Lasers Med Sci (2015) 30:831–835
DOI 10.1007/s10103-013-1442-y

ORIGINAL ARTICLE

Efficacy of laser-based irrigant activation methods in removing debris from simulated root canal irregularities

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Received: 14 June 2013 / Accepted: 16 September 2013 / Published online: 5 October 2013

Abstract In root canal therapy, irrigating solutions are essential to assist in debridement and disinfection, but their spread and action is often restricted by canal anatomy. Hence, activation of irrigants is suggested to improve their distribution in the canal system, increasing irrigation effectiveness. Activation can be done with lasers, termed laser-activated irrigation (LAI). The purpose of this in vitro study was to compare the efficacy of different irrigant activation methods in removing debris from simulated root canal irregularities. Twenty-five straight human canine roots were embedded in resin, split, and their canals prepared to a standardized shape. A groove was cut in the wall of each canal and filled with dentin debris. Canals were filled with sodium hypochlorite and six irrigant activation procedures were tested: conventional needle irrigation (CI), manual-dynamic irrigation with a tapered gutta percha cone (manual-dynamic irrigation (MDI)), passive ultrasonic irrigation, LAI with 2,940-nm erbium-doped yttrium aluminum garnet (Er:YAG) laser with a plain fiber tip inside the canal (Er-flat), LAI with Er:YAG laser with a conical tip held at the canal entrance (Er-PIPS), and LAI with a 980-nm diode laser moving the fiber inside the canal (diode). The amount of remaining debris in the groove was scored and compared among the groups using non-parametric tests. Conventional irrigation removed significantly less debris than all other groups. The Er:YAG with plain fiber tip was more efficient than MDI, CI, diode, and Er:YAG laser with PIPS tip in removing debris from simulated root canal irregularities.

Keywords Root canal irrigation · Laser-activated irrigation · Erbium laser · Diode laser · Passive ultrasonic irrigation · Manual-dynamic irrigation

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Introduction

Root canal treatment is performed to prevent or treat apical periodontitis. It involves the cleaning and shaping of the root canal system, a complex three-dimensional microstructure in which irregular structures such as isthmuses, apical deltas, and lateral canals may be present. The shaping phase aims to enlarge the canal yet simultaneously creates a smear layer along the root canal walls [1] and packs debris in the canals' irregularities [2]. The instruments, however, do not address the entire canal system [3]. Therefore, mechanical instrumentation is always combined with irrigation in order to clean the areas that cannot be reached by instruments, to remove the smear layer, and to promote disinfection.

Irrigation of the root canal is traditionally performed using a syringe-needle combination. However, the penetration of irrigant in the apical third and beyond the main canal is limited [4, 5], and activation is suggested to improve their distribution in the canal system and increase irrigation effectiveness.

Passive ultrasonic irrigation (PUI) [6] refers to the activation of irrigants through an oscillating non-cutting file placed in the prepared root canal, and its efficacy has been demonstrated in numerous studies [4, 7]. Although cavitational effects have been observed with PUI [8], its main cleaning action is attributed to acoustic microstreaming.

In manual-dynamic irrigation (MDI), a gutta percha cone with dimensions corresponding to these of the prepared root canal is used with push-pull strokes. MDI appears to clean canal surfaces better than conventional irrigation [9] and results in improved penetration and exchange of irrigating solutions [10].

Laser-activated irrigation (LAI) refers to the activation of irrigant solutions with lasers. In this respect, erbium lasers (erbium, chromium doped yttrium scandium gallium garnet (Er,Cr:YSGG)—2.780 nm or erbium-doped yttrium aluminum garnet (Er:YAG)—2.940 nm) have been shown to be very effective [11]. The efficacy of erbium lasers is attributed to real cavitation effects, namely the formation and immediate implosion of vapor bubbles at the fiber tip, causing very rapid fluid movement in the canal [12, 13]. Together with the shock waves [14] and accompanying secondary cavitation bubbles, removal of debris from regions which remain untouched by endodontic instruments during shaping procedures is enhanced. In fact, LAI with erbium lasers has been proven to be more effective than PUI and conventional needle irrigation (CI) in the removal of debris [11, 15, 16] and apical smear layer [17, 18]. LAI is mostly done with flat-ended fiber tips. Recently, a tip with a tapered radial firing end and 3-mm denuded fiber (photon-initiated photoacoustic streaming or PIPS tip) was introduced [18, 19].

It appears that LAI can also be obtained with near infrared diode lasers [20]. This is of particular interest as these devices are markedly cheaper and more compact than solid-state erbium laser systems.

The purpose of this in vitro study was to compare the efficacy of different laser- and non-laser-based irrigant activation methods in removing debris from artificial grooves in root canal walls.

Materials and methods

Study model

The experimental setup was based on the model described by Lee et al. [4] and modified by De Moor et al. [11, 16]. Straight roots (n=25) from extracted human maxillary canines were selected. The canals were prepared to an ISO size 30 up to their working length (1-mm short of the apical foramen) with a 6 % taper using profile series (Dentsply Maillefer, Ballaigues, Switzerland), under 2.5 % sodium hypochlorite (NaOCl, University Hospital Pharmacy, Ghent, Belgium) irrigation using a 27-gage endodontic needle (Monoject; Sherwood Medical, St. Louis, MO, USA). The roots were imbedded in acrylic (Orthocryl, Dentaurum GmbH & Co., Germany) and sliced longitudinally in the root's mesio-distal plane using an IsoMet low-speed saw (Buehler, Dusseldorf, Germany). The two obtained halves were reassembled and fixated with the help of metal bolts through holes that were made in the resin block prior to slicing (Fig. 1). Using a customized ultrasonic tip (Dentsply Maillefer), a groove of 4 mm in length, 0.5-mm deep, and 0.2-mm wide, was made in the wall of one half of each root canal. The 6 % taper ISO 30 Profile (Dentsply Maillefer), was then re-inserted to remove accumulated debris and refine the preparation. The groove started 1-mm short of working length and was filled with a mixture of dentin debris and 2.5 % NaOCl solution. The models were reassembled and canals were filled to the brim with 2.5 % NaOCl. Pilot tests had shown that a single model could be reused up to six times without any visible damage to the canal wall at microscopic level. Therefore, the 25 models were used repeatedly in the six experimental groups, which are shown in Table 1.

Irrigation protocols

Six irrigation methods were studied, each repeated 20 times. 2.5 % NaOCl was used as the irrigating solution in all instances. In group 1 (conventional irrigation, CI), syringe irrigation with 4 ml of NaOCl was performed using a 27-gage endodontic needle (Monoject; Sherwood Medical, St Louis, MO, USA) placed 1-mm short of the working length. The needle was moved up and down at the apical half of the canal, with a flow rate of approximately 0.3 mL/s. The canal was dried using paper points ISO 30, 2 % taper.

In group 2, MDI was used. A well-fitting ISO 30 taper 0.06 gutta percha cone (Henry Schein, Vilvoorde, Belgium) was inserted to working length. A total of 100 push-pull strokes were performed during approximately 60 s.

In group 3 (PUI), a non-cutting #20 file (Irrisafe, Satelec Acteon, Mérignac, France) driven by an ultrasonic device (Suprasson Pmax Newtron, Satelec) at a power setting of 50 % was used in the canal for 20 s. The tip of the Irrisafe was kept steady 1-mm short of working length.

In group 4 (Er-flat), a 2.940-nm Er:YAG laser (AT Fidelis, Fotona, Ljubljana, Slovenia) equipped with a hand piece (R14, Fotona) holding a plain 300-μm diameter fiber tip, 14 mm in length (PRECISO 300/14, Fotona) was used to activate the irrigant. The tip was inserted 5 mm above the working length and held still during 5 s of laser activation, four repetitions with 5-s interval. The pulse energy was 60 mJ at 20 Hz and 50 μs of pulse length. The efficiency of the fiber is 90 %; the air and water spray was turned off.

The same Er:YAG laser was used in group 5 (Er-PIPS) with a conical fiber tip, 14 mm in length (PIPS 300/14, Fotona). The laser tip was introduced no further than 4 mm in the canal and held still. The laser was operated with a hand piece (R14 PIPS, Fotona) at 40 mJ, 20 Hz, and pulse length of 50 μs for 5 s, four repetitions as described in group 4. The efficiency of the fiber is 90 %; the air and water spray was turned off.

In group 6 (diode), a 980-nm diode laser (Fox diode laser, A.R.C. laser GmbH, Nürnberg, Germany) was used. The 200-μm plain fiber was inserted in the root canal no further than 2 mm from working length and moved in an up and down motion along the groove. The fiber was activated for 18 s at an output power of 7.5 W and 25 Hz. This particular setting was based on pilot investigations where it was observed that activity remained limited to the fiber tip and the effects as described by Hmud et al. [20] did not occur below 7.5 W.

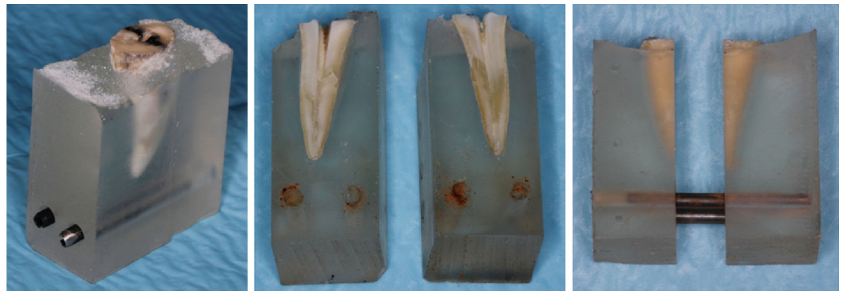

Fig. 1 The root canal groove model as used in this study

At the end of the procedures, all roots from groups 2–6 were rinsed with 2-ml NaOCl (2.5 %) and dried with paper points ISO 30, 2 % taper (Dentsply Maillefer).

Evaluation of dentin debris removal

Pictures (×13.6 magnification) of each groove were taken before and after each irrigation procedure using a digital camera mounted on an operating microscope (OPMI Pico, Carl Zeiss, Göttingen, Germany). The sequence of all the pictures was randomized, and two calibrated examiners blinded to the irrigation protocol scored each picture twice, with a 2-week interval. The following scoring system was used to quantify the debris; 0—the groove was empty, 1—less than half the groove was filled with debris, 2—more than half of the groove was filled with debris, and 3—the groove was completely filled with debris. If the scores amongst the two examiners differed, the picture was discussed until a consensus was reached.

Statistical analysis

The inter- and intra-rater agreement was determined (Cohen kappa). The differences in debris scores between the groups were analyzed by means of the Kruskal–Wallis and the Mann–Whitney *U* test. The significance level was set at 0.05.

Table 1 Distribution of debris scores for each irrigant activation method

Activation method	Debris scores (%)				
	0	1	2	3	Number
CI	0	6 (30)	9 (45)	5 (25)	20
MDI*'	10 (50)	10 (50)	0	0	20
PUI*	14 (70)	6 (30)	0	0	20
Er-flat*	17 (85)	3 (15)	0	0	20
Er-PIPS*'	8 (40)	12 (60)	0	0	20
Diode*'	9 (45)	9 (45)	2 (10)	0	20

CI conventional irrigation, *MDI* manual-dynamic irrigation, *PUI* passive ultrasonic irrigation

*Significantly different from CI

Significantly different from Er-flat

Results

The debris scores after irrigation with the six different techniques are displayed in Table 1. The Cohen kappa coefficient of inter-rater agreement was 0.74, whilst the intra-observer reliability scores were 0.9 and 0.92. Conventional irrigation removed significantly less debris from the groove than the three laser groups, MDI and PUI ($P<0.001$). The erbium laser with the flat fiber tip removed significantly more debris than the diode laser ($P=0.007$), the MDI ($P=0.02$), and the erbium laser using the PIPS tip ($P=0.004$), but the amount of debris was not statistically different from that found in the PUI group. No statistically significant differences were observed between PUI, MDI, and Er-PIPS groups.

Discussion

The experimental model of the present study has been used in previous studies to investigate the efficacy of irrigant activation devices or techniques [15, 16, 21]. The groove in the root canal wall simulates an irregularity inaccessible to instruments but in which significant amounts of debris can remain or be packed during shaping procedures [2]. Removal of debris of such groove thus is an indication of cleaning beyond the main canal. The advantage of the groove model is the standardized dimensions of the canal and the groove, allowing a consistent evaluation. Although artificial grooves may not represent the complexity of the root canal system, this setup allows a standardized comparison between different irrigation protocols.

All tested activation methods produced cleaner canal wall grooves compared to syringe irrigation. This observation is in accordance with other studies investigating the efficacy of manual-dynamic irrigation [22, 23], PUI [4] and LAI with erbium lasers [16].

The 980-nm diode laser with its present power settings was significantly more effective at removing debris from the groove than conventional irrigation performed with a syringe, but significantly less effective than the Er:YAG laser with conventional fiber. Hmud et al. [20] observed formation of cavitations at the end of the fiber tip with 940- and 980-nm diode lasers. Depending on the output power, these cavitations developed after several seconds 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 [12]. For the 980-nm diode laser, 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. Although the models were reused a limited number of times, one study model in the diode group had to be replaced after four activations because of damage in the form of carbonization of the root canal wall (Fig. 2), indicating excessively high local temperatures. The absorption of diode laser radiation in aqueous solutions is far less than that of erbium lasers [24] and contact of the fiber with the root canal wall dentin then results in burning of the dentin. Pilot observations also revealed that the fluid movement induced by the diode laser was limited to the tip of the fiber and hence the fiber was constantly moved up and down in the canal along the groove. Given the limited cleaning action for a high output power, the 980-nm diode laser does not seem to be an efficient tool for NaOCl activation.

According to the manufacturer, the PIPS tip has a greater lateral emission of energy compared to plain fibers, due to the conical end and the distal 3-mm without coating. Together with very short pulses, this enables better use of the laser energy, creating photoacoustic shockwaves in the irrigant, enhancing their effectiveness. LAI with the Er:YAG laser with a conventional flat-ended fiber was significantly more effective than with a PIPS tip. According to the manufacturers' guidelines, the PIPS tip was held in the coronal portion of the canal. When the laser was activated, bits of NaOCl were forced out of the canal with every pulse, resulting in the PIPS tip to be in a fluid-free canal entrance after about 4 s. This evidently limits the further action of the tip. No such problem was encountered using the plain tip at 5 mm from working length.

Fig. 2 Carbonization of the root canal wall in a diode laser-treated sample

While LAI with flat tips results in rapid fluid motion through expanding and imploding vapor bubbles [13], the cleaning mechanism of PIPS is unclear and differs from reported investigations [18]. Whether cavitation bubbles as with plain-ended fibers do occur with PIPS tips is unknown. The suggested photoacoustic shockwave resulting in streaming of the irrigant (PIPS) through the entire canal system remains unknown and is still to be proven.

A previous study [16] demonstrated that 4×5-s LAI with Er:YAG resulted in significantly less debris in the grooves than when exposed to 20 s of PUI. However, no significant difference between these groups was noted in the present study. The most likely explanation for this difference in outcome is higher pulse energy and a smaller fiber diameter (75 mJ and 200 μm respectively) in the former study. Smaller fiber diameters and higher pulse energies produce higher fluences and might enhance cavitation. The 300-μm fiber used in the present study was the smallest available diameter for the device and the energy settings were those recommended by the manufacturer of the fiber tip. The present data also confirm the effectiveness of PUI being in accordance with previous studies [25, 26].

MDI produced better cleaning efficacy than syringe irrigation but significantly worse than LAI with plain tip. An additional finding after MDI was accumulation of debris in the canal portion apical to the groove in 40 % of the teeth, indicating that debris from the groove had been displaced apically. This observation raises concerns as apical displacement of debris may provoke extrusion beyond the apical foramen and result in post-operative pain [27].

Conclusion

In this in vitro model, conventional irrigation removed significantly less debris than all other groups. The Er:YAG laser with plain fiber tip inside the canal was more efficient than manual-dynamic irrigation, 980-nm diode laser and Er:YAG laser with PIPS tip in removing debris from simulated root canal irregularities.

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