Coaxial Water Mist Spray Alters the Ablation Properties of Human Radicular Dentine for the Holmium:YAG Laser

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Purpose: This laboratory study examined the ablative processes in human radicular dentine using the Ho:YAG laser (2100 nm wavelength, pulse duration 250-350 µs, spot size 320 µm).

Materials and Methods: The study followed a matrix design, with pulse energies from 0.5 to 1.6 J and pulse frequencies from 1 to 6 Hz, in either the presence or absence of water mist spray (1.5 ml/min). Dentine surfaces of extracted teeth were lased with collateral water mist spray or without irrigation. Diameters and depths of impact craters were measured, and the nature of the lased surface was assessed using light microscopy and SEM.

Results: When used with collateral water mist spray, the ablation craters had smooth outlines indicative of an entirely explosive process without adjacent collateral damage. In contrast, in the absence of water spray, peripheral carbonization and vitrification zones were seen. There was a significant correlation between the depth and diameter of the craters and the applied energy of the laser pulse.

Conclusions: These laboratory findings suggest that when used with collateral water spray, the Ho:YAG laser can ablate human dentine in a controlled manner without adverse thermal effects. Because it can be delivered through glass optical fibers, this wavelength may have application for dental hard tissue preparation or modification.

Keywords: laser dentistry, holmium lasers, dentine ablation, SEM evaluation.

J Oral Laser Applications 2007; 7: 225-231. *Submitted for publication: 26.07.07; accepted for publication: 26.08.07.*

Holmium:yttrium aluminium garnet (Ho:YAG) lasers emit energy in the middle infrared region of the electromagnetic spectrum (2.1 µm wavelength), where water is the major absorber.[1] Because of the absorption of this laser in soft tissues, it has proven useful in vascular surgery, urology, neurosurgery, and arthroscopic surgery, including within the temporomandibular joint, providing effective ablation without collateral thermal damage.

Despite the various uses of the Ho:YAG laser in medicine and oral surgery since the late 1980s, this laser wavelength has not found wide application for dental hard tissue modification or ablation. Because the 2.1 µm matches a harmonic for water absorption, the possibility of ablation of dental hard tissues, and in particular radicular dentine, using Ho:YAG laser energy is of interest for possible clinical use, for example, in endodontics. Unlike the Er:YAG and Er,Cr:YSGG wavelengths, Ho:YAG laser energy can be delivered effectively using flexible quartz glass optical fibers.

Compared to the erbium lasers, interactions of the Ho:YAG laser with dental hard tissues have been less extensively examined. Initial studies of enamel and dentine ablation suggested that the wavelength had promise, particularly when compared to less well absorbed wavelengths in the near infrared region.[2] In these previous studies, the laser energy was delivered without accompanying water mist spray, and thermal side effects were a concern.

Past work has not examined the possible modifying factor of water mist spray on the ablative process in dental hard tissues. As with the erbium lasers that are now used widely in clinical practice, the inclusion of water would be expected to alter dramatically the nature of the surface interaction, and to reduce thermal insults to the tissue accompanying each pulse.

When Ho:YAG laser energy interacts with the water contained within the enamel and dentine, it causes ablation by a process that has been described as "spallation", a photodisruptive effect with fragmentation of the substrate, caused by the shallow depth of penetration of the laser energy within hard tissue, and its high peak power which results in an outwardly explosive process. From a theoretical standpoint, this shallow process could be exploited for selectively modifying dental hard tissues at both the macroscopic and microscopic levels. Previous work has shown the potential for Ho:YAG laser energy for enlarging the root canal[3] and removing the smear layer,[4] although low pulse energies were needed to keep thermal changes at a level regarded as safe.[5]

The aims of the present study were to extend previous work by comparing the ablative process in human dentine using the Ho:YAG laser with a range of pulse energies and frequencies both in "dry" mode and when accompanied by a coaxial water mist spray ("wet" mode). To our knowledge, no previous work has addressed the use of collateral water mist spray with this laser type.

MATERIALS AND METHODS

Sample Preparation

A total of 24 extracted human premolars were used. The surfaces of the roots were scaled with an ultrasonic scaler and hand curettes to ensure complete removal of cementum, as confirmed by microscopic examination, then stored in tap water until used. The teeth were divided into two groups of 12 each, for ablation of the radicular external dentine under "dry lasing" or "wet lasing" conditions. Teeth were maintained in a fully hydrated state at all times in the study.

Laser Treatment

A medical Ho:YAG laser system designed for orthopaedic surgery and urology (model Smart 2100 Plus, Deka; Florence, Italy) was used. This system operates in free running pulsed mode, with a pulse duration of 250 to 350 µs and a maximum pulse energy of 2 J. A 365- to 320-µm diameter tapered glass optical fiber was used to deliver the laser energy. The terminus of the fiber was kept at a constant distance of 1 mm from the sample to be ablated, in a perpendicular orientation to the dentine surface. The fiber terminus was cleaved between experiments, and whenever the fiber tip was visibly damaged. The fiber terminus was observed for a uniform Gaussian visible red Helium-Neon laser aiming beam before ablation trials. In the wet ablation series, the air-water mixture from the low-speed handpiece irrigant line of a dental handpiece was delivered through flexible polyvinyl chloride tubing directly onto the side of the delivery fiber. The water flow rate was 1.5 ml/min. Each exposure series was limited to 1 s, with excess water removed from the dentine surface immediately before lasing, using blotting to give a moist surface with no visible water film thickness present at the time of lasing.

The study followed a matrix design. Samples in each group were subjected to 8 different pulse energies, as follows: 0.5 J, 0.6 J, 0.7 J, 0.8 J, 1.0 J, 1.2 J, 1.4 J and 1.6 J. The available range of pulse energies on the system was 0.5 to 2.0 J. Irradiation trials were undertaken using pulse frequencies from 1 through to 6 Hz, giving a total of 48 unique irradiation parameters, for both the dry and wet ablation series. Eight replicate craters were created for each of the unique irradiation conditions. By dividing each root sample into four regions, it was possible to test four different pulse energies on the surface of each sample. Only low repetition rates were used, as pilot work had shown that high repetition rates, even when used with water spray, caused adverse effects because of heat accumulation and conduction through dentine.

Microscopic Analysis

The diameter and surface topography of the craters were examined using a binocular microscope at a final magnification of 40X. Each crater was then photographed using a 3.3 megapixel digital camera fitted to the microscope via a beam splitter. A micrometer scale was incorporated so the maximum diameter of each crater could be measured. The crater depths were measured using a contact dial micrometer fitted with a 0.4 mm diameter blunt-ended penetration needle, to an accuracy of 0.01 mm. Group means for crater depths and diameters were calculated, and the data sets assessed for normality using the Kolmogorov-

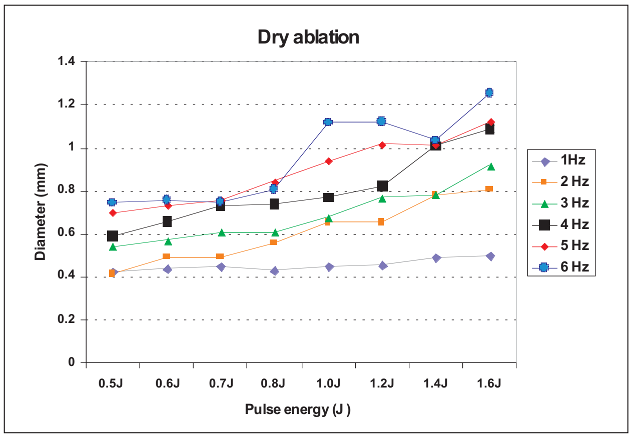

Fig 1 Diameter of craters when lasing dentine under dry conditions.

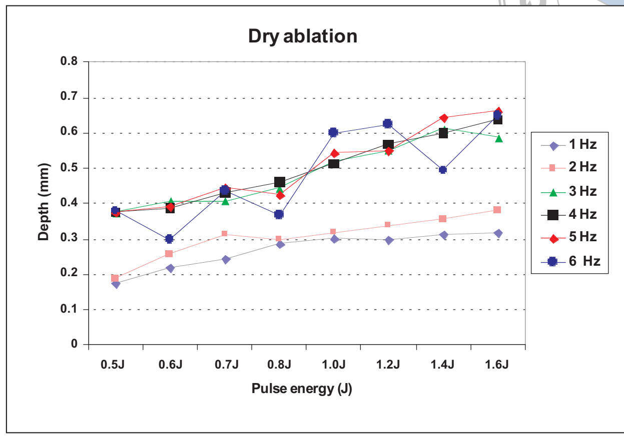

Fig 2 Depth of craters when lasing dentine under dry conditions.

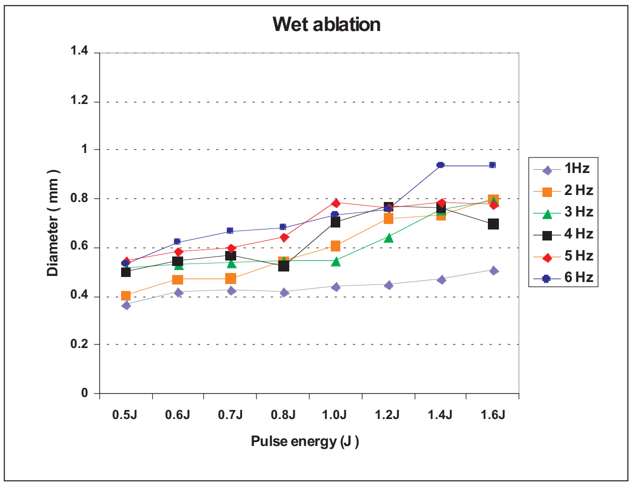

Fig 3 Diameter of craters when lasing dentine under wet conditions.

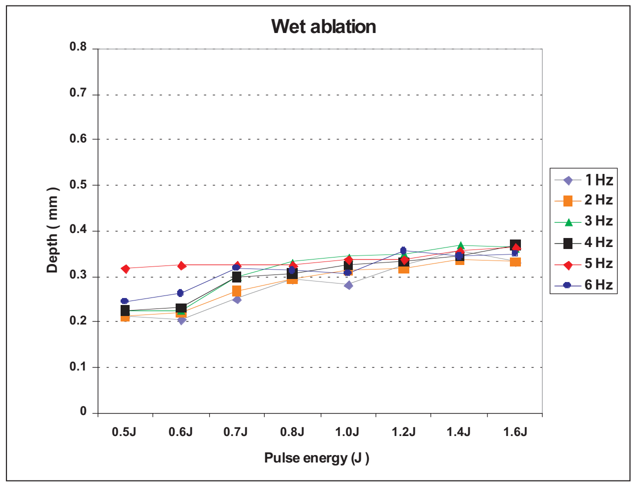

Fig 4 Depth of craters when lasing dentine under wet conditions.

Smirnov test. Differences between dry and wet ablation series were determined using a repeated measures two-way analysis of variance.

Finally, samples were dehydrated in a graded series of ethanol (from 70% to 100%) in four increments over 96 h, mounted on stubs, sputter coated with platinum, and observed at an accelerating voltage of 12 kV using a JEOL 6400F scanning electron microscope (SEM) under low vacuum conditions.

RESULTS

Dimensions of Laser-induced Craters

The mean crater depth and diameter increased with increasing pulse energy and increasing pulse frequency in both the dry and wet ablation series (Figs 1 to 4), with the greatest ablation seen at 1.6 J and 6 Hz, the maximum settings used in the study. Examining the influence of water, at low pulse rates (1 Hz and 2 Hz), there was no significant difference in the depth or diameter of the craters comparing wet and dry conditions. However, at pulse frequencies of 3 Hz and above, the dry group consistently showed a greater depth and diameter of craters across all energies, which was statistically significant ($p < 0.05$).

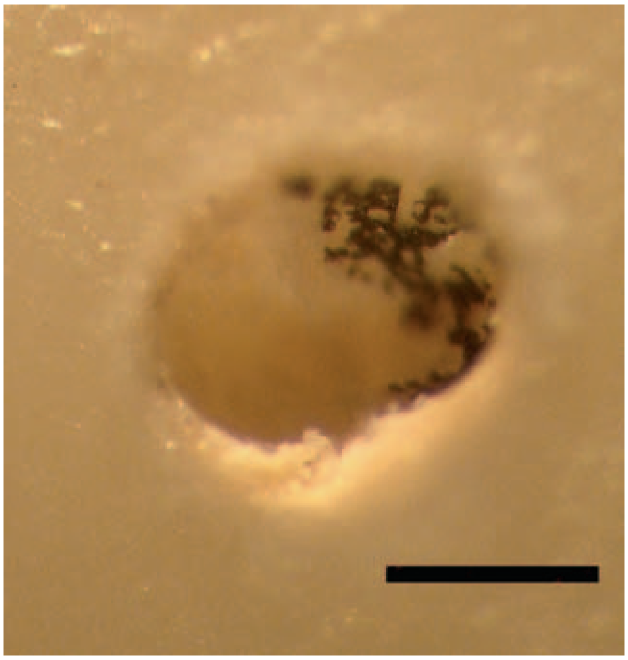

Fig 5 Dry ablation (0.6 J, 2 Hz). Some carbonization is seen at the margins of the crater (40X magnification; scale bar = 0.5 mm).

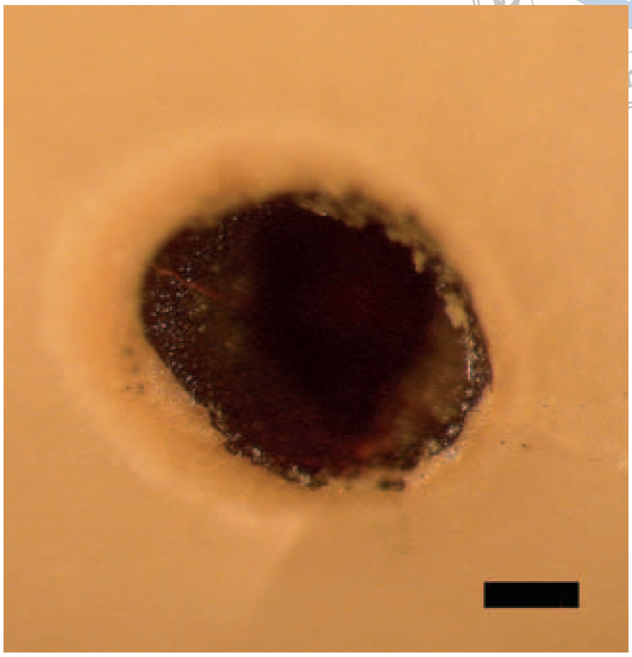

Fig 6 Dry ablation (1.0 J, 6 Hz). Carbonization is extensive throughout the crater. The crater base is macroscopically rough (40X magnification; scale bar = 0.5 mm).

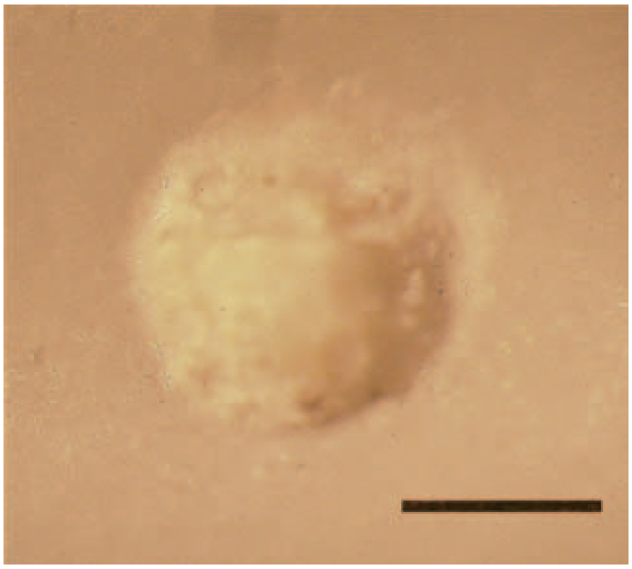

Fig 7 Wet ablation (0.6 J, 1 Hz). No carbonization is seen at the margins of the crater, and the crater base appears macroscopically smooth (40X magnification; scale bar = 0.5mm).

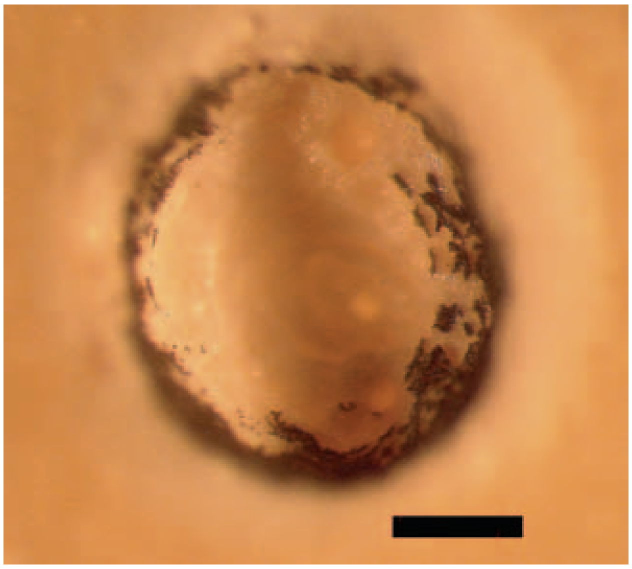

Fig 8 Wet ablation (0.6 J, 6 Hz). Carbonization of the margins is seen at this higher pulse frequency (40X magnification; scale bar = 0.5 mm).

Microscopic Findings

Microscopically, craters were deeper and also more irregular in the dry group. Charring of the crater walls and base was seen consistently and the extent of this was proportional to the pulse energy and frequency (Figs 5 and 6).

In the wet ablation group, no visible charring occurred at pulse energies from 0.5 to 1.6 J, provided the frequency was 4 Hz or less (Fig 7). At higher pulse

Table 1 Microscopic effects of Ho:YAG laser treatment of dentine

Hz	Charring of the crater margins		Charring of the crater base	
	Wet ablation	Dry ablation	Wet ablation	Dry ablation
1	None	None	None	None
2	None	Minimal	None	None
3	None	Moderate	None	None
4	None	Moderate	None	Moderate
5	Minimal	Extensive	None	Extensive
6	Moderate	Very extensive	Minimal	Very extensive

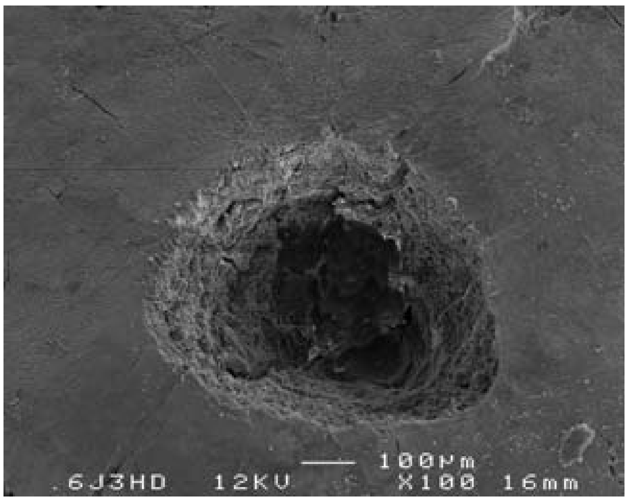

Fig 9 Dry ablation (0.6 J, 3 Hz). The crater walls and margins are irregular. The crater is deeper than when lasing is undertaken under wet conditions (compare with Fig 10) (100X magnification; scale bar = 0.1 mm).

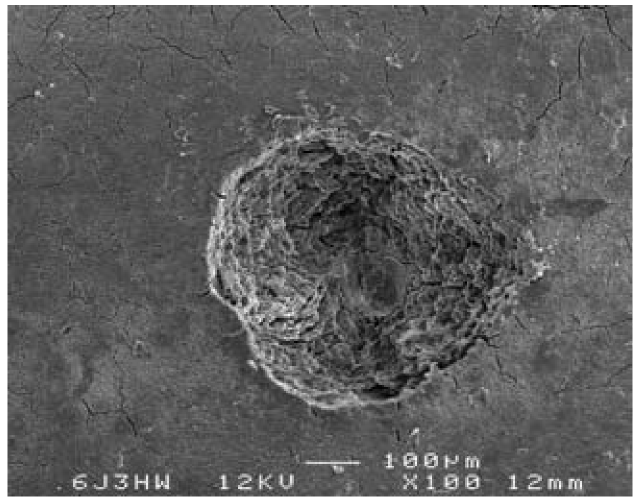

Fig 10 Wet ablation (0.6 J, 3 Hz). The crater is shallower than when lasing is undertaken in wet conditions (100X magnification; scale bar = 0.1 mm).

frequencies, peripheral charring of a mild extent occurred (Fig 8).

Ablation of dentine without water and at higher energies led to production of plume (vapour) and plasma, with visible flashes of light from the impact site and visible alterations to the fiber terminus, which as a result required frequent cleaving. Under wet ablation conditions, once the initial surface layer of dentine was ablated and the surface became irregular, water pooled in the crater and the tendency for charring effect was immediately reduced. However, at high energies and high frequencies, even the presence of water spray did not prevent charring of the margins, since desiccation of the dentine surface could be seen to occur with each pulse. A summary of the surface characteristics is presented in Table 1.

SEM Observations

SEM examination revealed rough and irregular margins (deep undercuts, jagged margins, or multiple pitting) in both groups; however, no evidence of fissuring or fracturing of the surrounding dentine was seen (Figs 9 and 10). At higher powers, there was evidence of lava-like melting and fusing of the dentine in the dry group, particularly along the crater walls (Fig 11). No such alterations were seen on the walls of craters in the wet group, but at the base of the crater, closure of dentine tubules could be seen, signifying that some vitrification of the dentine had occurred.

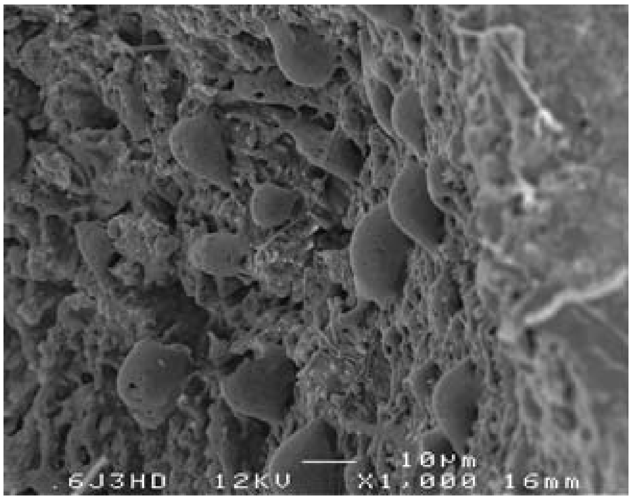

Fig 11 Dry ablation (0.6 J, 3 Hz). This higher power view shows melting and fusing of the dentine (1000X magnification; scale bar = 10 micrometers).

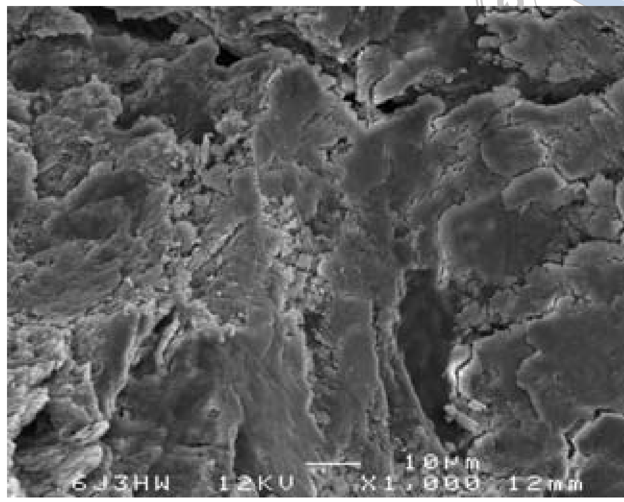

Fig 12 Wet ablation (0.6 J, 3 Hz). This higher power view shows the microscopically irregular surface on the lased dentine (1000X magnification; scale bar = 10 micrometers).

DISCUSSION

While past studies have examined the ablation of dentine with Ho:YAG laser energy, no previous studies have examined the influence of a water mist spray on this process. The results of the present study indicate that wet ablation conditions alter the effect obtained, with less plasma production, less carbonization, and an attenuated ablation effect (craters with less depth and diameter). Importantly, the pattern of thermal effects on the dentine surface, such as vitrification and fusion, is considerably less, as demonstrated by SEM examination.

Taken together, these results suggest that when used with collateral water spray, the Ho:YAG laser could be used to achieve controlled ablation of dentine. In making this statement, one must recognize that the relative absorption of Ho:YAG laser radiation in both water and dentine is much less than that of the Er:YAG, Er,Cr:YSGG, or carbon dioxide laser wavelengths, where relatively strong absorption is related to a relatively low fluence required to initiate ablation. Unfortunately, these longer wavelengths cannot employ small diameter flexible glass optical fibers, as can the Ho:YAG, which provides an advantage to the latter in terms of potential use in the root canal system. Furthermore, the results in this study for ablation under wet conditions indicate that this mode would be preferred, as there would be less thermal damage to both the dentine and the end of the optical fiber. The latter aspect would be particularly important for using the Ho:YAG wavelength within the root canal system. If used under dry conditions, damage to the fiber terminus would make predictable lasing (to achieve disinfection or removal of smear layer)[5-7] technically difficult.

The present study also sheds light onto appropriate parameters required for Ho:YAG laser ablation for dentine. Past studies have explored the effect of pulse energy but did not examine the effect of frequency. This is an important parameter, since with increasing frequency, there is a theoretical possibility that the material ejected from the crater or the plume (vapour) may interact with the incoming beam and attenuate it. This may explain in part why there was a diminishment of crater depth with increasing pulse frequency (Fig 1). An additional relevant factor is that desiccation of the dentine surface with higher pulse frequencies removes from the dentine tubules the water which is the major absorbing molecule for this laser wavelength. Variations in pulse width with higher pulse frequencies could also occur, although this aspect was not explored to any extent.

The present results indicate that ablation under wet conditions, whilst slower, is more controlled and does not result in damage to the delivery fiber (from plasma). The lased dentine surface of the crater base shows less dramatic thermal change. Because an excessively thick water film on the dentine surface would absorb laser energy and decrease the rate of ablation, controlling the water delivery rate would be an important consideration in any practical system for endodontics use based on the Ho:YAG laser. Past studies with the carbon dioxide laser, operating in the far infrared region of the spectrum, have shown the possible attenuating effects of excessive surface water on ablation.[8]

An outcome which was not assessed in this study was the potential thermal effects of the different energy levels and pulse frequencies on the pulp and periodontal ligament. The extent of this thermal stress would be expected to vary with dentine thickness, with thicker dentine providing a greater heatsink effect. Greater water flow would provide continuous conductive cooling to the tooth, as well as evaporative cooling during evaporation of material from the tooth. Because excessive water would attenuate the incoming beam and thereby reduce the efficiency of ablation, it would be sensible to use high pulse energies and low pulse frequencies and water flow, at settings at least equal to that employed in the present study as a starting point for further investigations. Adaptation of medical Ho:YAG systems along these lines would seem a worthwhile avenue to explore.

CONCLUSION

This laboratory study indicates that the Ho:YAG laser is suitable for ablation of dentine, and that this process should be conducted with coaxial water spray in order to minimize carbonization and provide cooling to the tooth. Further studies should examine thermal changes in the dental pulp and periodontal ligament as a necessary step before considering further the potential clinical applications of this laser wavelength.

The ability to ablate dentine under wet lasing conditions, and the ability to be transmitted through glass optical fibers offers promise for the application of the Ho:YAG laser for endodontics procedures, particularly shaping the root canal system. Fiber modifications should be explored to allow maximum efficiency for this.

ACKNOWLEDGMENTS

This study was supported in part by the Australian Dental Research Foundation. We thank High Tech Laser Australia (Brisbane) for the loan of the laser system used in this study.

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