the use of the laser.

A nurse or laser technician should be responsible for controlling the laser panel during surgery, and should place the laser on stand-by when the surgeon is temporarily suspending its use. The laser should be placed in a containing device to prevent the potential igniting of a drape when it comes in contact with the hot laser tip.

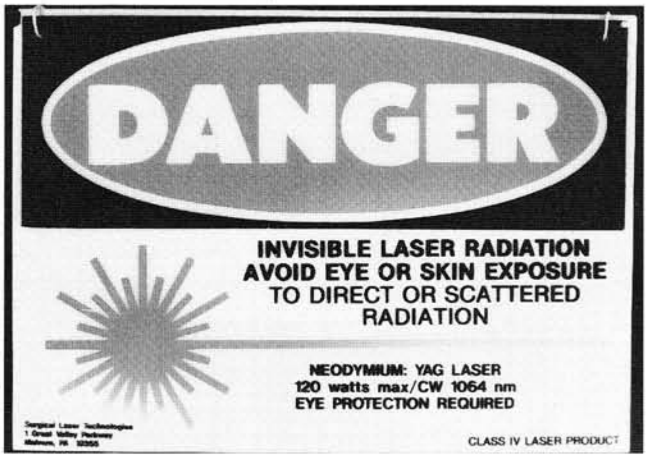

Figure 15: Typical warning sign indicating laser procedure in progress.

The ND:YAG laser is activated by either a hand piece or foot pedal. It is important to activate the laser only when the tip is in contact with tissue. The sapphire tip or probe of the laser can be damaged or disintegrate due to the high temperature produced. When using the laser, the foot pedal should be isolated from any other pedals (i.e. electrocautery) to avoid accidental discharge of the laser.

The laser plume is smoke generated by vaporizing tissue when using the laser. Class 4 lasers such as the ND:YAG release noxious airborne contaminants that can cause lacrimation, nausea, abdominal cramping, and vomiting. Additionally, research has identified bacteria, viruses, and cellular pathology present in the smoke generated from laser surgery. The effects of breathing the plume for long periods of time is not well documented. Therefore, a smoke evacuation system should be used to rapidly remove the plume from the operating room (Fig. 16).

There are several organizations involved in laser surgery which may be of interest to the surgeon performing laser surgery. These organizations include The American National Standards Institute (ANSI), Occupational Health and Safety Administration (OSHA), Food and Drug Administration (FDA), and the Center for Devices in Radiological Health (CDRH). Additionally, many states have organizations that are concerned with specific state regulations and requirements.

Figure 16: Commonly used smoke evacuation system.

CLINICAL APPLICATIONS

Over the past two-and-a-half years, the author has performed over 1350 laser procedures on over 250 patients involving forefoot, rearfoot, ankle, and lower leg surgery. The power density setting on the laser ranged from 12,000 to 30,000 (1,000 to 25,000 watts per cm2). In more delicate procedures, such as a neurolysis or neuroma surgery, the power density was decreased to 6,000-10,000 watts per cm2. Both frosted and non-frosted sapphire tips were used. Non-frosted tips are applicable for more precise dermal laser dissection, when energy is focused at the tip of the laser scalpel, particularly for skin incisions or dissection where increased cutting power is necessary. The use of the non-frosted, or cutting scalpel tip is advantageous in skin incisions, and incisions involving capsular dissection surrounding osseous structures. The frosted tip is used for subcutaneous dissection because of its coagulation ability. The frosted tips are also used for higher power density settings, primarily for subcutaneous dissections, where significant coagulation is desired during the dissection process. This provides a great benefit in decreasing postoperative pain and edema by controlling hemostasis without the use of tourniquets.

The skin incision is typically made with a conventional number 10 blade. This initial skin incision is carried to the superficial level of the dermis, followed by dissection utilizing the ND:YAG laser with a frosted tip at a setting of 10,000-14,000 watts per cm2. The dissection is continued, utilizing linear strokes in the conventional proximal to distal fashion. Thorough intra-operative lavage with sterile water is important. Control of the thermal effect on the tissue is monitored by palpation. In many cases, the complete surgical procedure can be performed with minimal use of sharp dissection, by combining the laser with blunt finger dissection and the use of surgical scissors. This is of importance due to the potential for exposure to blood-borne infections (Hepatitis or HIV) through accidental lacerations.

Dissection of bone is primarily performed with the cold steel technique due to the potential adverse thermal effect of the laser on the small periosteal arteries and blood supply to the bone. During soft tissue dissection, the surgeon allows the soft tissues to undergo periods of thermal relaxation by removing the laser and irrigating with copious amounts of sterile water. This is also effective in preventing the adjacent tissues from being thermally injured, which may result in periostitis or capsulitis in the small joints of the forefoot.

In podiatric surgery, the full potential of the ND:YAG laser is utilized on soft tissue dissection rather than on more dense structures in the foot. Dissection through capsule and tendon structures can cause a thermal effect, leading to charring, eventual fibrosis, and extensive scarring.

Following laser surgery, patients have reported decreased swelling thus effecting the postoperative course with earlier ambulation and return to work. These findings are primarily subjective, based on a postoperative comparison of patients who underwent laser surgery on one foot and cold steel surgery on the opposite foot. The importance of further research, utilizing the research method with randomization, will assure future studies with more validity. It is the author's opinion that no final conclusions can be made from the last two-and-a-half years of investigations until a more intensive investigative study is completed. It is hoped that this paper will stimulate interest in the use of laser technology in podiatric surgery, and aid in developing a research protocol to determine the effectiveness of this new technology.

COMPLICATIONS

It is important that both the surgeon and patient have realistic expectations as to the desired effects of the surgery, and also be aware of the potential complications. Laser surgery due to its nature and physics, has potential complications which may include hyperthermal injury effects such as periostitis, neurothermal shutdown of a peripheral nerve, excessive postoperative edema, hematoma complicated by infection, or generalized irritation and inflammation due to excessive thermal effects. The patient should be informed of the potential complications inherent to laser surgery. In many instances, the patient may be under the false assumption that lasers provide painless surgery. Additionally, the patient may have the misconception that the entire procedure will be performed by laser, however, current laser technology does not provide lasers of sufficient high density to perform osseous surgery without any thermal injury to the bone and adjacent structures.

Recent developments with the Holmium laser have demonstrated its use in a liquid medium during arthroscopic techniques. The adverse thermal effect is prevented in these cases, since it is utilized in a liquid media during arthroscopic dissection. This technique had demonstrated great effectiveness in ankle arthroscopy techniques involving removal of osteophytic impingment lesions on the tibia and talus, debridement of osteochondral fractures, partial synovectomy, partial fracture debridement, and chondroplasty. The Holmium and other powerful laser systems are now under investigation at the Podiatry Institute for their application in surgery. The importance of proper training of the surgeon is emphasized in utilizing various laser technology as an adjunctive tool to the surgeon.

GLOSSARY OF LASER TERMS AND CONCEPTS

ABLATION: Volume removal of tissue by vaporization.

ABSORPTION: Uptake of light energy by tissue, converting it into heat.

ACTIVE MEDIUM: (Laser Medium) the material used to emit the laser light.

AIMING BEAM: A HeNe laser (or other light source) used as a guide light. Used coaxially with infrared or other invisible light.

AMPLITUDE: The maximum height of a wave. Implies power.

ARGON LASER: A laser in which argon gas is used as a laser medium. It emits blue/green light at 488 and 515nm.

BEAM: A collection of rays that may be parallel, divergent, or convergent.

CARBON DIOXIDE LASER: (CO_2) molecule used as a laser medium. Emits far infrared light at 10600nm.

COAGULATION: Destruction of tissue by heat without physically removing it.

COHERENCE: All of the waves of the electromagnetic radiation are exactly in step (phase) with each other in both space and time.

COMBINER MIRROR: The mirror in a laser which combines two or more wavelengths into a coaxial beam, i.e. CO2 and HeNe beams.

CONTINUOUS WAVE: (CW) constant, steady state delivery of laser power.

COLLIMATION: Ability of the laser beam to not spread (low divergence) with distance.

DOSIMETRY: Measuring the amount (joules) and intensity (watts/cm2) of light delivered to tissue.

ELECTRON: Negatively charged particle of an atom.

ELECTROMAGNETIC SPECTRUM: The span of frequencies (wavelengths) considered to be light-from radio and TV waves to gamma and cosmic rays.

ENERGY: Expressed in joules (watts-seconds).

ENERGY SOURCE: High voltage electricity or intense flashes of light used to excite laser medium.

EXCIMER LASER: A laser in which a mixture of rare gases and halogens is the active medium. The mixture of these gases determine the exact ultraviolet wavelength. Wavelengths range from 157-353.

EXCITATION: Energizing a material into a state of population inversion.

FOCAL POINT: That distance from the focusing lens where the laser beam has the smallest spot diameter and hence greatest intensity.

HELIUM-NEON LASER: A laser in which a mixture of helium and neon gases is the active medium. A HeNe laser is used as the red "aiming beam" for infrared lasers.

Ho:YAG LASER: A laser in which a combination of holmium, yttrium, aluminum, and garnet is the solid active medium. It produces a near infrared radiation at 2100nm.

IMPACT SIZE: The size crater or width of incision left by a laser impact.

IONIZING RADIATION: Radiation commonly associated with x-ray, that is of a high enough energy to cause DNA damage with no direct, immediate thermal effect. Contrasts with non-ionizing radiation of surgical lasers.

IRRADIANCE: See Power density.

JOULE: A unit of energy. Laser powers are sometimes described in joules per second. A power of 1 joule per second is known as 1 watt and is the rate of energy delivery.

KTP: Potassium titanyl phosphate. A crystal used to change the wavelength of a Nd:Yag laser from 1060nm (infrared) to 532nm (green).

LASER: Light amplification by the stimulated emission of radiation. A device that produces intense beams of pure colors of light.

LASER MEDIUM: (Active medium) material used to emit the laser light and for which the laser is named. Any selected substance capable of giving rise to laser light.

MICRON: A measurement. One millionth of a meter.

MICROPROCESSOR: A digital chip (computer) that operates and monitors some lasers.

MODE: A term used to describe how the power of a laser beam is distributed within the geometry of the beam. Also used to describe the operating mode of a laser such as continuous or pulsed.

MONO-CHROMATICITY: Waves are monochromatic when they are all of the same wavelength (color).

NANOMETER: Abbreviated nm - a measurement of length. One nm equals 10 meters, and is the usual measure of light wavelength. Visible light ranges from about 400nm in the purple to about 750nm in the deep red.

NANO-SECOND: 10 (one billionth) of a second. Longer than a picosecond or femtosecond, but shorter than a microsecond. Associated with Q-switched ophthalmic Nd:YAG lasers.

NEODYMIUM: The rare earth element that is the active element in a Nd:YAG laser.

Nd:YAG LASER: Neodymium: yttrium aluminum garnet. A mineral crystal used as a laser medium to produce 1060nm light.

OPTICAL CAVITY: Space in between the laser mirrors where lasing action occurs.

PHOTO-COAGULATION: Tissue coagulation caused by light (laser).

PHOTON: A bundle of energy emitted in the form of light by excited atoms or molecules. The basic particle of light.

POWER: The rate of energy delivery expressed in watts (joules per second).

POWER DENSITY: (Irradiance) the amount of energy concentrated into a spot of particular size. It is expressed in watts per square centimeter and is the brightness of the spot.
WATTS x TIME ÷ SPOT SIZE = POWER DENSITY

PLUME: A bundle of energy emitted in the form of light by excited atoms or molecules.

PULSE: A discontinuous burst of laser as opposed to a continuous beam. A true pulse achieves higher peak powers than that attainable in a continuous wave output-usually pulsed in microseconds or shorter.

RESONATOR: A part of the laser that houses the principle laser components (energy source, lasing medium, parallel mirrors).

SPONTANEOUS EMISSION: A process by which a laser's energy source causes the atoms of its laser medium to become excited and emit a photon of laser energy.

THERMAL EFFECT: Laser energy absorption in tissue resulting in heating of the tissue in the target area.

THERMAL RELAXATION TIME: The rate at which a structure can conduct heat. When pulse times of laser are shorter than the time required for heat to spread out of a target, the heat damage will be confined to that target.

TRANSMISSION: The passing of electromagnetic radiation through a medium.

VAPORIZATION: The conversion of a solid or liquid into a vapor by the application of laser energy.

WATT: A unit of power. One watt is equivalent to one joule per second.

WAVE-LENGTH: The distance from crest to crest in an electromagnetic wave. A laser's wavelength is determined by its specific laser medium and is measured in nanometers.

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