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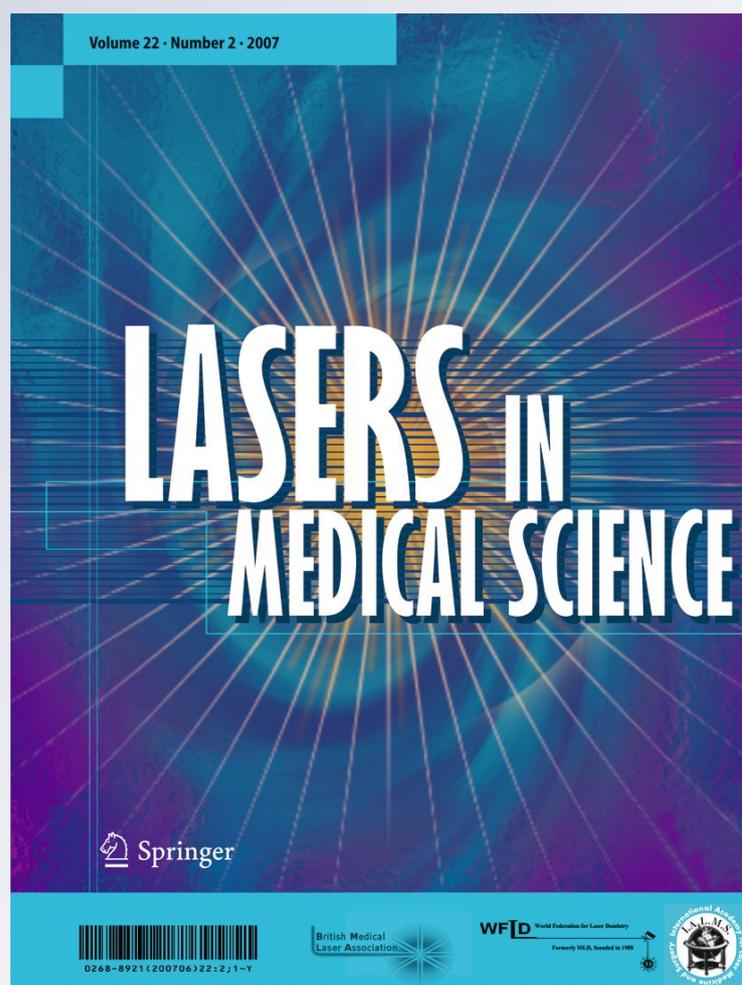
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Effectiveness of the erbium:YAG laser and new design radial and stripped tips in removing the smear layer after root canal instrumentation

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Abstract The aim of this study was to analyze in vitro the debriding ability of an Er:YAG laser system (2,940 nm) equipped with a newly designed radial and stripped tip of 400 µm diameter by scanning electron microscopy (SEM). A total of 80 single-rooted extracted human teeth were endodontically prepared with rotary instrumentation and standardized chemical irrigation using 5.25% sodium hypochlorite. At the end of mechanical instrumentation, four different final protocols were used. Group 1 was irrigated for 2 min with saline water as a control group. Groups 2, 3 and 4 were irradiated with an Er:YAG laser at 25 mJ and 15 Hz with a pulse duration of 50 µs and laser spray off using the tip in the coronal opening of the wet root canal. Different solutions and irradiation times were used: *group 2* 20 s, laser irradiation in sterile distilled water, wet canal; *group 3* 20 s, laser irradiation in 17% EDTA, wet canal; and *group 4* 40 s, laser irradiation in 17% EDTA, wet canal. Debridement of and smear layer removal from the

apical third of root canals were evaluated by SEM. The study showed that standardized instrumentation, followed by a final Er:YAG laser irradiation in wet canals with EDTA irrigation resulted in more cleaning of the root canal walls and a higher quantity of open tubules in comparison with the traditional irrigation method.

Keywords Erbium:YAG · Laser · Smear layer · EDTA

Introduction

The ability to successfully treat and remove the smear layer and bacteria continues to be a challenge in nonsurgical endodontic treatment of the root canal system. The shaping and cleaning of root canals is a key step during root canal treatment and unless all remnants of debris are removed, subsequent stages of obturation may also be jeopardized [1, 2]. Clinically, endodontic procedures use both mechanical instrumentation and chemical irrigants in the attempt to three dimensionally debride, clean and decontaminate the endodontic system [3, 4]. Some of these irrigation techniques include manual irrigation with needles and canulas, and the use of machine-assisted agitation systems and sonic and ultrasonic energy sources [5]. All file systems generate a smear layer and leave debris in the root canal. Irrigation with 5.25% sodium hypochlorite alone is unable to remove debris and the smear layer [6]. Other irrigants such as 2% chlorhexidine gluconate, 17% ethylene diamine tetraacetic acid (EDTA) and 10% citric acid have been used to help remove debris, but many studies have demonstrated the limited ability to effectively reach all internal faces of seemingly complicated root canal architecture [1, 2, 4, 6–8]. Although a recent study

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[9] has shown excellent ability of a new file system operated with a continuous irrigation device to remove debris and the smear layer also from the apical third of the root canal, the literature shows that when compared to the coronal and middle thirds of relatively clean canals, the apical third of the root canal always presents a problem in regard to the ability to achieve the same cleanliness [5, 6, 10–12]. This fact may be of significance during root canal treatment because the presence of a smear layer and debris may prevent sealer adaptation to the canal walls and impede penetration of irrigants into dentinal tubules and accessory canals. Accordingly, some alternative, more effective method to debride, clean and penetrate the dentinal walls should be explored.

The effectiveness of lasers in dentistry continues to be an area of discussion. Although the use of lasers for nonsurgical endodontic treatment of the root canal system has been reported since the early 1970s [13, 14], acceptance has been slow. A common feature of dissatisfaction has been the thermal damage associated with the application of laser photonic energy [15–19]. Laser treatment can be a valuable tool for the removal of the dentinal smear layer, as a debridement device during endodontic treatment. The Er:YAG laser (wavelength 2,940 nm) is approved by the FDA for cleaning, shaping and enlarging the root canal [20]. Previous studies have tested the ability and the effects of this laser on root canal walls and have indicated that the Er:YAG laser is a suitable instrument for removal of the smear layer in root canals [21–26]. Furthermore, George et al. in an investigation of the ability of both the Er:YAG and Er,Cr:YSGG lasers equipped with conical shaped radially firing tips and plain tips to remove the smear layer from the apical third of the root canal showed a laser activation of EDTA and a better performance of conical fibers compared to plain fibers for improving the action of EDTAC in dissolving smear layer [27].

The aim of this *in vitro* study was to evaluate by scanning electron microscopy (SEM) the ability and effectiveness of the Er:YAG laser in removing the smear layer and debriding the root canal. A newly designed tip with a tapered radial firing end and 3 mm of the polyamide sheath removed was used. Using specific pulse rates, a short microsecond pulse duration and low energy during application, the thermal morphological effects described in the literature were minimized [21–29].

Materials and methods

Sample preparation

In this study, 80 recently extracted single-rooted human teeth were used. They were stored in physiological saline solution until use.

Root canal treatment

The access cavity to the canal orifice was first prepared with a tapered diamond bur creating a glide path for insertion of the first instrument (size #10 K file). The teeth were then minimally prepared using nickel/titanium rotary instruments in a sequential crown down method to a size 20/.06 (Profile GT; Dentsply Tulsa Dental, Tulsa, OK). The canals were irrigated during preparation with sodium hypochlorite. After reaching the final instrumentation size of 20/.06, an additional two 30-s cycles of irrigation with saline only were applied. The samples were then ready to be treated with the various laser protocols described.

Laser parameters

An Er:YAG laser with a wavelength of 2,940 nm (Fidelis; Fotona, Ljubljana, Slovenia) was used to irradiate the root canals after traditional instrumentation. A newly designed 12-mm long 400- μ m quartz tip was used. The tip, as received directly from the manufacturer, was tapered and had 3 mm of the polyamide sheath stripped back from its end (Fig. 1a). The laser operating parameters used for all of the treatment groups (using the free-running emission mode) were as follows: 20 mJ per pulse, 15 Hz, and 50 μ s pulse duration. The coaxial water spray feature of the handpiece was set to 'off'. The tip was placed into the coronal access opening of chamber only, and was kept stationary and not advanced into the orifice of the canal (Fig. 1b).

Laser irradiation and irrigation methods

After the mechanical preparation, the teeth were randomly divided into four groups (20 teeth each) and treated according to the following protocol:

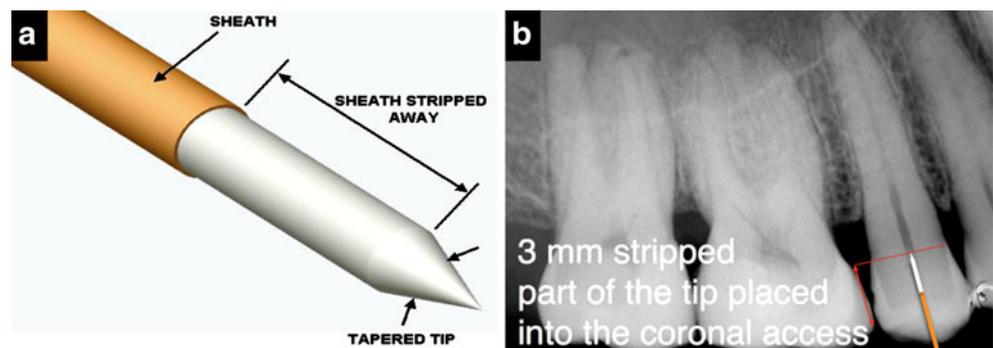
- Group 1 Saline water irrigation for 2 min as control group
- Group 2 Laser irradiation, 20-s cycle in sterile distilled water
- Group 3 Laser irradiation, 20-s cycle in 17% EDTA
- Group 4 Laser irradiation, 40-s cycle in 17% EDTA

During the laser irradiation cycles, the root canals were continuously irrigated with 2 ml of fluid to maintain hydration and levels using a hand syringe with a 25 gauge needle positioned above the laser tip in the coronal aspect of the access opening, accordingly to the above protocol.

Temperature measurements

To identify possible thermal side effects, the temperature changes on the external root surface of three teeth in each laser group (for a total of nine teeth) were measured.

Fig. 1 **a** Diagram of the radial and stripped tip used in this laser study (courtesy of Medical Dental Advanced Technology Group). **b** Radiograph showing positioning of radial and stripped tip placed into the coronal access opening of the fluid filled chamber only and not advanced into the orifice of the canal



A modified thermocouple measurement sensor of 1.5 mm diameter (K-Type NiCr-Ni immersion sensor; TEL-Atomic, Jackson, MI) was placed on the root surface and attached with a silicon-based heat-conductive compound (340 heat sink compound; Dow Corning, Midland, MI) 5 mm from the apex. The temperature changes were monitored continuously throughout all the irradiation procedure periods (20 s for groups 2 and 3, and 40 s for group 4) starting from a room temperature of 21°C and recorded using a digital thermometer (digital quick response pocket thermometer; TEL-Atomic). The average value and the standard deviation of the three measurements per laser group were calculated. The temperatures were digitally displayed on the thermometer and subject to sensor errors of $\pm 0.2^\circ\text{C}$.

Scanning electron microscopy

A F4000 field emission scanning electron microscope (Hitachi, Tokyo, Japan) was used. The prepared samples were sectioned longitudinally, dried, sputter-coated and only the apical third of the root canal (5 mm) examined. More than 150 photographs were taken at various magnifications ranging from $\times 300$ to $\times 10,200$ by the same operator and were evaluated by two additional blinded observers.

Quantitative evaluation

The smear layer was defined as the film retained on the dentin surfaces after application of the nickel/titanium rotary instruments. A scoring method for smear layer removal suggested by Hülsmann et al. was applied [10]. The three observers evaluated the amount of remaining smear layer. SEM images at magnifications in the range $\times 1,000$ to $\times 2,000$ were used for this quantitative assessment. A mean smear layer score was calculated for each specimen. The overall agreement of the observers was very good as indicated by a Fleiss' kappa of 0.82. A scoring index of 1 through 5 was used as described below:

- Score 1 No smear layer; dentinal tubules open
- Score 2 Small amount of smear layer; many dentinal tubules open
- Score 3 Homogeneous smear layer covering the root canal walls; only a few dentinal tubules open
- Score 4 Complete root canal wall covered by a homogeneous smear layer; no dentinal tubules open
- Score 5 Heavy, nonhomogeneous smear layer completely covering root canal walls

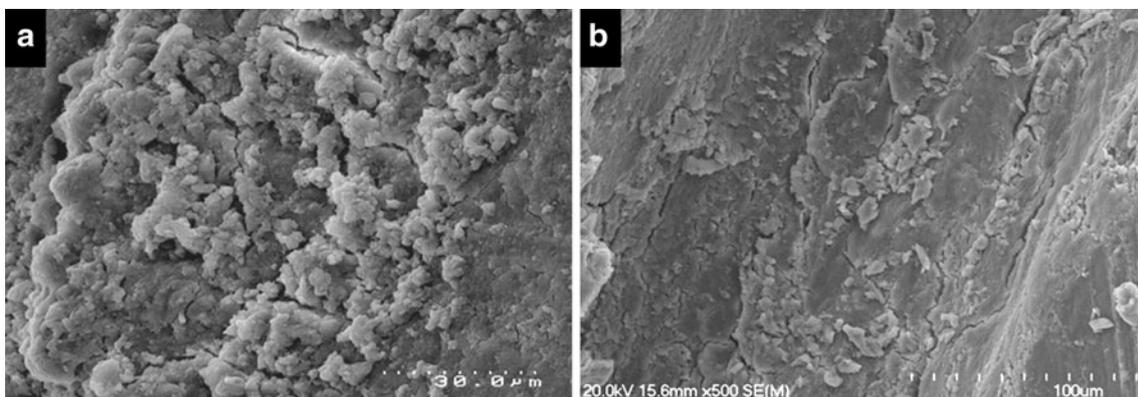


Fig. 2 Group 1. Representative images of a root canal wall (**a** $\times 1,220$. **b** $\times 300$) after a 2-min saline water flush. The canal surface shows a noticeable smear layer and occluded dentinal tubules. Smear layer score 5

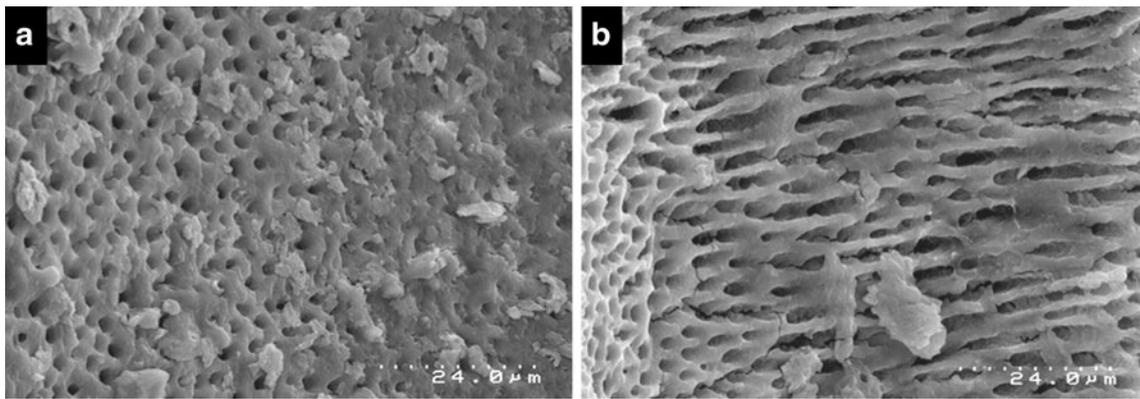


Fig. 3 Group 2. Representative images of a root canal wall ($\times 1,680$) after Er:YAG laser irradiation (20 mJ per pulse, 15 Hz, 50 μ s pulse duration) for 20 s in sterile distilled water (wet canal). The canal

surface shows open tubules, residual debris and a smear layer still present. Smear layer score 3

The resulting data were nonparametric in nature and hence statistical analysis was performed using the Kruskal-Wallis and the Mann-Whitney Wilcoxon U tests; a level of $p < 0.05$ was considered statistically significant.

Results

SEM observations

Control group specimens (group 1) consistently exhibited a thick smear layer. SEM examination demonstrated that when only water irrigation was applied, a noticeable smear layer and occluded dentinal tubules remained on the treated surface (Fig. 2). Debris, defined as dentin chips and pulp remnants loosely attached to the internal surface of the root canals, was present in specimens of group 1.

Group 2 specimens treated for 20 s with the Er:YAG laser together with irrigation with sterile distilled water showed improved cleaning compared to group 1 specimens. The root canal surfaces exhibited open tubules, scattered

residual debris and a thinner smear layer compared to the group 1 (control) specimens (Fig. 3).

Group 3 specimens treated for 20 s with the Er:YAG laser together with EDTA irrigation showed improved cleaning and debridement compared to group 2 specimens and group 1 (control) specimens (Fig. 4). Group 4 specimens treated for 40 s with the Er:YAG laser together with EDTA irrigation showed the most effective removal of the smear layer from the root canal walls (Fig. 5). SEM images at higher magnifications (from 3600X to 10200X) showed exposed and intact collagen fibers and evidence of an unaltered collagen matrix (Fig. 6). None of the SEM micrographs indicated signs of dentin fusion from excessive heat.

Quantitative evaluation

To quantify the differences in smear layer removal, a five-step scoring method was used. The scores of all laser-treated groups differed significantly from each other and from that of the control group. Group 1, the control group, had the highest (i.e. least acceptable) mean score, and

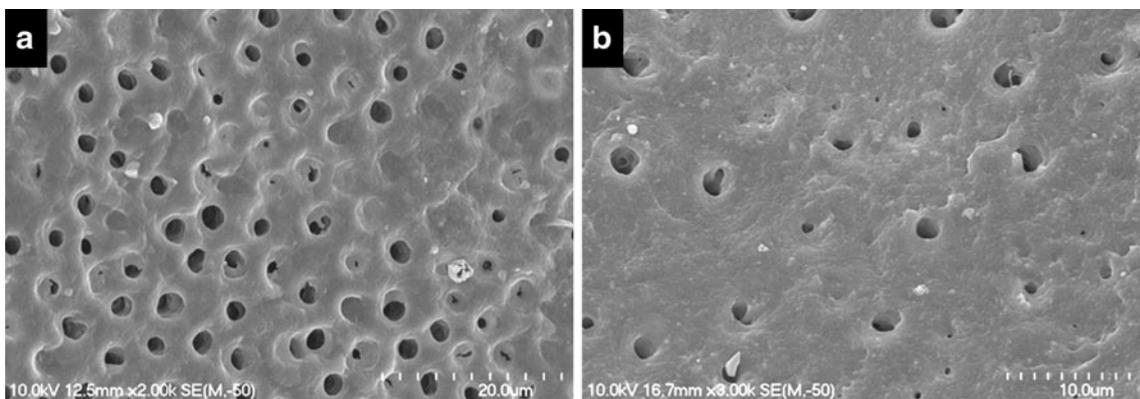


Fig. 4 Group 3. Representative images of a root canal wall (**a** $\times 1,820$, **b** $\times 2,470$) after Er:YAG laser irradiation (20 mJ per pulse, 15 Hz, 50 μ s pulse duration) for 20 s in 17% EDTA (wet canal). The root

canal surface shows significantly better cleaning and debridement than group 1 (control) specimens. Smear layer score 2

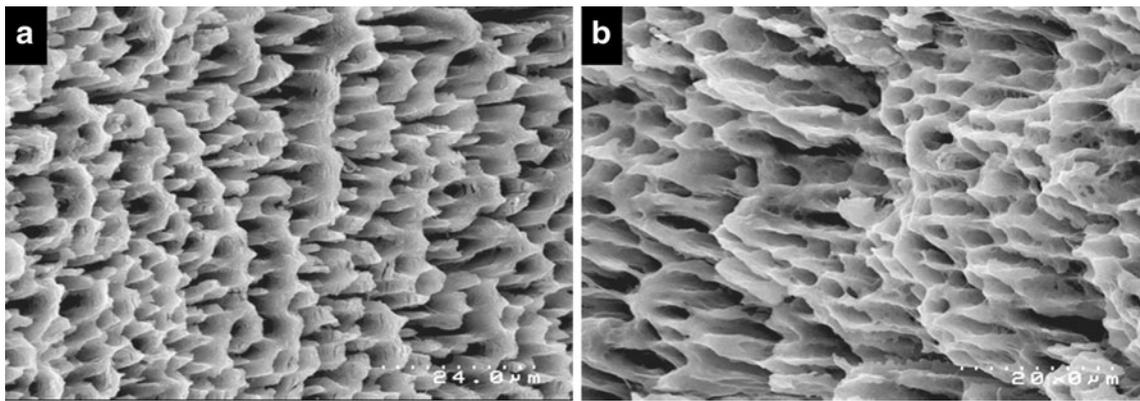


Fig. 5 Group 4. Representative images of a root canal wall (**a** $\times 1,680$, **b** $\times 1,820$) after Er:YAG laser irradiation (20 mJ per pulse, 15 Hz, 50 μ s pulse duration) for 40 s in 17% EDTA (wet canal). The root canal surface shows effective removal of the smear layer. Smear layer score 1

groups 2 through 4 had progressively lower (i.e. more acceptable) mean scores (Table 1).

The significance of differences in the cleanliness of the root canal wall between the groups were determined using nonparametric tests (Tables 1 and 2). The Kruskal-Wallis test showed an overall significant difference among the four groups ($p < 0.001$). A subsequent pair-wise comparison showed statistical significant differences in smear layer

removal from the apical third of root canal walls between the groups ($p < 0.001$).

Temperature measurements

Minimal average temperature increases were observed at the root surface during laser irradiation, with increases of 1.2°C and 1.5°C in the 20-s and 40-s irradiation time groups, respectively.

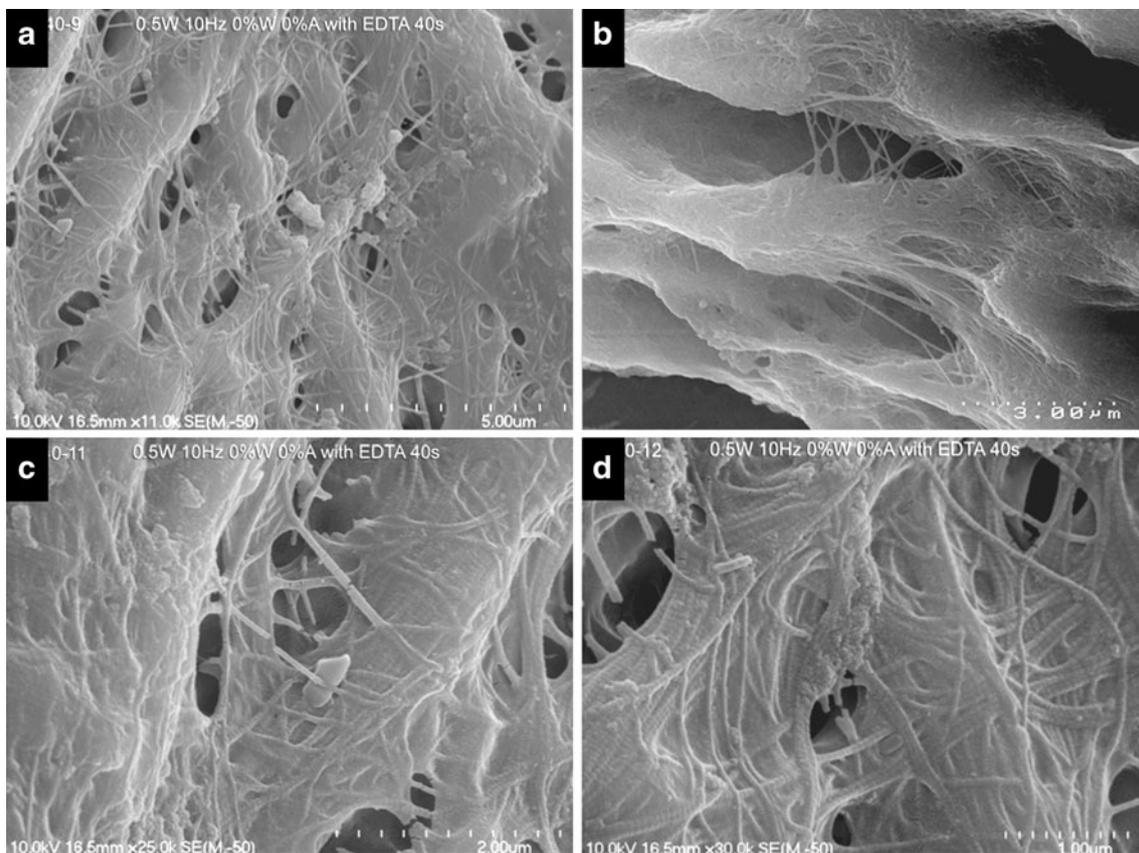


Fig. 6 Group 4, representative sample images at apical third; Er laser irradiation (20 mJ per pulse, 15 Hz, 50ms pulse duration) 40s in 17% EDTA wet canal. SEM at higher magnifications (from 3600X to

10200X) shows exposed and intact collagen fibers and evidence of an unaltered collagen matrix. Smear layer score 1

Table 1 Results of Kruskal-Wallis tests of differences in mean ranks among the study groups

Group	Treatment	<i>n</i>	Mean rank of scores	Kruskal-Wallis chi-squared	df	<i>p</i>
1 (control)	2-min saline water flush	20	70.45	66.069	3	<0.001
2	Laser irradiation, 20-s cycle in sterile distilled water wet canal	20	46.18			
3	Laser irradiation, 20-s cycle in 17% EDTA wet canal	20	31.68			
4	Laser irradiation, 40-s cycle in 17% EDTA wet canal	20	13.70			

Discussion

Current instrumentation techniques using rotary instruments and chemical irrigation still fall short of successfully removing the smear layer from inside the root canal system. This was confirmed by the results seen in the control group (group 1) where the conventional technique was employed.

The Er:YAG laser used in this investigation was equipped with a novel 400 μm diameter radial and stripped tip. Using subablative parameters (average power 0.3 W, 20 mJ at 15 Hz) proved to be more effective than traditional techniques at removing the smear layer. This finding could be attributed to the photomechanical effect seen when light energy is pulsed in liquid [30–32]. When activated in a limited volume of fluid, the high absorption of the Er:YAG wavelength in water, combined with the high peak power derived from the short pulse duration that was used (50 μs), resulted in a photomechanical phenomenon. We speculate that this phenomenon was responsible for the removal of the smear layer in group 2, in which laser irradiation was combined with saline, which alone does not affect the smear layer [10–12]. A profound “shockwave-like” effect is observed when radial and stripped tips are submerged in a liquid-filled root canal. As a result of the very small volume, this effect may remove the smear layer and residual tissue tags and potentially decrease the bacterial

load within the tubules and lateral canals [28, 29, 33]. By using lower subablative energy (20 mJ) and restricting the placement of the tip to within the coronal portion of the tooth only, the undesired effects of the thermal energy, previously described in the literature, was avoided [22–26].

In the current study the smear layer and debris were not removed by thermal vaporization, but probably by photo-mechanical streaming of the liquids, which were laser activated in the coronal part of the tooth. The authors describe this light energy phenomenon as photon induced photoacoustic streaming (PIPS). The effect of irradiation with the Er:YAG laser equipped with a tip of novel design at subablative power settings (0.3 W, 20 mJ) is synergistically enhanced by the presence of EDTA; this leads to significantly better debridement of the root canal contributing to an improvement in treatment efficacy.

The SEM images verified the efficient and minimally disruptive effects on the canal walls, dentinal tubules and even the hydroxyapatite surfaces. No thermal damage was seen in any PIPS-treated samples and temperature increases at the external root surfaces were minimal (<1.5°C). Furthermore, the laser energy activates the EDTA solution, amplifying its surface cleaning action [27]. However, at high magnification, the intertubular dentin around tubular openings appeared to show some signs of erosion with the dentin collagen architecture visible and intact (Fig. 6).

Table 2 Results of pair-wise comparison between the mean ranks of the groups

Pair-wise comparison	<i>n</i>	Mean rank	Sum of ranks	Mann-Whitney <i>U</i>	Distribution mean	<i>Z</i>	<i>p</i>
Group 1 (control)	20	30.50	610.00	0.000	200	-5.724	<0.001
Group 2	20	10.50	210.00				
Group 1 (control)	20	30.45	609.00	1.00	200	-5.696	<0.001
Group 3	20	10.55	211.00				
Group 1 (control)	20	30.50	610.00	0.000	200	-5.724	<0.001
Group 4	20	10.50	210.00				
Group 2	20	26.98	539.50	0.000	200	-3.728	<0.001
Group 3	20	14.03	280.50				
Group 2	20	29.70	594.00	16.000	200	-5.236	<0.001
Group 4	20	11.30	226.00				
Group 3	20	28.10	562.00	48.000	200	-4.350	<0.001
Group 4	20	12.90	258.00				

With conventional treatment protocols (without a laser), an irrigation syringe is more effective when the tip is placed closer to the working length. With this new laser system, the laser tip is not placed within the canal itself, but is rather confined to the coronal chamber above the orifice. It is suggested that this allows easy access for the photomechanical effects to occur within the root canal, which may assist in cleaning canals of various shapes.

A standard ISO size #30 file preparation is needed to allow traditional laser tips (200–320 μm) to reach close to the apex [28, 29, 33]. Using the radial and stripped design with PIPS, the apex can be reached without the need to negotiate the tip close to the apex. Correspondingly, this would allow a less-invasive preparation using an ISO size #20/.06 file, according to the method described.

Irrigation with chelating agents following the current conventional instrumentation procedure requires more time to initiate a satisfactory debridement (EDTA placed passively into the prepared root canal) [11, 34]. The PIPS technique resulted in pronounced smear layer removal when used together with EDTA and at the settings outlined.

Published material on endodontic techniques using the Er:YAG laser provides differing operating parameters [35]. These authors recommend the use of higher average power (1.125–1.5 W) delivered through end-firing laser tips. Additionally, these tips need to be placed 1–2 mm from the root apex.

Conclusion

The Er:YAG laser used in this study showed significantly better smear layer removal than traditional syringe irrigation. At the energy levels and with the operating parameters used, no thermal effects or damage to the dentin surface was observed. In this study the Er:YAG laser with the current settings produced a photomechanical effect demonstrating its potential as an improved alternative method for debriding the root canal system in a minimally invasive manner.

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