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Near-IR imaging of Erbium Laser Ablation with a Water Spray

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Abstract

Near-IR (NIR) imaging can be used to view the formation of ablation craters during laser ablation since the enamel of the tooth is almost completely transparent near 1310-nm¹. Laser ablation craters can be monitored under varying irradiation conditions to assess peripheral thermal and transient-stress induced damage, measure the rate and efficiency of ablation and provide insight into the ablation mechanism. There are fundamental differences in the mechanism of enamel ablation using erbium lasers versus carbon dioxide laser systems due to the nature of the primary absorber and it is necessary to have water present on the tooth surface for efficient ablation at erbium laser wavelengths. In this study, sound human tooth sections of approximately 2-3-mm thickness were irradiated by free running and Q-switched Er:YAG & Er:YSGG lasers under varying conditions with and without a water spray. The incision area in the interior of each sample was imaged using a tungsten-halogen lamp with a band-pass filter centered at 1310-nm combined with an InGaAs area camera with a NIR zoom microscope. Obvious differences in the crater evolution were observed between CO₂ and erbium lasers. Ablation stalled after a few laser pulses without a water spray as anticipated. Efficient ablation was re-initiated by resuming the water spray. Micro-fractures were continuously produced apparently driven along prism lines during multi-pulse ablation. These fractures or fissures appeared to merge together as the crater evolved to form the leading edge of the ablation crater. These observations support the proposed thermo-mechanical mechanisms of erbium laser involving the strong mechanical forces generated by selective absorption by water.

Keywords

near-infrared imaging; Er:YAG laser; Er:YSGG laser; dental hard tissues; laser ablation; thermal damage; water-mediated ablation

2. INTRODUCTION

Last year we showed that near-IR (NIR) imaging can be used to image the formation of ablation craters during carbon dioxide laser ablation since the enamel of the tooth is almost completely transparent near 1310-nm in the near-infrared¹. That study showed that there is great potential for near-IR imaging to monitor laser-ablation events in real-time to: assess safe laser operating parameters by imaging thermal and stress-induced damage, elaborate the

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mechanisms involved in ablation such as dehydration, and monitor removal of demineralized enamel. In this paper, we present near-IR (NIR) imaging measurements involving ablation with erbium laser systems that specifically target water in the tissue for selective absorption. Other studies have demonstrated that NIR light at 1310-nm is ideally suited for the transillumination of interproximal dental caries (dental decay in between teeth) and that it can also be used to image decay in the pits and fissures of the occlusal (biting) surfaces of posterior teeth where most new dental decay occurs and even image interproximal lesions from the occlusal surface²⁻⁵.

There are fundamental differences in the mechanism of enamel ablation involving erbium and carbon dioxide laser systems. These differences are based primarily on the nature of the principal absorber in the tissue⁶. Dental hard tissue ablation is a water-mediated explosive process at 2.94 and 2.79 μm ^{7,8}. During rapid heating the inertially confined water can create enormous subsurface pressures that can lead to the explosive removal of the surrounding mineral matrix.^{9,10,11} Studies of hard tissue ablation in the $\lambda=3\text{ }\mu\text{m}$ region indicate that large intact particles are ejected with high velocity from the irradiated tissue^{7,8}. Moreover, the normal highly ordered structure of dentin and enamel is conserved during the ablation process¹². In contrast, the mechanism of ablation of dental hard tissue at the highly absorbed CO_2 wavelengths of 9.3 and 9.6 μm is apparently mineral mediated and SEM micrographs show that the tissue morphology is markedly changed after irradiation^{13,14}. Although, it is advantageous to ablate enamel at lower surface temperatures to avoid heat deposition, it may also be useful to heat the tissue peripheral to the ablation site to temperatures exceeding 400 °C. This creates a zone of increased acid resistance around the restoration site which may occur to a greater degree after Er:YSGG and CO_2 laser irradiation¹⁵ than with Er:YAG laser irradiation.

Laser light near 3.0 μm is efficiently absorbed by the intrinsic H_2O and the OH^- in the apatite mineral of dental hard tissues^{9,16,17}. Er:YSGG laser emission is coincident with the narrow (OH) absorption band at $\lambda=2.8\text{ }\mu\text{m}$ while Er:YAG emission overlaps the broad water absorption centered at $\lambda=3\text{ }\mu\text{m}$. It is the generally accepted hypothesis that the subsurface expansion of water is the primary mechanism responsible for exfoliation or spallation of the enamel mineral at temperatures below the melting point of the tissue ($\sim 1200^\circ\text{C}$) during irradiation near $\lambda=3\text{ }\mu\text{m}$ ^{7,9,10,12,16,18-22}. During rapid heating, the inertially confined water can create enormous subsurface pressures that can lead to the explosive removal of the surrounding mineral matrix¹¹. Several studies of hard tissue ablation in the $\lambda=3.0\text{ }\mu\text{m}$ region indicate that large particles are ejected with high velocity from the irradiated tissue^{7,9,10,20,23}. This observation strongly supports the mechanism of a water-mediated explosive process. Time-resolved radiometry measurements provide significant information about the nature of absorption in dental enamel and the mechanism of ablation. Surface temperatures at the ablation threshold for enamel indicate that the mechanism of ablation is thermal and occurs at approximately 300-400°C for Er:YAG, 800°C for Er:YSGG and 1200°C for CO_2 lasers.^{24,25} The most convincing evidence for mechanistic differences in ablation is provided by microscopic examination of the enamel surface after ablation. Keller and Hibst¹² published the first SEM micrographs showing the marked differences in surface morphology produced between CO_2 and Er:YAG laser ablation. Enamel surfaces irradiated by erbium lasers appeared etched in contrast to the CO_2 laser irradiated surfaces that had the

characteristic glassy appearance indicative of melting. After CO₂ irradiation there is almost complete fusion of the enamel rods and the grain size of the individual crystals has increased over an order of magnitude from 40 nm to 500 nm.^{13,14} More recent SEM micrographs show that the prisms fuse together during CO₂ irradiation and they are cleanly ejected for Er:YAG ablation⁶. High resolution, (60,000x) examination of the ablated area after Er:YAG irradiation shows no fusion of the individual enamel crystallites¹⁵. Therefore the mechanism is markedly different between 2.94 and 10.6 μm even though the absorption coefficient is similar, therefore there is a fundamental difference in the mechanism of ablation due to the nature of the absorber.

3. MATERIALS AND METHODS

3.1 Tooth Samples

Thirty-four tooth sections approximately 3-mm thick were prepared from extracted human 3rd molars that were stored in water with only 0.1% thymol added to inhibit bacteria and fungal growth. Surfaces were serially polished to a finish of 0.1- μm using embedded diamond polishing discs. A near-IR image of one of the samples is shown in Fig. 1. The high transparency of the enamel enables imaging of the formation of the ablation craters.

3.2 Near Infrared Imaging (near-IR)

A three component, modular 7X NIR precision zoom lens consisting of a focusable lower module, a manual upper zoom module and a 1.5 TV tube from Edmund Scientific (Barrington, NJ) was used with the InGaAs FPA. The field of view was adjustable from 0.81 to 5.6-mm, the magnification from 1.7X to 11.8X, and the numerical aperture from 0.036 to 0.12. Light from a 150-W fiber-optic illuminator FOI-1 E Licht Company (Denver, CO) coupled to an adjustable aperture and a 90-nm bandpass filter centered at 1310-nm, Filter# BP-1300-090-B Spectrogon US Inc.(Parsippany, NJ) was used to illuminate the samples. An InGaAs area camera, the Alpha NIRTM from Indigo Systems (Goleta, CA) with a 318 $\times$ 252 pixel focal plane array was used to acquire all the images. The acquired 12-bit digital images were analyzed using IRVistaTM software Indigo Systems (Goleta, CA).

3.3 Ablation Apparatus

Samples were irradiated using a Model-123 Er:YAG laser operating in free running mode that was originally manufactured by Schwartz Electro-optics 123 (Orlando, FL). The free-running laser pulses were generated using a Analog Modules (Longwood, FL) Model 8800 variable pulse power supply that generates a square shaped flash lamp drive pulse. The flash lamp drive pulse was varied in order to generate laser pulses from 35-200- μs duration. A second Model-123 Er:YSGG (2.79- μm) laser system also manufactured by Schwartz Electro-optics (Orlando FL) operating with a rotating-mirror Q-switch that was custom manufactured by Shiva Laser (Los Angeles, CA) was used to produce a short high intensity laser pulse of 500-ns duration. The laser pulse temporal profiles were measured with a room temperature HgCdTe detector with a response time of a few ns, Boston Electronics (Brookline, MA). The beam diameter at the position of irradiation was 300- μm , measured by scanning with a razor blade across the beam. The spot profile was single mode and fluences were defined using a Gaussian beam with a $1/e^2$ beam diameter. An irradiation intensity of 8

J/cm² was used to produce the three incisions on each sample. The sample was continuously scanned across the laser beam at a rate of 0.25 mm/sec and a pulse repetition rate of 5-Hz. A low volume/low pressure air-actuated fluid spray delivery system consisting of a 780S spray valve, a Valvemate 7040 controller, and a fluid reservoir from EFD, Inc. (East Providence, RI) was used to provide a uniform spray of fine water mist onto the enamel surfaces at 2 mL/min. The setup showing the respective positions of the tooth section, laser hand-piece, light-source, camera and lens and water-spray nozzle are shown in Fig. 2.

3.4 Experimental Procedures

Fifty-eight ablation holes were drilled in the first group of twelve tooth sections with the Er:YAG laser at repetition rates ranging from 5 to 10 Hz with and without a water spray. Sixteen tooth sections were used to make thirty-four incisions in the second group of experiments with the Er:YAG laser beam by scanning across the tooth section at a rate of 1.5 mm/sec at repetition rates ranging from 5 to 10 Hz with and without a water spray. Twenty-two ablation craters were drilled in the last group of four additional sections with the Q-switched Er:YSGG laser at repetition rates of 3 Hz with and without a water spray.

4. RESULTS

For the first group of samples, the position of the Er:YAG laser was held fixed and ablation craters were drilled into the tooth section to a depth of 1 - 2 mm with a water spray. Six such holes are shown in Fig. 3. Videos for Fig. 3 were acquired at ten frames per second for a period of 30 seconds during ablation and the rate of progression of the holes and peripheral changes in the opacity of the enamel could be followed in real-time. There is high contrast between the sound enamel and the ablation crater and there appears to be no thermal damage at the site of ablation. The ablation craters extend approximately 1 to 2 mm into the enamel and are not highly conical in shape as was observed with the ablation videos for the CO₂ laser¹. Er:YAG laser ablation proceeded at an irregular rate and was not uniform. The ablation started and stopped and then continued and stalling was not predictable from sample to sample. In Figs. 3&4, the size and shape of the craters were highly variable even through the ablation conditions were similar. The images presented in Fig. 4 were taken at a higher magnification as the craters evolved in time, small fractures or surface protrusions formed at the front of the ablation. The micro-fractures occur over a wide area of the crater and they are not localized towards the center of the laser beam.

Figure 5(A) shows an incision made with the Er:YAG laser at a repetition rate of 5 Hz and an incident fluence of 60 J/cm² with a continuous water spray. The laser beam was scanned back and forth over a scanning distance of 2 mm at a rate of 1.5 mm/sec for 60 seconds. There were no visible changes in the surrounding sound enamel during ablation and the ablation produced a nice clean uniform cut through the enamel when a continuous water spray was used. A second crater on the same sample was produced without the water spray, Fig. 5(B), and ablation quickly stalled after ten seconds without a continuous water spray producing a crater with a highly irregular shape. Ablation resumed in the same location, Fig. 5(C), after reapplication of the continuous water spray and the water could be observed moving inside the ablation crater in the video as ablation proceeded.

The last group of samples were ablated with a Q-switched Er:YSGG laser. In Fig. 6, the frames extracted from the video shows the micro fractures that developed as the crater advanced. At very high irradiation intensities, namely 120 J/cm^2 , the ablation continued to slowly proceed even though a continuous water spray was not used—water was applied between each 30-second period of ablation. We anticipated seeing many stress cracks due to the higher power densities of the Q-switched pulses, however, the ablation craters looked similar to the free-running Er:YAG and there were no cracks formed peripheral to the ablation sites.

5. DISCUSSION

Laser ablation craters could be imaged through sound human tooth sections of approximately 3-mm thickness with high detail during their formation. Tooth samples were irradiated with a fixed spot or were scanned to make incisions with and without the water spray. Due to the high transparency of enamel at 1310-nm, laser-incisions were clearly visible to the dentin-enamel junction. Obvious differences in the crater evolution were observed between CO_2 and erbium lasers. Ablation stalled after a few laser pulses without a water spray as anticipated for erbium laser ablation and efficient ablation was re-initiated by resuming the water spray. Micro-fractures were continuously produced apparently driven along prism lines during multi-pulse ablation. These fractures/fissures appeared to merge together as the crater evolved to form the leading edge of the ablation crater. Such micro-fractures were not observed with evolution of the CO_2 laser ablation craters¹. The ablation craters produced by the erbium lasers with a continuous water spray were very clean without large cracks or peripheral thermal damage. It is important to note that even though we have labeled the surface protrusions at the end of the ablation crater “micro-fractures” we have no evidence that these small fractures evolve into larger cracks that undermine the mechanical strength of the enamel. Another important distinction between erbium and carbon dioxide crater formation is that the erbium craters did not produce as highly conical a shape as the CO_2 laser ablation craters. This is likely due to the differences in the mechanism of ablation. In summary, our observations of the evolution of the erbium laser ablation craters support the proposed thermo-mechanical mechanisms of erbium laser hard tissue ablation involving strong mechanical forces generated by selective absorption by water.

6. ACKNOWLEDGEMENTS

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Fig. 1.
NIR image of a 3 mm tooth section showing the high-transparency of dental enamel and the site of ablation.

Fig. 2.
Imaging Setup. (A) InGaAs FPA with zoom lens, (B) water spray nozzle, (C) laser hand-piece, (D) fiber-optic illuminator, (E) sample holder and tooth section.

Fig. 3.

(A) NIR image through side of tooth section with ablation crater produced in enamel with a water spray at a repetition rate of 5 Hz, a fluence of 65 J/cm^2 and energy of 45 mJ per pulse with a $100 \text{ }\mu\text{s}$ pulse. (B) NIR image of two additional ablation craters showing surface protrusions at ablation front. (C) NIR image of three additional ablation craters highlighting water droplets inside the ablation crater and surface protrusions at ablation front.

Fig. 4.

(A) Magnified NIR image of an enamel tooth section with three ablation craters produced using an Er:YAG laser with a water spray at a repetition rate of 5 Hz, a fluence of 65 J/cm^2 , an energy of 45 mJ per pulse and a 100- μs pulse duration. (B) Magnified NIR image of another enamel tooth section with same conditions. (C) Reflected light image of the tooth surface containing the three ablation craters shown in B.

Fig. 5.

(A) NIR images of incisions in a sample produced by scanning across the Er:YAG laser beam with a water spray at a repetition rate of 5 Hz, a fluence of 60 J/cm^2 and an energy of 40 mJ per pulse with a $125 \text{ }\mu\text{s}$ pulse length. (B) NIR image extracted from video with initial ablation crater from A and second irregular ablation crater that stalls without a continuous water spray. (C) NIR image extracted from video with second ablation crater that resumes with water spray. (D) Reflected light images of incision after ablation showing clean incision.

Fig. 6.

(A and B) High-magnification NIR image extracted from video of enamel tooth section with ablation crater produced with a Q-switched Er:YSGG without water spray at a repetition rate of 3 Hz, a fluence of 120 J/cm^2 and an energy of 90 mJ with a short $0.5 \mu\text{s}$ pulse .