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Ablation of Dental Hard Tissues with a Microsecond Pulsed Carbon Dioxide Laser Operating at 9.3-*μ*m with an Integrated Scanner

Shlomo Assa and **Steve Meyer**

Inlight Corporation, San Diego, CA 92127

Daniel Fried

Department of Preventative and Restorative Dental Sciences, University of California, San Francisco School of Dentistry, CA 94143-0758

Abstract

Pulsed carbon dioxide lasers operating at the highly absorbed 9.3 and 9.6-µm wavelengths with pulse durations in the microsecond range are ideally suited for dental hard tissue modification and removal. The purpose of these studies was to demonstrate that a low cost 9.3-*μ*m CO_2 laser system utilizing low-energy laser pulses (1-5 mJ /pulse) delivered at a high repetition rate (400-Hz) is feasible for removing dental hard tissues. The laser beam was focused to a small spot size to achieve ablative fluence and an integrated/programmable optical scanner was used to scan the laser beam over the desired area for tissue removal. Pulse durations of 35, 60 and 75-µs were employed and the enamel and dentin ablation rate and ablation efficiency were measured. Laser irradiated human and bovine samples were assessed for peripheral thermal and mechanical damage using polarized light microscopy. The heat accumulation during rapid scanning ablation with water-cooling at 400-Hz was monitored using micro-thermocouples. The laser was able to ablate both enamel and dentin without excessive peripheral thermal damage or heat accumulation. These preliminary studies suggest that a low-cost RF excited CO_2 laser used in conjunction with an integrated scanner has considerable potential for application to dental hard tissues.

Keywords

CO_2 laser; caries removal; dentistry; enamel; dentin; laser ablation

2. INTRODUCTION

Increasing emphasis is being placed on more conservative approaches to restorative dentistry such as caries risk assessment, early caries detection and micro-preparation. Lasers are ideally suited for micro-preparation and conservative caries removal with minimal loss of healthy tissue. Laser pulses can preferentially ablate carious tissue due to the higher volatility of water and protein that are present in carious tissue at a higher ratio then in normal tissue and laser pulses can be tightly focused to drill holes with very high aspect ratios (depth/height) well beyond those obtainable by the dental drill that is limited by the size of the dental burr (>1 mm). Conservation of enamel structure is paramount for preservation of the natural dentition for retention of sealants and to limit exposure to wear.

The laser can be precisely focused into the carious fissure of a molar to remove any debris and bacteria, ablate away the carious tissue and enlarge the narrow neck of the fissure leaving a smooth crater. A flowable composite can subsequently be applied for a highly conservative restoration. Moreover, laser irradiation does not produce a smear layer that needs to be removed, hence restorative materials can be applied directly to the ablated area without the need for further surface preparation and etching. This advantage is of great importance since fissure areas are difficult to etch by conventional means due to the unique enamel morphology. The enamel on the shoulder at the entry to the fissure is often prismless and irregular and may not accept a good etch pattern, so attachment of the resin may be tenuous. Therefore, laser preparation may be superior to the conventional acid etch in pits and fissures. CO_2 laser radiation vaporizes water and protein and changes the chemical composition of the remaining mineral of enamel and dentin, thus decreasing the solubility to acids around the periphery of the restoration site to leave a smooth surface with an enhanced resistance to secondary caries. [1-6,11] By taking this approach the dentist can intervene in a conservative manner before the lesion has progressed to the point that conventional surgical intervention is necessary. Lasers are also less likely to require anesthesia and induce less noise and pain.[7-10] Therefore they are advantageous for treating children, and patients with dental phobias. Thus, lasers are ideally suited for minimally invasive surgical intervention and have the potential of markedly reducing or eliminating the loss of adjacent healthy tissue during the removal of carious tissue or the removal of existing composite restorations. CO_2 lasers are the most common lasers found in clinics today and have been used for soft tissue surgical procedures for three decades. The CO_2 laser can be designed to operate or “lase” at discrete wavelengths between λ= 9 to 11-μm. Early studies using continuous wave CO_2, lasers operated at 10.6-μm reported extensive cracking and charring of surrounding enamel, dentin and bone. Based on these disappointing initial observations, many laser researchers overlooked the potential of CO_2 laser based systems for hard tissue ablation.[12-22] Recent studies using pulsed TEA and RF-excited CO_2 laser pulses of sub-millisecond duration indicate that dental hard tissues can be ablated efficiently without generating peripheral damage.[23-27] Ivanenko et al. [28] demonstrated that a mechanically Q-switched 10.6 μm CO_2 industrial laser could be used to cut bone rapidly at 300 Hz without thermal damage. The peak absorption of dental hard tissues occurs at 9.3 and 9.6-μm where the incident laser light will be absorbed at a depth of under 1-2 μm (see Fig. 1). CO_2 lasers operating at 9.3 and 9.6-μm with a pulse duration in the microsecond range are well suited for the ablation of enamel, dentin and bone with minimal thermal damage.[29,30]

Previous efforts focused on the 9.3 and 9.6-μm TEA lasers that employ a simple high voltage discharge to excite the gas mixture. [23-27,29,30] In contrast, Radio Frequency (RF) excited slab lasers use a radiofrequency source to excite the CO_2 gas and can be operated efficiently with a completely sealed gas mixture. The principal advantages of the RF-slab laser over the TEA laser are small size and sealed gas mixture.Systems with output in the range of 10-30 W are now available at relatively low-cost that do not require water-cooling. One potential disadvantage of these RF-excited systems is the greater potential for peripheral thermal damage since these lasers are operated most efficiently with longer pulse durations greater than 60-μs, much longer than the thermal relaxation time of 1-2-μs for 9.3 and 9.6-μm CO_2 laser wavelengths in enamel. The RF-excited slab laser operates most

efficiently with pulse durations of 60-μs to 5-ms, and repetition rates in the tens of kHz are feasible as long as a 50% duty cycle is not exceeded. Visuri investigated a RF-excited slab laser operating at 9.4-μm with a pulse duration of 300-μs for laser ablation of dentin and enamel.[31] He observed ablation rates of ~80-μm per pulse for dentin and 44-μm per pulse for enamel with a fluence of 66 J/cm^2 per pulse with and without a water flow rate of 11.3 ml/min. The maximum repetition rate investigated was limited to 10-Hz. Recent developments on RF-excited slab lasers such as the GEM and Diamond series lasers produced by Coherent have reduced the pulse duration to the 25-35-μs range and the laser employed by Inlight Inc. for these studies was operated with pulse durations as short as 36-μs (see Fig. 2). The purpose of these studies was to demonstrate that a low cost 9.3-μm CO_2 laser system utilizing low-energy laser pulses (1-5 mJ /pulse) delivered at a high repetition rate (400-Hz) is feasible for removing dental hard tissues. The laser beam was focused to a small spot size to achieve ablative fluence and an integrated/programmable optical scanner was used to scan the laser beam over the desired area for tissue removal.

3. MATERIALS AND METHODS

3.1 Sample Preparation

Blocks of approximately 5 × 5 × 2 mm^3, of bovine enamel were prepared from extracted bovine tooth incisors acquired from a slaughterhouse. The enamel surfaces were serial polished to one micron using embedded diamond polishing discs. Sections of human enamel and dentin also approximately 2-mm thick were prepared from extracted human teeth.

3.2 Laser Treatment

Samples were irradiated with a custom modified GEM-40A RF-excited CO_2 laser from Coherent (Santa Clara, CA) with an integrated scanner operating at 9.3 μm with set pulse durations of 35, 60, and 75-μs operating with a pulse repetition rate of 400-Hz. The laser was focused to a spot size of 135-μm on the tissue surface. The laser was operating in a single spatial mode. Samples were kept well hydrated before ablation and either cooled using a computer controlled water spray or left dry during ablation. A low volume / low pressure air-actuated fluid spray delivery system consisting of a EFD 780S-SS Spray valve, a Valvemate 7040 controller and a fluid reservoir from EFD INC. (East Providence, RI) controlled by LABVIEW 4.0 software was used to provide a uniform spray of water on the tissue surface. The spray angle was 50° and the distance was 45 mm producing a circle of 20.5 mm diameter at the position of the surface of the 5.5-mm block. The volume of water delivered per minute was 5.5 ml. The laser pulse duration was measured using a high-speed HgCdTe detector (Boston Electronics PD-10.6-3, Boston, MA). The profiles for the 35 and 60-μs pulses are shown in Fig. 2. The pulse durations for the 50, 75 and 100-μs settings for the RF-power supply were ~ 35, 60 and 75-μs in duration. The 2.5-ms pulse spacing was also measured and is shown at the bottom of Fig. 2. The actual laser pulse durations were shorter than those set by the power supply.

3.3 Polarized Light Microscopy (PLM)

After laser irradiation, samples were cut into sections approximately 200-μm thick using an Isomet 5000 saw, Buehler (Lake Bluff, IL) for examination with polarized light microscopy

(PLM). Sections were made perpendicular to the direction of the lateral incisions to view them in cross-section. After cutting, sections were imbibed with water and viewed in the optical microscope using crossed polarizers and a Red I wave-plate. Polarized light microscopy was carried out using a Scientific Series 7 optical microscope (Westover Scientific, Mill Creek, WA) with an integrated digital camera, Canon EOS Digital Rebel XT (Canon Inc., Tokyo, Japan). A grating with 100 lines per mm was used to make measurements on the digital photos. All photos are 100x magnification. Thermally modified areas appear dark due to loss of birefringence. The thickness of the thermally modified areas were assessed using the spatial measurements function of the Image Processing Package bundled with Igor Pro software (Wavemetrics, Lake Oswego OR). The scaling data was calibrated from the images and the lesion depths were measured in microns.

3.4 Thermocouple Measurements

Prefabricated insulated thermocouples, type K Chromel-Alumel, 0.005” wire diameter, (OMEGA Technologies, Stamford, CT) were placed against the center of the backside of 5×5 mm bovine blocks consisting of both an enamel and dentin approximately 2-mm thick. The thermocouple was held in good thermal contact using a thermally conductive paste, OMEGATHERM® 201, (OMEGA Technologies, Stamford, CT). The thermocouple voltage was monitored with a Stanford Research SR630 thermocouple controller (Stanford, CA) interfaced to a lab-top computer. Thermocouple voltages were converted to temperatures using an 7th order polynomial curve-fit. A temperature rise of 5.5 °C above ambient is considered excessive based on the seminal study of Zach and Cohen. [32] A circular ablation pattern 3-mm across (see Fig. 5) was produced on the enamel surface at the center of each bovine block at 400-Hz with the 75-*μ*s pulse. The scans were repeated 11 times in a 2-minute interval and the temperature was monitored on the backside of each block.

4. RESULTS

4.1 Ablation Depth in Enamel and Dentin

Laser Incisions in Enamel and Dentin were produced on nine human enamel and dentin sections using the laser with 400-Hz and a 49% overlap between laser pulses. Samples were irradiated with a 75-*μ*s pulse duration (average power= 2.0 W), a 60-*μ*s pulse duration (average power= 1.5 W), and 35-*μ*s pulse (average power= 0.9 W). The scanner was programmed to deliver 1, 5 or 10 pulses per spot. Figure 3 shows incisions produced on a tooth section with enamel and dentin with the 60-*μ*s laser pulses. The crater depth was measured using two techniques. It was not possible to get good cross sections of the enamel so the ablation depth was measured by scanning the image plane of a calibrated microscope from the position of the crater surface to the maximum crater depth. It is important to note that the base of the craters was not uniform. For dentin the ablation depth was measured by taking thin sections (200-*μ*m thick). Both the maximum depth and minimum crater depth are indicated in Tables I and II.

The scanner could be set to scan the laser over a programmable area to prepare cavities of circular or rectangular dimensions. Figure 5 shows a circular pattern that was produced in the enamel surface that is approximately 200-*μ*m deep and 2-mm across after scanning for 2-

minutes with the 75-μs pulse setting at a repetition rate of 400-Hz. Figure 6 shows a square hole drilled by scanning a 2×2 mm^2 pattern. For this sample the laser drilled through both the enamel and dentin and the hole is more than 2 mm deep.

4.2 Peripheral Thermal Changes

Polarized light microscopy was used to determine the thickness of thermal damage produced while creating our lateral incisions. Figure 4 shows a PLM image of a cross-section taken of a laser-incision produced with the 60-µs laser pulses. Thermally transformed areas lose their birefringence and appear dark brown to black. The wave-plate introduces a phase retardation of 530-nm so that addition and subtraction colors introduced by the tissue birefringence induce resolvable changes in color. In the case of thermal damage, increased attenuation of the illumination light causes altered tissue to appear black, which is easier to discern under polarized light. Peripheral thermal modification data on dentin is tabulated in Table II. Note the thermal damage zones also include the edge effect of the ablation crater so that the actual width of the thermal damage zone is less than the measured width.

4.3 Thermocouple Heat Accumulation Measurements

A sample thermocouple temperature reading is shown in Fig. 7. The laser was operated in a specific scan mode to produce a 3 mm circular scan on the surface of the block at 400-Hz (2.0 Watts average power) that was repeated 11 times in a 2-minute interval. This procedure was repeated on each of the five 5×5 mm^2 bovine blocks. The ambient temperature was 22.6 ± 0.5°C and the temperature dropped to 17.9 ± 0.1°C after application of the water-spray. The temperature rose to a maximum of 21.4 ± 1.1°C during the laser irradiation for an increase of 3.5±1.1°C, however that temperature rise was still below the ambient temperature of 22.6 ± 0.5°C.

5. DISCUSSION

These promising results suggest that a low-cost RF-excited CO_2 laser operating at the highly absorbed 9.3-µm wavelength with pulse durations in the range from 40-100-µs and single pulses energies of 1-5 mJ focused to a beam diameter ~100-µm in diameter can be used to ablate both enamel and dentin when the laser is operated at high repetition rates and the laser beam is scanned over the tooth surface using an integrated scanner. With the laser operating at 400-Hz with water-cooling changes on dentin were limited to a peripheral zone of less than 20-µm and there was minimal peripheral thermal damage to enamel. Further studies will explore the influence of varying the single pulse energy, repetition rate on ablation rate and efficiency, peripheral thermal damage in dentin and adhesion to restorative materials.

6. ACKNOWLEDGEMENTS

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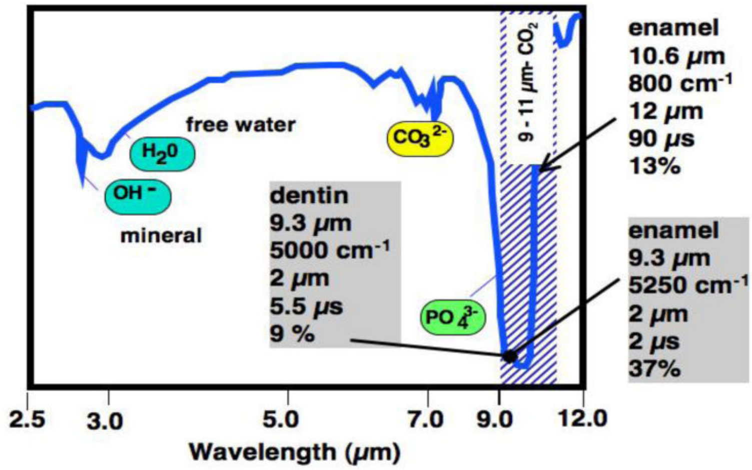

Fig. 1.

Optical properties of human dental enamel and dentin at 10.6 and 9.6-μm CO_2 laser wavelengths. The wavelength, absorption coefficient, (1/e) absorption depth, thermal relaxation time, and % reflectance are listed for each laser wavelength.

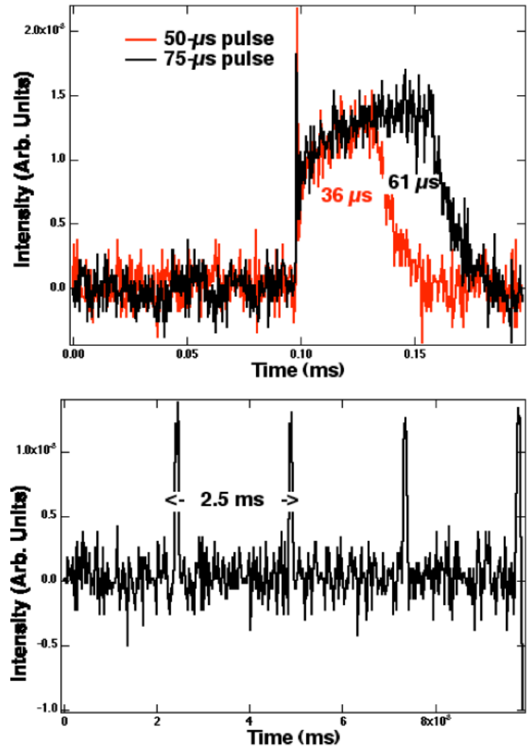

Fig.2.

(top) The temporal pulse profiles for the individual 50-μs and 75-μs RF-excited CO_2 laser pulses. (bottom) The laser pulses were spaced 2.5-ms apart (400-Hz).

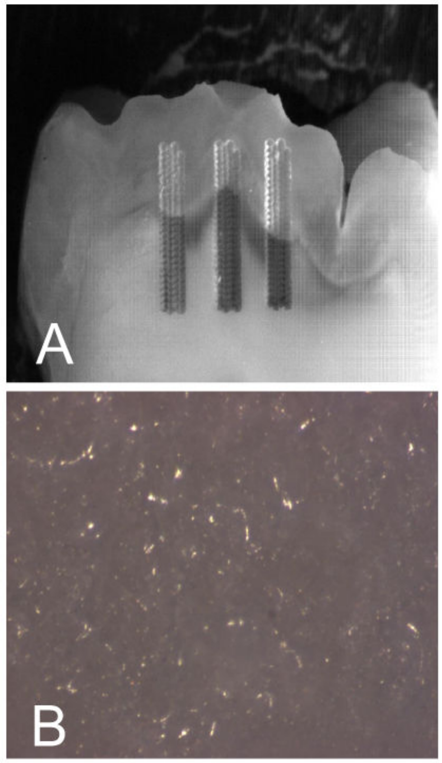

Fig. 3.

(A) Incisions in a tooth sectionproduced with the Inlight laser (9.3-µm, 400-Hz, 60-µs pulse). (B) High-magnification image of the enamel surface showing the enamel is melted.

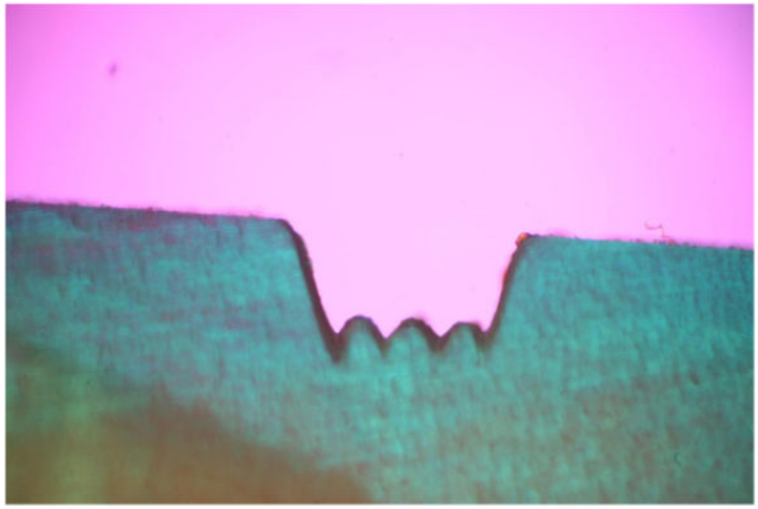

Fig. 4.

Cross section in dentin produced with the Inlight laser (9.3-μm 400-Hz, 60-μs pulse).

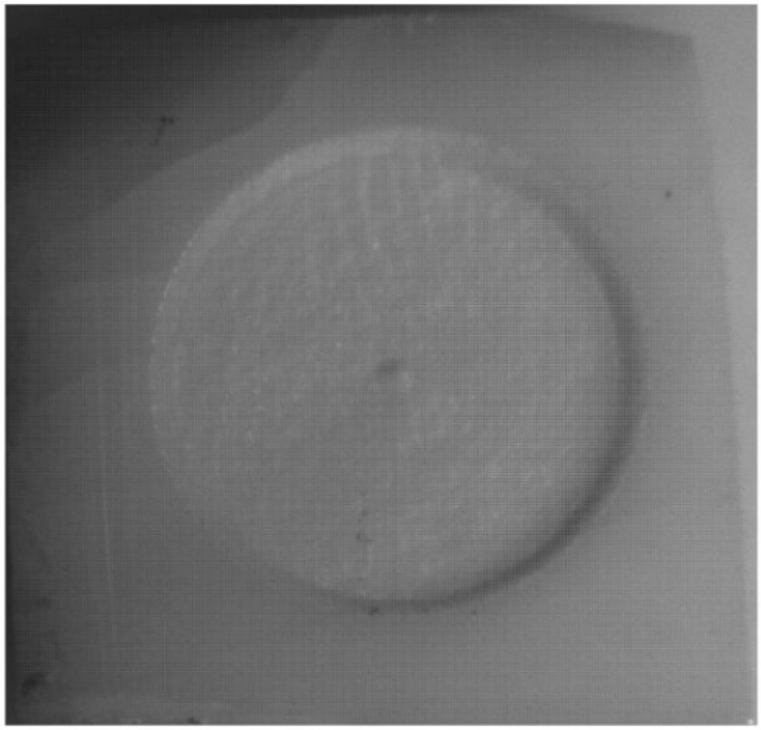

Fig. 5.

Circular scanned ablation pattern produced in enamel (200-µm deep and 3-mm across (9.3-µm 400-Hz, 75-µs pulse).

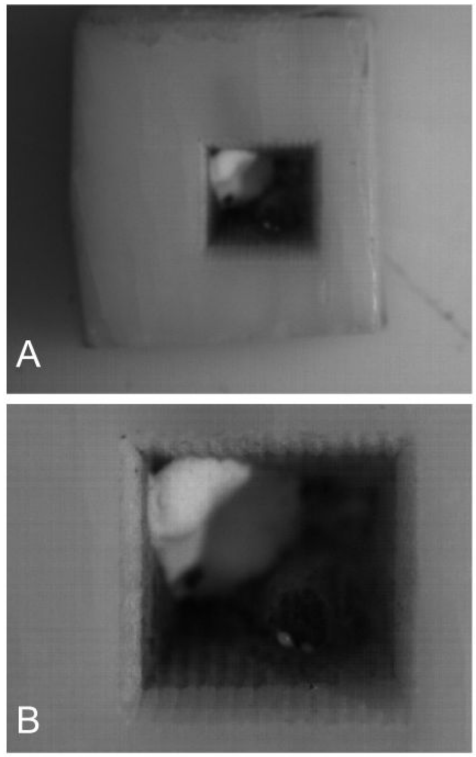

Fig. 6.

Scanned ablation 2×2 mm^2 patterns produced enamel and dentin (2-mm deep) with the Inlight laser (9.3-μm 400-Hz, 75-μs pulse).

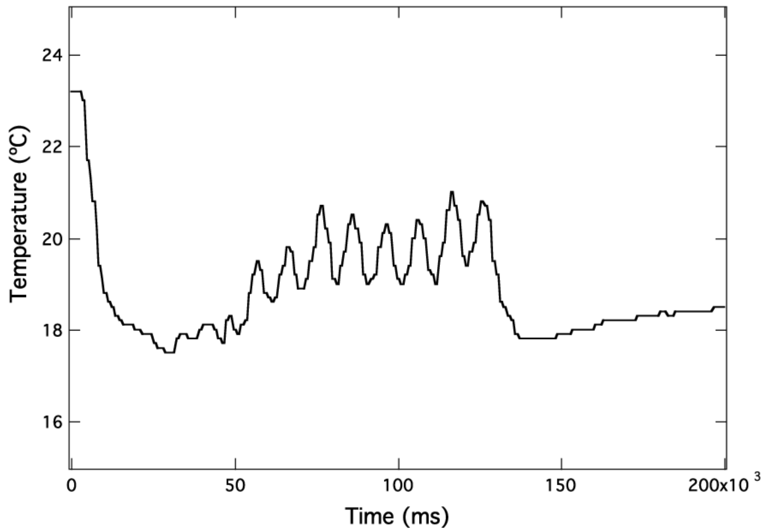

Fig. 7.

Thermocouple reading for bovine block exposed for 11 scans in a 2-minute interval with water-cooling. The temperature dropped ~ 5°C with the water-spray and then rose ~ 3°C with the laser irradiation but remained below the ambient temperature.

Table I

Enamel Ablation depths (μm), mean (s.d), n=3

Pulse Duration	Max. Depth 10 pulses	5 pulses	1 pulse
75-μs	195	105	30
60-μs	130(18)	77(16)	20(5)
35-μs	72(10)	52(18)	20(9)

Table II

Dentin Ablation depths and thermal damage zones

Dentin (75-μs)	**10 pulses**	**5 pulses**	**1 pulse**
Depth (Max)	335(62)	180(34)	41(13)
Depth (Min)	297(38)	139(15)	23(5)
Thermal Zone	19(5)	17(3)	15(4)

Dentin (60-μs)	**10 pulses**	**5 pulses**	**1 pulse**
Depth (Max)	231(23)	125(15)	31(5)
Depth (Min)	206(20)	93(15)	16(5)
Thermal Zone	16(3)	17(1)	15(3)

Dentin (35-μs)	**10 pulses**	**5 pulses**	**1 pulse**
Depth (Max)	127(20)	68(10)	21(5)
Depth (Min)	89(30)	41(9)	13(3)
Thermal Zone	18(4)	15(5)	11(5)