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REVIEW
High-Power Lasers in Endodontics - Fiber Placement for Laser-Enhanced Endodontics: in the Canal or at the Orifice?

Roeland J.G. De Moor, Maarten Meire
Ghent University & Ghent University Hospital, Dental School, Ghent Dental Photonics Research Clustre, Ghent Dental Laser Centre, Ghent, Belgium

ABSTRACT

The aim of this review is to give a survey of the use of high-power lasers for root canal cleaning and disinfection. There are two approaches: the first using a fiber in a dry root canal and exposing the root canal wall to the laser light with a spiral motion, and the other using the fiber in irrigant in the root canal or at the orifice. The laser-target interaction is different: a direct exposure of the substrate to laser light is the aim of the spiral motion, whereas the aim of the second technique is activation and agitation of the irrigant (laser activated irrigation / LAI). A limitation of the fiber is the straight forward emission. Modification of the fiber tip into a more conical shape allows for more lateral emission. This modification, however, does not result in far better cleaning and disinfection. Taking into account that all irrigants are water-based solutions, it is possible to create cavitation bubbles and to induce shockwaves and agitation in the irrigant with Erbium lasers. The newer technology allows for the use of low energy during a very short exposure time, resulting in high peak powers. Investigations on the latter topic have demonstrated that the creation of cavitation resulting in the induction of liquid agitation and shock waves in the irrigant may result in an in-depth cleaning and disinfection. Erbium lasers are the first choice for the activation of endodontic irrigants. Research in this respect has demonstrated that LAI performs "equal to" or "better than" ultrasonic activation. Other wavelengths with a solid absorption in water are now to be explored.

Key words: Er:YAG, Er,Cr:YSGG, endodontics, laser-activated irrigation, cavitation.

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I. CONVENTIONAL APPROACH FOR CLEANING AND DISINFECTION OF THE ROOT CANAL SYSTEM

a) Root canal treatment: some critical thoughts regarding optimal cleaning and shaping – the first era of root canal irrigants.

The aim of root canal treatment is to maintain or obtain periradicular health, through the prevention or control of root canal infection, thereby keeping the tooth functional, without signs or symptoms of endodontic origin. Basically it comes down to "the prevention or the treatment of apical periodontitis".

Root canal therapy involves the shaping and simultaneous cleaning of the root canal system, the space confined within the hard tissues of crown and root with a highly complex micro-anatomic structure. Preparation of this system includes both enlargement and shaping of the complex endodontic space together with its disinfection [1]. During this phase vital and/or necrotic tissues are removed from the root canal system; instruments will also help to remove (infected) root canal dentine as well as disrupt the biofilm when present; in cases of retreatment there is also the removal of non-metallic and/or metallic obstacles.

The role of root canal shaping has undergone a paradigm shift from one fulfilling a prime debriding function, to one regarded more as a radicular access to the complex root canal system, allowing an avenue for irrigants and root filling material [2]. As 35-53% of the root canal surface remains uninstrumented, the role of irrigants next to their flushing action is the debridement of the uninstrumented root canal walls [3-5]. In this respect it is worth mentioning that also anterior maxillary teeth have significant proportions of their root canal surfaces left uninstrumented [6].

A by-product of root canal preparation is the smear layer. It is formed wherever instruments exert their action on the root canal walls. The smear layer covers the instrumented root canal walls, and together with the debris that is produced by (rotary) instruments during shaping [7], it may block or be packed in areas such as anastomoses, fins, isthmus, and canal irregularities as well as in dentinal tubules. Removal of the smear layer is advocated because this layer may harbor microorganisms [8], may prevent diffusion of irrigants or medicaments in these areas [9], and it may jeopardize a good three-dimensional obturation with sealer in tight contact with the root canal walls [10].

These findings are the basis of the traditional chemomechanical preparation protocol where root canal shaping is done in the presence of NaOCl (0.5 – 5%), frequently refreshed, and final rinses with EDTA and again NaOCl in order to allow a more profound cleaning and disinfection once the remaining debris, smear layer and smear plugs are removed (especially in these areas that were blocked by smear layer and in the open dentinal tubules) [11]. The combination of NaOCl and EDTA produces a synergistic effect, resulting in effective removal of the entire smear layer [12].

b) The second era of root canal irrigants

It is clear that irrigation is an essential part of root canal debridement because it allows for cleaning beyond what might be achieved by root canal instrumentation alone [5]. To date, there is no product irrigant that meets all the requirements for an ideal irrigant, namely: (1) wetting and removal of debris, (2) destruction of microorganisms and their toxins, (3) dissolution of organic matter, (4) removal of smear layer and softening of dentine, (5) cleaning in areas, inaccessible to mechanical cleansing methods [13]. Therefore, combinations of irrigants such as NaOCl and EDTA are used in order to overcome the limitations of the use of one single irrigant. Alternative chemical compositions have been proposed (e.g. MTAD, Qmix), but their benefit remains to be proven. Another important issue is the distribution of irrigants into the confines and extremities of the canal system. Specific focus is needed on the apical portions of (small) root canals and the isthmus areas. Traditional irrigation using a syringe-needle combination is limited in its 3D-spreading of the liquid. The irrigant does not reach further than 1-2 mm beyond the tip of the needle; the size and rigidity of the needle frequently does not allow insertion into the apical third, and removal of debris in lateral extensions or isthmuses is limited. Therefore, more effective irrigant delivery and agitation systems for root canal irrigation are developed [14]. Both manual agitation techniques and machine-assisted agitation devices are marketed (Fig 1).

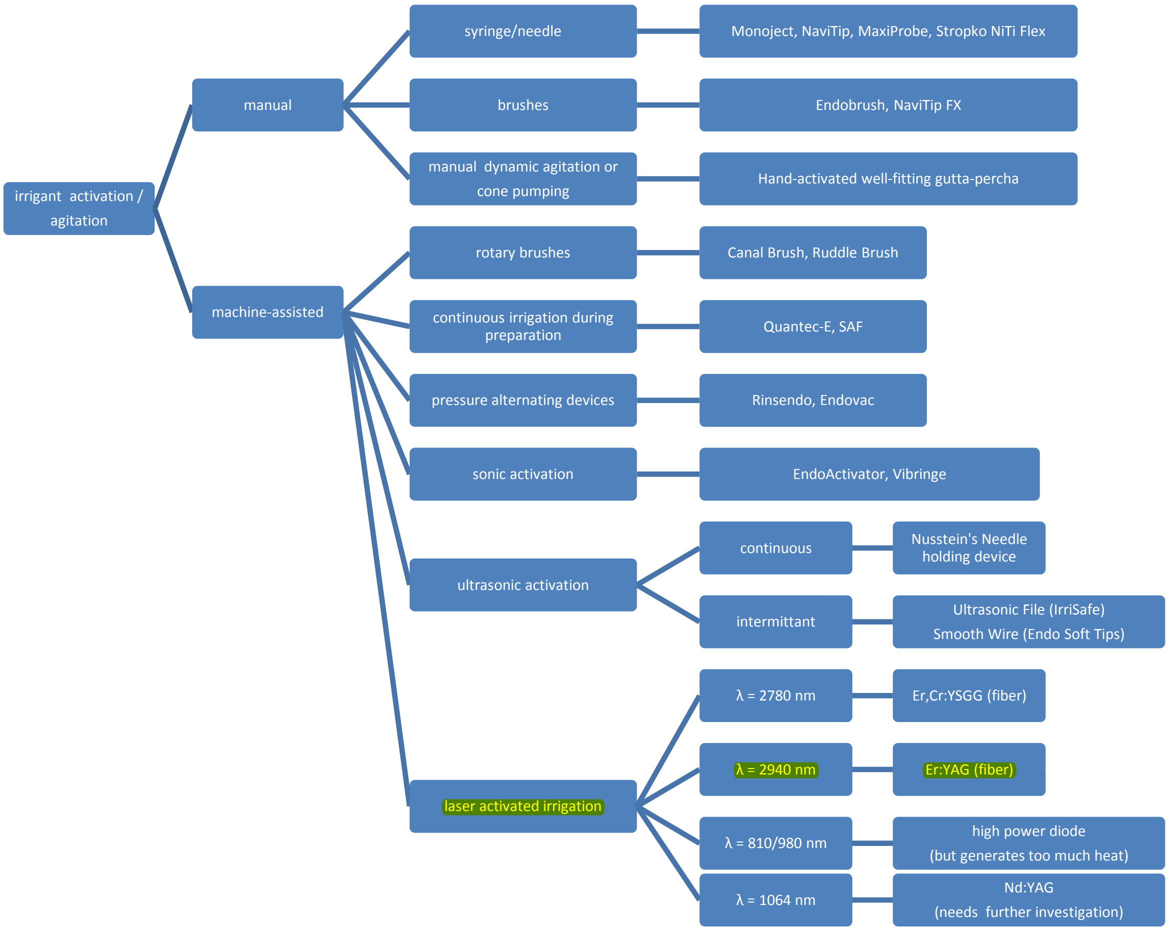

Fig. 1: Summary of the types of endodontic irrigant agitation or activation devices and techniques

Around 2005 the dental world was confronted with a reintroduction in endodontics of sonic and ultrasonic systems to agitate irrigants [15]. This has led to the introduction of passive ultrasonic irrigation (PUI). In vitro studies have shown PUI to be more efficient than conventional irrigation in the removal of pulpal tissue and debris [16-18], smear layer [19,20] and micro-organisms [21-24]. PUI also increases the NaOCl reactivity and heats the irrigant [25]. It proves to be more efficient with greater apical taper [26] and works better in straight canals [27]. Oscillation of the instrument can be performed in the direction of the groove[28].

At present a generally advocated protocol is the one with a NaOCl-supported root canal preparation, EDTA rinse after the shaping procedure (contact time of 1 minute before refreshment) and final rinse with NaOCl, ultrasonically activated with PUI 3x 20 sec.

II. HIGH-POWER LASERS IN ENDODONTICS FOR CLEANING AND DISINFECTION OF THE ROOT CANAL SYSTEM

a) The first era – direct irradiation of the root canal walls through intracanal fiber placement and movement

The interest in lasers in endodontics arose because of different reasons: (1) light might reach areas inaccessible to instruments and chemicals, (2) monochromaticity will lead to wavelength-specific interactions, and (3) parallel bundle and pulsed mode may result in localized energy densities.

NIR LASERS:

- **Nd:YAG (1064 nm)**

Nd:YAG is the most investigated wavelength in endodontics. The first reports on the use of Nd:YAG in a root canal were published in 1984 [29] and 1985 [30,31]. More extensive research started in the beginning of the 1990's. The FDA approved the marketing of a free-running, pulsed Nd:YAG laser for soft-tissue surgical applications in May 1990. Since then Nd:YAG was also introduced for other indications.

When root canal walls are irradiated with an Nd:YAG laser, aspects of glazing, vitrification, melting and evaporation of the smear layer are described. These typical alterations of the surface morphology refer to thermal processes. Safety criteria were set: 1.5 Watt – 15 Hz – 100 mJ / application during 5 seconds in the root canal with a spiral motion of the fiber/ a dwell time of 20 seconds / procedure to be repeated 4 times [32]. Investigations demonstrated that the temperature at the root surface rose up to 38°C [33] with settings of 1.5 W – 15 Hz and application for 90 sec. Matsumoto et al. [34] emphasized the limitations of the use of a fiber in the root canal: uniform coverage of the root canal walls is impossible because the laser is emitted straight forward. In addition, transmission of radiation beyond the apex is to be avoided; a risk when the fiber tip is close to the apical foramen.

A critical analysis of the literature on Nd:YAG and root canal wall modification shows that glazing effects especially occur when no EDTA is used to remove the smear layer. Michiels et al. [35] demonstrated that the effect on the root canal wall after rinsing with EDTA is limited, small glass particles were found as a result of remains of the smear layer, the typical glazing affect were only seen in areas where the fiber has touched the root canal wall.

The antibacterial effect once again is merely based on temperature interactions with biofilm and micro-organisms, unless the laser beam is exposed to black pigmented micro-organisms such as P. Gingivalis [36]. Resultant heating of the substrate causes a local rise in temperature high enough to result in cell death of attached micro-organisms. It is a question whether the rise in temperature at settings of 1.5 W – 15 Hz is high enough to result in substantial killing. The bactericidal effect is also decreased in curved canals [37] once again due to the need to use the optical fiber in a spiral motion. Meire et al. [38], in this respect, demonstrated that a total kill of a 1x108 was only possible with 1000 J. For E. Faecalis biofilms, Nd:YAG was less effective than Photoactivated disinfection with low power diodes.

Taking into account that there is no absorption in the root canal wall, an effect of Nd:YAG is registered up to a depth of 1000 µm in dentine at settings of 1.5 W and 15 Hz [39,40]. Bacterial reduction with NaOCl is seen at a depth of 100 µm [41].

The use of Nd:YAG can be advocated as a part of root canal treatment. Its use, however, must be seen more as an adjunct to conventional root canal decontamination procedures to compensate for the limitations of the irrigant(s) used.

The antibacterial effect of the Nd:YAG laser has been convincingly demonstrated. However, comparative studies in simulated root canal infections in vitro have shown that the effect is at best equal to or weaker than that of irrigation with sodium hypochlorite. Obtaining high enough energy densities required for effective disinfection over the entire root canal surface with the Nd:YAG laser remains difficult if not impossible. Therefore, using the Nd:YAG laser, a significant improvement in root canal disinfection over traditional root canal disinfection measures is not to be expected.

- **Diode lasers – high power use (810, 830, 940, 980 nm)**

The interest of dentists in diode lasers today is greater because of its size as a compact device, lower cost and the possibilities of use in diverse areas in dentistry.

For as far as its effect is concerned the same conclusions as with Nd:YAG 1064 nm can be drawn. The study of Pirnat et al. [36] has demonstrated that the effect of 1.5 W - 20 Hz with an 808 nm diode laser (fiber diameter 300 µm) is comparable with the Nd:YAG. The effect of Nd:YAG on pigmented microorganisms was greater as with the diode laser.

The mechanism of high-power NIR laser bacteria inactivation was investigated by Hibst et al. [42] with a 940 nm diode laser. A comparison was made with warm water baths at the same temperature as gained by the emitted diode laser beam. They concluded that inactivation of E. Coli is solely based on a thermal process and they found no signs of photochemical interactions.

NIR LASERS AND THEIR BACTERICIDAL EFFECTS

The α of dentine is low in the NIR region [43]. High penetration depth is possible, though, high energy densities are required. Furthermore, obtaining high energy densities uniformly through the root canal is practically very difficult due to the need of a spiral motion with the optical fiber. The risk of thermal damage needs to be avoided with higher energy densities. Therefore, NIR lasers are probably not the most efficient lasers for root canal disinfection.

- **Erbium lasers (2940 nm Er:YAG / 2780 nm Er,Cr:YSGG)**

Erbium lasers are the most suitable lasers for removal of dental hard tissue, since this wavelength correlates closely with the absorption maximum of hydroxyapatite, and it has the highest absorption in water of any dental wavelength. When irradiated, water contained in the dental hard tissues evaporates instantaneously and thereby ablates the surrounding tissues with only minimal thermal side effects [44,45].

Experimental studies on the efficacy of Er:YAG laser irradiation for cleaning root canal walls have already demonstrated that this type of laser is more effective in removing the smear layer than other laser types and endodontic irrigants [46,47]. The dentinal walls mostly show open tubules [48-51] and are free of debris or a smear layer [48,49,51]. The fiber can be used with minimal thermal side effects [52].

The laser effects depend, among other factors, on the power setting, the mode of energy delivery, the type and condition of the laser, the target tissue [53] and water cooling [54]. As the laser is used in a circular motion whilst withdrawing the optical fiber, in some of the areas irradiated, not all of the tubules are completely open [52,55]. Differences in power settings do not appear to result in significant differences in efficacy for removing the smear layer [49,56,57]. Using the Erbium fiber in a spiral motion within the root canal space, however, will not result in the exposure of the whole root canal surface to the laser beam.

For as far as the antibacterial effect is considered, Moritz et al. [58] demonstrated a higher efficacy than for Nd:YAG and Ho:YAG lasers. Furthermore, Schoop et al. [40] demonstrated a far higher bactericidal efficacy of the Er:YAG laser than of the Nd:YAG and diode laser in the deep layers of the dentine. These findings were confirmed by Yasuda et al.[37] demonstrating a higher bactericidal effect for Er:YAG as compared to Nd:YAG in straight and curved canals. The already mentioned limitations of exposure during the spiral motion of the fiber resulted in a higher bactericidal effect in straight than in curved canals.

Schoop et al. [59] used an infected tooth model and reported a bactericidal effect of the Er:YAG laser on all the species investigated. This effect was dependent on the applied output power and specific for the different species of bacteria. Moritz et al. [58](1999) obtained a 99.76 % reduction of intracanal bacteria with Er:YAG laser. Mehl et al.[60] (1999) found that Er:YAG irradiation of 45 J was equally effective as the NaOCl treatment. Vezzani et al.[61] (2006) and Perin et al.[62] (2004) came to the same conclusion: no significant differences between Er:YAG laser treatment and NaOCl control. They all used an infected tooth model.

To overcome the limitations associated with the spiral motion of an Erbium fiber, Stabholz et al. [63] developed a side firing tip. This endodontic side-firing spiral tip is a hollow conical golden tip. The tip is sealed at its far end, preventing transmission through the apical foramen. It emits the Er:YAG laser irradiation laterally to the walls of the root canal through a spiral slit located all along the tip. Stabholz et al. [63] demonstrated smear layer and debris free and clean surfaces. The limitations of this tip, however, remain (1) the size: apical preparation up to size ISO 60 is needed and (2) the closed apical end: there is no exposure of the apical end of the prepared canal to the laser beam, which limits/inhibits removal of the smear layer.

b) The second era – part I: activation of the irrigant in the root canal and induction of cavitation and fluid motion – fiber in the canal: Conventional Laser Activated Irrigation or C-LAI

o Laser-Activated Irrigation (LAI) with Erbium lasers

A study of Blanken et al. [64] demonstrated that when an Er,Cr:YSGG laser is used within the canal with a plain endodontic tip (Biolase Z4 Endotip), fluid movement within the root canal occurs immediately following each pulse, with fluid speeds up to 100 km/hr. The working mechanism of the laser in the root canal was attributed to cavitation effects inducing these high speed fluid motions into and out the canal. The bubbles were created at settings of 12.5 mJ, 50 mJ, 75 mJ, 125 mJ and 250 mJ at 20Hz. A setting of minimal 75 mJ was needed to remove dye colored liquid out of the apical third. It was also demonstrated that the thermal components were moderate. However, the first high-speed photography images of these types of laser-induced bubbles were by Lauterborn in 1972.

The mechanism of laser-activated irrigation has been described by Blanken and Verdaasdonk [65], Blanken et al. [64], de Groot et al. [66], Matsumoto et al. [67] and Gregorcic et al. [68] based on high-speed imaging methods. These recordings have demonstrated that there is vaporization of the irrigant resulting in high pressure vapor due to instant heating. This will result in the formation of bubbles, which expand and implode. Interesting from the endodontical point of view is that the process of the creation of bubbles is identical in both water and the sodium hypochlorite solution.

The energy of Erbium laser irradiation is almost completely absorbed in the irrigant solution to a thickness of 10 µm right beside the laser tip. The aqueous solution is instantly heated to a boiling point and turned into vapor in 1 microsecond. With the expansion of the vapor bubble, a void is formed in front of the laser light. The vapor bubble expands until irradiation ends. At the moment of the irradiation stop, the vapor bubble starts shrinking. The liquid surrounding the bubble then flows inside the decompressed vapor gap. At this moment of implosion, pressure waves traveling at supersonic speed (shock waves) in the beginning and at sonic speed (acoustic waves) later are generated [69]. There is also formation of a high-speed liquid jet during the bubble collapse, as a result of the bubble-substrate and/or bubble-free surface interaction [70] and [71]. After total collapse of this large vapor bubble, a number of new smaller cavitation bubbles are seen. These bubbles are formed due to an abrupt and extensive change of the pressure of the water around the laser fiber tip, nucleating a number of new cavitation bubbles. This phenomenon is generally called a rebound. The second cavitation bubbles are much smaller than the first vapor bubble. Also these secondary cavitation bubbles may collapse, forming even smaller bubbles, which can disappear repeatedly in decreasing numbers. Matsumoto et al found that the number of cavitation bubbles and the frequency of cavitation appearance were higher in a root canal model than in free water.

In this set-up, the laser tip is inserted inside the root canal and irradiation is performed within the liquid. Collapsing shock waves and rapid streaming caused by laser-induced bubbles are responsible for the cleaning process. A free expansion of the bubble laterally, however, is not possible in the root canal, and hence the irrigant is pushed forward and backward in the canal. Since the irrigant solution obstructs the expansion of the vapor in the forward direction, the bubble grows backwards along the fiber. The pressure inside the bubble remains high for a long time, since it has to fight against the resistance of the water which has to be displaced in the small canal. This process delays the dynamics of expansion and implosion compared to a free water situation. In a previous study it was demonstrated that this process takes 3 times longer [65]. So the lateral and forward expansion in the root canal is limited by the root canal wall, while the backward expansion is blocked by the fiber, making the lumen of the canal even smaller. These differences with a free water situation result in the creation of shear stress along the wall of the canal, which increase the cleaning action of the irrigant. Moreover, the secondary cavitation bubbles are activated by subsequent laser pulses, and when located along the root canal wall, their implosion creates microjets perpendicular to the wall with very high forces locally. This mechanism might also contribute to the disruption of cells and the smear layer at the wall.

Different laser parameters are influencing the cavitation phenomenon:

1. The pulse energy will influence the life time and the size of the bubble.
2. The size of the bubble will increase with increase of the diameter of the fiber.
3. The pulse length determines the size, and to a lesser extent, the shape of the bubble. Shorter pulses yield wider bubbles. The size of the bubble decreases with longer pulses.
4. The fiber tip shape to a great extent determines the shape of the cavitation. Plain fiber tips result in prolate spheroidal bubbles. One pole of the spheroid is located at the fiber tip, the other one is

located a few millimeters distally of the tip. Tapered fiber tips result in more spherical bubbles, with the fiber tip acting as the center of the sphere. A conical tip with flat end will result in an apple-shaped bubble.

5. The influence of pulse frequency is not investigated. Frequencies of 15, 20 and 35 Hz have been used. Increases of frequency may result in an overlap of pulse effects and waves. A problem is that a number of lasers have a fixed frequency.

When the laser fiber tip is used inside the canal at distances of 5 mm of the apex, subablative settings are used. In the studies evaluating removal of debris in simulated canal irregularities, pulse durations from about 140 microseconds for the Er,Cr:YSGG (Waterlase, Biolase; Ervine, CA-USA) to 250 microseconds for the Er:YAG (Versawave, Hoya ConBio; Fremont, Ca, USA) have been used. The length of a pulse is important, as decreasing the pulse duration with the same energy will result in higher peak powers.

Application of LAI with the fiber in the canal, be it stationary [72-74] or in up and downward movement over a distance from 1 mm up to 4 mm from the apex [66], has resulted in a better removal of debris in simulated canal irregularities compared to the use of PUI. The apical smear layer is also removed better (George et al. 2008).

o Laser-Activated Irrigation (LAI) with Erbium and apical extrusion

George and Walsh [75] in an in vitro dye study, reported extrusion of irrigant when using both Er:YAG and Er,Cr:YSGG lasers as well as with needle irrigation (conventional needle 25 G and Max-I-Probe). There were no significant effects for the variables of laser type (Er:YAG with 400 micron flat tip at 1 W for 5 sec = Er,Cr:YSGG with 400 micron conical tip at 0.75 W for 5 sec) or optical tip design (straight = conical ends). The variable of distance of the instrument tip from the apex was only significant for the two needle groups (5 mm > 10 mm) but not for any of the laser groups.

In all laser groups, considerable apical extrusion occurred, with the maximum distance of extrusion from the apex being some 90 mm. The maximum concentration of dye (measured by pixels per grid square) was observed at a distance of 20 mm from the apex in all laser experimental groups. There was a three-fold increase in dye extrusion in the ISO #20 apex group versus the ISO #15 group when matched for the same laser system, fiber design, and distance from the apex.

Overall, for the same apical foramen size, there was no statistically significant difference between the various laser groups and the conventional needle control in terms of the volume of fluid extrusion. However, with the laser treatments, the irrigant was distributed further from the apex by a factor of approximately four times.

George and Walsh [75] concluded that pulsed erbium lasers can create pressure waves of sufficient force to propel microdroplets of aqueous irrigant beyond the apical constriction, especially when the apical foramen is larger or when the fiber is positioned too close to the apical foramen. Thus, caution should be used when using such lasers in combination with irrigants such as sodium hypochlorite.

o Laser-Activated Irrigation (LAI) with Diode-lasers

Hmud et al. [76] examined whether near infrared 940 and 980 nm diode lasers (Biolase Ezlase and Sirona Sirolaser, respectively) could induce cavitations in aqueous media (distilled water, water, aerated tap water, degassed distilled water, ozonated water, 3 and 6% hydrogen peroxide). It appeared that both diode laser systems could induce cavitation in water-based media by the formation and implosion of water vapor. Laser power played a more important role than pulse frequency or pulse interval. These cavitations, however, developed after several seconds of laser operation and were visible to the human eye with the aid of light and magnification. This clearly differs from the action of erbium lasers, where the bubble forms instantly (only a few microseconds after onset of the pulse) at the fiber tip and is invisible to the human eye because it exists for only a few hundred microseconds (Blanken et al. 2009).

Deleu et al. [74] investigated cavitation with a 980-nm diode laser (Fox diode laser, A.R.C. laser GmbH, Nürnberg, Germany). Bubble formation was only observed beyond 7 W. However, this setting can present serious concerns towards thermal safety in the clinical situation and should be considered inappropriate. In this study, the diode laser was significantly more effective at removing debris from the groove than conventional syringe irrigation, but significantly less effective than the Er:YAG laser with conventional fiber (Deleu et al. 2013). The bubble formation for the diode laser was limited to the area just around the fiber tip and was considered more to be the result of steaming than of generation of vapor bubbles (cavitation).

o Laser-Activated Irrigation (LAI) with Nd:YAG 1320 nm

This Nd:YAG laser operates at a higher wavelength than the classical Nd:YAG laser of 1064 nm. This higher wavelength may result in a better absorption in water, and hence the formation of cavitation bubbles.

Moon et al. [77] using 1320-nm Nd:YAG laser activation with either NaOCl or EDTA demonstrated a better sealer penetration into dentinal tubules than NaOCl irrigation alone and as effective as EDTA final flush. Additional use of laser with EDTA did not improve the quality of obturation in the curved canals.

c) The second era – part II: activation of the irrigant in the root canal and induction of cavitation and fluid motion – laser fiber hovering over the root canal orifice: Hovering Laser-Activated Irrigation or H-LAI

- **Erbium lasers**

In 2010, DiVito introduced another design of the erbium laser tip, the so called PIPS-tip, which stands for "Photon-Initiated Photoacoustic Streaming" [78]. This tip has a tapered radial firing end with the distal 3 mm of the polyamide sheath removed. In comparison to other tips, the PIPS tip is to be held in the pulp chamber, instead of being inserted into root canal. Pulsed laser operation induces photoacoustic shockwaves in the irrigant which travel throughout the RC system and allow their 3-D movement. Using low, sub-ablative pulse energies (only 10 or 20 mJ) the PIPS technique minimizes undesirable thermal effects on the dentinal walls seen with other methodologies. The use of very short (50 microseconds) laser pulses results - even with low pulse energies - in high peak powers, enables this powerful physical phenomenon, resulting in increased debris and smear layer removal with minimal or no thermal damage to the organic dentinal structure.

Evaluation of the PIPS technique has been performed in vitro both in EDTA and in NaOCl showing a three-dimensional reduction of the bacterial load and its associated biofilm in the root canal system [79, 80]. With conical tips the optodynamic energy conversion efficiency is three times higher in comparison to when flat tips are used.

A comparison between the PIPS tips 400/14 & 600/9 versus the XPulse tips 400/14 & 600/14 (both Fotona, Ljubljana, Slovenia) demonstrated that the tips (PIPS versus XPulse and with the same fiber diameter) demonstrated comparable results for debris removal out of a root canal wall groove model with the tips at the level of the orifice and when pulse energy was kept identical for the fiber diameter (20 mJ or 40 mJ) respecting a pulse time of 50 microseconds. The setting at 40 mJ performed better than at 20 mJ. Care however has to be taken with the 40 mJ energy. The present findings are based on yet unpublished data from the Ghent Dental Photonics Research Clustre.

- **Apical extrusion**

Peeters and Moodutu [81] investigated irrigant extrusion with LAI in vivo. Endodontic treatment of necrotic teeth was performed using radio-opaque NaOCl as the irrigant, activated with an Er,Cr:YSGG laser at 1W and 35Hz (28.5 mJ) with a plain quartz tip of 400 µm diameter hovering above the orificium (60s for teeth with one canal or two canals and 120s for teeth with three or four canals). This clinical study did not show evidence of apical extrusion after laser activation of the irrigants.

III. CONCLUSION

There are today two approaches to using endodontic fibers for root canal cleaning and disinfection.

The first approach is to use the fiber in a dried root canal. Due to the straight forward laser beam, a spiral motion with the fiber is needed in order to expose the root canal wall. Removal of debris and smear layer, and interaction with the biofilm is possible. The effect of NIR lasers is predominantly based on photothermal interaction. With MID lasers ablation damage is possible, although subablative energies are recommended.

The second approach is the use of the fiber in the irrigant itself. This can be done in the root canal or in the pulp chamber at the level of the orifice. The aim is to create cavitation or liquid motion (laser-activated irrigation / LAI). Cavitation is based on the creation of vapor bubbles. Liquid agitation is possible thanks to expanding and imploding bubbles. With the present day technology it is possible to use low energy and short activation times. The combination results in the creation of high peak powers. The result is the agitation of the liquid without risk of thermal damage. Care, however, has to be taken. Although there are no clinical reports published yet on the risk of over-extrusion of the liquid, it is clear that violent fluid agitation is possible with erbium-lasers. LAI has also been proven to be at least as effective but even better than ultrasound for biofilm removal and debris removal.

REFERENCES

1. Hülsmann M, Peters OA, Dummer PMH (2005) Mechanical preparation of root canals: shaping goals, techniques and means. Endod Topics 10:30-76.
2. Gulabivala K, Patel B, Evans G, Ng Y-L (2005) Effects of mechanical and chemical procedures on root canal surfaces. Endod Topcis 10:103-122.

3. Peters OA, Laib A, Göhring TN, Barbakow F (2001a) Changes in root canal geometry after preparation assessed by high-resolution computed tomography. J Endod 27: 1–6.
4. Peters OA, Schönenberger K, Laib A (2001b) Effects of four Ni–Ti preparation techniques on root canal geometry assessed by micro-computed tomography. Int Endod J 34: 221–230.
5. Peters OA, Peters CI, Schönenberger K, Barbakow F (2003) ProTaper rotary root canal preparation: effects of canal anatomy on final shape analysed by microCT. Int Endod J 36: 86–92.
6. Mannan G, Smallwood E, Gulabivala K (2001) The influence of access cavity design on filing of canals in anterior teeth. Int Endod J 34: 176–183.
7. Paqué F, Laib A, Gautsci H, Zehnder M (2009) Hard tissue debris accumulation analysis by high-resolution computed tomography scans. J Endod 2009 35:1044-1047.
8. Sen BH, Wesselink PR, Tûrkûn M (1995) The smear layer: a phenomenon in root canal therapy. Int Endod J 28: 141–148
9. Ørstavik D, Haapasalo M (1990) Disinfection by endodontic irrigants and dressings of experimentally infected 9. dentinal tubules. Endod Dent Traumatol 16: 142–149.
10. Saunders WP, Saunders EM (1992) The effect of smear layer upon the coronal leakage of gutta-percha fillings and a glass ionomer sealer. Int Endod J 25: 245–249.
11. Baumgartner C, Mader CL (1987) A scanning electron microscopic evaluation of four root canal irrigation regimens. J Endod 13: 147–156.
12. Baumgartner JC, Ibay AC. (1987) The chemical reactions of irrigants used for root canal debridement. J Endod 13: 47–51.
13. Sundqvist G, Figdor D. (1998) Endodontic Treatment of apical periodontitis. In: Orstavik D, Pitt Ford T.R. (eds) Essential Endodontology - Prevention and treatment of apical periodontitis, Blackwell Science,London, pp 243-27714.
14. Gu LS, Kim JR, Ling J, Choi KK, Pashley DH, Tay FR (2009) Review of contemporary irrigant agitation techniques and devices. J Endod 35:791-80415.
15. van der Sluis LW, Versluis M, Wu MK, Wesselink PR (2007) Passive ultrasonic irrigation of the root canal: a review of the literature. Int Endod J 40:415-426.
16. Metzler RS, Montgomery S (1989) The effectiveness of ultrasonics and calcium hydroxide for the debridement of human mandibular molars. J Endod 15: 73-78.
17. Sabins RA, Johnson JD, Hellstein JW (2003) A comparison of the cleaning efficacy of short-term sonic and ultrasonic passive irrigation after hand instrumentation in molar root canals. J Endod 29: 674-678.
18. Lee SJ, Wu MK, Wesselink PR (2004) The effectiveness of syringe irrigation and ultrasonics to remove debris from simulated irregularities within prepared root canal walls. Int Endod J 37: 672-678.
19. Cameron JA (1987) The use of 4 per cent sodium hypochlorite, with or without ultrasound, in cleansing of uninstrumented immature root canals; SEM study. Aust Dent J 32:204-213.
20. Alaçam C (1987) Scanning electron microscope study comparing the efficacy of endodontic irrigating systems. Int Endod J 20:287-294.
21. Cunningham WT, Martin H (1982) A scanning electron microscope evaluation of root canal débridement with the endosonic ultrasonic synergistic system. Oral Surg Oral Med Oral Pathol 53:527-531
22. Huque J, Kota K, Yamaga M, Iwaku M, Hoshino E (1998) Bacterial eradication from root dentine by ultrasonic irrigation with sodium hypochlorite. Int Endod J 31:242-250
23. Spoleti P, Siragusa M, Spoleti MJ (2003) Bacteriological evaluation of passive ultrasonic activation. J Endod 29:12-14.
24. Weber CD, McClanahan SB, Miller GA, Diener-West M, Johnson JD (2003) The effect of passive ultrasonic activation of 2% chlorhexidine or 5.25% sodium hypochlorite irrigant on residual antimicrobial activity in root canals. J Endod 29:562-564 .
25. Macedo RG, Wesselink PR, Zaccheo F, Fanali D, Van Der Sluis LW (2010) Reaction rate of NaOCl in contact with bovine dentine: effect of activation, exposure time, concentration and pH. Int Endod J 43: 1108-111.
26. Lee SJ, Wu MK, Wesselink PR (2004) The effectiveness of syringe irrigation and ultrasonics to remove debris from simulated irregularities within prepared root canal walls. Int Endod J 37: 672-678.
27. Amato M, Vanoni-Heiniken I, Hecker H, Weiger R (2011) Curved versus straight root canals: the benefit of activated irrigation techniques on dentin debris removal. Oral Srg Oral Med Oral Pathol Oral Radiol Endod 111: 529-53428. Jiang LM, Verhaagen B, Versluis M, Van Der Sluis (2010) Influence of the Oscillation Direction of an Ultrasonic File on the Cleaning Efficacy of Passive Ultrasonic Irrigation. J Endod 36:1372-1376.
29. Dederich DN, Zakariasen KL, Tulip J (1984) Scanning electron microscopic analysis of canal wall dentin following nedodymium-yttrium-aluminum-garnet laser irradiation. J Endod 10:428-431.
30. Dederich DN, Zakaraisen KL, Tulip J (1985) SEM analysis of dyed canal dentin following Nd:YAG laser irradiation J Dent Res 64:329.
31. Zakariasen KL, Dederich DN, Tulip J (1985) Nd:YAG laser fusion of dentin plugs in root canals. J Dent Res 64:239.
32. Gutknecht N, Behrens VG (1991) Instrumentation of root canal walls with Nd-YAG laser. ZWR 100:748-50, 752, 755.
33. Behrens V, Gutknecht N, Reuziehausen R, Lampert F (1993) Die Transmission und Absorption der Temperatur und Energie des Nd-YAG-lasers im Dentin. ZWR 102:629-634.
34. Matsumoto H, Yoshimine Y, Akamine A (2011) Visualization of Irrigant Flow and Cavitation Induced by Er:YAG Laser within a Root Canal Model. J Endod 37:839-843.
35. Michiels R, Vergauwen TE, Mavridou A, Meire M, De Bruyne M, De Moor RJ (2010) Investigation of coronal leakage of root fillings after smear-layer removal with EDTA or Nd:YAG lasing through capillary-flow porometry. Photomed Laser Surg 28 Suppl 2:S43-50.
36. Pirnat S, Lukac M, Ihan A. Study of the direct bactericidal effect of Nd:YAG and diode laser parameters used in endodontics on pigmented and nonpigmented bacteria. Lasers Med Sci. 2011 26:755-61.
37. Yasuda Y, Kawamorita T, Yamaguchi H, Saito T (2010) Bactericidal effect of Nd:YAG and Er:YAG lasers in experimentally infected curved root canals. Photomed Laser Surg 28 Suppl 2:S75-8.
38. Meire MA, Coenye T, Nelis HJ, De Moor RJ (2012) Evaluation of Nd:YAG and Er:YAG irradiation, antibacterial photodynamic therapy and sodium hypochlorite treatment on Enterococcus faecalis biofilms. Int Endod J 45:482-491.
39. Klinke T, Klimm W, Gutknecht N (1997) Antibacterial effects of Nd:YAG laser irradiation within root canal dentin. J Clin Laser Med Surg 15:29-31.
40. Schoop U, Kluger W, Moritz A, Nedjelik N, Georgopoulos A, Sperr W (2004) Bactericidal effect of different laser systems in the deep layers of dentin. Lasers Surg Med 35:111-116.
41. Orstavik D, Haapasalo M (1990) Disinfection by endodontic irrigants and dressings of experimentally infected dentinal tubules. Endod Dent Traumatol 6:142-149.
42. Hibst R, Graser R, Udart M, Stock K (2010) Mechanism of high-power NIR laser bacteria inactivation. J Biophotonics 3:296-30343.
43. Kishen A, Asundi A. (2007) Fundamentals and applications of biophotonics in dentistry. Imperial College Press, London.
44. Meire M, De Moor RJG (2007) Lasers in endodontics: laser disinfection, an added value? ENDO 3, 159-172.
45. De Moor RJG, Torbeyns D, Meire M (2009) Lasers in endodontics. Part 2: Root canal wall cleanliness and modification. ENDO 3, 19-33.
46. Takeda FH, Harashima T, Kimura Y, Matsumoto K (1998) Comparative study about the removal of smear layer by three types of laser devices. J Clin Laser Med Surg 16:117-122.
47. Takeda FH, Harashima T, Kimura Y, et al (1999) A comparative study of removal of smear layer by three endodontic irrigants and two types of laser. Int Endod J 32:32-39.
48. Takeda FH, Harashima T, Eto JN, et al (1998) Effect of Er:YAG laser treatment on the root canal walls of human teeth: an SEM study. Endod Dent Traumatol 14:270-273.
49. Takeda FH, Harashima T, Kimura Y, Matsumoto K (1998) Efficacy of Er:YAG laser irradiation in removing debris and smear layer on root canal walls. J Endod 24:548-551.

50. Kimura Y, Yonaga K, Yokoyama K, Kinoshita J-I, Ogata Y, Matsumoto K (2002) Root surface temperature increase during Er:YAG laser irradiation of root canals. J Endod 28:76-78.
51. Vergauwen TE, Michiels R, Torbeyns D, Meire M, De Bruyne M, De Moor RJ (2014) Investigation of Coronal Leakage of Root Fillings after Smear Layer Removal with EDTA or Er,Cr:YSGG Laser through Capillary Flow Porometry. Int J Dent 2014:593160.
52. Kesler G, Gal R, Kesler A, Koren R (2002) Histological and scanning electron microscope examination of root canal after preparation with Er:YAG laser microprobe: a preliminary in vitro study. J Clin Laser Med Surg 20:269-277.
53. Harashima T, Takeda FH, Zhang C, Kimura Y, Matsumoto K (1998) Effect of argon laser irradiation on instrumented root canal walls. Endod Dent Traumatol 14:26-30.
54. Ebihara A, Majaron B, Liaw LH, Krasieva TB, Wilder-Smith P (2002) Er:YAG laser modification of root canal dentin: influence of pulse duration, repetitive irradiation and water spray. Lasers Med Sci 17: 198-207.
55. Biedma BM, Patino PV, Park SA, et al. (2005) Comparative study of root canals instrumented manually and mechanically, with and without Er:YAG laser. Photomed Laser Surg 23:465-469.
56. Matsuoka E, Kimura Y, Matsumoto K (1998) Studies on the removal of debris near the apical seats by Er:YAG laser and assessment with a fiberscope. J Clin Laser Med Surg 16:255-261.
57. Matsuoka E, Yonaga K, Kinoshita J, Kimura Y, Matsumoto K (2000) Morphological study on the capability of Er:YAG laser irradiation for root canal preparation. J Clin Laser Med Surg 18: 215-219.
58. Moritz A, Schoop U, Goharkhay K, Jakolitsch S, Kluger W, Wernisch J, Sperr W (1999) The bactericidal effect of Nd:YAG, Ho:YAG, and Er:YAG laser irradiation in the root canal: an in vitro comparison. J Clin Laser Med Surg 17:161-164.
59. Schoop U, Moritz A, Kluger W et al. (2002) The Er:YAG laser in endodontics: results of an in vitro study. Lasers Surg Med 30:360-364.
60. Mehl A, Folwaczny M, Haffner C, Hickel R (1999) Bactericidal effects of 2.94 microns Er:YAG laser radiation in dental root canals. J Endod 25:490-493.
61. Vezzani MS, Pietro R, Silva-Sousa YT, Brugnera-Junior A, Sousa-Neto MD (2006) Disinfection of root canals using Er:YAG laser at different frequencies. Photomed Laser Surg 24:499-502.
62. Perin FM, Franca SC, Silva-Sousa YT et al. (2004) Evaluation of the antimicrobial effect of Er:YAG laser irradiation versus 1% sodium hypochlorite irrigation for root canal disinfection. Austr Endod J 30:20-22 .
63. Stabholz A, Zeltser R, Sela M, Peretz B, Moshonov J, Ziskind D, Stabholz A (2003)The use of lasers in dentistry: principles of operation and clinical applications. Compend Contin Educ Dent. 24:935-948.
64. Blanken JW, De Moor RJG, Meire M, Verdaasdonk RM (2009) Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal: part 1—a visualization study. Lasers Surg Med 41:514–519.
65. Blanken JW, Verdaasdonk RM (2007) Cavitation as a working mechanism of the Er,Cr:YSGG laser in endodontics: a visualization study. J Oral Laser Appl 7:97–106.
66. de Groot SD, Verhaagen B, Versluis M, Wu MK, Wesselink PR, van der Sluis LW (2009)Laser-activated irrigation within root canals: cleaning efficacy and flow visualization. Int Endod J 42:1077–1083.
67. Matsumoto H, Yoshimine Y, Akamine A (2011) Visualization of irrigant flow and cavitation induced by Er:YAG laser within a root canal model. J Endod 37:839-43.
68. Gregoric P, Jezersek M, Mozina J (2012) Opto-dynamic energy conversion efficiency during an Er:YAG laser pulse delivery into a liquid through different fiber-tip geometries. J Biomed Opt 17:075006-1-919.
69. Flotte TJ, Doukas A (1992) Laser induced pressure effects. SPIE, Laser Tissue Interaction, 1646 :295–300.
70. Song WG, Hong MH, Lukyanchuk B, Chong TC (2004) Laser-induced cavitation bubbles for cleaning of solid surfaces. J Appl Phys 95:2952–295621.
71. Brujan EA (2009) Cardiovascular cavitation. Med Eng Phys 31:742–751.
72. De Moor RJ, Blanken JW, Meire M, Verdaasdonk RM (2009) Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal: part 2—evaluation of the efficacy. Lasers Surg Med 41:520–523.
73. De Moor RJG, Meire M, Goharkhay K, Moritz A, Vanobbergen J (2010) Efficacy of ultrasonic versus laser-activated irrigation to remove artificially placed dentin debris plugs J Endod 36:1580–1583.
74. Deleu E, Meire MA, De Moor RJ (2013) Efficacy of laser-based irrigant activation methods in removing debris from simulated root canal irregularities. Lasers Med Sci. Oct 5. [Epub ahead of print].
75. George R, Meyers IA, Walsh LJ (2008) Laser activation of endodontic irrigants with improved conical laser fiber tips for removing smear layer in the apical third of the root canal. J Endod 34:1524-1527.
76. Hmud R, Kahler WA, George R, Walsh LJ (2010) Cavitational effects in aqueous endodontic irrigants generated by near-infrared lasers. J Endod. 36:275-278.
77. Moon YM, Kim HC, Bae KS, Baek SH, Shon WJ, Lee W (2012) Effect of laser-activated irrigation of 1320-nanometer Nd:YAG laser on sealer penetration in curved root canals. J Endod 38:531-535.
78. DiVito E, Peters OA, Olivi G (2012) Effectiveness of the erbium:YAG laser and new design radial and stripped tips in removing the smear layer after root canal instrumentation. Lasers Med Sci 27:273-280.
79. Peters OA, Bardsley S, Fong J, Pandher G, Divito E (2011) Disinfection of root canals with photon-initiated photoacoustic streaming. J Endod 37:1008-1012.
80. Lukaz M, Pustovrh G (2013) Modeling Photoacoustic efficiency during Erbium laser endodontics. J LA & HA 2 :1-7.
81. Peeters HH, Mooduto L (2013) Radiographic examination of apical extrusion of root canal irrigants during cavitation induced by Er,Cr:YSGG laser irradiation: an in vivo study. Clin Oral Invest 17:2105-2012.