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Dent Clin N Am 48 (2004) 751–770

THE DENTAL CLINICS OF NORTH AMERICA

Fundamentals of dental lasers: science and instruments

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In 1960, Theodore Maiman [1], a scientist with the Hughes Aircraft Corporation, developed the first working laser device, which emitted a deep red-colored beam from a ruby crystal. During the next few years, dental researchers studied possible applications of this visible laser energy. Dr Leon Goldman [2], a dermatologist who had been experimenting with tattoo removal using the ruby laser, focused two pulses of that red light on a tooth of his dentist brother in 1965. The result was painless surface crazing of the enamel.

Studies in the 1970s and 1980s turned to other devices, such as CO_2 and neodymium YAG (Nd:YAG), which were thought to have better interaction with dental hard tissues. The medical community in the mid to late 1970s had begun to incorporate lasers for soft-tissue procedures, and oral surgeons added the technology in the early 1980s. Frame [3], Pecaro [4], and Pick [5] cited the benefits of CO_2 laser treatment of oral soft-tissue lesions and periodontal procedures. A portable tabletop model was made available in 1987, and 2 years later Myers and Myers [6] received the US Food and Drug Administration's permission to sell a dedicated dental laser, a Nd:YAG device. Since that time, numerous instruments have been made available for use in dental practice, and more are being developed.

The clinician must be familiar with the fundamentals of laser physics and tissue interaction so that the proper laser device is used to obtain the treatment objective safely and effectively. This article features topics of laser science, machine characteristics, and tissue interaction that provide the foundation for the many applications of the use of lasers in dentistry described in subsequent articles.

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doi:10.1016/j.cden.2004.05.003

Basic laser science

The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. A study of each of these words offers an understanding of the basic principles of how a laser operates.

Light

Light is a form of electromagnetic energy that behaves as a particle and a wave. The basic unit of this energy is called a photon [7]. Laser light and ordinary light are significantly different. Ordinary light produced by a table lamp, for example, is usually a white diffused glow, although it is the sum of the many colors of the visible spectrum—violet, blue, green, yellow, orange, and red. You can use a prism to separate the individual colors in the same way that raindrops break up sunlight into the colors of a rainbow. Laser light is one specific color, a property called monochromacity; in dental applications that color may be visible or invisible. Laser light possesses three additional characteristics: collimation, coherency, and efficiency.

Collimation refers to the beam having specific spatial boundaries, which insures that there is a constant size and shape of the beam emitted from the laser cavity. A dental x-ray machine produces radiation with this property.

Coherency means that the light waves produced in the instrument are all the same. They are all in phase with one another and have identical wave shapes; that is, all the peaks and valleys are equivalent.

The clinically useful feature of laser light is efficiency. Using the table lamp as an example, a large amount of heat is produced as a by-product of illumination. A 100-watt light bulb produces about 20 watts of luminescence and approximately 80 watts of invisible radiant energy that warms the area surrounding it but does not provide light; however, 2 watts of Nd:YAG laser light provides the thermal energy to precisely incise a gingival papilla [8].

There are three measurements that can define the wave of photons produced by a laser. The first is velocity, which is the speed of light. The second is amplitude, which is the total height of the wave oscillation from the top of the peak to the bottom on a vertical axis. This is an indication of the amount of intensity in the wave: the larger the amplitude, the greater the amount of useful work that can be performed. The third property is wavelength, which is the distance between any two corresponding points on the wave on the horizontal axis. This is measurement of physical size, which is important in determining how the laser light is delivered to the surgical site and to how it reacts with tissue. Wavelength is measured in meters, and, for the wavelengths used in dentistry, smaller units of this measurement are used: microns (10^{-6} m) or nanometers (10^{-9} m). A property of waves that is related to wavelength is frequency, which is the measurement of the number of wave oscillations per second. Frequency is inversely proportional to wavelength: the shorter the wavelength, the higher the frequency, and vice versa.

Amplification

Amplification is part of a process that occurs inside the laser. Identifying the components of a laser instrument is useful in understanding how light is produced.

An optical cavity is at the center of the device. The core of the cavity is comprised of chemical elements, molecules, or compounds and is called the active medium. Lasers are generically named for the material of the active medium, which can be a container of gas, a crystal, or a solid-state semiconductor. There are two gaseous active medium lasers used in dentistry: argon and CO_2. The remainder that are available are solid-state semiconductor wafers made with multiple layers of metals such as gallium, aluminum, indium, and arsenic or solid rods of garnet crystal grown with various combinations of yttrium, aluminum, scandium and gallium and then doped with the elements of chromium, neodymium, or erbium. There are two mirrors, one at each end of the optical cavity, placed parallel to each other.

Surrounding this core is an excitation source, either a flash lamp strobe device or an electrical coil, which provides the energy into the active medium. A cooling system, focusing lenses, and other controls complete the mechanical components (Fig. 1).

Stimulated emission

The term ‘‘stimulated emission’’ has its basis in the quantum theory of physics, introduced in 1900 by the German physicist Max Planck [9] and

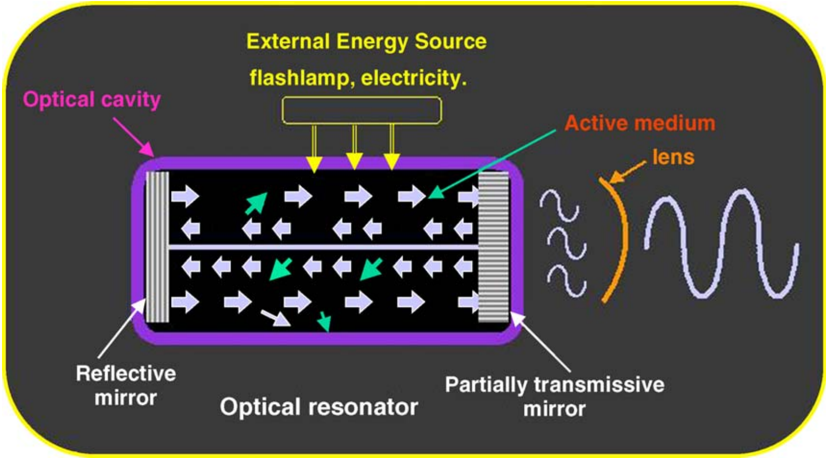

Fig. 1. The basic components of a laser. The excitation source provides energy so that stimulated emission will occur within the active medium. The photons are then amplified by the mirrors and emerge as laser light.

further conceptualized as relating to atomic architecture by Niels Bohr [10], a physicist from Denmark. A quantum, the smallest unit of energy, is absorbed by the electrons of an atom or molecule, causing a brief excitation; then a quantum is released, a process called spontaneous emission. This quantum emission, also termed a photon, can be of various wavelengths because there are several electron orbits with different energy levels in an atom. Incandescent light is produced in this manner: Electrical energy energizes the tungsten filament of a household lamp, causing it to glow. Albert Einstein [11] theorized that an additional quantum of energy traveling in the field of the excited atom that has the same excitation energy level would result in a release of two quanta, a phenomenon he termed stimulated emission. This process would occur just before the atom could undergo spontaneous emission. The energy is emitted, or radiated, as two identical photons, traveling as a coherent wave (Fig. 2).

These photons are able to energize more atoms, which further emit additional identical photons, stimulating more surrounding atoms. If the conditions are right, a population inversion occurs, meaning that a majority of the atoms of the active medium are in the elevated rather than the resting state. There must be a constant supply of energy, called a pumping mechanism, to maintain this excitation.

The mirrors at each end of the active medium reflect these photons back and forth to allow further stimulated emission, and successive passes through the active medium increase the power of the photon beam: This is the process of amplification. There is some heat generated in the process, and the optical cavity must be cooled. The parallelism of the mirrors insures that the light is collimated. One of the mirrors is selectively transmissive, allowing light of sufficient energy to exit the optical cavity.

Radiation

Radiation refers to the light waves produced by the laser as a specific form of electromagnetic energy. The electromagnetic spectrum is the entire

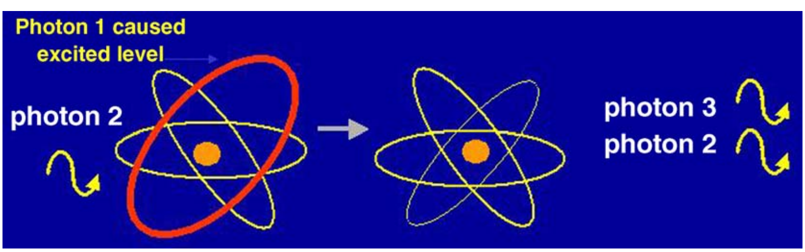

Fig. 2. Stimulated emission. Photon 2 is an additional quantum of energy that enters the field of the already excited atom. There is emission of photon 3, and the atom returns to its resting state. Photons 2 and 3 are identical, and this is the beginning of laser light.

collection of wave energy ranging from gamma rays, whose wavelength are about 10^{-12} m, to radio waves, whose wavelength can be thousands of meters. The very short wavelengths, those below approximately 300 nm, are termed ionizing. This term refers to the fact that higher-frequency (smaller wavelength) radiation has a large photon momentum, measured in electron volts per photon [12]. This higher photon energy can deeply penetrate biologic tissue and produce charged atoms and molecules. Wavelengths larger than 300 nm have less photon energy and cause excitation and heating of the tissue with which they interact. All available dental laser devices have emission wavelengths of approximately 0.5 μm (or 500 nm) to 10.6 μm (or 10,600 nm) (Fig. 3). They are therefore within the visible or the invisible infrared nonionizing portion of the electromagnetic spectrum and emit thermal radiation. The dividing line between the ionizing (ie, the cellular DNA mutagenic portion of the spectrum) and the nonionizing portion is on the junction of ultraviolet and visible violet light.

In summary, a laser consists of a lasing medium contained within an optical cavity, with an external energy source to maintain a population inversion so that stimulated emission of a specific wavelength can occur, producing a monochromatic, collimated, and coherent beam of light.

Terminology

All of the laser instruments used in dentistry feature parameters that are adjustable by the clinician. Each wavelength has photon energy. The laser light photons produce a tissue effect, known in basic physics as work. Energy is the ability to perform work and is expressed as joules or millijoules. Power is the measurement of the work completed over time

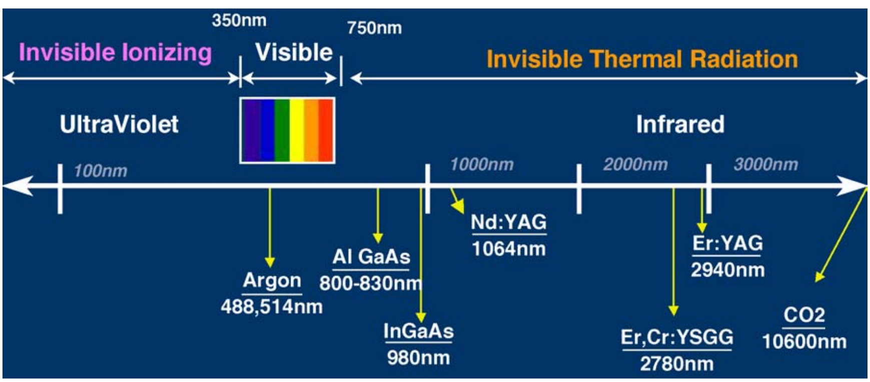

Fig. 3. A portion of the electromagnetic spectrum showing dental laser wavelengths being used for treatment.

and is measured in watts. One watt equals 1 joule delivered for 1 second. One or both of these quantities can be modulated on each device. The "average power" is the power that affects the tissue on a sustained basis over a period of time. Some lasers produce multiple pulses of light in 1 second, which can be selected on certain instruments. "Pulse duration" defines the emission length of time of an individual pulse. Also known as pulse width, pulse duration is measured in seconds, although some lasers deliver short pulses of a few ten thousandths of a second. The word "hertz" defines pulses per second. For pulsed lasers, average power is the product of the energy per pulse multiplied by hertz. Each pulse of laser light can have a much higher peak power, which is numerically expressed as the energy per pulse divided by the pulse duration. The "beam diameter" is determined by the delivery system, explained below, and interacts with the target spot on the tissue. One can express the concentration of photons in a unit area in power density or energy density, using watts or joules per square centimeter, respectively. Energy density is also known as "fluence."

Laser delivery systems

The coherent, collimated beam of laser light should be delivered to the target tissue in a manner that is ergonomic and precise. There are two delivery systems used in the available North American dental lasers. One is a flexible hollow waveguide or tube that has an interior mirror finish. The laser energy is reflected along this tube and exits through a handpiece at the surgical end with the beam striking the tissue in a noncontact fashion. An accessory tip of sapphire or hollow metal can be connected to the end of the waveguide for contact with the surgical site.

The second delivery system is a glass fiber optic cable. This cable can be more pliant than the waveguide, has a corresponding decrease in weight and resistance to movement, and is usually smaller in diameter (some soft tissue lasers have optic fibers with sizes ranging from 200–600 μm). Although the glass component is encased in a resilient sheath, it can be fragile and cannot be bent into a sharp angle. The fiber fits snugly into a handpiece with the bare end protruding or, in the case of the erbium family of lasers, with an attached sapphire or quartz tip. This fiber system can be used in contact or noncontact mode. Most of the time it is used in contact fashion, directly touching the surgical site.

All conventional dental instruments, hand or rotary, physically touch the tissue being treated, giving the operator instant feedback. Dental lasers can be used in contact or out of contact. Clinically, a laser used in contact can provide easy access to otherwise difficult-to-reach areas of tissue. For example, a fiber tip can be used around the lining of a periodontal pocket to remove small amounts of granulation tissue. When used out of contact, the beam is aimed a few millimeters away from the target. This modality is useful for following various tissue contours, but the loss of tactile sensation demands that the surgeon pays close attention to the tissue interaction with the laser energy. All the invisible dental lasers are equipped with a separate aiming beam, which can be laser or conventional light. The aiming beam is delivered coaxially along the fiber or waveguide and shows the operator the spot where the laser energy will be focused.

In either modality, lenses within the laser instrument focus the beam. With the hollow waveguide, there is a spot of a specific diameter where the beam is in sharp focus and where the energy is the greatest. That spot, called the focal point, should be used for incisional and excisional surgery. For the optic fiber and accessories, the focal point is at or near the tip, which has the greatest energy. In either case, the beam becomes divergent and defocused as the handpiece is moved away from the focal point. At a small divergent distance, the laser light can cover a wider area, which is useful in achieving hemostasis. At a greater distance, the beam looses its effectiveness because the energy dissipates, with a proportional decrease in power density.

Lasers with shorter emission wavelengths, such as argon, diode, and Nd:YAG, can be designed with small, flexible glass fibers. The Er,Cr:YSGG and Er:YAG devices present challenges to fiber manufacturing because their wavelengths are large and do not easily fit into the crystalline molecules of the conducting glass. Additionally they are highly absorbed into water, so a special and costly fiber design with a structure of minimal hydroxyl content, incorporating peripheral cooling air and water spray for the handpiece, is necessary. The largest dental wavelength, CO_2, is beyond the transmission window of current fiber optic technology and has to be conducted in a hollow tube.

Laser emission modes

The dental laser device can emit the light energy in two modalities as a function of time, constant on or pulsed on and off. The pulsed lasers can be further divided into two distinctive ways in which the energy is delivered to the target tissue. Thus, three different emission modes are described.

The first is continuous wave, meaning that the beam is emitted at only one power level for as long as the operator depresses the foot switch. The second is termed gated-pulse mode, meaning that there are periodic alternations of the laser energy, much like a blinking light. This mode is achieved by the opening and closing of a mechanical shutter in front of the beam path of a continuous wave emission. All surgical devices that operate in continuous wave have this gated pulsed feature. One variation of this type of pulsing is the superpulsed mode, which significantly shortens the pulse width to <50 milliseconds. Peak powers of about 10 times that of continuous wave power measurements are produced, and charring of the tissue can be reduced.

The third mode is termed free-running pulsed mode, sometimes referred to as "true pulsed." This emission is unique in that large peak energies of laser light are emitted for a short time span, usually in microseconds, followed by a relatively long time in which the laser is off. For example, a free-running pulsed laser with a pulse duration of 100 microseconds with pulses delivered at 10 per second means that the energy at the surgical site is present for 1/1000 of a second and absent for the remaining 99.9% of that second. Free-running pulsed devices have a rapidly strobing flashlamp that pumps the active medium. The timing of this emission is computer controlled, not mechanically controlled as in a gated pulse device. With each pulse, high peak powers in hundreds or thousands of watts are generated. However, because the pulse duration is short, the average power that the tissue experiences is small. Free-running pulsed devices do not have a continuous wave or gated pulsed output.

Medical and scientific laser instruments are available whose pulse durations are in the nanosecond (one billionth of a second) and picosecond (one trillionth of a second) and smaller range. These can generate tremendous peak powers, but the calculated pulse energies are small, allowing increased surgical precision. Some similar instruments can be controlled to emit a single pulse.

The important principle of any laser emission mode is that the light energy strikes the tissue for a certain length of time, producing a thermal interaction [13]. If the laser is in a pulsed mode, the targeted tissue has time to cool before the next pulse of laser energy is emitted. In continuous wave mode, the operator must cease the laser emission manually so that thermal relaxation of the tissue may occur.

Thin or fragile soft tissue, for example, should be treated in a pulsed mode, so that the amount and rate of tissue removal is slower, but the chance of irreversible thermal damage to the target tissue and the adjacent nontarget tissue is minimal. Longer intervals between pulses can also help to avoid the transfer of heat to the surrounding tissue. In addition, a gentle air stream or an air current from the high volume suction aids in keeping the area cooler. Similarly, when using hard-tissue lasers, a water spray helps to prevent microfracturing of the crystalline structures and reduces the possibility of carbonization. Conversely, thick, dense, fibrous tissue requires more energy for removal, and, for the same reason, dental enamel with its higher mineral content requires more ablation power than softer, more aqueous caries. In either case, if too much thermal energy is used, healing can be delayed, and increased postoperative discomfort can occur.

Laser energy and tissue temperature

The principle effect of laser energy is photothermal (ie, the conversion of light energy into heat) [13]. This thermal effect of laser energy on tissue depends on the degree of temperature rise and the corresponding reaction of the interstitial and intracellular water. The rate of temperature rise plays in important role in this effect and is dependent on several factors, such as cooling of the surgical site and the surrounding tissue's ability to dissipate the heat. The various laser parameters used for the procedure are also important, such as the emission mode, the power density, and the time of exposure. As the laser energy is absorbed, heating occurs (Table 1).

The first event, hyperthermia, occurs when the tissue is elevated above normal temperature but is not destroyed. At temperatures of approximately 60°C, proteins begin to denature without any vaporization of the underlying tissue. The tissue whitens or blanches, which can be seen when an egg white's albumin changes from clear to milky during cooking. This phenomenon is useful in surgically removing diseased granulomatous tissue because if the tissue temperature can be controlled, the biologically healthy portion can remain intact. Coagulation refers to the irreversible damage to tissue, congealing liquid into a soft semi-solid mass. This process produces the desirable effect of hemostasis, by the contraction of the wall of the vessel.

Soft tissue edges can be "welded" together with a uniform heating to 70°C to 80°C where there is adherence of the layers because of stickiness due to the collagen molecule's helical unfolding and intertwining with adjacent segments. When the target tissue containing water is elevated to a temperature of 100°C, vaporization of the water within occurs, a process also called ablation. There is a physical change of state; the solid and liquid components turn into vapor in the form of smoke or steam. Because soft tissue is composed of a high percentage of water, excision of soft tissue commences at this temperature. The apatite crystals and other minerals in dental hard tissue are not ablated at this temperature, but the water component is vaporized, and the resulting jet of steam expands and then explodes the surrounding matter into small particles. This mixture of steam and solids is then suctioned away. This micro-explosion of the apatite crystal is termed "spallation."

If the tissue temperature continues to be raised to about 200°C, it is dehydrated and then burned in the presence of air. Carbon, as the end product, absorbs all wavelengths. Thus, if laser energy continues to be applied, the surface carbonized layer absorbs the incident beam, becoming

Table 1
Target tissue effects in relation to temperature

Tissue temperature (°C)	Observed effect
37–50	Hyperthermia
60–70	Coagulation, protein denaturation
70–80	Welding
100–150	Vaporization, ablation
>200	Carbonization

a heat sink and preventing normal tissue ablation. The heat conduction causes a collateral thermal trauma to a wide area.

Laser–tissue interaction

Laser light can have four different interactions with the target tissue, depending on the optical properties of that tissue. Dental structures have complex composition, and these four phenomena occur together in some degree relative to each other.

The first and most desired interaction is the absorption of the laser energy by the intended tissue. The amount of energy that is absorbed by the tissue depends on the tissue characteristics, such as pigmentation and water content, and on the laser wavelength and emission mode. Tissue compounds called chormophores preferentially absorb certain wavelengths (Fig. 4) [14]. Hemoglobin, the molecule that transports oxygen to tissue, reflects red wavelengths, imparting color to arterial blood. It therefore is strongly absorbed by blue and green wavelengths. Venous blood, containing less oxygen, absorbs more red light and appears darker. The pigment melanin, which imparts color to skin, is strongly absorbed by short wavelengths. Water, the universally present molecule, has varying degrees of absorption by different wavelengths.

Dental structures have different amounts of water content by weight. A ranking from lowest to highest would show enamel (with 2% to 3%), dentin, bone, calculus, caries, and soft tissue (at about 70%). Hydroxyapatite is

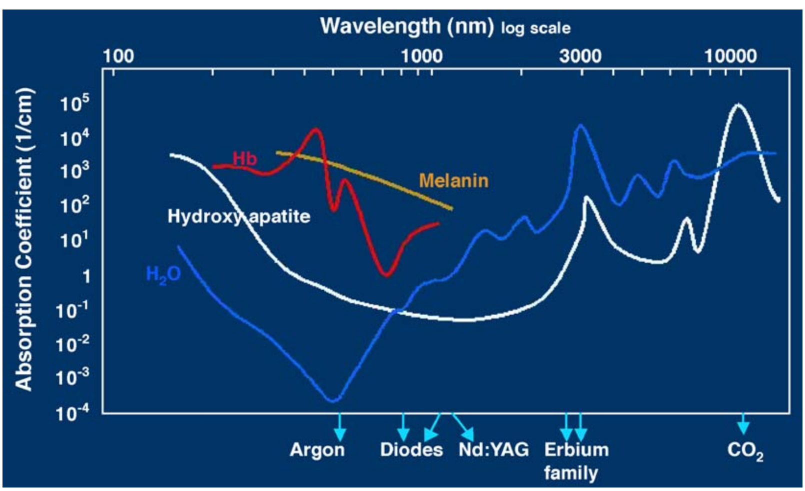

Fig. 4. Approximate absorption curves of different dental compounds by various wavelengths of dental lasers.

the chief crystalline component of dental hard tissues and has a wide range of absorption depending on the wavelength.

In general, the shorter wavelengths (from about 500–1000 nm) are readily absorbed in pigmented tissue and blood elements. Argon is highly attenuated by hemoglobin. Diode and Nd:YAG have a high affinity for melanin and less interaction with hemoglobin. The longer wavelengths are more interactive with water and hydroxyapatite. The largest absorption peak for water is just below 3000 nm, which is at the Er:YAG wavelength. Erbium is also well absorbed by hydroxyapatite. CO_2 at 10,600 nm is well absorbed by water and has the greatest affinity for tooth structure.

The second effect is transmission of the laser energy directly through the tissue with no effect on the target tissue, the inverse of absorption. This effect is highly dependent on the wavelength of laser light. Water, for example, is relatively transparent to the shorter wavelengths like argon, diode, and Nd:YAG, whereas tissue fluids readily absorb the erbium family and CO_2 at the outer surface, so there is little energy transmitted to adjacent tissues. Fig. 5 depicts this interaction by showing relative depth of penetration in water of various wavelengths. The depth of the focused laser beam varies with the speed of movement and the power density. In general, the erbium family acts mainly on the surface, with an absorption depth of approximately 0.01 mm, whereas the 800-nm diodes are transmitted through the tissue to depths up to 100 mm, a factor of 10,000. As another example, the diode and Nd:YAG lasers are transmitted through the lens, iris, and cornea of the eye and are absorbed on the retina.

The third effect is reflection, which is the beam redirecting itself off of the surface, having no effect on the target tissue. A caries-detecting laser device uses the reflected light to measure the degree of sound tooth structure. The reflected light could maintain its collimation in a narrow beam or become more diffuse. The laser beam generally becomes more divergent as the distance from the handpiece increases. However, the beam from some lasers can have adequate energy at distances over 3 m. This reflection can be dangerous because the energy is directed to an unintentional target, such as

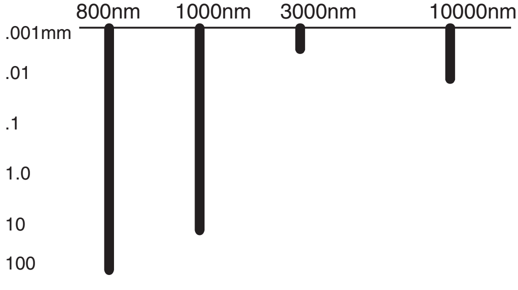

Fig. 5. Relative depth of penetration in millimeters of different wavelengths in water. The vertical scale is logarithmic.

the eyes; this is a major safety concern for laser operation. The safety aspects of laser use are discussed later.

The fourth effect is a scattering of the laser light, weakening the intended energy and possibly producing no useful biologic effect. Scattering of the laser beam could cause heat transfer to the tissue adjacent to the surgical site, and unwanted damage could occur. However a beam deflected in different directions is useful in facilitating the curing of composite resin or in covering a broad area.

Absorption of the laser light by the target tissue is the primary and beneficial effect of laser energy. The goal of dental laser surgery is to optimize these photobiologic effects [15]. Using the photothermal conversion of energy, incisions and excisions with accompanying precision and hemostasis are some of the many advantages of laser devices. There are photochemical effects from laser light that can stimulate chemical reactions (eg, the curing of composite resin) and breaking of chemical bonds (eg, using photosensitized drugs exposed to laser light to destroy tumor cells, a process called photodynamic therapy). A special group of lasers that emit in the ultraviolet ionizing range, the excimers, have enough photon energy to directly break the chemical bond of an organic molecule without any thermal damage [16]. These are being investigated for hard tissue ablation procedures. Certain biologic pigments, when absorbing laser light, can fluoresce, which can be used for caries detection within teeth. A laser can be used with powers well below the surgical threshold for biostimulation, producing more rapid wound healing, pain relief, increased collagen growth, and a general anti-inflammatory effect. The pulse of laser energy into a crystalline structure can produce an audible shock wave, which could explode or pulverize the tissue with mechanical energy. This is an example of the photoacoustic effect of laser light.

To summarize the tissue interaction effect of a particular machine, several factors must be considered. Each laser has common internal parts but different delivery systems and emission modes. The laser wavelength affects certain components of the target tissue; the water content, the color of the tissue, and the chemical composition are all inter-related. The diameter of the laser beam, whether delivered in contact or noncontact with the tissue, creates a certain energy density—the smaller the beam, the greater the energy density. For example, a beam diameter of 200 μm has over twice as much energy density as a beam diameter of 300 μm. The result of using the smaller fiber is greatly increased thermal transfer from the laser to the tissue and a corresponding increase in absorption of heat in that smaller area. The amount of time that the beam is allowed to strike the target tissue affects the rate of tissue temperature rise. That time can be regulated by the repetition rate of the pulsed laser emission mode as well. The amount of cooling of the tissue by the use of a water or air spray also affects the rate of vaporization.

Laser wavelengths used in dentistry

There are several laser manufacturers with various product offerings, and the reader should consult other sources for specific information for current details about companies and their instruments. The marketplace continues to change, and so does the availability of the devices. The following are brief descriptions of laser devices that have dental applications. The lasers are named according to their active medium, wavelength, delivery system, emission mode(s), tissue absorption, and clinical applications. The shortest wavelength is listed first.

Argon

Argon is laser with an active medium of argon gas that is energized by a high-current electrical discharge. It is fiberoptically delivered in continuous wave and gated pulsed modes and is the only available surgical laser device whose light is radiated in the visible spectrum. There are two emission wavelengths used in dentistry: 488 nm, which is blue in color, and 514 nm, which is blue green.

The 488-nm emission is the wavelength needed to activate camphoroquinone, the most commonly used photoinitiator that causes polymerization of the resin in composite restorative materials. The beam divergence of this blue light, when used in a noncontact mode, produces an excessive amount of photons, providing curing energy. Some studies demonstrate some increase in the strength of the laser-cured resin when compared with resin cured with ordinary blue filtered light [17]; moreover, the curing time is significantly shorter than the recommended exposure time of conventional units. The argon laser can also be used with other laboratory and chairside materials, such as light-activated whitening gels and impression materials.

The 514-nm wavelength has its peak absorption in tissues containing hemoglobin, hemosiderin, and melanin; thus, it has excellent hemostatic capabilities. The small-diameter flexible glass fiber is normally used in contact with the surgical target tissue. This fiber is easily maintained and sterilized. The end must have a well-defined edge, called a cleave, which must be inspected and re-cleaved during the procedure. Surgical by-products that accumulate on the fiber must be wiped clean because that debris absorbs the laser energy and affects efficiency. Acute inflammatory periodontal disease and highly vascularized lesions, such as a hemangioma, are ideally suited for treatment by the argon laser [18].

Neither wavelength is well absorbed in dental hard tissues or in water. The poor absorption into enamel and dentin is advantageous when using this laser for cutting and sculpting gingival tissues because there is minimal interaction and thus no damage to the tooth surface during those procedures. Both wavelengths can be used as an aid in caries detection. When the argon laser light illuminates the tooth, the diseased, carious area appears a dark orange-red color and is easily discernible from the surrounding healthy structures [19].

Many dental clinicians use argon laser devices; however, they are not offered for sale in North America because of product line shifts to medical disciplines from the manufacturers.

Diode

Diode is a solid active medium laser, manufactured from semiconductor crystals using some combination of aluminum or indium, gallium, and arsenic. This ‘‘chip’’ of material has the optical resonator mirrors directly attached to its ends, and an electrical current is used as the pumping mechanism. The available wavelengths for dental use range from about 800 nm for the active medium containing aluminium to 980 nm for the active medium composed of indium, placing them at the beginning of the near-infrared portion of the invisible nonionizing spectrum. Each machine delivers laser energy fiberoptically in continuous wave and gated pulsed modes and is used in contact with soft tissue for surgery or out of contact for deeper coagulation.

Similar to the argon instrument, the optic fiber needs to be cleaved and prepared before initial use and during the procedure to ensure the efficient operation. Some clinicians prefer to initiate the end of the fiber with a small amount of carbon pigment and refer to this as a ‘‘hot tip.’’ This method focuses a large amount of laser energy at the contact point and accelerates tissue incisions, but the operator must inspect the tip frequently to avoid it being transformed into a ragged ‘‘branding iron’’ because of the rapid build up of ablated products.

All of the diode wavelengths are highly absorbed by pigmented tissue and are deeply penetrating, although hemostasis is not as rapid as with the argon laser. These lasers are relatively poorly absorbed by tooth structure so that soft tissue surgery can be safely performed in close proximity to enamel dentin and cementum. Also, similar to an argon instrument, the continuous wave emission mode of the diode laser can cause a rapid temperature rise in the target tissue. The clinician should use air and sometimes water to cool the surgical site and to continue to move the fiber around the treatment area. The diode is an excellent soft tissue surgical laser and is indicated for cutting and coagulating gingiva and mucosa and for sulcular debridement [20,21]. The chief advantage of the diode lasers is one of a smaller size, portable instrument.

In addition to the surgical diode lasers, there are other instruments used in dentistry. One manufacturer offers a visible red diode with a wavelength of 655 nm and 1 milliwatt of power (Diodent; Kavo, Lake Zurich, Illinois). This red energy excites fluorescence from carious tooth structure, which is reflected back into a detector in the unit, which analyzes and quantifies the degree of caries [22].

Low-level laser therapy is provided by semiconductor instruments emitting visible and invisible near infrared light energy at powers significantly below any surgical interactive threshold. They can provide biostimulation and pain relief and are discussed in another article in this issue.

Neodynium:YAG

Nd:YAG has a solid active medium, which is a garnet crystal combined with rare earth elements yttrium and aluminum, doped with neodymium ions. This active medium is much different than the semiconductor wafer of the diode laser, and the pumping mechanism is a flashlamp. The available dental models have an emission wavelength of 1064 nm, which is in the invisible near-infrared portion of the electromagnetic spectrum. These instruments operate only in a free-running pulsed mode (a continuous wave model is no longer being manufactured for the dental market), with short pulse durations in the hundreds of microseconds, and feature small flexible bare optic fibers that can contact tissue. The laser energy is highly absorbed by melanin but is less absorbed by hemoglobin than the argon laser and is approximately 90% transmitted through water. Using the high peak powers of a free-running pulse emission with relatively long tissue cooling time, common clinical applications are for cutting and coagulating of dental soft tissues and sulcular debridement [23–25]. The free-running pulse mode also allows the clinician to treat thin or fragile tissue with a greater safety margin of preventing heat buildup in the surrounding area. Nd:YAG laser energy is slightly absorbed by dental hard tissue, but there is little interaction with sound tooth structure, allowing soft tissue surgery adjacent to the tooth to be safe and precise. Pigmented surface carious lesions can be vaporized without removing the healthy surrounding enamel [26].

The Nd:YAG optical fiber needs to be cleaved and cleaned; otherwise, the laser light will rapidly loose its effectiveness. When used in a noncontact, defocused mode, this wavelength can penetrate several millimeters, which can be used for procedures such as hemostasis, treatment of aphthous ulcers, or pulpal analgesia.

Holmium:YAG

The manufacture of the only holmium laser dental instrument ceased several years ago. It contains a solid crystal of yttrium aluminum garnet sensitized with chromium and doped with holmium and thulium ions and is fiberoptically delivered in free-running pulsed mode. The wavelength produced by this laser is 2100 nm, also in the near infrared portion of the invisible nonionizing radiation spectrum. It is absorbed by water 100 times greater than Nd:YAG is, and using high peak powers it can ablate hard, calcified tissue; however, as a soft-tissue instrument it does not react with hemoglobin or other tissue pigments [27]. The holmium laser is frequently used in oral surgery for arthroscopic surgery on the temporomandibular joint and has many medical applications [28].

The erbium family

There are two distinct wavelengths that use erbium, and these two lasers are discussed together because of their similar properties. Erbium, chromium:YSGG (2780 nm) has an active medium of a solid crystal of yttrium scandium gallium garnet that is doped with erbium and chromium. Erbium:YAG (2940 nm) has an active medium of a solid crystal of yttrium aluminum garnet that is doped with erbium. Both of these wavelengths are placed at the beginning of the mid infrared, invisible, and nonionizing portion of the spectrum.

In North America, the delivery systems of Er:YAG instruments are a hollow wave-guide or a fiberoptic bundle, whereas Er,Cr:YSGG only use fiberoptics. Both wavelengths are emitted in a free-running pulsed mode. The technical challenge in building an optic fiber system stems from the fact that the wavelength cannot easily be transmitted along the glass molecules, so the fiberoptic bundle is costly and can be fragile and less flexible than those of argon, diode, or Nd:YAG. The fiber diameter is also much larger and requires an air coolant for proper operation.

At the end of either delivery system, a handpiece and a small-diameter glass tip concentrate the laser energy down to a convenient surgical size, approximately 0.5 μm. Additional air and water spray are provided for dental procedures. These two wavelengths have the highest absorption in water of any dental wavelength and have a high affinity for hydroxyapatite [29–32]. The laser energy couples into the hydroxyl radical in the apatite crystal and into the water that is bound to the crystalline structures of the tooth. The vaporization of the water within the mineral substrate causes a massive volume expansion, and this expansion causes the surrounding material to literally explode away [33]. The free-running pulse mode provides the peak power to facilitate the explosive expansion, and laboratory studies indicate that the pulpal temperature of the treated tooth may decrease by as much as 5°C during laser treatment [34].

Caries removal and tooth preparation are easily accomplished [35]. Additionally, sound tooth structure can be better preserved when the carious material is being ablated [36]; the increased water content in dental caries allows the laser to preferentially interact with that diseased tissue [37,38]. The healthy enamel surface can be modified for increased adhesion of restorative material by exposing it to the laser energy [39]. The current indication for use of these lasers dictates that they not be used for removal of amalgam or other metal. However, the noninteraction with precious metal and fused porcelain allows the practitioner to remove caries surrounding these restorations without any damage.

The natural progression of technology leads to the expansion of osseous surgical techniques and endodontic procedures, and the erbium family of instruments provides the tissue interaction characteristics to perform effective root canal therapy and bone removal.

For endodontics, removal of pulpal tissue and dentin is easily accomplished with these wavelengths [40]. There are three challenges, however. One is to maintain the water spray during the hard-tissue ablation so that the temperature of the target tissue and surrounding structures is kept from being elevated. The second is to design a flexible and durable fiber to conduct the laser energy. The third is more problematic. Most tips are end cutting, and shaping the canal space requires a side-cutting accessory, which is currently under development.

Osseous removal proceeds easily due to this wavelength's affinity for the composition of osseous tissue [41,42]. However, accessibility to the surgical area can be limited with the existing delivery system, and the clinical technique must prevent overheating the tissue. In addition, the volume and pressure of the air spray should be monitored to prevent the possibility of surgical emphysema.

Both lasers can readily ablate soft tissue because of its high water content. In this modality, some clinicians turn off the water spray normally used for hard-tissue procedures and use lower energy settings. The hemostatic ability is limited, however, because only the water on the surface of the blood in the surgical site is vaporized. There is neither deep penetration nor sustained heat to provide rapid vessel shrinkage [43,44].

The advantage of erbium lasers for restorative dentistry is that a carious lesion in close proximity to the gingiva can be treated and the soft tissue recontoured with the same instrumentation. Furthermore, one study showed that tissue retraction for uncovering implants is safe with these wavelengths because there is minimal heat transferred during the procedure [45].

CO_2

The CO_2 laser is a gas-active medium laser that incorporates a sealed tube containing a gaseous mixture with CO_2 molecules pumped via electrical discharge current. The light energy, whose wavelength is 10,600 nm, is placed at the end of the mid-infrared invisible nonionizing portion of the spectrum, and it is delivered through a hollow tube-like waveguide in continuous or gated pulsed mode.

This wavelength is well absorbed by water, second only to the erbium family. It can easily cut and coagulate soft tissue, and it has a shallow depth of penetration into tissue, which is important when treating mucosal lesions, for example. In addition, it is useful in vaporizing dense fibrous tissue. There is rapid tissue interaction. Because this wavelength was one of the earliest used in general medical surgery, there are numerous published papers verifying its efficacy [3–5,46–49].

The CO_2 laser cannot be delivered in a conventional optic fiber. The North American products use a hollow waveguide with a handpiece and accessory tips. The laser energy is conducted through the waveguide and is focused onto the surgical site in a noncontact fashion. The loss of tactile sensation could pose a disadvantage for the surgeon, but the tissue ablation can be precise with careful technique. Large lesions can be treated using a simple back and forth motion; the procedure proceeds quickly because there is no need to touch the tissue. The noncontact mode thus has an advantage when treating movable oral structures, such as the tongue and floor of the mouth. After surgery is completed, many clinicians use a defocused beam to place a biologic bandage called an eschar on the wound surface.

This wavelength has the highest absorption in hydroxyapatite of any dental laser, about 1000 times greater than erbium. Therefore, tooth structure adjacent to a soft-tissue surgical site must be shielded from the incident laser beam; usually a metal instrument placed in the sulcus provides the protection. The continuous wave emission and delivery system technology of CO_2 devices limit hard-tissue applications because carbonization and crazing of tooth structure can occur due to the long pulse duration and low peak powers [50]. However, ongoing research using experimental devices with extremely short pulses shows favorable results for surface modification and strengthening of tooth enamel for increased caries resistance [51].

Summary

The scientific basis and tissue effects of dental lasers have been discussed. It is most important for the dental practitioner to become familiar with those principles and then choose the proper laser(s) for the intended clinical application. Each wavelength and each device has specific advantages and disadvantages. The clinician who understands these principles can take full advantage of the features of lasers and can provide safe and effective treatment.

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