Fundamentals of Lasers in Dentistry: Basic Science, Tissue Interaction, and Instrumentation

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SYNOPSIS

This article describes the fundamentals of laser science and the basic elements of a typical device. The principles of laser-tissue interaction, photo-thermal events, and different absorption characteristics of dental tissues by laser energy are discussed. The clinician should become familiar with these concepts so that the proper dental laser is used to accomplish the treatment objective safely and effectively.

The first laser specifically designed for dentistry was marketed in 1989.[1] In medicine, the technology was first used in 1963, and carbon dioxide (CO_2) lasers were being employed during the 1980s for general and oral surgery.[2-3] Less than ten percent of dentists worldwide own lasers, but there are more than two dozen indications for use for oral procedures. Research studies continue to enumerate new possible clinical applications and unique patient benefits. This article is intended to provide information about the basic science and tissue interaction of dental lasers, and demonstrate examples of clinical use.

BASIC LASER SCIENCE

The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation. Elaboration of each of those words will give an overview of basic laser principles, although they will be taken slightly out of order.

Light

Light is a form of electromagnetic energy that behaves both as a wave and a particle. The basic unit of this energy is called a photon.[4] Normal light and laser energy (or "laser light") are significantly different. Ordinary light, usually appearing white, is the sum of the many colors of the visible spectrum – violet, blue, green, yellow, orange, and red. Laser energy is one specific color, a property called *monochromaticity;* in dental applications that color may be visible or invisible. This energy also possesses a property known as coherency, meaning that the waves produced in the laser instrument are all in phase with one another and have identical shapes when plotted on a graph.

The beam itself is *collimated* (in other words, the rays or beams are all parallel) within the laser instrument. However, a lens system in the aperture focuses the beam into a delivery system and the emitted energy can either continue as a constant diameter or will diverge at a specific angle.

The wave of photons, moving at the speed of light, can be defined by two properties. The first is *amplitude,* which is the total height of the wave oscillation from the top of the peak to the zero line 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 second property is *wavelength,* which is the distance between any two corresponding

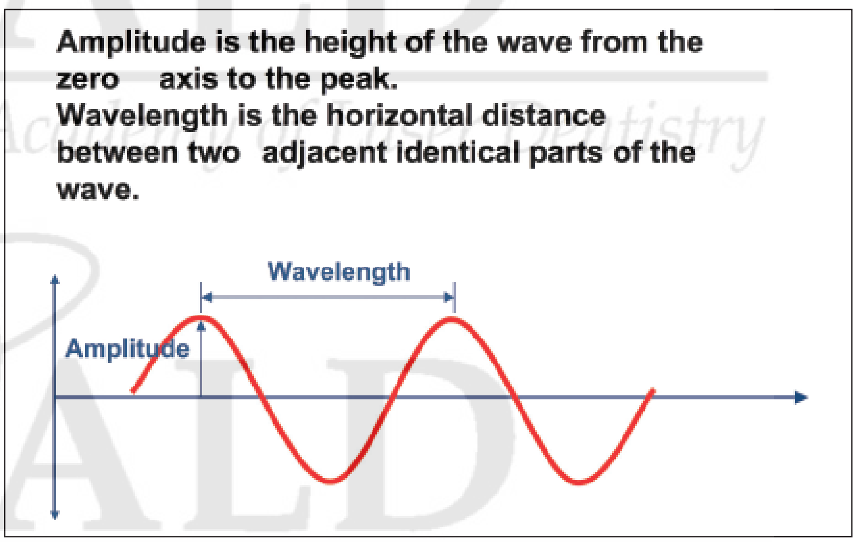

Figure 1: Graphic depiction of amplitude and wavelength

points on the wave on the horizontal axis. Figure 1 graphically depicts both amplitude and wavelength. This is the physical size of the wave, which can be important to how it interacts with tissue. Wavelength is generally measured in meters; but dental lasers use a smaller unit, either a micron (10^{-6} meter) or nanometer (10^{-9} meter).

Stimulated Emission

The German physicist Max Planck[5] introduced quantum theory in 1900 which was further conceptualized as relating to atomic architecture by Niels Bohr,[6] a physicist from Denmark. When a quantum, the smallest unit of energy, is absorbed by the electrons of an atom or molecule, a brief excitation occurs. Since natural order prefers substances to be in a resting state, that quantum is soon released, a process called *spontaneous emission.* The emitted energy packet was previously described as a photon. In 1916 Albert Einstein[7] theorized that an additional photon traveling in the field of the excited atom that has the same excitation energy level would result in a release of two quanta, or coherent wave of two photons, a phenomenon he termed *stimulated emission.*

Amplification

If this process were to continue, more atoms would be energized, more identical photons would be emitted, and further propagation of this stimulatory wave would result. At some point, a population inversion occurs, meaning that a majority of the atoms of the active medium are in the elevated rather than the resting state. A pumping mechanism offering a constant supply of energy is necessary to maintain this excitation.

The photons are reflected back and forth within the active medium to further enhance stimulated emission, and successive passes through the active medium increase the power of and ultimately collimate the photon beam. This is the process of amplification.

Radiation

The laser energy produced in the above model is radiated in a specific form of electromagnetic energy. The entire array of wave energy is described by the electromagnetic spectrum, with a range from gamma rays, whose wavelength are typically less than 10^{-10} m, to radio waves, whose wavelength can be thousands of meters in size.[8] Very short wavelengths below approximately 350 nm are termed ionizing, and can deeply penetrate biologic tissue, produce charged atoms and molecules, and have a mutagenic effect on cellular DNA. Wavelengths greater than 350 nm cause excitation and heating of the tissue with which they interact. The accepted dividing line between ionizing and nonionizing wavelengths is at the junction of ultraviolet and visible violet light on the spectrum. All available dental laser devices are classified as nonionizing because their emission wavelengths exceed 350 nm and are shown in Figure 2.

COMPONENTS OF A LASER

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. These materials, when stimulated, produce specific wavelengths.

The primary gaseous active medium dental laser is carbon dioxide (CO_2). The other available dental lasers have either 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 to which an element, such as chromium, neodymium, or erbium, is added (a process called *doping*). In the garnet and gas lasers, there are two mirrors, one at each end of the optical cavity, placed parallel to each other (Figure 3). The semiconductor lasers are similarly configured,

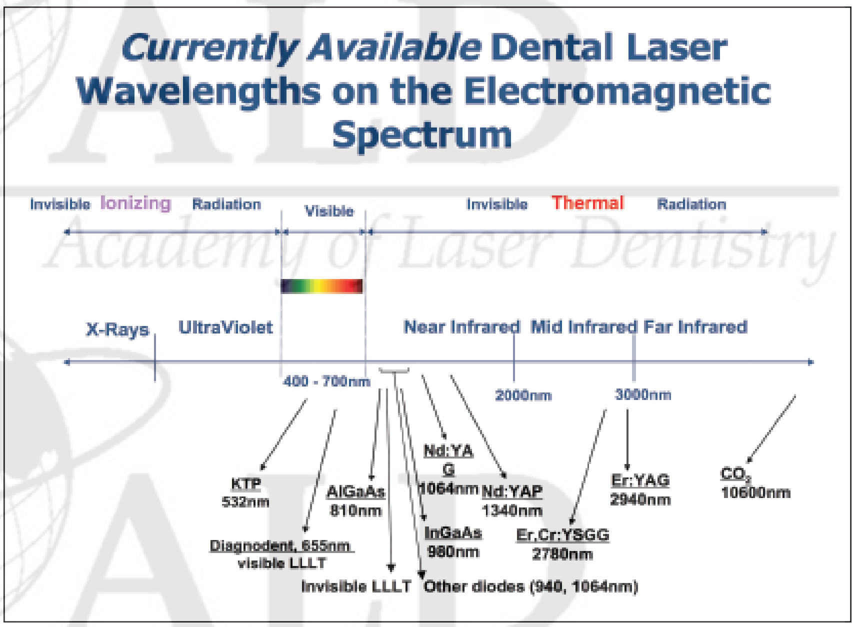

Figure 2: Available dental laser wavelengths presented graphically on a portion of the electromagnetic spectrum

although the active medium is "sandwiched" between silicon wafers which have precisely polished edges of the wafer for reflection. One wafer is positively charged and one is negatively charged; and the discharge of current from one to the other, crossing over the active medium, releases the photons (Figure 4). Surrounding this core is an excitation source, either a flash-lamp strobe device or an electrical field or coil, which provides the energy to the active medium. A cooling system, focusing lenses, and other controls are additional essential components.

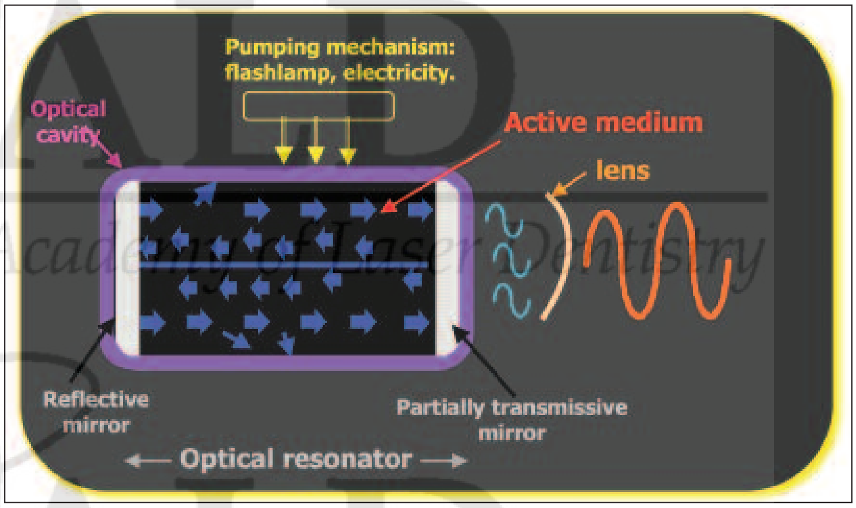

Figure 3: Typical gas or solid laser components in schematic form

TERMINOLOGY

The clinician can adjust many parameters of the laser instrument's emission, except the wavelength, which has its unique photon energy. These photons produce a tissue effect, known in basic physics as *work.* The ability to perform work is termed *energy* and is expressed as Joules or milliJoules. The measurement of the work completed over time is called *power,* and is measured in Watts. One Watt equals 1 Joule delivered for 1 second, and the power can be selected by the operator on each device.

Unless set in a continuous mode (see below), lasers can produce multiple pulses of energy in one second. The length of each pulse, called *pulse width or pulse duration,* can be as short as a few ten-thousandths of a second on certain instruments. The word *hertz* describes pulses per second.

The *average power* is the power that affects the tissue on a sustained basis over a period of time. If the laser is operating in a continuous mode, then the average power is the output power. When the laser is pulsed, the average power is the output power divided by the percentage of the time the laser is emitting. For example, if the laser operates for 0.5 second and then is off for 0.5 second with an output power of 2 Watts, the average power is 1 Watt. If the energy per pulse is known, the average power is the product of that energy multiplied by hertz. For example, 100 milliJoules per pulse at 20 pulses per second equals 2 Watts.

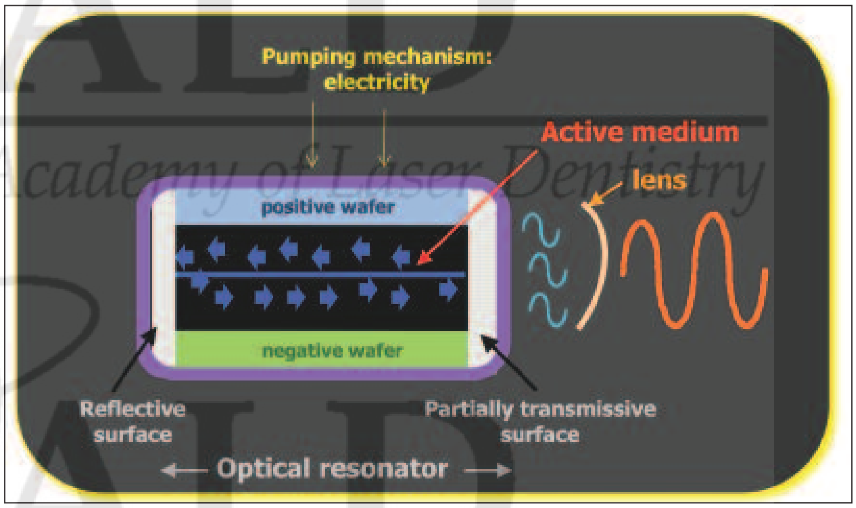

Figure 4: Typical diode laser components

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. For those lasers with millisecond pulse durations, individual pulses of hundreds or thousands of Watts could be produced. For example, a pulse of 100 milliJoules emitted for 1 millisecond has a peak power of 100 Watts.

The actual size of the target spot on the tissue is called the *beam diameter,* which influences the concentration of photons in that area. The term *power density* describes the Watts per square centimeter; *energy density,* expressed in Joules per square centimeter, is also called *fluence.*

LASER OPERATION

There are two basic emission modes for dental lasers – continuous-wave and free-running pulsed.

Continuous wave means that energy is emitted constantly for as long as the laser is activated.

Thermal Effect of Lasers on Soft Tissues

Tissue Temperature (°C)	Observed Effect
> 37	Hyperthermia
> 50	Non-sporulating bacteria inactivated
> 60	Coagulation, Protein denaturation
70-80	Tissue welding
100	Vaporization
> 200	Carbonization

Figure 5: Summary of thermal effects on soft tissue

Carbon dioxide and diode lasers operate in this manner. A gated or superpulsed laser is a variation of continuous-wave and is accomplished with an electronic control and/or a mechanical shutter. This "gating" helps to minimize some of the undesirable residual thermal damage usually associated with continuous-wave devices.

Free-running pulsed mode is produced by a flashlamp, where true pulses – on the order of a few ten-thousandths of a second – emanate from the instrument. Nd:YAG, Nd:YAP, Er:YAG, and Er,Cr:YSGG devices operate as free-running pulsed lasers.

The energy of certain laser wavelengths can be delivered from the laser instrument to the target tissue via flexible, small-diameter glass fibers, which usually directly contact the tissue and are used in KTP, diode, Nd:YAG, and Nd:YAP instruments. Erbium and carbon dioxide devices use more rigid glass fibers, semi-flexible hollow waveguides, or rigid sectional articulated arms. Some of these systems employ additional small quartz or sapphire tips, which attach to the operating handpiece. Other systems are used without contacting the tissue.

In either emission mode, lenses within the laser instrument focus the beam. With hollow waveguides or articulated arms without a contact tip, 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. Conversely, if the beam is not in focus, the energy that is applied to the tissue is lessened; moreover, the beam diverges as it exits the tip, further decreasing the energy.

LASER-TISSUE INTERACTION

The goal of dental laser surgery is to optimize various photobiologic effects.[9] The photothermal conversion of energy permits soft tissue incisions and excisions to be accomplished with accompanying precision and hemostasis, some of the many advantages of laser devices over conventional modalities. Photo-activated disinfection (PAD) is an example of a photochemical effect, known in medicine as *photodynamic therapy.*[10] PAD utilizes a solution of tolonium chloride that, when activated with visible red laser energy, releases a singlet oxygen radical that ruptures cell membranes. Studies show this therapy is effective in helping to disinfect root canals during endodontic therapy.[11] Certain biologic pigments, when absorbing laser light, can fluoresce, a property which can be used for caries detection. 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.[12]

Photothermal Events

The principle effect of laser energy is photothermal (i.e., 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 (Figure 5). The rate of temperature rise plays an 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 that heat. The various laser parameters used for the procedure are also important, such as the emission mode, the power density, and the duration of exposure. As the laser energy is absorbed, heating occurs. If the laser is in a pulsed mode, the targeted tissue has some 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.

The first event, hyperthermia, occurs when the tissue is elevated above normal temperature but is not destroyed. Non-sporulating bacteria are readily inactivated at 50° C.[14]

Proteins begin to denature at temperatures of approximately 60° C, and coagulation occurs.[15] The clinician can utilize laser parameters to keep the tissue temperature in this range and can thus remove diseased granulomatous tissue, destroying those cells without vaporization.[16]

At 70° to 80° C, uniform heating will produce adherence of the layers because of stickiness due to the collagen molecule's helical unfolding and intertwining with adjacent segments, a process sometimes termed tissue welding or anastomosis.[17]

When the target tissue containing water is elevated to a temperature of 100° C, vaporization of the water within occurs and that tissue is ablated.[18] Thus excision of soft tissue can begin at this temperature, but the apatite crystals in dental hard tissue will not be ablated. However, water molecules dispersed throughout mineral structure are vaporized, and the resulting jet of steam expands and then explodes, removing the tooth structure. This water-mediated explosive removal transfers minimal heat to the adjacent tissue.[19]

Continued application of energy will raise the tissue temperature. At about 200° C, dehydration is complete and the tissue carbonizes. 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 a heat sink. Collateral thermal damage can spread rapidly, preventing normal tissue ablation, and causing tissue necrosis.[20]

Laser energy can interact in one of four ways 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.[21]

The first effect is *transmission* of the laser energy directly through the tissue which is the inverse of absorption. Like absorption, this effect is wavelength-dependent. Shorter wavelengths like KTP, diode, and Nd:YAG pass relatively easily through oral soft tissues whereas the water-containing tissue fluids readily absorb the erbium family and CO_2 laser wavelengths at the outer surface, so there is little energy transmitted to adjacent tissues.

The second effect is *reflection,* which is the beam redirecting itself off the surface, having no effect on the target tissue. A reflected laser beam could become dangerous when redirected to an unintentional target such as the eyes. By contrast, a caries-detecting laser device processes reflected light to measure the degree of sound tooth structure.

The third effect is a *scattering* of the laser energy, with a corresponding decrease of that energy. Unwanted damage could occur if the beam is scattered to tissue adjacent to the surgical area. Likewise, some backscattering occurs in short wavelength lasers like diode and Nd:YAG when the incident beam strikes the tissue. However a defocused beam deflected in different directions is useful in covering a broad area when treating an aphthous ulcer.

Absorption, the fourth effect, is the direct opposite of transmission and is the primary and beneficial effect of laser energy. Each wavelength has a unique effect on dental structures because of the specific absorption by one or more chromophores of that particular light energy in the tissue.[22] Some laser wavelengths are absorbed primarily by the chromophores of blood and tissue pigments,[23] while others are absorbed mainly by water as well as "hard" tissue, such as enamel, dentin, and bone (Figure 6).

More specifically, the currently available wavelengths can be categorized into two groups:

1. Soft Tissue Lasers
KTP, diode, and Nd:YAG laser wavelengths have chromophores of the pigments in soft tissue and pathogens such as *Porphyromonas gingivalis,* as well as inflammatory and vascular tissue. Carbon dioxide lasers also easily interact with free water molecules in soft tissue, as well as vaporize the intracellular water of pathogens.

2. Soft and Hard Tissue Lasers
Erbium lasers (Er,Cr:YSGG and Er:YAG) are sometimes called "all-tissue" instruments because of their excellent absorption in both apatite crystals as well as their maximum absorption by water content of soft and hard tissue. However, these wavelengths have limited hemostatic ability because they are not absorbed by hemoglobin and have very short pulse durations.

(As a note to the above, present-day CO_2 lasers, while having excellent absorption in tooth mineral, are not indicated for use for dental hard tissue because their long pulse durations cause cracking and carbonization.)

LASERS FOR THE DENTAL CLINICIAN

A variety of laser wavelengths, described above, are marketed for dentistry. In the United States, the U.S. Food and Drug Administration regulates laser manufacturers and grants a marketing clearance on a specific device for a particular procedure. The practitioner will then be able to find an indication for use in the operating manual which gives instructions for the device and the treatment. Certain

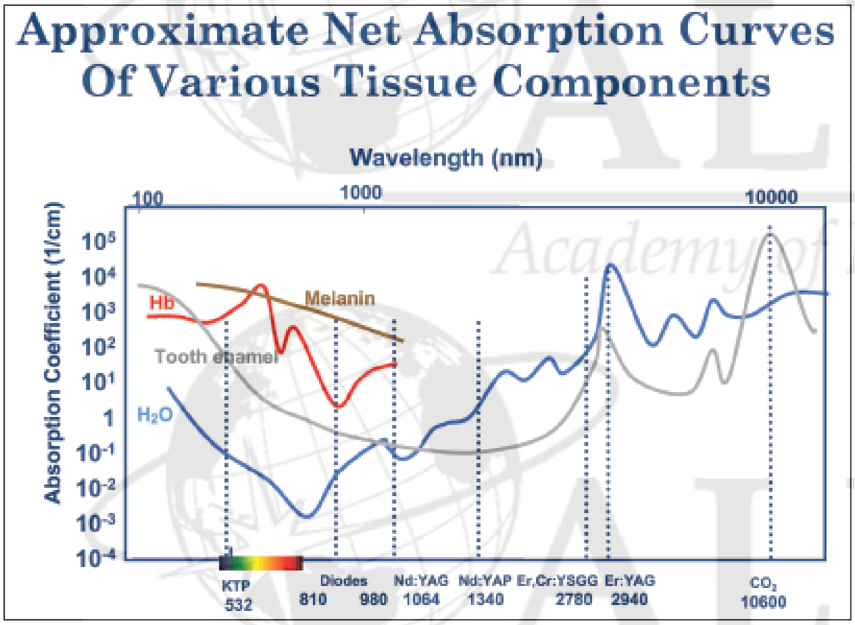

Figure 6: Approximate absorption curves of dental tissue components

other countries have similar regulatory agencies.

All currently available dental laser instruments and their emission wavelengths have indications for use for incising, excising, and coagulating oral soft tissue surgery. Only some devices have other specifically cleared procedures, which include treatment of aphthous ulcers and herpetic lesions, sulcular debridement, and aid in carious lesion diagnosis. At present, only the erbium family of lasers, Er:YAG and Er,Cr:YSGG, can be marketed for carious lesion removal, tooth preparation, and osseous surgery.

Research is being actively conducted for new wavelengths and new clinical applications. Three such projects are investigating selective calculus and carious lesion ablation, improving the evaluation of hard and soft tissue by using laser optical coherence tomography, and laser hardening of enamel for caries resistance.

With the varying absorption characteristics and the varied composition of dental tissues, there is still no one perfect laser for all treatment plans. Moreover, the laser practitioner must utilize the instrument in accordance with his or her clinical experience and scope of practice. Each device has features, advantages, and drawbacks; however, all provide a very useful addition to the dental armamentarium.

AUTHOR BIOGRAPHY

Donald J Coluzzi, DDS is a 1970 graduate of the University of Southern California School of Dentistry. He recently retired, after 35 years, from his general dental practice in Redwood City, California, and continues as an Associate Clinical Professor at the University of California San Francisco School of Dentistry Department of Preventive and Restorative Dental Sciences. He is past president of the Academy of Laser Dentistry and holds Advanced Proficiency certificates in Nd:YAG and Er:YAG laser wavelengths. Dr. Coluzzi is a fellow of the American College of Dentists, and holds Mastership from the Academy of Laser Dentistry. He has received the Leon Goldman Award for Clinical Excellence and the Distinguished Service Award from the Academy of Laser Dentistry. He is the Editor-in-Chief of the *Journal of Laser Dentistry.* He co-edited and co-authored the October 2004 issue of *Dental Clinics of North America,* and recently co-authored the *Atlas of Laser Applications in Dentistry,* published by Quintessence. He has published peer-reviewed manuscripts about lasers in dentistry, and has trained practitioners throughout the world. Dr. Coluzzi can be reached at don@laser-dentistry.com.

Disclosure: *Dr. Coluzzi currently has no financial interest in any laser manufacturer. In the past, he has received honoraria from HOYA ConBio for education and training courses.*

REFERENCES

1. Myers TD. Lasers in dentistry. *J Am Dent Assoc* 1991;122(1):46-50.
2. Pecaro BC, Garehime WJ. The CO_2 laser in oral and maxillofacial surgery. *J Oral Maxillofac Surg* 1983;41(11):725-728.
3. Pick RM, Pecaro BC, Silberman CJ. The laser gingivectomy. The use of the CO_2 laser for the removal of phenytoin hyperplasia. *J Periodontol* 1985;56(8):492-496.
4. *The photonics dictionary*. 46th ed. Pittsfield, Mass.: Laurin Publishing, 2000.
5. Gillispie CC, editor. *Dictionary of scientific biography*, volume 2. New York: Charles Scribner's Sons, 1970:239-254.
6. Bohr N. *The theory of spectra and atomic constitution. Three essays.* Cambridge: Cambridge University Press, 1922.
7. Einstein A. Strahlungs-emission und -absorption nach der quantentheorie. *Verh Dtsch Phys Ges* 1916;18:318-323. German.
8. The Columbia Electronic Encyclopedia. Available at: http://www.encyclopedia.com. Accessed July 30, 2008.
9. Dederich D. Laser/tissue interaction. *Alpha Omegan* 1991;84(4):33-36.
10. Ackroyd R, Kelty C, Brown N, Reed M. The history of photodetection and photodynamic therapy.

Photochem Photobiol 2001;74(5):656-669.

11. Bonsor SJ, Nichol R, Reid TMS, Pearson GJ. Microbiological evaluation of photo-activated disinfection in endodontics (an *in vivo* study). *Br Dent J* 2006;200(6):337-341.

12. Tunér J, Hode L. *Laser therapy: Clinical practice and scientific background.* Grängesburg, Sweden: Prima Books AB, 2002:61-238.

13. White JM, Goodis HE, Kudler JJ, Tran KT. Photothermal laser effects on intraoral soft tissue, teeth and bone in vitro. *Proceedings of the ISLD Third International Congress on Lasers in Dentistry,* August 6-8, 1992, Salt Lake City, Utah. Salt Lake City: University of Utah, 1992:189-190.

14. Russell AD. Lethal effects of heat on bacterial physiology and structure. *Sci Prog* 2003;86(1-2):115-137.

15. Knappe V, Frank F, Rohde E. Principles of lasers and biophotonic effects. *Photomed Laser Surg* 2004;22(5):411-417.

16. Joffe SN. *Lasers in medicine.* In: Driggers RG, editor. Encyclopedia of optical engineering, volume 2. New York: Marcel Dekker, Inc., 2003:1045-1056.

17. Springer TA, Welch AJ. Temperature control during tissue welding. *Appl Optics* 1993;32(4):517-525.

18. McKenzie AL. Physics of thermal processes in laser-tissue interaction. *Phys Med Biol* 1990;35(9):1175-1209.

19. Rechmann P, Goldin DS, Hennig T. Er:YAG lasers in dentistry: An overview. In: Featherstone JDB, Rechmann P, Fried DS., editors. *Lasers in dentistry IV,* January 25-26, 1998, San Jose, Calif. Proc. SPIE 3248. Bellingham, Wash.: SPIE – The International Society for Optical Engineering, 1998:2-13.

20. Miserendino LJ, Levy G, Miserendino CA. Laser interaction with biologic tissues. Chapter 3 in: Miserendino LJ, Pick RM, editors. *Lasers in dentistry.* Chicago: Quintessence Publishing Co., Inc., 1995:39-55.

21. Parker S. *Lasers in dentistry.* London: British Dental Association, 2007:12-13.

22. Manni JG. *Dental applications of advanced lasers (DAAL^{tm}).* Burlington, Mass.: JGM Associates, Inc., 2004:5-5.

23. Goldman L. Chromophores in tissue for laser medicine and laser surgery. *Lasers Med Sci* 1990;5(3):289-292.

SUGGESTED TEXTS AND READING MATERIALS

Textbooks

- Coluzzi DJ, Convissar RA. *Atlas of laser applications in dentistry*. Chicago, Quintessence Publishing Co., Inc., 2007.
- Coluzzi DJ, Convissar RA, editors. *Lasers in clinical dentistry.* Philadelphia, Pa.: W.B. Saunders Company, *Dent Clin North Am* 2004;48(4).
- Convissar RA, editor. *Lasers and light amplification in dentistry.* Philadelphia, Pa.: W.B. Saunders Company, *Dent Clin North Am* 2000;44(4).
- Manni JG. *Dental applications of advanced lasers (DAAL^{tm}).* Burlington, Mass.: JGM Associates, Inc., 2007.
- Miserendino LJ, Pick RM. *Lasers in dentistry.* Chicago: Quintessence Publishing Co., Inc., 1995.
- Moritz A, editor. *Oral laser application.* Berlin: Quintessenz Verlags, 2006.
- Parker S. *Lasers in dentistry.* London: British Dental Association, 2007.
- Tunér J, Hode L. *Laser therapy: Clinical practice and scientific background.* Grängesburg, Sweden: Prima Books AB,.2002.

Journals

- *Lasers in Medical Science.* London: Springer.
- *Lasers in Surgery and Medicine.* Hoboken, N.J.: Wiley-Liss, Inc.
- *Photomedicine and Laser Surgery* (formerly titled *Journal of Clinical Laser Medicine and Surgery*). Larchmont, N.Y.: Mary Ann Liebert, Inc.
- *Journal of Oral Laser Applications.* Surrey, Great Britain: Quintessence Publishing Co., Ltd.