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Factors Influencing the Ablative Potential of the Er: YAG Laser When Used to Ablate Radicular Dentine

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Purpose: The use of Er:YAG lasers for intracanal ablation of dentine, as part of biomechanical preparation in endodontics, is attracting interest. However, this process is yet to be optimized fully in terms of mode of operation, delivery system, and irrigation. Water irrigation is useful for reducing thermal stress to dental hard and soft tissues during laser treatment. The aim of this study was to compare the ablation characteristics of dentine when ablated from the root canal (radicular) aspect compared with the external root (periodontal) aspect, and examine the effect of water mist spray flow rate on the efficiency of ablation. The application of these parameters to direct ablation of smear layer in the root canal environment was then tested, comparing lasing with a 400-µm fiber to the passive effects of EDTA during and after rotary Ni-Ti preparation.

Materials and Methods: In part 1, single-rooted extracted teeth were split into two parts, and the surfaces of the split roots irradiated at 1 Hz for 5 pulses with a KaVo KEY3 Er:YAG laser at pulse energies of 250, 300, 400 or 500 mJ. This was undertaken with either a low (0.5 ml/min) or high (1.5 ml/min) water flow rate. A total of 10 sites were irradiated for each of the 16 unique energy/water flow rate/site combinations, giving 160 sites. Crater depth, diameter, and volume were measured, and differences between groups also assessed using light microscopy and SEM. In part 2, root canals prepared using rotary Ni-Ti instruments were irradiated in the presence of water using an optical fiber, and the effects on dentine assessed using image analysis.

Results: All dentine sites showed ablation at 250 mJ/pulse. There was a consistent increase in crater depth and diameter with increasing energy in all subgroups, with larger craters with low water flow than with high water flow on the external (periodontal aspects). Comparing the effect of location, there was significantly greater ablation on the periodontal aspect in the low water flow group than on the root canal (radicular) aspect. In contrast, in the high water flow group, there was no significant difference between the two locations. Irradiated surfaces had open dentinal tubules but no carbonization, cracking or other microscopic types of surface thermal injury. Lasing in the canal with an optical fiber in the presence of water had a limited and irregular effect on a thick smear layer, when compared to the passive effect of EDTA.

Conclusion: These results indicate that significant interactions occur between dentine ablation and the variables of water spray flow rate and dentine location. This will be useful for developing methods to ensure that sufficient energy can be delivered to radicular dentine to achieve effective ablation for the biomechanical preparation of root canal dentine. Excess water can attenuate effective dentine ablation with the Er:YAG when used in the root canal.

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Many authors have demonstrated the effectiveness of the Er:YAG laser in endodontic applications, particularly for removing intracanal debris and achieving disinfection.[1-4,7] Er:YAG lasers have been shown to be effective in preparing straight as well as curved canals up to a 10 degree curvature under ideal laboratory conditions.[5] When used in the root canal system without water irrigation, concerns of thermal stress to

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the periodontium arise for all laser systems that are strongly absorbed in water. A number of studies have documented this issue. Amyra and Walsh noted thermal stress with Nd:YAG and CO_2 lasers used within the root canal under both wet and dry conditions,[6] while Yamazaki et al, when using an Er,Cr:YSGG laser at 6 W, reported a maximum temperature increase of 37°C for lasing without cooling (50% water and 48% air), but only 8°C when cooling was used.[4] For Er:YAG lasers, a water mist spray can reduce thermal insult to hard tissues. Kimura et al observed that an Er:YAG laser used with water spray (20 ml/min) at 2 Hz and an exit energy up to 230 mJ/pulse from the tip for 1 minute gave a temperature rise of less than 6°C on the root surface at the root apex, and 3°C at the middle third of the root.[7]

Many studies indicate that water spray or a moist surface is essential for effective ablation of dentine, as it not only reduces thermal stress but also reduces charring of the ablated surface.[8-11] However, dramatically increasing the water flow rate could decrease the efficiency of dentine ablation by giving a thicker surface water layer. Fried et al reported that thick water films decrease the rate of ablation of enamel with Q-switched and free-running Er:YSGG (2.79 µm) and Er:YAG (2.94 µm) lasers, free-running Ho:YAG lasers and 9.6 µm TEA CO_2 lasers.[12,13] However a study by Visuri et al showed that their optimal water flow rate (4.5 ml/min) only minimally reduced the ablation rates of dentine with an Er:YAG laser, and did not significantly affect the ablation rates of enamel, compared with lasing under dry conditions.[13] In their study, the laser was used to produce linear incisions in enamel or dentine with or without water.

Obtaining and sustaining a thin water film in the root canal would require a low water flow rate. The ablative process for dentine within the root canal may also be affected by its physical makeup. While external (root surface) and internal (root canal) dentine has a similar overall chemical composition with respect to proteins and minerals, the level of water differs because the external dentine contains dentinal tubules that are smaller in diameter and fewer in number when compared to internal dentine. With more of the dentine volume occupied by tubules, it could be expected that internal dentine would ablate at greater efficiency for the same laser parameters. As no previous study has compared the differences in ablation between external and internal root canal dentine, this study was designed to address this question, using different water flow rates as a second major variable.

MATERIALS AND METHODS

In the first part of the study, a standardized exposure method with a noncontact handpiece was used. This approach was based on the methodology previously used by Fried to determine the ablation properties of human enamel with various overlying water films,[12,13] albeit used in this case for the Er:YAG laser rather than for the carbon dioxide laser. While not directly comparable to the clinical situation, it allowed precise control of all ablation parameters. Part 2 of the study examined the effect within root canals per se.

A total of 10 extracted human premolars were used in part 1. The surfaces of the roots were debrided with an ultrasonic scaler and hand curettes to ensure complete removal of cementum, as confirmed by microscopic examination. The teeth were then stored in tap water until used. The roots were divided longitudinally using a diamond disk. The cut internal surfaces of the split roots were flattened using a polishing disk to yield a flat surface. Samples were then allocated randomly to either the high or low water flow rate groups (1.5 ml/min and 0.5 ml/min, respectively). All samples were kept moist and were lased under moist conditions.

A free-running pulsed Er:YAG laser (KaVo KEY3, Model 1243; Biberach, Germany) was used at the following parameters: 250 to 500 mJ/pulse, fluence 44 to 88 J/cm^2, 250 µs pulse duration, pulse repetition rate 1 Hz) with a model 2060 noncontact sapphire window handpiece in focus (0.85 mm spot size at a working distance of 13 mm) at a frequency of 1 Hz for a total of 5 superimposed pulses on the same target spot, either with low or high water flow rates. The optimum working distance was maintained at 13 mm with the help of the integral diode aiming beam and a premeasured endodontic instrument attached to the front surface of the handpiece.

The external (periodontal) surface of the split root samples was subjected to pulse energies of 250, 300, 400 and 500 mJ, at 1 Hz for 5 pulses, delivered at 90 degrees to the surface. This procedure was repeated on the internal radicular (root canal) samples.

A total of 10 replicate sites were irradiated for each of the 16 unique energy/water flow rate/site combinations, giving 160 sites. The diameter of the craters created by lasing were measured with the aid of an Olympus binocular dissecting microscope with a micrometer scale, while the depth of the craters was measured using a contact micrometer with a penetration needle (to an accuracy of 10 microns).

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The craters were photographed with a 3.34 megapixel digital camera attached to the microscope (at a final magnification of 30X), and the samples dehydrated, mounted on stubs, sputter coated with platinum, and examined under low vacuum at 10 kV using a JEOL 6400F SEM system (JEOL; Tokyo, Japan).

The volume of dentine ablated was determined taking into account the proportion of the sample occupied by dentine tubules. First, SEM images were used to estimate the diameter of dentine tubules in the sample; next the number of tubules across the crater area was estimated from the SEM images. The tubule number was then multiplied by the mean diameter (per tubule, assuming circular cross sectional profiles) and finally by the crater depth, to give the total tubule volume. Typical tubule densities were 45,000 and 19,000/mm^2, with mean diameters of 2.5 and 0.5 µm, for the internal and external dentine surfaces, respectively. The corrected volume of the crater was determined by multiplying the crater area by the crater depth, to give the total volume, and then subtracting the volume occupied by the dentine tubules. Using the Kolmogorov-Smirnov normality test, numerical data sets for crater parameters (diameter, depth and volume) were found to be normally distributed in all groups, and thus intergroup differences were analyzed using one-way ANOVA, and repeated measures t- tests.

In the second part of the study, the effects of the Er:YAG laser on dentine ablation within the root canal were examined using 400 µm endodontic laser fibers (KaVo) attached to the 2062 handpiece of the KEY3 laser. A total of 21 single rooted teeth were used; these were stored in water saturated with thymol until used. Patency of the apical opening was confirmed with an ISO #08 K file passed in a retrograde manner. Access to the root canal space was established using conventional rotary cutting instruments, and the working length establishing by passing a ISO #08 K file to the apex in an anterograde direction, and then backing off the measurement by 1 mm. Teeth used had an apical foramen size of either ISO #15 or ISO #20. All root canals were prepared with rotary nickel-titanium instruments to 1 mm short of the apex to size F5 (0.50 mm) using Protaper (Dentsply Maillefer; Ballaigues, Switzerland) instruments, following the manufacturer's guidelines. The teeth were then divided into 3 groups, the first of these being the positive control group, in which both 1% sodium hypochlorite and 1% EDTA were used during endodontic therapy, in order to ensure complete removal of smear layer, and thus allow precise quantification of dentine tubule density. In the remaining two groups, during rotary instrument preparation of the canals, water was used as an irrigant rather than EDTA or sodium hypochlorite, to ensure that a smear layer was present at the end of sample preparation. In the lased group, after preparation, the root canal was filled with water using a syringe before inserting the laser fiber so that the terminus was 2 mm short of the apex (and thus 1 mm short of the working length). The KaVo KEY3 laser system was used at a panel setting of 200 mJ/pulse (4 W) and 20 pulses/s for 5 s. After placing more water in the canal, lasing was repeated, for a total of 10 cycles of irrigation followed by lasing. Each cycle was spaced by 5 s. The measured power output determined with a laser power meter placed at the terminus of the fiber was 1.0 W. The 2062 handpiece does not permit additional air or water from the laser system to be delivered, thus the only water present was that added into the canal before inserting the fiber. Each tooth was treated with a new "3 ring" 400-µm fiber. During the time of lasing, the handpiece was moved in a circular motion and simultaneously withdrawn at a rate of 1 mm/s. Only the apical third of the root canal system was treated. The third group had the laser fiber placed (with the aiming beam activated) with EDTA present as the irrigant but without Er:YAG laser energy being delivered (sham irradiation).

After treatment, the roots were split to allow examination of the apical third, and the samples dehydrated, mounted on stubs, sputter coated with platinum and examined by SEM, with attention being paid to the effect of lasing on removal of smear layer and ablation of dentine. From the images, the proportions of open tubules in the control and lased groups were determined by image analysis using ImagePro Plus software (Media Cybernetics; Bethesda, MD, USA), using one image per sample at a magnification of 1000X, of the apical third of the root canal system. The number of pixels occupied by the openings of dentinal tubules was divided by the total area of pixels in the image to determine a percentage score, as a surrogate measure for dentine tubule "patency". Group data were pooled from the three groups, and assessed for normality using the Kolmogorov-Smirnov test. Differences between groups were then assessed using one-way ANOVA, and post-hoc Bonferroni tests.

RESULTS

In the first part of the study, the light microscopic evaluation of the impact sites showed that the craters were regular in pattern, with no cracks or fissures in the pe-

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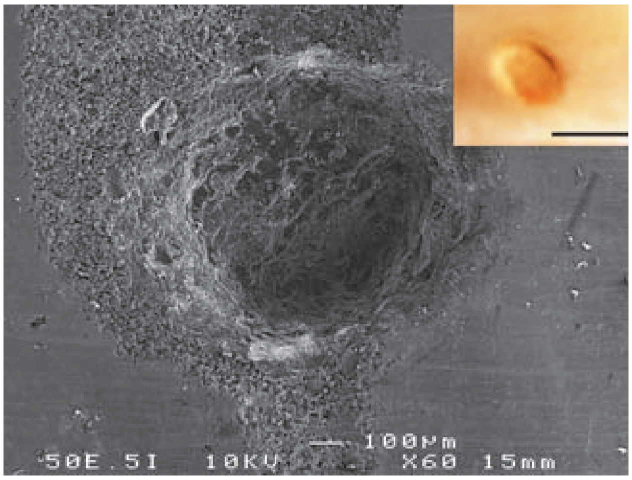

Fig 1 Crater from 500 mJ laser pulses on the internal dentine surface at 0.5 ml/min water flow rate show no charring, fissures, or microfractures of the surrounding dentine. The margins of the crater are perpendicular (SEM 60X magnification; inset: light micrograph with scale bar = 1 mm).

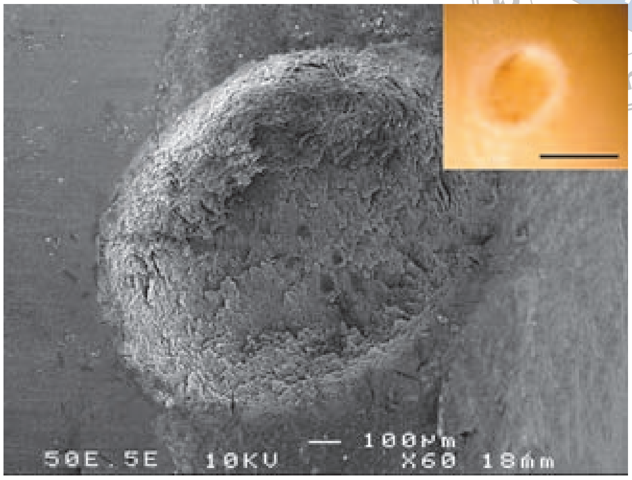

Fig 2 Crater from 500 mJ laser pulses on the external surface at 0.5 ml/min also show no charring, fissures, or microfractures; however, the margins of the crater are bevelled (SEM 60X magnification; inset: light micrograph with scale bar = 1 mm).

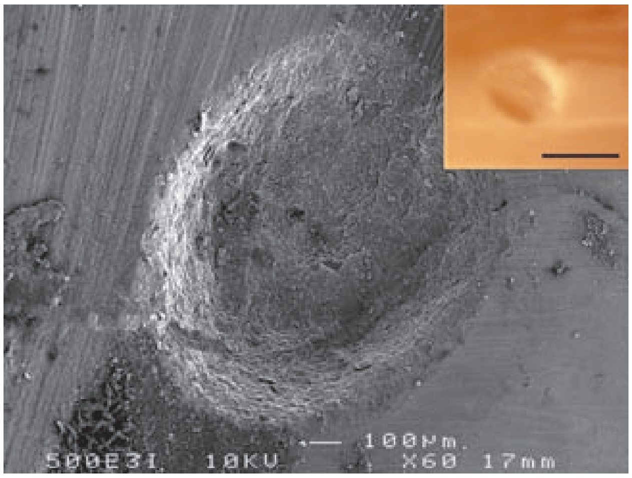

Fig 3 Crater from 500 mJ laser pulses on the internal dentine surface at 1.5 ml/min water flow rate show no charring, and perpendicular margins (SEM 60X magnification; inset: light micrograph with scale bar = 1 mm).

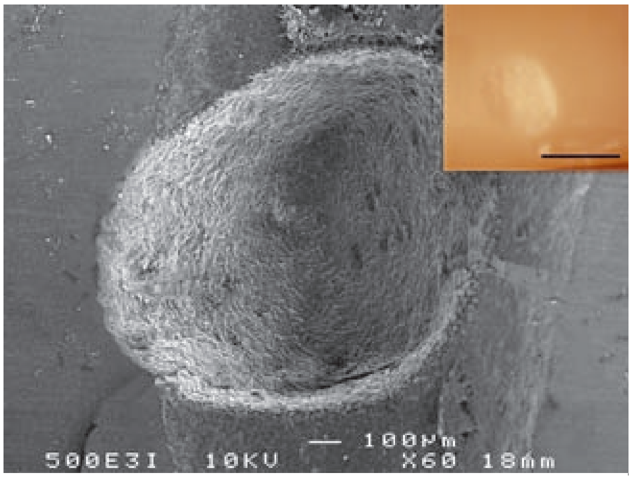

Fig 4 Crater from 500 mJ laser pulses on the external dentine surface at 1.5 ml/min water flow rate also show no charring, but margins of the crater are bevelled (SEM 60X magnification; inset: light micrograph with scale bar = 1 mm).

ripheral regions near the crater. Charring was not seen on the surface of craters in either water flow group. Of note, the margins of the craters on the external root surface had a bevelled surface, while the craters on the internal surface had a sharper perpendicular profile (insets in Figs 1 to 4).

SEM examination at low magnification (60X) showed that in all groups the craters had rough and irregular margins (Figs 1 to 4). At higher magnification (1000X), open tubules, lack of a smear layer, and a scaly surface with no melting or fusing of dentine were seen. Higher magnifications also demonstrated the structural variations between the external and internal dentine; larger numbers of tubules with larger diameters were observed on the internal dentine compared to the external dentine (Fig 5).

There was an increase in crater diameter, depth and volume with increasing pulse energy (Figs 6 to 8).

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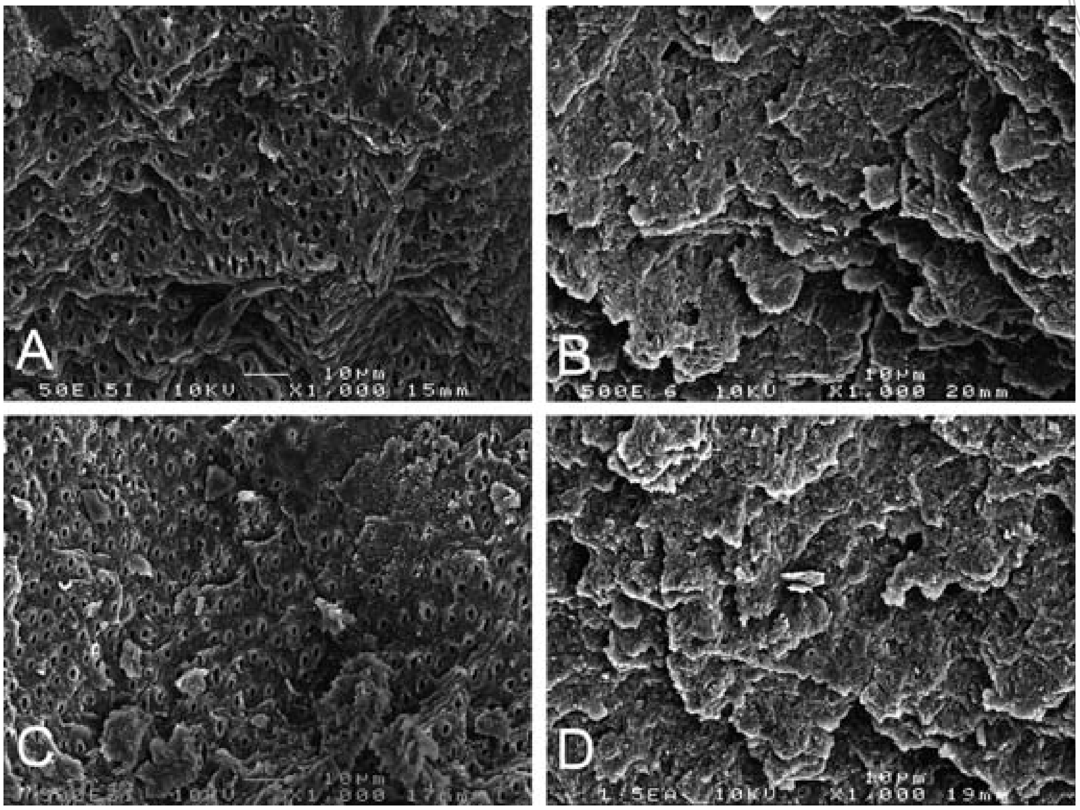

Fig 5 SEM examination of dentine tubules at the bases of craters (500 mJ) showing internal dentine (A and C) with 0.5 ml/min (A) or 1.5 ml/min (C), and external dentine (B and D) with 0.5 ml/min (B) or 1.5 ml/min (D). All views show patent dentinal tubules with no smear layer and no melting or fusing of dentine. Note the larger tubules and greater tubule density in internal dentine.

Under low water flow conditions, when comparing external vs internal dentine, there was a statically significant difference between the crater diameter and volume, with the external surface showing a larger crater diameter at all energy levels, and larger volume mineral loss at higher energy levels. The depth of craters was not statistically different between the two dentine locations. Under high water flow conditions, there was no statistical difference in crater diameters, depths and volumes between internal and external dentine.

For external dentine, the depths of the craters produced were greater in the low water flow group, while for internal dentine, both diameters and depth were significantly larger. At a given pulse energy, the total volume of mineral lost was significantly greater in the low water flow group for both internal and external dentine locations.

In the second part of the study, in which the effect of lasing in the canal with fibers was examined, no smear layer was present in the positive control group in which EDTA and sodium hypochlorite were used. A reduction in smear layer occurred during the passive exposure to 1% EDTA during sham treatment (a total of 2 min). Laser treatment in the presence of water in the root canal was only partially effective in removing the smear layer from the walls of the root canal. Isolated areas of dentine ablation were seen, whilst others showed minimal change (Fig 9). There was greatest dentinal tubule patency in the positive control (Ni-Ti plus EDTA irrigant) group ($p = 0.0051$), but no statistically significant difference between the sham irradiated and lased groups (Table 1).

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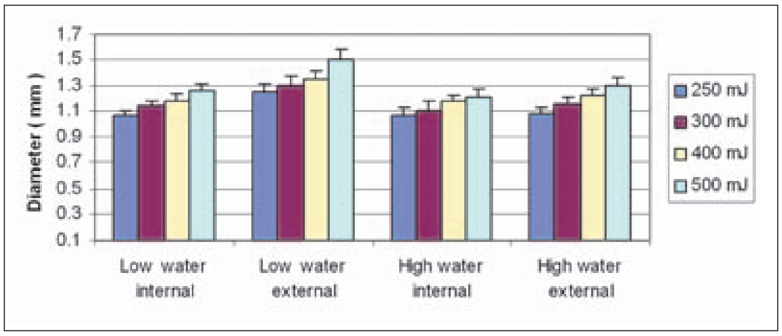

Fig 6 Crater diameters with varying irradiation conditions, dentine topography and water flow rates.

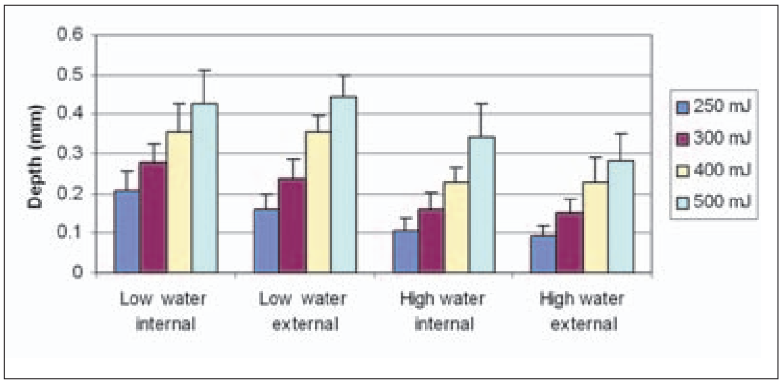

Fig 7 Crater depths with varying irradiation conditions, dentine topography and water flow rates.

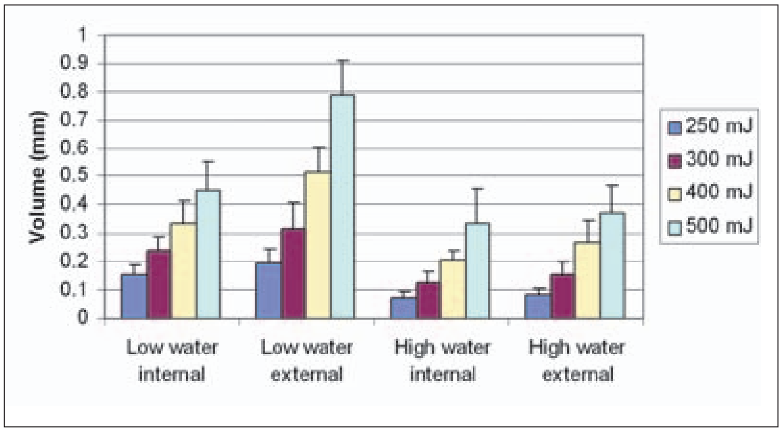

Fig 8 Estimated crater volumes with varying irradiation conditions, dentine topography and water flow rates.

Table 1 Dentine tubule patency expressed as a percentage of the total pixel area

Group	Lased	Sham	NiTi
Mean	0.77	3.01	5.97*
SD	0.61	0.55	4.37

* significantly greater than the other two groups.

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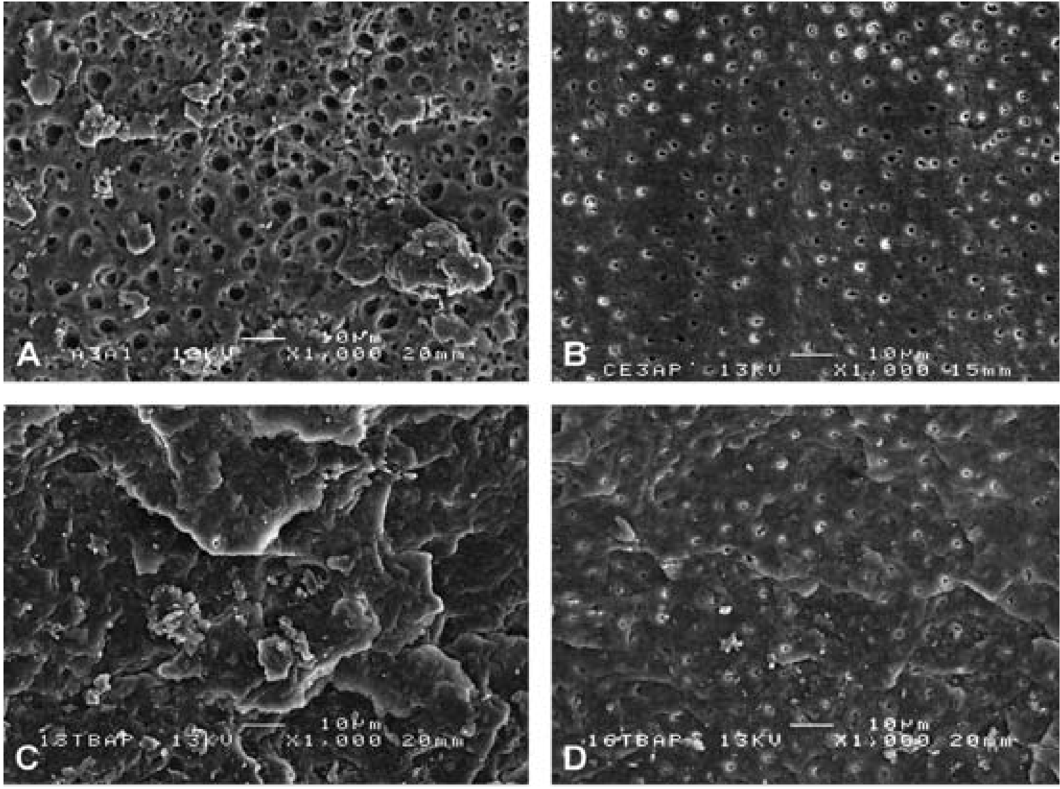

Fig 9 Effects of various treatments within the apical third of the root canal. A: Positive control of rotary NiTi with EDTA and sodium hypochlorite as irrigants. B: Effect of passive incubation with EDTA and sham irradiation on a thick smear layer. C and D: Er:YAG laser with accompanying water in the canal. All images are at the same magnification and are from similar locations in the apical third of the root canal.

DISCUSSION

Ablation characteristics of radicular dentine have been studied by a number of authors,[14-16] however, no previous study has reported the difference in the ablation rates and characteristics of radicular external and internal dentine. Variations in ablation characteristics were expected considering the differences in morphology as well as the content of water within the dentine, in particular the differences in tubule number and diameter, and this was confirmed by the experimental results. There was significantly greater ablation on the external (periodontal) aspect in the low water flow group, than on the root canal (radicular) aspect. In contrast, in the high water flow group, there was no significant difference between the two locations for the same pulse energy. There are several possible reasons for this.

Laser energy could result in the preferential evaporation of water within tubules, rather than intercrystalline water. The outer radicular surface contains more mineralized tissue and is more solid in nature, with the water found mostly in the dentine matrix rather than in the tubules. Thus, the matrix may disintegrate readily when the water is converted to steam. The internal root surface has, by comparison, more "free" water (ie, dentinal fluid within tubules), which would be preferentially vaporized, rather than intercrystalline water. The internal radicular dentine surface also has a different physical structure with minimal peritubular dentine and large tubule diameters, which in turn would affect the propagation of photomechanical shock waves which disrupt tissue by their explosive action.

Other contributing factors include the effect of the beam profile on the ablation process. The edge of the Gaussian (TEM00) beam profile is less energetic and may not deliver sufficient energy to reach the ablation threshold. This explains why the outer root surface dentine showed a crater with bevelled edges. In con-

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trast, on the inner radicular surface, craters had more vertical walls, indicating more effective ablation at the periphery. This difference in crater shape contributes to differences in the ablation volume between the two surfaces, under the same irradiation and flow rate conditions.

In relation to water flow rates, the depth of the craters in the low water flow group, however, did not vary significantly. Although we would have accepted a larger depth on the internal surface, this is not so and could be due the larger tubules acting as reservoirs of water pooling and hence this thick film of water could be responsible for the decrease depth of the crater.

Comparing the effect of location, there was significantly greater ablation on the periodontal aspect in the low water flow group than on the root canal (radicular) aspect. In contrast, in the high water flow group, there was no significant difference between the two locations in terms of diameter or depth of craters. The latter could be simply be due to the higher water flow rate causing an excess surface water film thickness, which then acts as an intermediary between the incoming laser pulse and the dentine surface. An effect of excess water has been reported previously.[12,13,17,18] In the root canal, one could expect a constant thickness of water due to pooling of water in the canal and its interaction with the dentine surface because of surface tension effects.

Direct evidence for the limited effect of lasing when in the presence of water was gained in the second part of the study, in which delivery of Er:YAG laser energy in the presence of water had, under the parameters used, a limited effect on the thick smear layer deliberately created by not using EDTA during rotary preparation. Of interest, a passive effect of EDTA during sham irradiation could be seen. While the use of water during rotary preparation is not realistic, it was useful for ensuring a thick smear layer, and thus providing a greater challenge to the laser in terms of ablation. Some areas of ablated dentine were seen whilst other areas were less affected, reflecting the problems of achieving a consistent effect with the delivery system used.

This study emphasizes the difference in the ablation patters of both external and internal root surface. Within the root canal, an irregular ablation pattern would be expected when using a conventional optical fiber with a perpendicular cleave, or a sapphire or quartz tip with a polished perpendicular end. A challenge with this end-firing approach, if used for physical preparation of the canal, is to achieve uniform ablation, whilst at the same time limiting heat transfer to the supporting periodontal tissues. Simple bevelled ends on fibers used with water spray would likely result in some parts of the canal being ablated more than others. Further studies of fibers for use in the root canal are needed to optimize their design and performance. To achieve a uniform and effective ablation of the root canal walls, factors such as the morphological variations of the radicular dentinal surface, the water flow rate (into the canal and out of the canal [due to evaporation or due to flow]), the fiber tip (shape, transmission profile, angulations to canal walls), the laser pulse energy settings, and the rate withdrawal of fiber from the canal need to be considered carefully.

CONCLUSIONS

Based on the present results, the quantity of water both contained within the dentinal tubules as well as the water spray flow rate itself, appears to have a marked influence on the ablation rate of dentine. Precise adjustment of the water spray flow rate needs to be undertaken so as to obtain optimal ablation with the lowest possible pulse energy level.

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