Laser Use in Endodontics: Evolution from Direct Laser Irradiation to Laser-Activated Irrigation

Giovanni Olivi, MD, DDS
University of Genoa and Private Practice, Rome, Italy

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SUMMARY

Laser technology applied to endodontics, initially investigated in 1971,[1] expanded in the 1990s with the development of fiber-optic delivery systems, and lately has undergone an important evolution. New technologies (including impulses of reduced length, radial-firing and stripped tips) and techniques (such as laser-activated irrigation [LAI] and photon-initiated photoacoustic streaming™ [PIPS™]) have simplified laser use in endodontics while minimizing undesirable thermal effects on the dentinal walls. The use of very low energy to activate (i.e., warm and agitate) the common endodontic irrigants, such as ethylenediaminetetraacetic acid (EDTA) or sodium hypochlorite, has proven effective for the LAI technique, enhancing both the smear layer cleaning ability and the bacterial reduction activity.

INTRODUCTION

Given the complex root canal anatomy and the limited ability of chemical irrigants to three-dimensionally clean and disinfect the entire endodontic space,[2-3] the use of lasers was seen as a possible means of adjunctively enhancing the effectiveness of endodontic treatment.[1, 4-7]

Many laser wavelengths (from 532 nm to 10,600 nm) clinically or experimentally used in dentistry have bactericidal capabilities because of their thermal effect which generates structural modifications in bacteria cells.[8-11] With the different penetration depths of various wavelengths and the varied morphological alterations of the root canal surface commonly observed after laser irradiation, an overall consensus on the positive effects of lasers in endodontics still has not been reached.

Conventional endodontics utilizes different types of activation of the irrigants. Sirtes *et al.* reported that warming the sodium hypochlorite from 20°C to 45°C enhanced the killing efficacy of sodium hypochlorite.[12] Stojicic *et al.* reported that the effect of agitation of irrigants on tissue dissolution was greater than that of temperature, and continuous agitation of sodium hypochlorite resulted in the fastest tissue dissolution.[13] Accordingly, different agitation techniques have been proposed to improve the efficacy of irrigation solutions, including hand agitation and sonic and ultrasonic devices.[13-14] Other studies have investigated the ability of some laser wavelengths to activate the commonly used irrigant solutions within the canal. This technique, called laser-activated irrigation (LAI), has been shown to be statistically more effective in removing debris and smear layer in root canals compared to traditional techniques (hand irrigation and passive ultrasonic irrigation).[15-17] Recent studies have also reported how the use of an Er:YAG laser, used at very low energy (20 to 50 mJ, 10 to 15 Hz, with a 400-micron tip in the so-called PIPS technique), in combination with commonly used irrigants, resulted in a superior debris and smear layer removal and bacterial reduction, without thermal damage to the organic dentinal structure, when compared to traditional and ultrasonic techniques.[18-20]

This manuscript describes and reviews the evolution of laser techniques and technologies in the cleaning and bacterial reduction of the endodontic system.

SCIENTIFIC BASIS FOR THE USE OF LASERS IN ENDODONTICS

A brief and simple introduction of basic laser physics is helpful in understanding the evolution of the laser techniques used in endodontics.

Laser Interaction with Target Substances

The interaction of light on a target follows the rules of optical physics. Light can be reflected, absorbed, diffused, or transmitted. The interaction of laser light with dentin occurs when there is optical affinity between them. This interaction is specific and selective, based on absorption and diffusion. The less affinity, the more light will be transmitted and/or reflected.

The near-infrared lasers (from 810 nm to 1340 nm) have negligible affinity for water and the hydroxyapatite of hard dental tissues and therefore penetrate to a large extent through dentinal tubules and are absorbed by the bacteria pigments. This allows for a bactericidal effect in deeper dentin layers.[8]

The mid-infrared lasers (2780 nm and 2940 nm) are primarily absorbed by water (and, to a lesser degree, hydroxyapatite) in the dentinal walls and their bactericidal effect, via photothermal energy, is more superficial.[9] Their affinity for water in dentin also performs a certain amount of ablation of the superficial dentin as a result of the photothermal effect.

The carbon dioxide laser (10,600 nm) has a strong affinity for water and especially hydroxyapatite. The inability of this wavelength to utilize a fiber-optic delivery system limits its utility in intracanal applications. In 1999 Kesler *et al.* evaluated the clinical use of a specially designed microprobe (coupled to a CO_2 laser handpiece) within the apical third and reported a level of success comparable to conventional endodontic treatment.[21]

The interaction of different laser wavelengths on different targets (such as bacteria, dentin, and irrigants), via absorption or diffusion, generates biological effects responsible for different therapeutic actions that can be summarized as:

- photothermal effects
- photochemical effects
- photothermal effects inducing photomechanical and photoacoustic effects.

Effects of Laser Light on Bacteria

At different power levels, all laser wavelengths destroy the cell wall because of their *photothermal effect.* The initial damage takes place in the cell wall via alterations in the osmotic gradient leading to swelling and cellular death.[9] Gram-negative bacteria, due to the structural characteristics of the different cell walls, are more easily destroyed with less energy and less irradiation than gram-positive bacteria.[9]

When erbium laser energy is delivered with very short pulse durations (less than 150 microseconds) in a liquid-filled environment, a shock wave phenomenon (*photo-mechanical-acoustic effect*) can occur. A recent study reported a direct bactericidal effect related to this shock wave-like phenomenon; a bacterial kill of 73% was seen when distilled water was activated by PIPS for 30 seconds in an *ex vivo* infected root canal.[22] The use of PIPS technique with sodium hypochlorite or EDTA is described later in this paper.

Morphological Effects of Laser Light on the Dentinal Surface

Besides these positive outcomes, the laser thermal effect can generate some damage to the dentin walls. Several studies have investigated the laser-induced morphological effects on root canal walls as collateral sequelae of cleaning and bacterial reduction performed with different lasers. When they are used on dry tissue, both the near-infrared and the mid-infrared lasers produce characteristic thermal effects.[23] Near-infrared lasers cause morphological alterations of the dentinal wall; the smear layer is only partially removed, and the dentinal tubules are primarily closed as a result of melting of the inorganic dentinal structures[24-26] (Figures 1-2). Mid-infrared lasers completely vaporize the smear layer, but also produce a superficial thermal phenomenon on the dentin[27-31] (Figure 3). When used in dry mode in narrow and/or curved canals, these lasers can produce over-enlarging of the coronal section, apical transportation, perforation, and root canal ledging[19, 32] (Figure 4). This is why recent investigations are looking for nonthermal laser bacterial reduction methods such as photo-activated disinfection (PAD) or LAI.

Effects of Laser Light on Irrigants

Investigations on laser-activated irrigation reported that pulsed erbium lasers can generate a movement of fluids at high speed through a cavitation effect. The expansion (via thermal effect) and successive vapor bubble implosion within irrigant fluids generate a secondary cavitation effect on the intracanal fluids.[33-35] The pulsed erbium lasers' effect on the irrigants within the root canal produced a clean and debrided dentin surface.[15-16] A particular type of laser activation of irrigants (PIPS) utilizes very low energy (ranging from 50 mJ to 20 mJ) at 10 to 15 Hz delivered with very short pulses (50 microseconds) to generate a more profound shock wave than cavitation. The final effect is similar to the previously described effect with LAI.[18-20]

When PIPS is used to activate 17% EDTA, a superior removal of smear layer and debris is obtained when compared to hand irrigation[18-19] (Figures 5-6). When PIPS is used to activate 6% sodium hypochlorite, an effective bacterial reduction in the endodontic system through a three-dimensional streaming of fluids is obtained[20, 36] (Figures 7-8).

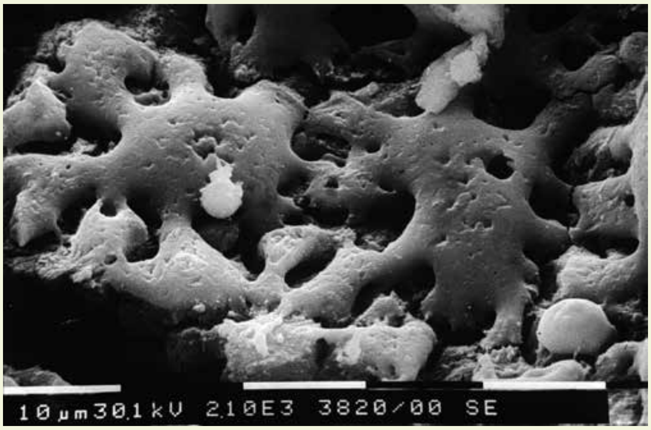


Figure 1: *Scanning electron micrographic (SEM) image of dentin irradiated with Nd:YAG laser, dry, at 100 mJ, 15 Hz, 1.5 W. Note the extensive areas of dentinal melting and bubbles.*

[Figure 1 is provided courtesy of Prof. Vasilios Kaitsas, and appears as Figure 9 in: Olivi G, Crippa R, DiVito E, Iaria G, Kaitsas V. Laser in endodontics: A review and outlook. Endo Tribune (Italian Edition) *2010;4(1):1, 13-18. Italian.]*

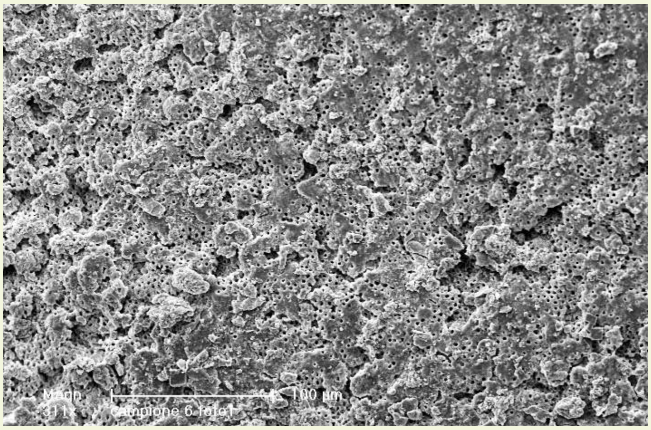


Figure 2: *SEM image of dentin irrradiated with 810-nm diode laser in dry mode, at 1.5 W, 50% time on / 50% time off, 200-micron fiber. Extensive areas of thermal damage, with flakes and smear layer.*

[Figure 2 is provided courtesy of Prof. Vasilios Kaitsas, and appears as Figure 11 in: Olivi G, Crippa R, DiVito E, Iaria G, Kaitsas V. Laser in endodontics: A review and outlook. Endo Tribune (Italian Edition) *2010;4(1):1, 13-18. Italian.]*

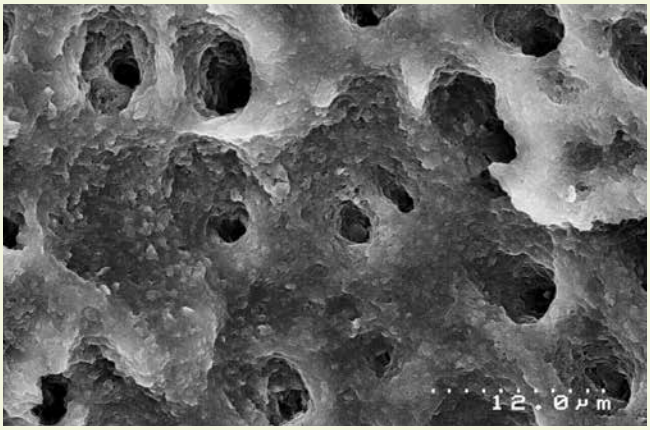


Figure 3: *SEM image at higher magnification of Er:YAG laser-ablated dentin at 75 mJ, 15 Hz, 1.1 W, 300-micron fiber, with end-firing tip. The absence of visible collagen fibrils in the intratubular dentin is consistent with vaporization via photothermal energy.*

[Figure 5 in: DiVito EE, Colonna MP, Olivi G. The photo-acoustic efficacy of an Er:YAG laser with radial and stripped tips on root canal dentin walls: An SEM evaluation. J Laser Dent *2011;19(1):156-161. Image reproduced with permission.]*

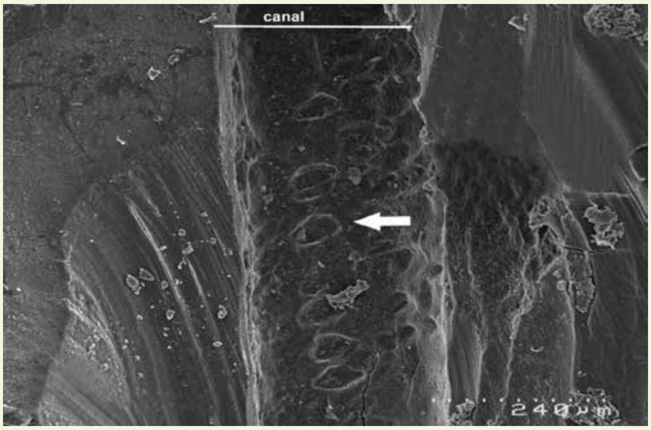


Figure 4: *SEM image shows "hot spots" striking up the middle third of the canal walls during the withdrawal of the end-firing tip from the apex. Er:YAG laser at 75 mJ, 15 Hz, 1.1 W, 300-micron end-firing tip.*

[Figure 2 in: DiVito EE, Colonna MP, Olivi G. The photo-acoustic efficacy of an Er:YAG laser with radial and stripped tips on root canal dentin walls: An SEM evaluation. J Laser Dent *2011;19(1):156-161. Image reproduced with permission.]*

Parameters that Influence the Emission of Laser Energy in Endodontics

In addition to the energy and power used, the emission mode of laser light is fundamental for the effects of laser on targets. Diode lasers emit their energy in a continuous-wave (CW) mode. A mechanical interruption of the energy emission is possible (properly called "gated" or "chopped"), allowing for better control of thermal emission and damage. The pulse duration and intervals are measured in milliseconds or microseconds (time on/off).

The Nd:YAG laser and the erbium laser family emit energy in a "pulsed" mode (also called "free-running pulse"), so that each pulse has a beginning time, increase, and an end time referred to as a Gaussian distribution. Between pulses, the tissue has time to cool somewhat (thermal relaxation time), allowing for better control of thermal effects.

Another important parameter to consider is the length of the pulse (from a few microseconds to milliseconds): shorter pulses (<150 microseconds) are responsible for higher peak power achievable with less energy and less thermal impact, and longer pulses are responsible for more thermal effects.

The tip design also affects the direction and amount of emission of the energy. Traditional laser tips and fibers are end-firing so that no energy is directed laterally. New tips are available today with different designs, tapered and tapered and stripped, so that more energy can be delivered laterally and less frontally.[18, 35, 37]

LASER TECHNIQUES IN ENDODONTICS

Lasers have been used with different techniques in endodontics (Table 1):

- Traditional laser endodontics (direct laser irradiation) involves the use of end-firing tips or fibers, positioned into the canal, 1 mm shorter than the working length, irradiating while withdrawing the fiber from the canal (Figure 9).
- Photo-activated disinfection (PAD), photodynamic therapy, or light-activated disinfection (LAD) requires the use of different photosensitizers with antimicrobial activity that are selectively activated by different wavelengths.
- Laser-activated irrigation (LAI and PIPS) involves the use of radial-firing tips (which may be tapered, tapered and chemically modified, or tapered and stripped) to improve the lateral emission of photons to activate the irrigants (Figures 10-11).

Table 1: Laser Types and Techniques in Endodontics

Laser Wavelength	Laser Technique	Target Chromophore	Laser-Tissue Interaction	Laser Effects
Near-Infrared	direct irradiation	bacteria pigment	diffusion	photothermal
Mid-Infrared	direct irradiation	water content of dentin	absorption	photothermal
Visible Near-Infrared	PAD	photosensitizers	absorption	photochemical
Mid-Infrared	LAI	water content of irrigants	absorption	cavitation via photothermal
Mid-Infrared	PIPS	water content of irrigants	absorption	cavitation-shock wave via photothermal, photomechanical, and photoacoustic

TRADITIONAL LASER ENDODONTICS (DIRECT IRRADIATION)

Bacterial Reduction with Near-Infrared Lasers

Laser-assisted canal bacterial reduction performed with the near-infrared laser requires the canals to be prepared in the traditional way; the apical preparation is performed with ISO 30/40 files, depending on the laser fiber diameter used. The irradiation is performed at the end of the traditional endodontic treatment, as a final procedure to reduce bacteria in the endodontic system before obturation. A flexible optical fiber of 200-300-micron diameter is placed 1 mm from the apex and withdrawn coronally with different techniques, such as a vertical or helical movement (at 1 or 2 mm/sec according to different procedures).

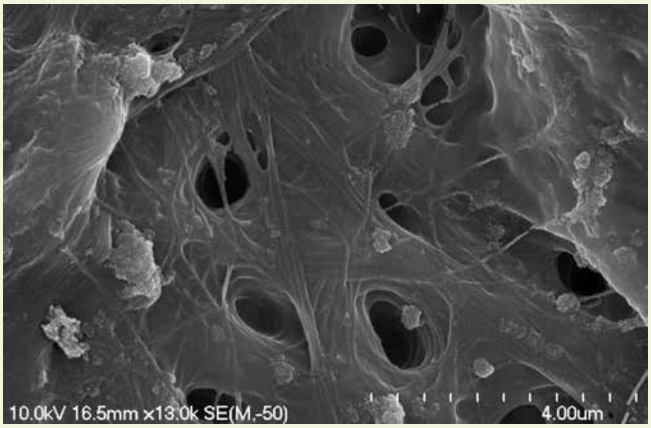


Figure 5: *SEM image of apical third of the canal walls presents completely removed smear layer from the dentin tubules following Er:YAG laser irradiation in 17% EDTA-wetted canal for 40 seconds. There is no evidence of morphological thermal damage at 20 mJ, 10 Hz, 0.2 W, 400-micron tapered and stripped tip.*

[Figure 12 in: DiVito EE, Colonna MP, Olivi G. The photo-acoustic efficacy of an Er:YAG laser with radial and stripped tips on root canal dentin walls: An SEM evaluation. J Laser Dent *2011;19(1):156-161. Image reproduced with permission.]*

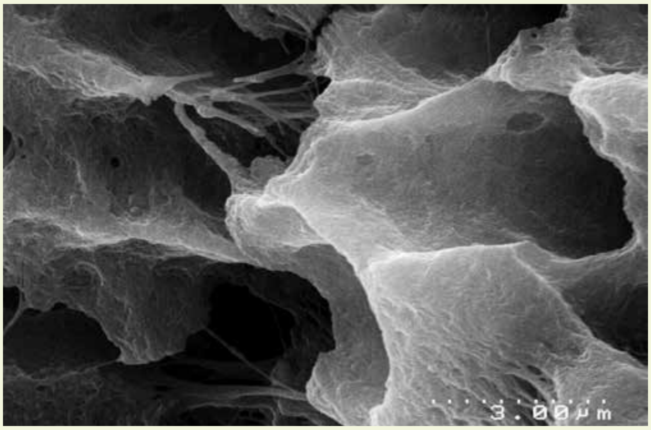
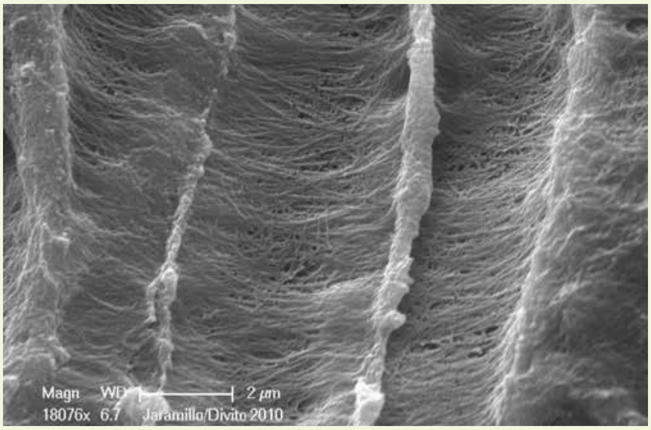
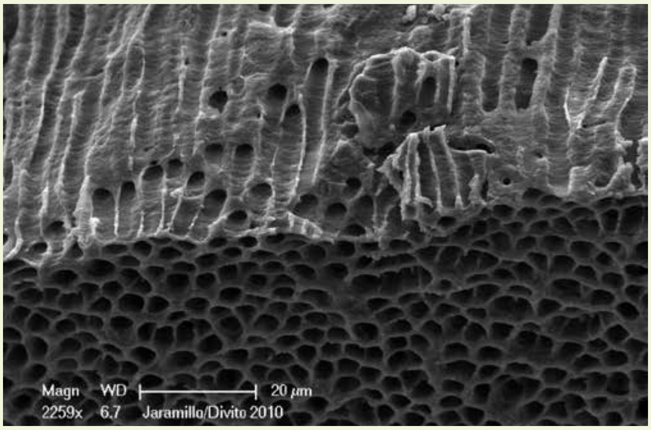


Figure 6: *SEM image of middle third of the canal walls shows the collagen fibers and internal hydroxyapatite matrices left intact, indicating the absence of Er:YAG laser thermal energy, at 2 mJ, 10 Hz, 0.2W, 400-micron tapered and stripped tip.*

[Figure 13 in: DiVito EE, Colonna MP, Olivi G. The photo-acoustic efficacy of an Er:YAG laser with radial and stripped tips on root canal dentin walls: An SEM evaluation. J Laser Dent *2011;19(1):156-161. Image reproduced with permission.]*





Figures 7-8: *SEM images of radicular dentin previously covered with bacterial biofilm of* E. faecalis, *after irradiation with Er:YAG laser at 20 mJ, 15 Hz, PIPS tip with irrigation (EDTA). Images show destruction and detachment of bacterial biofilm and its complete vaporization from the principal root canal and from lateral tubules.*

[Figure 7 is provided courtesy of Enrico E. DiVito, DDS, and appears as Figure 26 in: Olivi G, Crippa R, DiVito E, Iaria G, Kaitsas V. Laser in endodontics: A review and outlook. Endo Tribune (Italian Edition) *2010;4(1):1, 13-18. Italian.]*

[Figure 8 is provided courtesy of Enrico DiVito and David E. Jaramillo, DDS, and appears as Figure 5 in: Jaramillo DE, Aprecio RM, Angelov N, DiVito E, McClammy TV. Efficacy of photon induced photoacoustic streaming (PIPS) on root canals infected with Enterococcus faecalis: *A pilot study.* Endod Prac *2012;5(3):28-33.]*

Moritz *et al.* demonstrated on an experimental model how lasers spread their energy and penetrate into the dentinal wall, showing them to be physically more efficient than traditional chemical irrigant systems in bacterial reduction in the dentinal walls.[38] The Nd:YAG (1064 nm) laser demonstrated a bacterial reduction of three log steps at 1 mm,[38] while in other studies an 810-nm CW diode laser with an output power of 0.6 W achieved a mean bacterial reduction of 74% in a 500-micron slice of dentin[39] and a 980-nm CW diode laser achieved a maximum bacterial reduction of 66% at 2.3 W and 86% at 2.8 W in a 500-micron slice of dentin.[40] These differences in penetration are due to specific optical characteristics of these wavelengths and specific modality of energy emission. The diffusion capacity, which is not uniform, allows the light to reach and destroy bacteria by penetrating via thermal effect.

Many other microbiological studies have confirmed the strong bactericidal action of the diode and Nd:YAG lasers with reduction up to 100% of the bacterial load in the principal canal,[41-44] but also many studies reported undesirable thermal morphological effects related to the contact of the fiber on the dentinal walls during the withdrawing movement.[24, 45-48]

Bacterial Reduction with Mid-Infrared Lasers

Given the low efficacy in canal preparation and shaping with the erbium lasers, the use of traditional techniques for canal preparation is required. Canals need to be prepared at the apex with ISO 30/40 instruments. The final passage with the laser is possible through the use of long, thin tips (200 and 320 microns) available from various erbium laser manufacturers, allowing for easier approach to the working length (1 mm from the apex). In this methodology, the traditional technique is to use a helical movement when withdrawing the tip (over a 5-10 sec interval), repeating 3-4 times depending on the procedure. Traditionally these techniques are performed in dry canals and without any irrigation. Moritz *et al*. obtained an almost total eradication of 99.64% of bacteria at 1.5 W,[49] however these systems did not have a bactericidal effect in penetration depth in the lateral canals. Testing showed only 250 microns of penetration depth when tested in the width of the radicular wall.[9, 38]

Additional studies have investigated the ability of the Er,Cr:YSGG laser to reduce bacteria in traditionally prepared canals. With low power (0.5 W, 20 Hz, 25 mJ) complete eradication of bacteria was not obtained,[49] while better results for the Er,Cr:YSGG laser were obtained at 1 W with a 77% reduction and at 1.5 W with 96%.[43] A new area of research has investigated the capacity of the Er:YAG laser for the removal of bacterial biofilm from the apical third[50] and a recent *in vitro* study has further validated the capacity of the Er:YAG laser to remove endodontic biofilm from numerous bacterial species (*Actinomyces naeslundii, Enterococcus faecalis, Propionibacterium acnes, Fusobacterium nucleatum, Porphyromonas gingivalis*, and *Prevotella nigrescens*), with considerable reduction of bacterial cells and disintegration of biofilm. The exception to this was the biofilm formed by *Lactobacillus casei*.[51]

Erbium lasers with "end-firing" tips, with frontal emission at the end of the tip, have little lateral penetration of the dentinal wall, so that a radial-emitting tip was proposed in 2007 for the Er,Cr:YSGG laser;[52-53] Gordon *et al.* have studied the antimicrobial effects[52] and Schoop *et al.* the morphological and bactericidal effects of this laser system.[53]

The Gordon group used a 200-micron diameter tip with radial emission; the maximum bactericidal power was reached at the maximum tested power (0.4 W, 20 Hz), with a 4-minute exposure time, without water in dry mode, with a bacterial eradication of 99.71%. The minimum time of irradiation of 15 sec with the minimum power (0.2 W, 20 Hz), with water spray, obtained 94.7% bacterial reduction.[52]

The Schoop study examined parameters of 0.6 W and 0.9 W with a 200-micron fiber that produced a very contained thermal rise respectively of 1.3°C and 1.6°C, showing a high bactericidal effect on *E. coli* and *E. faecalis*.[53]

Photo-Activated Disinfection

Certain chemical substances such as indocyanine green, methylene blue, toluidine blue, and tolonium chloride are known as photosensitizers that increase the sensitivity of bacteria to optical irradiation. The use of diode lasers (low-power visible 633 nm and invisible 805 nm) was found to be effective in producing reactive oxygen through a *photochemical reaction* in these exogenous photosensitizers, especially tolonium chloride and indocyanine green.[54-56] Antibacterial action via photoactivated disinfection (PAD) was found to be improved by an increase in laser energy dose (albeit not always significantly), but not by tolonium chloride concentration. Killing of many types of bacteria can be achieved, but some endodontic pathogens that grow as single-species biofilms are difficult to eradicate.[57-58]

Laser-Activated Irrigation

Water, present in the endodontic irrigant solutions, limits the thermal interaction of the laser beam on the dentinal wall but at the same time can work synergistically when activated by a mid-infrared laser (water is a target chromophore) to clean the canal. In fact, irrigation is an essential part of root canal therapy because it allows for cleaning and bacterial reduction beyond what might be achieved by root canal instrumentation alone. Sodium hypochlorite (NaOCl) is the most commonly used root canal irrigant because it can dissolve organic tissue, kill microorganisms,[59-60] and act as a lubricant. However, because of high surface tension, sodium hypochlorite penetrates only

130 µm into dentinal tubules,[3] while bacteria can colonize the dentinal tubules deeply up to the periodontal surface (1100 µm from the canal lumen).[61] High temperature and agitation were shown to enhance the efficacy of sodium hypochlorite; the effect of agitation on tissue dissolution was reportedly greater than that of temperature, with continuous agitation of sodium hypochlorite resulting in the fastest tissue dissolution.[13]

Accordingly, different agitation techniques have been proposed to improve the efficacy of irrigation solutions, including hand agitation as well as sonic and ultrasonic devices.[14, 62]

Lasers have been recently proposed to activate irrigation solutions by the transfer of pulsed energy.[33-35] Laser-activated irrigation by Er:YAG and Er,Cr:YSGG laser light has been suggested to be more effective in removing dentin debris and smear layer in comparison to hand irrigation[15, 18-19] or passive ultrasonic irrigation (PUI).[16, 20] Recently the use of laser energy has been also proposed to enhance the antimicrobial action of sodium hypochlorite.[20, 36]

Hmud *et al.* confirmed the possibility of using near-infrared lasers (940 nm and 980 nm) with a 200-micron fiber to activate the irrigants with powers of 4 W at 10 Hz and 2.5 W at 25 Hz, respectively, and thereby remove debris and smear layer.[63] It is important to call attention to the lack of affinity between these wavelengths and water; consequently, higher powers are needed to produce, via thermal energy, more heating of fluids than agitation or cavitation in the root canal leading to a possible increased capacity of removal of debris and smear layer. In a later study, the authors also verified the safety of using these higher powers that caused a rise in temperature of 30°C in the intracanal irrigant solution with only a maximum of 4°C on the external root surface.[64]

Photothermal and Photomechanical Phenomena for the Removal of the Smear Layer

George *et al.* examined the capacity of lasers to activate the irrigating liquids inside the root canal to increase its action. In their study of both Er:YAG and Er,Cr:YSGG lasers, they used 400-micron diameter tips, both flat and conical; the conical tips were etched with hydrofluoric acid to increase the lateral diffusion of energy. The study involved the irradiation of root canals inside of which a thick smear layer was prepared experimentally. The study compared the results of the groups that were laser-irradiated with the groups that were not laser-treated, and reported that the laser activation of irrigants (EDTA with Cetavlon in particular) brought about better cleaning and removal of the smear layer from the dentinal surfaces.[15] In a later study, the authors reported that this procedure produced an increase in temperature of only 2.5°C without causing damage to the periodontal structures.[65]

De Moor *et al.* also examined the effects of laser activation of irrigants, comparing it to conventional irrigation (CI) and to passive ultrasound irrigation (PUI). In their study an Er,Cr:YSGG laser was used, 4 times for 5 seconds at 75 mJ, 20 Hz (1.5 W) with an endodontic tip (200-micron diameter, with flat tip), held steady at 5 mm from the apex, to activate sodium hypochlorite at 2.5%. The removal of the smear layer performed with this procedure resulted in significantly better results with respect to the other two methods.[34] It was not necessary to move the fiber up and down in the canal, but was sufficient to keep it steady in the middle third at 5 mm from the apex.[34] This concept greatly simplifies the laser technique, without the need to approach the apex and to negotiate radicular curves.

The high-speed microphotographic study related to this previous experiment suggested that the laser generates a movement of fluids at high speed through a cavitation effect. The expansion and successive implosion of irrigant fluids (by thermal effect) generates a secondary cavitation effect on the intracanal fluids.[33] These processes are the same as those reported by Matsumoto *et al.* with an Er:YAG laser.[35] A study by de Groot *et al.* also reported the efficacy of the technique of laser activation of irrigants and the improved results obtained in comparison with the passive ultrasonic technique (PUI). The authors suggested the concept of streaming due to the collapse of the laser-induced bubbles in the irrigant solutions used as the main cleaning mechanism of LAI.[16]

Also De Moor *et al.*, comparing the LAI technique to the passive ultrasound irrigation (PUI), concluded that the laser technique (4 x 5 seconds) is more effective in removing debris than PUI for 20 seconds.[17]

Macedo *et al.* referred to the main role of activation as a strong modulator of the reaction rate of NaOCl. During the rest interval of 3 minutes with no activation, the consumption of available chlorine increased significantly more after laser activation of the irrigant compared to passive ultrasonic or traditional irrigation.[66]

Photomechanical Phenomena for the Removal of the Smear Layer and Bacterial Biofilm

The specific LAI technique called *Photon Induced Photoacoustic Streaming (PIPS)* presupposes the use of an Er:YAG laser (LightWalker AT, Fotona, Ljubljana, Slovenia) and its interaction with irrigant solutions (sodium hypochlorite, EDTA, distilled water)[18-20, 36] differently from the preceding LAI. This technique uses more of the photoacoustic and photomechanical phenomena rather than the photothermal, with parameter settings that use the subablative energy levels of 20 to 50 mJ at 10 to 15 Hz, with impulses of only 50 microseconds of duration. With an average power of only 0.2-0.5 W, each impulse interacts with the water molecules with a nominal peak power of 400-1000 Watts, creating a shock wave-like phenomenon

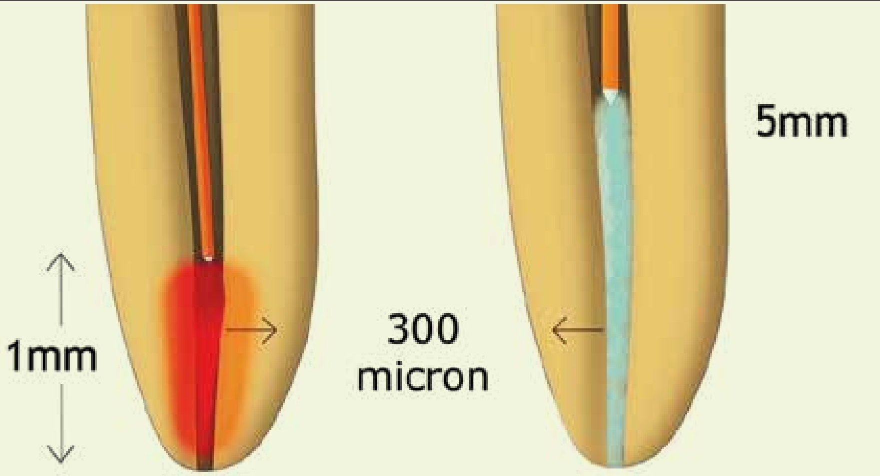


Figure 9: *Position of the laser fibers in the traditional laser endodontic technique: 1 mm short of the apex (left) and in LAI (right), 5 mm short of the apex.*

[Figure 9 is provided courtesy of Giovanni Olivi, MD, DDS, and appears as Figure 17(a) in: Olivi G, Crippa R, DiVito E, Iaria G, Kaitsas V. Laser in endodontics: A review and outlook. Endo Tribune (Italian Edition) *2010;4(1):1, 13-18. Italian.]*

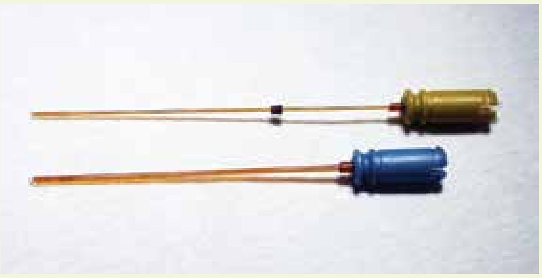


Figure 10: *Z2 and Z3 endo tips (200 and 300 microns) for an Er,Cr:YSGG laser (Waterlase MD, Biolase, Irvine, Calif., USA).*

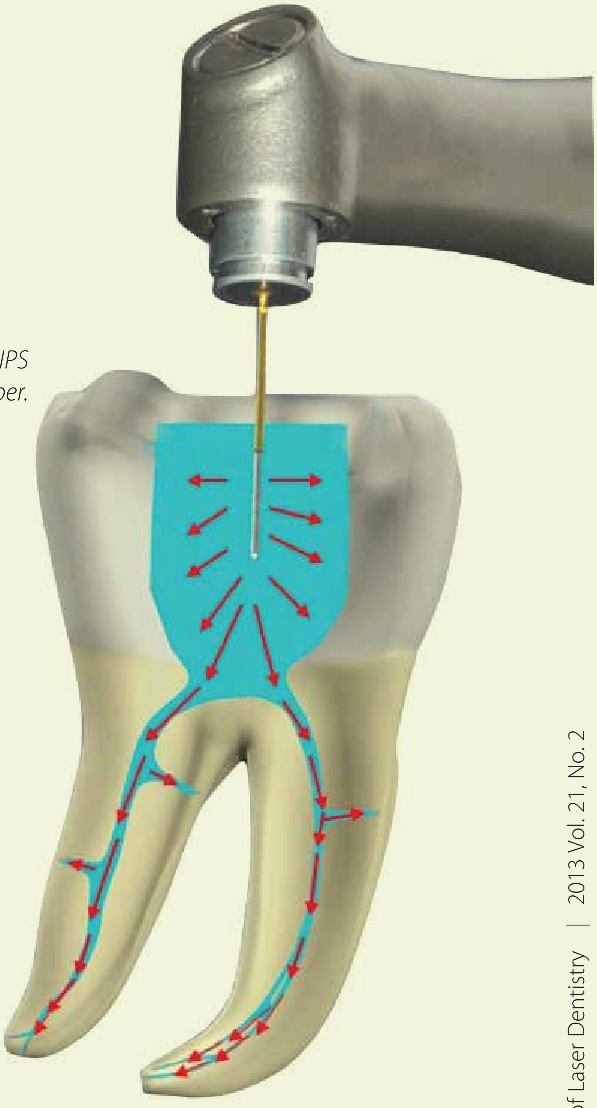


Figure 11: *Position of the laser tip in the PIPS technique: steady in the pulp chamber.*

Figure 12: *PIPS 400/12 and 600/9 tips (Light-Walker AT, Fotona, Ljubljana, Slovenia).*

leading to the formation of a powerful streaming of fluids inside the canal, without generating the undesirable thermal effects seen with other methodologies. The study with thermocouples applied to the radicular apical third revealed only 1.2°C of thermal rise after 20 seconds and 1.5°C after 40 seconds of continuous irradiation.[18]

Results from as-yet-unpublished fluid dynamics studies from the University of Southern California demonstrate significant differences in velocities and movement when ultrasonic irrigation was compared to PIPS. Ultrasonic analysis showed a more "linear" and standing wave-type of fluid movement which was located only within 0.5 to 1.0 mm of the tip. Activity was measured at distances in 3 mm increments from the tip to 21 mm and no significant movement was seen past 3 mm. This confirms the reports from Matsumoto and Ahmad that found reduced vibration activity in narrow and curved canals with PUI.[35, 67] PIPS on the other hand showed a more dramatic "turbulent" flow movement when compared to the use of ultrasonic. Of particular interest was the ability of this technique to show significant movement not only near the tip, but distant from the tip. At 21 mm the velocities achieved with PIPS were 4 times greater than those with the ultrasonic device. This makes PIPS a useful irrigation tool for the clinician to more effectively move and drive irrigants three-dimensionally to all the smaller and complex dental morphologies often seen in the difficult-to-reach apical third and also allows for cleaning and bacterial reduction of the root canal efficiently without the need to enlarge the apical preparation. This ultimately leads to improving the success rate of therapies in both narrow and curved canals without the need to enlarge the apical preparation, contributing to a more minimally invasive preparation and methodology.

Moreover, this stronger activation of the irrigants lends itself to the considerable advantage of placing the newly designed tip in the pulp chamber only, without the problematic insertion of the tip into the middle third of the canal or at 1mm from the apex as required by the other techniques (LAI and traditional). The latest tip available is only 9 mm in length, 600 micron in diameter, with a "radial and stripped" designed terminal. The final 4 mm are without coating to allow a greater lateral emission of energy compared to the frontal tip (Figure 12). This mode of energy emission makes better use of the laser energy when, at subablative levels, it is delivered with very high nominal peak powers for each single pulse of 50 microseconds (400 W). This in turn produces powerful shock waves in the irrigants leading to a demonstrable and significant mechanical effect on the dentinal wall.

Studies showed the laser-assisted removal of the smear layer to be superior to the control groups with only EDTA or distilled water. The samples treated with laser and EDTA for 20 and 40 seconds show a complete removal of the smear layer with open dentinal tubules (score 1 according to Hulsmann) and the absence of undesirable thermal phenomena, which is characteristic in the dentinal walls treated with traditional laser techniques. With high magnification, the collagen structure is maintained intact suggesting the hypothesis of a minimally invasive endodontic treatment.[18-19]

The main role of laser activation as a strong modulator of the reaction rate of NaOCl, reported by Macedo *et al.*,[66] suggested new studies to investigate the ability of PIPS and sodium hypochlorite to improve the bacterial reduction of *ex vivo* infected root canals through the PIPS technique. Few studies have investigated the ability of lasers to remove bacterial biofilm from canal walls.[20, 36] Bacterial biofilm is a thin layer of microorganisms in which cells adhere to each other on a surface, frequently embedded within a self-generated matrix of extracellular polymeric substance that protect them from chemical and physical forces. In contrast, planktonic cells of the same organism are single cells that may float or swim in a liquid medium and may be easily destroyed by chemical irrigants or lasers. Peters *et al.* reported a significant reduction of the bacterial load of 99.5% of 3 week-incubated bacterial biofilm, by using PIPS and NaOCl for 30 seconds with 30 seconds of resting time.[20] Pedullà *et al.* also reported a strong reduction of bacterial load of 99.8% of *Enterococcus faecalis* cells incubated for 15 days by using 30 seconds of Er:YAG laser activation. This study also indicated that laser activation of distilled water alone was not sufficient to yield bacteria reduction (73%); this report underscored the role of sodium hypochlorite in root canal disinfection but also the importance of physical impact of the shock wave in bacterial cell destruction.[22]

Tables 2 and 3 summarize the differences between the laser techniques.

Table 2: Intracanal Laser Techniques

LASER TECHNIQUE	LASER EFFECTS	TIP POSITION	TIP SIZE	TIP DESIGN	APICAL PREPARATION
Direct Irradiation	photothermal	Apex 1 mm shorter	200-300 micron	end-firing	ISO 30-40
LAI	photothermal, cavitation	Middle Third 5 mm shorter	200-300-400 micron	tapered and/or chemically modified	ISO 30-40
PIPS	Photothermal, photomechanical, photoacoustic shock wave	Pulp Chamber	400 micron	tapered and stripped	ISO 20-25

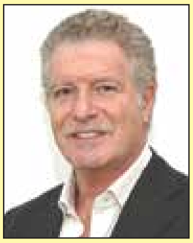
Table 3: Investigations of Laser Techniques in Endodontics

Author Reference	Laser Technique	Laser Energy (mJ)	Pulse Duration (microseconds)	Nominal Peak Power (Watts)	Fiber (microns)	Fiber Position	Apical Preparation	Erbium Laser Wavelength (nm)
George *et al.*[15]	LAI 10 x 5 sec	37.5	140 200	267 187	400 conically modified	Working Length less 1 mm	ISO 50/5 Working Length	2780 2940
de Moor *et al.*[17]	LAI 4 x 5 sec	75	140 250	535 300	200	Working Length less 5 mm, stationary	ISO 40/6 Working Length	2780 2940
Macedo *et al.*[66]	LAI 1 min	65	250	260	280	Working Length less 1 mm, moved up and down x 4 mm	Bovine Teeth, Standardized 0.23 mm	2940
Matsumoto *et al.*[35]	LAI	11 18 26	250	44 72 104	300 cone-shaped	Working Length less 2 or 5 mm, stationary	Glass Model 1 mm	2940
DiVito *et al.* (2012)[18]	PIPS 20-40 sec	20	50	400	400 PIPS	Pulp Chamber, stationary	ISO 20/.06	2940

DISCUSSION AND CONCLUSIONS

Laser technology used in endodontics during the last 20 years has undergone an important evolution. Research in recent years has been directed toward producing laser technologies (such as impulses of reduced length, radial-firing and stripped tips) and techniques (such as LAI and PIPS) that are able to simplify laser use in endodontics and minimize the undesirable thermal effects on the dentinal walls, using lower energies in the presence of chemical irrigants. EDTA has proved to be the best solution for the LAI technique that activates the liquid and enhances its cleaning of the smear layer. The use of a laser (PIPS) to activate sodium hypochlorite increases its antimicrobial activity. Finally, the PIPS technique reduces the thermal effects and exerts both a stronger cleaning and bactericidal action, because of its streaming of fluids initiated by the photonic energy of the laser. Further studies are necessary to validate the LAI and PIPS techniques as innovative technologies in modern endodontics.

AUTHOR BIOGRAPHY



Giovanni Olivi,
MD, DDS

Dr. Giovanni Olivi is an Adjunct Professor of Endodontics at the University of Genoa School of Dentistry, and a Board member and Professor in the Master Course in Laser Dentistry at the same University. In 2002 he completed the postgraduate laser course at the University of Firenze, and two years later received laser certification from the International Society for Lasers in Dentistry (ISLD). In 2006 he achieved Advanced Proficiency from the Academy of Laser Dentistry (ALD) and received Mastership in 2009. Dr. Olivi is the 2007 recipient of ALD's Leon Goldman Award for Clinical Excellence. He has authored more than 50 articles on dentistry topics and is a co-author of the books *I Laser in Traumatologia Dentale* (in Italian, Martina Publishing, Bologna, Italy, 2010) and *Pediatric Laser Dentistry: A User's Guide* (in English, Quintessence Publishing, Chicago, Ill., USA, 2011). Dr. Olivi maintains a private practice in endodontics, restorative, and pediatric dentistry in Rome, Italy. Dr. Olivi may be contacted by e-mail at olivilaser@gmail.com.

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