Title
Selective Removal of Residual Orthodontic Composite Using a Rapidly-Scanned CO2 Laser

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Publication Date
2012

Peer reviewed|Thesis/dissertation

Selective Removal of Residual Orthodontic Composite Using a Rapidly Scanned CO_2 Laser with Spectral Feedback

by

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Oral and Craniofacial Sciences

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, SAN FRANCISCO

[redacted]

Acknowledgment

Thank you to Daniel Fried for the opportunity to conduct research in his laboratory and complete this master's thesis. Also, for his consistent guidance and support throughout these past 7 years. I enjoyed working on cutting-edge technology and being able to incorporate some of my engineering background into my research. Thank you to Arthur Miller and Cynthia Darling for being on my committee and helping with the scope and flow of the project and much paper editing. I would also like to recognize Arndt Klocke for his clinical insight early in the project.

I appreciated the help of Hobin Kang with the PS-OCT scans and analysis. In particular, I would like to recognize Kenneth Chan for his Labview programming skills, the technical operation of the laser and feedback program, and spending many hours with me in the lab to successfully complete this project. This project would not have been possible without the entire team.

Finally, we appreciated the support of Ormco Corporation for the GrenGloo™ composite, OrthoSolo, etchant and brackets. This study was supported by NIH/NIDCR grant RO1-DE19631.

Abstract

Background and Objective: Excessive heat accumulation within the tooth, incomplete removal of composite, and variable damage to the enamel are shortcomings of using conventional burs to remove residual orthodontic composite after debonding fixed appliances. The objective of this study was to determine if composite could be selectively removed from the enamel surface using a rapidly scanned carbon dioxide laser controlled by spectral feedback.

Materials and Methods: A carbon dioxide laser operating at a wavelength of 9.3 μm with a pulse duration of 10-15 μs and a pulse repetition rate of ~ 200 Hz was used to selectively remove composite from the buccal surfaces of 21 extracted teeth. GrenGloo™ composite was used to better visualize residual composite and the amount of enamel lost was measured with optical microscopy. A spectral feedback system utilizing a miniature spectrometer was used to control the laser scanning system. Pulpal temperature measurements were performed during composite removal to determine if there was excessive heat accumulation.

Results: The amount of enamel lost averaged 22.7μm ± 8.9 and 25.3 μm ± 9.4 for removal at 3.8 and 4.2 J/cm^2, respectively. An average maximum temperature rise of 1.9°C ± 1.5 was recorded, with no teeth approaching the critical value of 5.5°C. The average time of composite removal was 19.3 ± 4.1 seconds.

Conclusions: Residual orthodontic composite can be rapidly removed from the tooth surface using a rapidly scanned CO_2 laser with spectral feedback, with minimal temperature rise within the pulp and with minimal damage to the underlying enamel surface.

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Background and Objective

After fixed appliance therapy, debonding of orthodontic brackets typically involves bracket removal by mechanical means followed by residual adhesive removal. A wide variety of modalities have been recommended for the removal of residual composite, most commonly including high-speed and low-speed handpiece attachments: tungsten carbide burs, polishing discs and points, and rubber cups and polishers.[1-4] Iatrogenic sequelae associated with the use of high-speed and low-speed handpieces include variable enamel scratches and loss, incomplete removal of composite, time consumption, and heat accumulation. Current procedures for residual composite removal are often user-dependent. The mean loss after the removal of residual composite with carbide burs has been reported to be 55.6 µm, [5] 47.7 µm [6] as measured with a profilometer, and 50.5 µm (± 31.3 µm) as measured with 3D scanning technology.[7] A mean surface change as small as 4.1 µm (±15.4 µm) has also been reported.[1] In a study by Ryf et al., polishing procedures were performed until no traces of composite were observed, but traces of composite were still observed under closer examination in 27% of the samples.[1] Heat accumulation can also be a factor when removing composite with a high-speed handpiece. Uysal found that removal using a high-speed handpiece without water cooling produced a change in temperature of 7.6°C ± 1.8°C which exceeded the critical safe limit of 5.5°C for pulpal health as defined in the Zach and Cohen study in primates.[8, 9]

Lasers have the potential to selectively ablate residual composite with minimal damage to the enamel surface, decreased time for the clinician, and minimal temperature elevation to the pulp. The applicability of lasers for the removal of dental composite has been investigated using several laser wavelengths. Dumore et al. used a Q-switched Er:YAG laser and a pulsed TEA (transverse excited atmospheric pressure) CO_2 laser at 10.6 μm to remove composite, and determined that the TEA CO_2 laser pulses were better suited for selective ablation.[10] Alexander demonstrated that the frequency tripled Q-switched Nd:YAG laser (λ=355-nm) could remove composite through selective ablation without thermal or mechanical damage to underlying enamel. [11] Louie et al. used optical coherence tomography to show that a near-ultraviolet laser (λ=355-nm) could selectively remove composite sealants from the occlusal surface.[12] Even though the 355-nm wavelength exhibits the highest selectivity, higher than CO_2 and erbium wavelengths, there is concern about the use of UV photons. Moreover, a laser system capable of clinically acceptable removal rates is very expensive, and the 355-nm wavelength is only well suited for composite removal and is not suitable for caries removal or soft tissue application, making it, therefore, very limited in application.

The debonding of esthetic ceramic brackets has been demonstrated with the use of laser energy to thermally degrade the adhesive resin with the bracket still in place.[13] In particular, Dostalova et al. used a Tm:YAP laser to decrease tensile strength for bracket debonding.[14] There has been much work in the literature on the thermal debonding of brackets, but, in comparison, this study focused on the removal of residual orthodontic composite after the bracket had been removed by mechanical means from the tooth surface.

Carbon dioxide lasers, which have been used extensively for decades for soft tissue surgery, have also been advocated for use in caries removal and caries protection due to their high absorption by carbonated apatite in dental enamel. Enamel surfaces irradiated by pulsed CO_2 lasers at both ablative and subablative fluence show increased resistance to acid dissolution. [15-20] Enamel absorption is 5-6 times higher at 9.3 and 9.6-μm than the more commonly used 10.6-µm wavelength which allows more efficient heating and ablation of dental hard tissues. [21, 22] In addition to its caries protection benefits, the pulsed CO_2 laser produces minimal heat accumulation within the tooth under the optimum conditions for laser ablation. Staninec et al. have shown that the microsecond pulsed 9.3µm CO_2 laser can ablate enamel *in vivo* without harming the pulp operating at 25 or 50 Hz using an incident fluence of 20 J/cm^2 for a total of 3,000 laser pulses (36 J) with water cooling. [23] Therefore, a pulsed CO_2 laser operating at 9.3-µm is not only suitable for the selective removal of composite, but it can also be used for caries removal. Moreover, the enamel under the composite will be modified to a more acid resistance phase after composite removal.

During laser ablation of a substance, a luminous emission plume is produced that is unique to each tissue or material. Individual peaks can be identified with wavelength tables of elemental spectra.[24, 25] Therefore, it is possible to differentiate enamel and composite spectra by their distinct component peaks. Dumore et al. showed that the spectral analysis of dental enamel possesses distinct calcium emission lines that are strong between 580 and 650-nm, giving the plume a distinct red appearance. This region is lacking in composite resin and its fillers, and can thus distinguish enamel from composite.[10]

The objective of this study was to determine if residual orthodontic composite could be selectively removed from the enamel surface using a rapidly scanned carbon dioxide laser controlled by spectral feedback, without excessive heat accumulation within the pulp, and in a timeframe feasible for clinical application. Emphasis was paced on altering parameters that are clinically feasible.

Methods and Materials

Sample preparation

Thin sections of enamel and GrenGloo™ (Ormco) composite were prepared using a diamond saw (Isomet 5000, Buehler, Lake Bluff, IL), measuring about 1-2 mm thick for thin sections for perforation measurement. A range of fluence was assessed starting with the highest achievable fluence, and progressively reducing the fluence using Si and CaF_2 attenuators. Polarization sensitive optical coherence tomography (PS-OCT) was used to measure the depth per scan for both enamel and GrenGloo™ composite. [26] Three random PS-OCT scans per sample were analyzed with image analysis software, and the depth of ablation was averaged from samples at 3 points per scan (Figure 1)

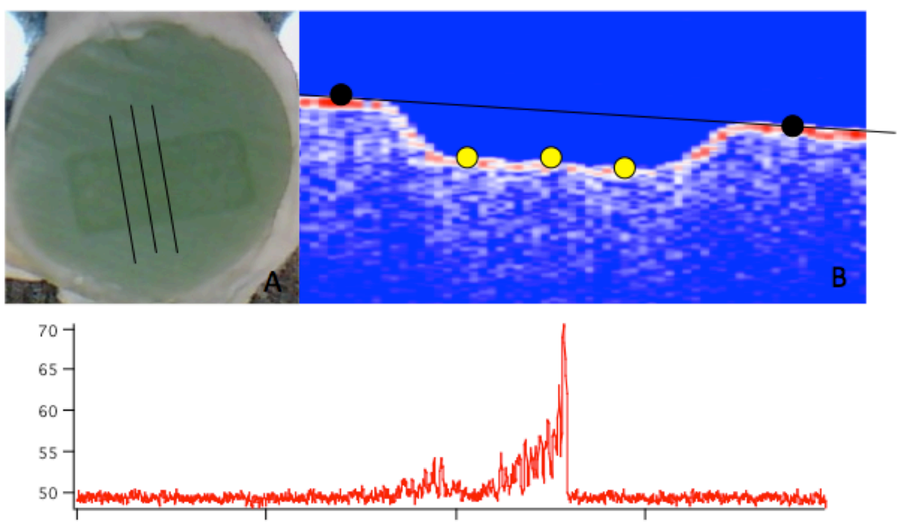

Figure 1: Thin disc of GrenGloo™ composite with laser scans (A); depth of removal was measured with PS-OCT image (B), difference between 3 points/scan (yellow dots) and untreated composite (black line); image analysis software gave profile which allowed measurement of depths

Twenty-one recently extracted, non-carious premolars and molars were collected from patients in the San Francisco Bay area, and sterilized with gamma radiation. The roots were removed and the teeth were sectioned mesially to distally so that the tooth was divided into buccal and lingual halves. Using epoxy resin, the sectioned teeth were glued onto resin blocks for consistent mounting during laser ablation. All specimens were photographed and imaged with a microscope. The bases of upper bicuspid orthodontic brackets were modified to reduce some retention in the mesh with a round bur. This allowed the brackets to be debonded leaving the majority of the composite on the tooth surface in a consistent size. The modified brackets were bonded to the sectioned surfaces with GrenGloo™ (Ormco) composite, Ortho Solo™ (Ormco) adhesive, and 37% phosphoric acid etchant according to the manufacturer's instructions. The teeth were then stored in 1% thymol for 24 hours. The brackets were removed and then photographed and imaged with optical microscopy. Half of the residual composite was removed in a rectangular matrix of about 2.5 x 5 mm^2 with the laser removal program.

Thermocouple measurements

Eleven extracted human premolars and molars were used for thermocouple measurements. The roots were left on each tooth and a small hole was drilled into the mesial or distal at the level of the cementoenamel junction with a high-speed dental handpiece and 1169L carbide bur. Microthermocouples (K type, 36 gauge) from Omega Engineering Inc (Stamford, CT) were inserted into the pulp chamber. A high-thermal-conductivity silicone paste (Omegatherm "201," OMEGA) was placed on the thermocouple wire tip to ensure thermal conductivity with the dentin of the pulpal wall on the buccal side of the tooth. Digital periapical films were taken to verify that the thermocouple wire was touching the dentin of the internal wall of the pulp chamber (Figure 2). Unmodified, new brackets were bonded to the buccal surface using GrenGloo™ composite, Ortho Solo™, and 37% phosphoric acid etchant according to manufacturer instructions. Brackets were removed and the temperature was assessed while computer-controlled galvanometers scanned the laser beam to remove all residual orthodontic composite from the tooth surface in a 5 x 5 mm^2 matrix. A thermocouple controller, Stanford Research SR630 (Stanford, CA) controlled by Labview software (National Instruments, Austin, TX) was used to record the thermal data. A continuous water spray was activated 5 seconds before and terminated after the laser program actively ablated the composite. The water used for the spray was at room temperature. A temperature rise of less than 5.5°C was considered critical for pulpal health.[8] The time taken to ablate all residual composite on the tooth surface was recorded, as well as the temperature change from the initial temperature to the maximum temperature just after removal.

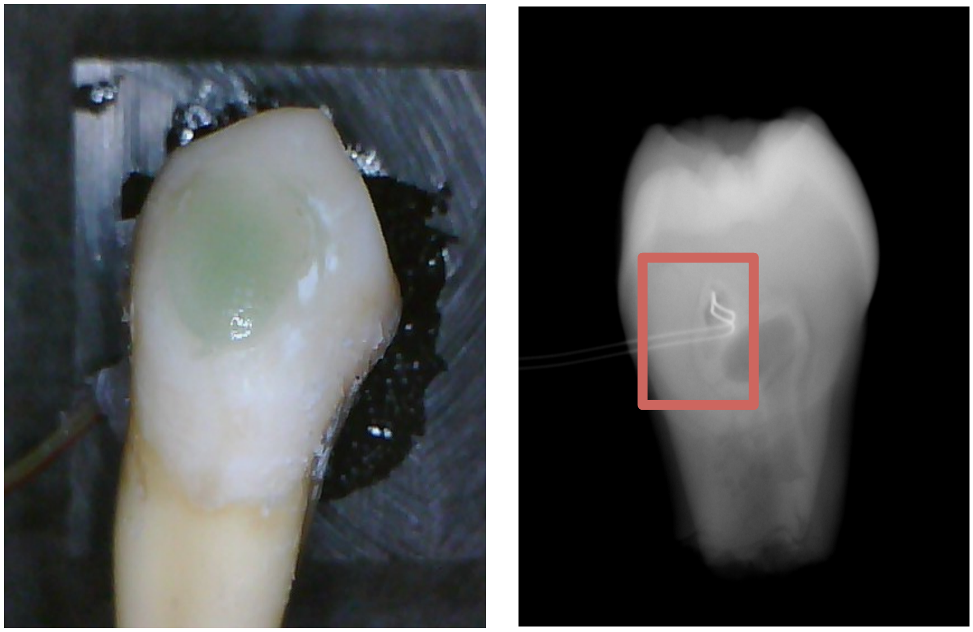

Figure 2: Tooth glued to delrin block with thermocouple wire inserted into CEJ of mesial or distal (A); periapical radiograph verified that thermocouple wire (red box) was touching buccal wall of pulp chamber (B)

Laser irradiation parameters

The carbon dioxide laser used in this study was an Impact 2500 from GSI Lumonics (Rugby, United Kingdom) operating at a wavelength of 9.3 μm. The laser was custom modified to produce a Gaussian output beam (single spatial mode) and a pulse duration of between 10-15 μs. This laser is capable of high repetition rates up to 500 Hz. In this study, the laser operated at 220 Hz, with a spot size of ~750 μm and a 150 μm scan width. An f-theta zinc selenide laser-scanning lens with a focal length of 90-mm from II-VI (Saxonburg, PA) focused the beam onto the tooth surface. The knife-edge method was used to determine the diameter ($1/e^2$) of the laser beam at the focal position. The laser beam was scanned over the tooth sample, using computer-controlled XY galvanometers, 6200HM series with MicroMax Series 671 from Cambridge Technology, Inc. (Cambridge, MA). A power meter EPM 1000, Coherent-Molectron (Santa Clara, CA) and a Joulemeter ED-200, Gentec (Quebec, Canada) monitored the energy output of the laser. The tooth was cooled with 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). It provided a pulsed uniform spray of fine water mist onto the tooth surfaces at about 0.5 mL/min, at 0.5 Hz and 0.25 duty cycle. The set-up is shown in Figure 3.

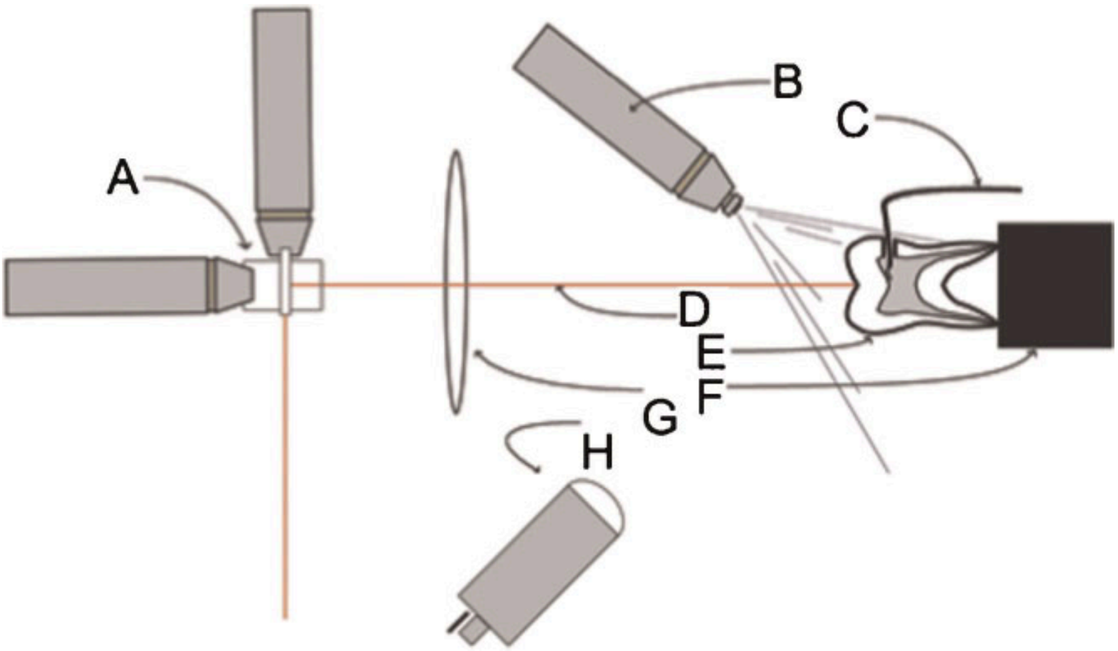

Figure 3: The experimental setup for selective ablation consists of (A) two galvanometers (XY axes), (B) water spray, (C) micro-thermocouples, (D) CO_2 laser beam (9.3 μm), (E) tooth, (F) delrin sample mount, (G) ZnSe f-theta scanning lens, and (H) imaging optics for spectrometer.

Optical feedback and composite selective removal

The laser was scanned from point to point over a 5 mm square area with the computer-controlled XY Galvanometer scanning system. A laser spot size of 750-μm was used with a spot to spot separation of 150-μm. The plume produced from laser irradiation of each spot was captured using a USB2000+ fiber optic spectrometer from Ocean Optics (Dunedin, FL) incorporating a 2048 element CCD detector that was used in conjunction with a 1-mm bare silica-fiber to acquire spectra. Since the intensity of the output from the spectrometer is dependent on the position of the optical fiber, an imaging system that viewed the entire plume was used to avoid excessive variation in the spectra. The fiber was attached to an XYZ stage and positioned to view the ablation plume produced in the 5 x 5 mm^2 area ablated. Distinct calcium emission lines only present in enamel were used to differentiate between the ablation of enamel and composite (Figure 4). Images of the spectra produced from the GrenGloo™ composite and enamel have been published.[26] Both have sodium peaks at around 580-nm, but the enamel peak is more intense. The composite spectrum is identical to the spectrum of glass which was observed previously.[27] Specific to enamel is a very strong calcium peak centered at 605-nm. The ratio and intensities of the 580 and 605-nm peaks were used to differentiate between composite and enamel.

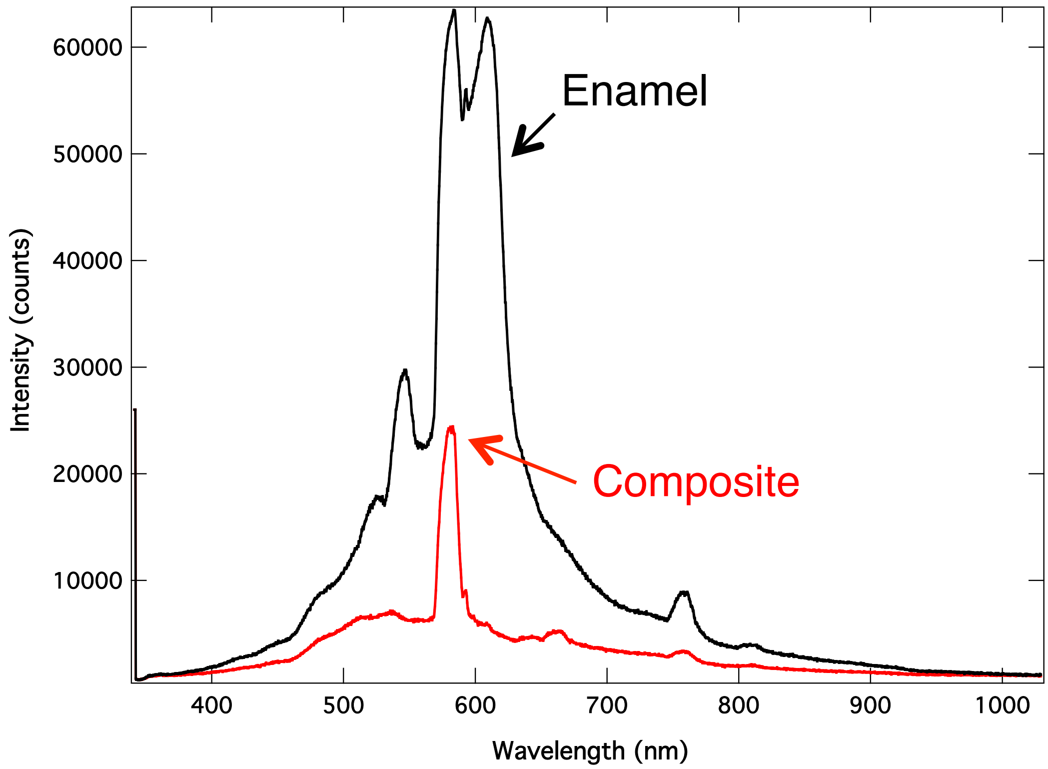

Figure 4: Plume emission spectra of dental enamel [black] and composite [red]. Note the higher intensity of emission from enamel, the common sodium emission line at 580-nm in both spectra and the strong calcium emission line at 605-nm in the enamel spectrum.

A program written in the Labview programming language was used to analyze the spectra, record the presence or absence of enamel in a matrix, and scan the laser beam over the tooth surface. The first scan consisted of a scan of the entire 5 x 5 mm^2 area or region of interest (ROI). All points in the ROI with the presence or absence of composite were subsequently stored in a matrix. The ROI was then rescanned and only the spots identified in the matrix as having composite were irradiated in subsequent scans, updating the matrix after each scan. Scans were repeated until the composite was completely removed from the ROI. Scanning over the entire ROI during each iteration and delivering laser pulses to individual spots with composite greatly reduces heat deposition. This approach is more efficient than delivering multiple pulses to individual spots without moving until the entire composite was removed from each spot. This approach also improves efficiency and prevents stalling since deep holes of high aspect ratio are not produced within the composite.

The laser was not operated at a fixed pulse repetition rate; the repetition rate was determined by the rate at which the program analyzed the plume and then subsequently triggered the laser. The number of spots irradiated per second fluctuated slightly and fell between 200-220. The flowchart in Figure 5 describes the program used for selective ablation. In order to ensure the clear absence of composite at a level smaller than the laser spot size, an additional final "clean up" scan was implemented. Within each laser spot it is possible to have both exposed enamel and residual composite, particularly at the outside border of the composite. This cleanup scan consisted of scanning the latter scan's array of saved points as well as shifting the scan area by 100 μm to the top right and bottom left corners of the scanning area. This eliminated composite-enamel edges that may contain trace amounts of composite. However, since enamel and composite could both be present in one laser spot area, enamel could also be removed in order to remove the existing composite. A large challenge was finding the appropriate balance between removing too much enamel and too little composite.

Various problems arise using the first iteration as the cleanup template: the first scan's emission plume spectra could become oversaturated due to the lack of hydration in the beginning, and trace amounts of composite around the border could be removed in the first couple iterations causing unnecessary damage to the enamel during the cleanup scan. Hence, the array in the fifth iteration of the initial scan was saved.

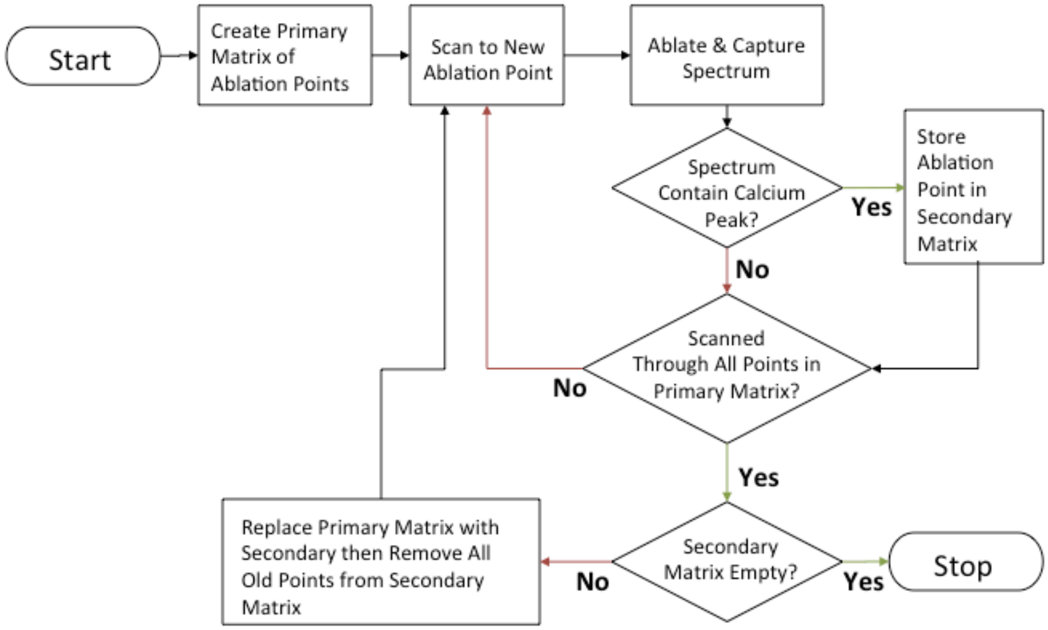

Figure 5: Flowchart of algorithm used for computer automated selective ablation process

Optical microscopy

The overall surface morphology was examined using a low magnification digital camera, Dino-lite Model Am-2011 from BigC (Torrance, Ca), and a low-resolution zoom microscope (7x and 15x magnification) from Navitar (Rochester, NY), with a DFK 31BF03 firewire camera from the Imaging Source (Charlotte, NC). Image analysis software was used to acquire images of the enamel before bonding, after enamel etching and bonding, and after composite removal. Previous studies[12] have used optical coherence tomography to assess residual composite and underlying damage to the enamel surface. However, the 10-20 μm resolution of OCT was not high enough to evaluate changes to the enamel surface from the laser irradiation and higher resolution light microscopy was used. After composite removal by the laser, the enamel surface was analyzed with a Leitz Secolux microscope with a magnification of 50 - 1000x and BF/DF/DIC capability interfaced to a digital firewire camera. Damage to the enamel surface appeared as a roughening of enamel, and the greatest damage occurred at the center of the Gaussian-shaped laser pulses. Damage was assessed by measuring the vertical deviation near the center of each pulse, or crater (Figure 6). A digital micrometer was seated on the microscope platform to measure the change in platform height as the image plane of the microscope was positioned on the surface and at the base of the deeper craters. Five of the deeper crater areas were measured per sample, and the mean was calculated.

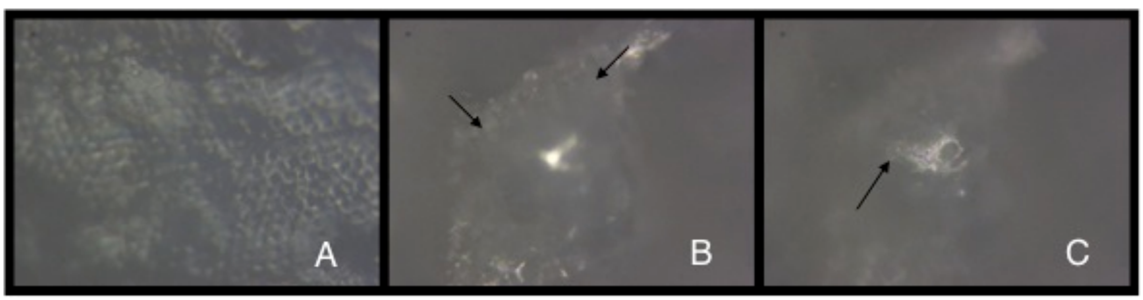

Figure 6: Untreated enamel (A) and laser ablated enamel (B, C) at 200x magnification. Laser produces crater-like deviations in the enamel. A micrometer measured the difference between focus on surface of deviation (arrows in B) and vertical deviation (arrow C)

Visual evaluation of tooth surface

All teeth were evaluated with no magnification by two observers. Teeth were categorized into 4 groups based on the degree of texture on the enamel surface after laser ablation of all 20 samples (1-minimal, 2-slight, 3-moderate, 4-severe).

Laser Irradiated Surface after Polishing

Six teeth of various visual evaluation scores were polished after laser irradiation. Three were polished with Renew™ Finishing System Points #383 on a high-speed handpiece and three were polished with prophy cups and prophy paste on a slow-speed handpiece. The teeth were then evaluated under the microscope and photographed.

Results

Perforation measurements

The ablation rate for GrenGlooTM composite and enamel were investigated at varying fluence in order to select the optimal incident laser fluence for removal. The measured relationship between ablation rate and fluence is shown in Figure 7. The composite ablation rate increased progressively with increasing fluence, whereas the enamel ablation rate peaked at about 20 μm/scan above approximately 8 J/cm2. The ideal fluence appears to be around 4 J/cm2, where the rate of composite removal is twice that of enamel, and the damage to sound enamel is limited to <10-μm.

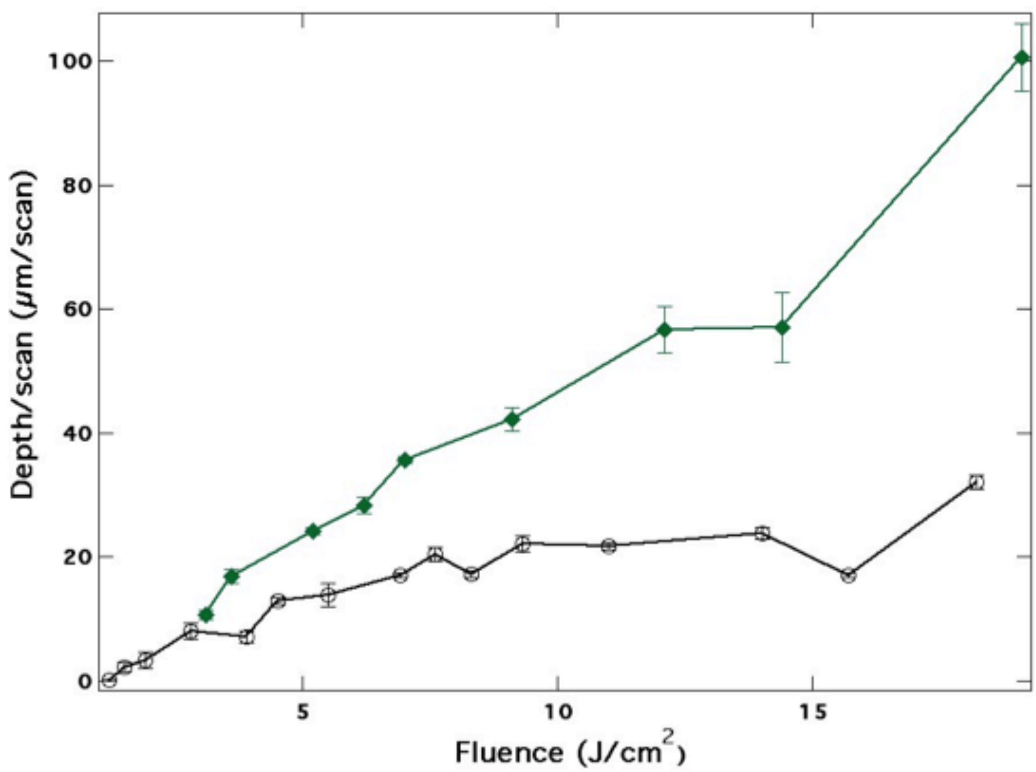

Figure 7: Mean ablation rate, micrometers/scan ± s.d. (n=9), for GrenGloo™ composite (solid diamonds) and enamel (open circles) as a function of laser fluence

Measurements of Surface Damage

Tooth samples were randomly assigned to groups and irradiated at either 3.8 J/cm^2 or 4.2 J/cm^2. Figure 8 shows examples of the tooth surface before and after composite removable with varying magnifications. The enamel surface was modified in the area of laser ablation, and showed surface melting with wavelike structures with the greatest removal at the center of each laser pulse, as previously described by Zuerlein et al.[21] Figure 9 shows the topography of the tooth surface using a Keyence VHX-1000 digital microscope system, including the perikymata of untreated enamel and the enamel after laser ablation. Using a high-resolution microscope at 200x, five of the most severely affected areas on the tooth surface were observed. At a fluence of 3.8 J/cm^2, the maximum vertical deviation averaged 22.7 μm ± 5.3 with a range of 6-49 μm. At 4.2 J/cm^2, the maximum vertical deviation averaged 25.3 μm ± 5.0 with a range of 11-50 μm. There was no significant difference between the maximum vertical deviations of the two fluence levels (t-test, $P>0.05$), Table I

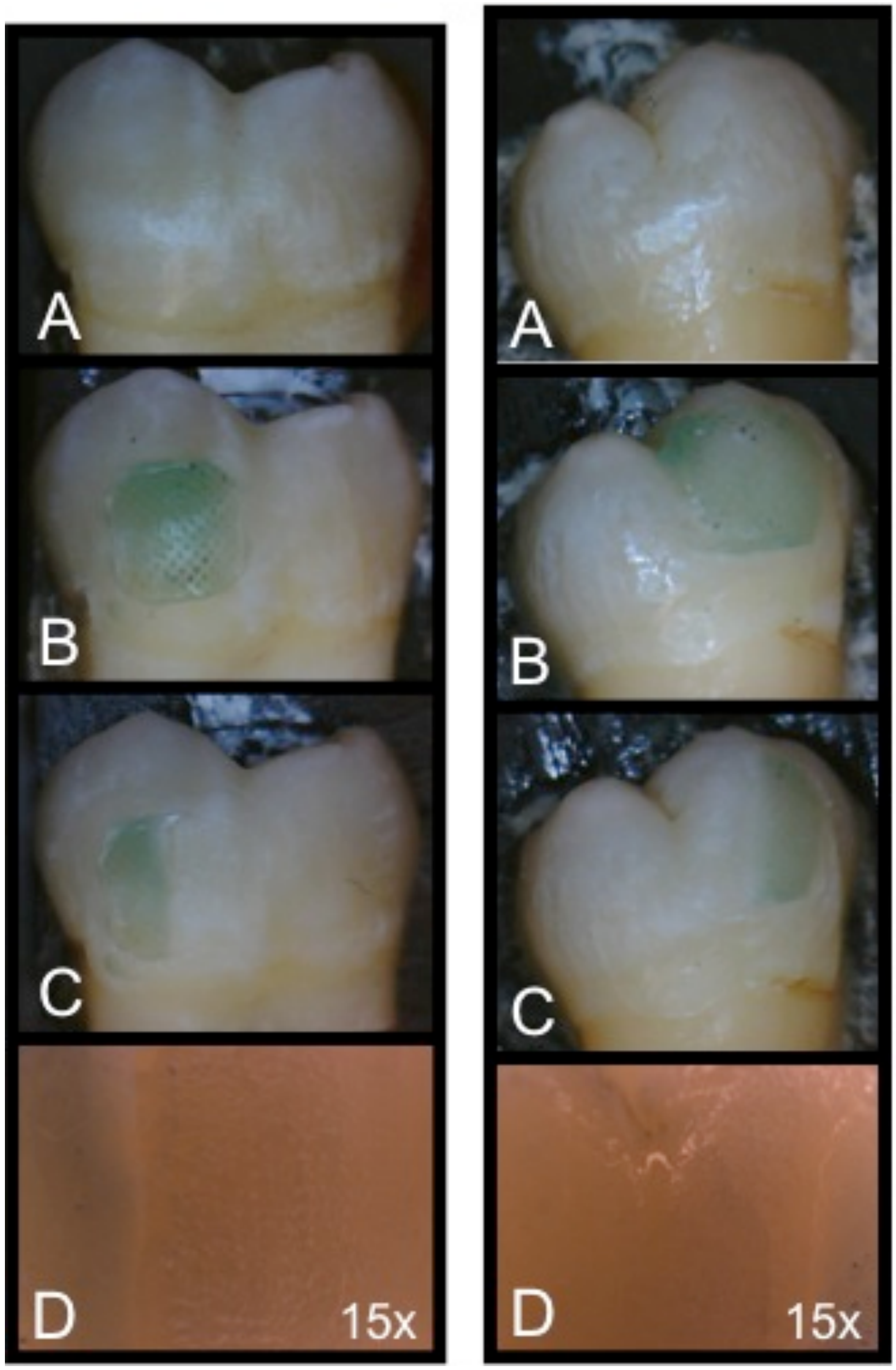

Figure 8: Photographs of GrenGloo™ composite on buccal surface, before (A), after composite placement (B), and after laser ablation (C). Microscope image at 15x magnification after laser ablation (D)

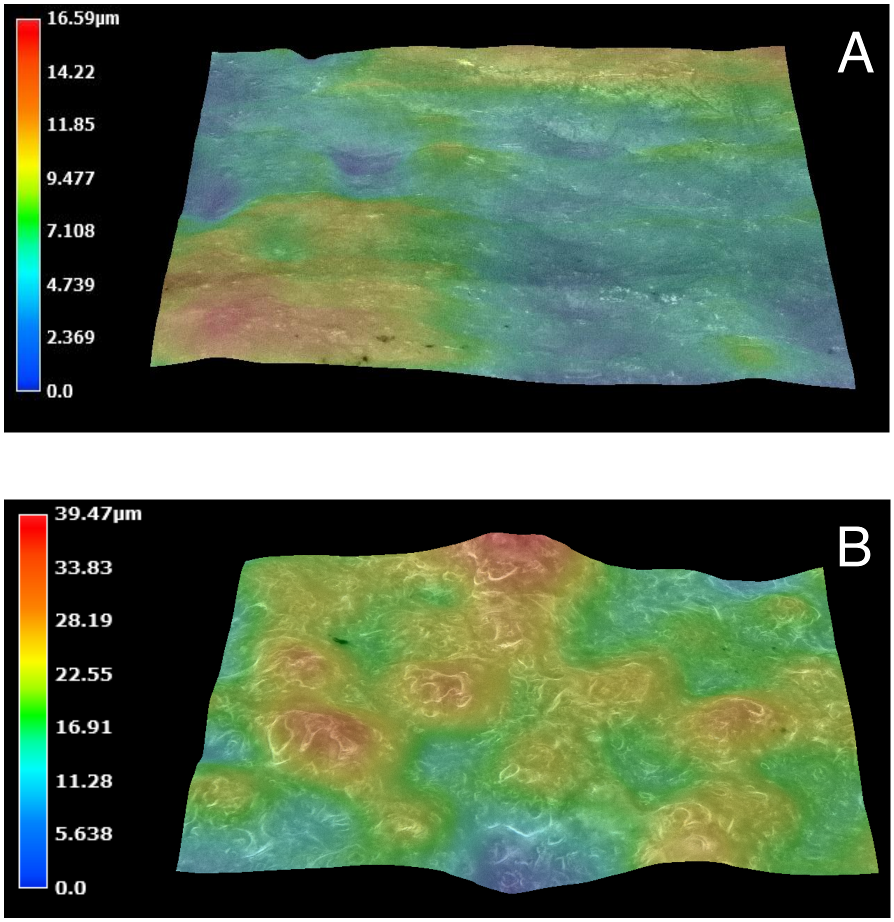

Figure 9: Optical micrograph showing topography of tooth surface untreated (A) and after laser ablation (B) at 1000x magnification

	Tooth #	Mean Vertical Deviation (μm)	Standard Deviation
Fluence 3.8 J/cm^2	1	25	7.9
	2	15.2	7
	3	19.8	7.6
	4	23.6	11.9
	5	15.6	4.2
	6	20.4	10.1
	7	21	5.7
	8	32.4	9.8
	9	23	9.5
	10	23.2	6.4
	11	30.4	5.6
Group Average		**22.7**	**7.8**
Fluence 4.2 J/cm^2	12	19.4	7.4
	13	23	6.2
	14	24.4	12.6
	15	31.8	10
	16	24	5.1
	17	28.2	5.5
	18	23.2	4.9
	19	30	14.2
	20	17.4	6.6
	21	31.6	11.4
Group Average		**25.3**	**8.4**

Table 1: Mean vertical deviation with standard devations (n=5) in micrometers for each tooth and averages of each fluence group. (t-test, P>0.05)

Pulpal Temperature Rise

The maximum temperature excursions at the position of the pulp chamber wall opposite the enamel surfaces irradiated by the laser were measured using microthermocouples. An average maximum temperature rise of 1.9°C ± 1.5 was recorded, with none of the measurements approaching the critical value of 5.5°C. The mean time to remove all composite was 19.3 ± 4.1 seconds. All teeth were irradiated using a fluence of 3.8 J/cm^2. Figure 10 shows the progression of temperature change in relationship to time during laser ablation.

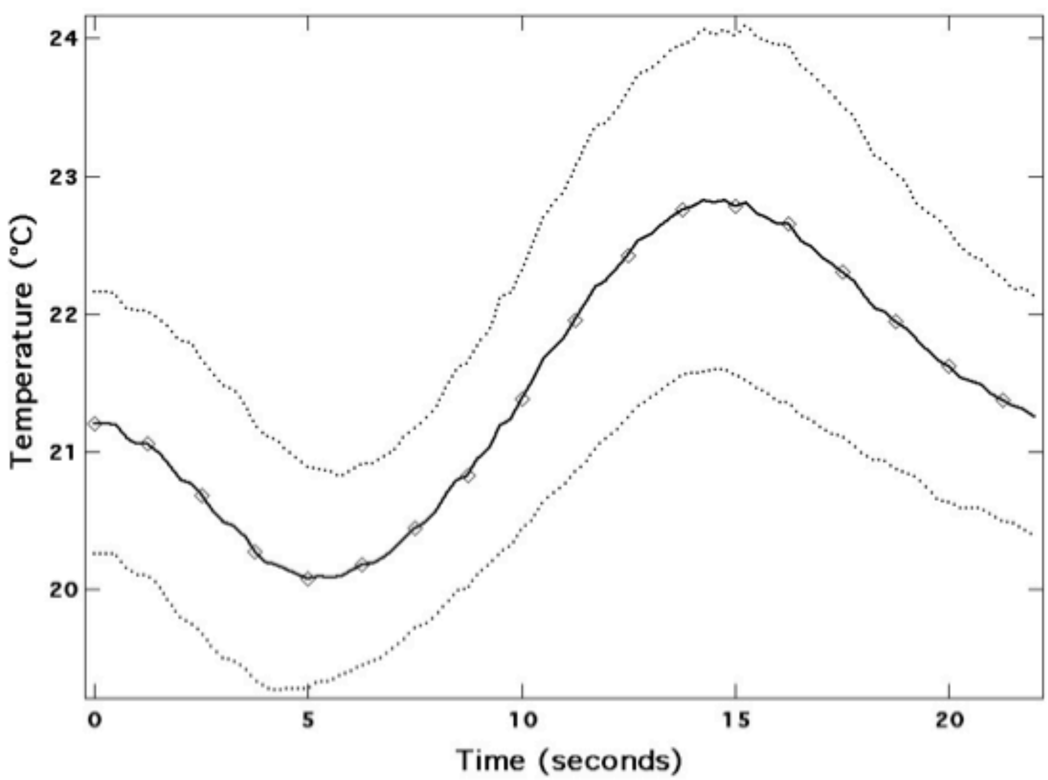

Figure 10: Average temperature increase as a function of time (open diamonds). Dotted line shows range of one standard deviation, n=11

Visual Evaluation of Tooth Surface

The teeth were ranked based on the degree of texture on the enamel surface after composite removal via the laser for all 20 samples (1-minimal, 2-slight, 3-moderate, 4-severe). The surface roughness (maximum vertical deviation) and the overall surface evaluation groups had a correlation coefficient of 0.51, $R^2 = 0.26$ (Figure 11), suggesting a moderate relationship between a visual evaluation of the tooth and the actual loss of the tooth surface determined quantitatively and objectively.

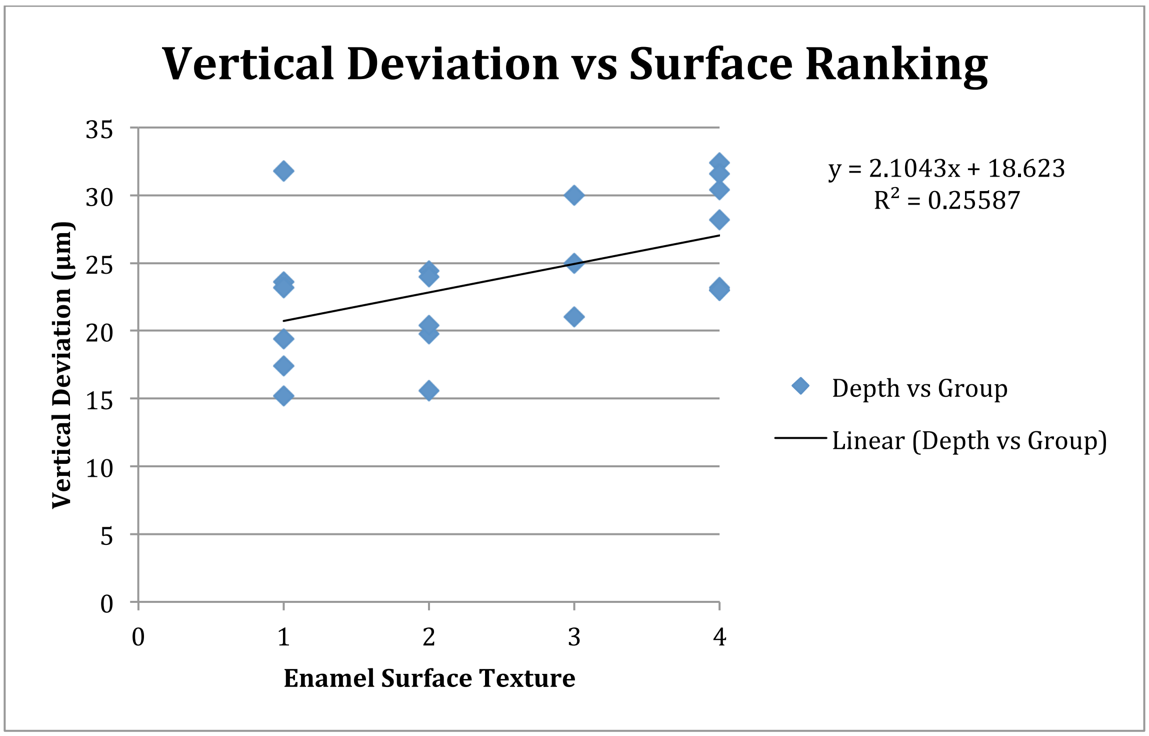

Figure 11: Relationship between vertical deviation depth and enamel surface texture rating, showing relationship between visual inspection and actual measured depth

Laser Irradiated Surface After Polishing

Polishing with the Renew™ Polishing System Points removed some of the surface texture but gave a highly glossed surface. The irradiated area was not detectable after polishing. When analyzed with the high-resolution microscope, the surface texture had a mean depth of 17.4 ± 6.6 μm, in comparison to 24.8 ± 6.9 μm immediately following laser irradiation. The use of prophy paste attached to a prophy cup lightly smoothed the surface texture while making the visual evaluation of the tooth surface more favorable. However, the surface texture was altered less with the prophy paste than with the Renew Polishing points. The surface texture had a mean of 19.1 ± 3.2 μm, in comparison to 21.1 ± 2.1 μm immediately following laser irradiation. Figure 12 shows examples of two teeth before and after polishing.

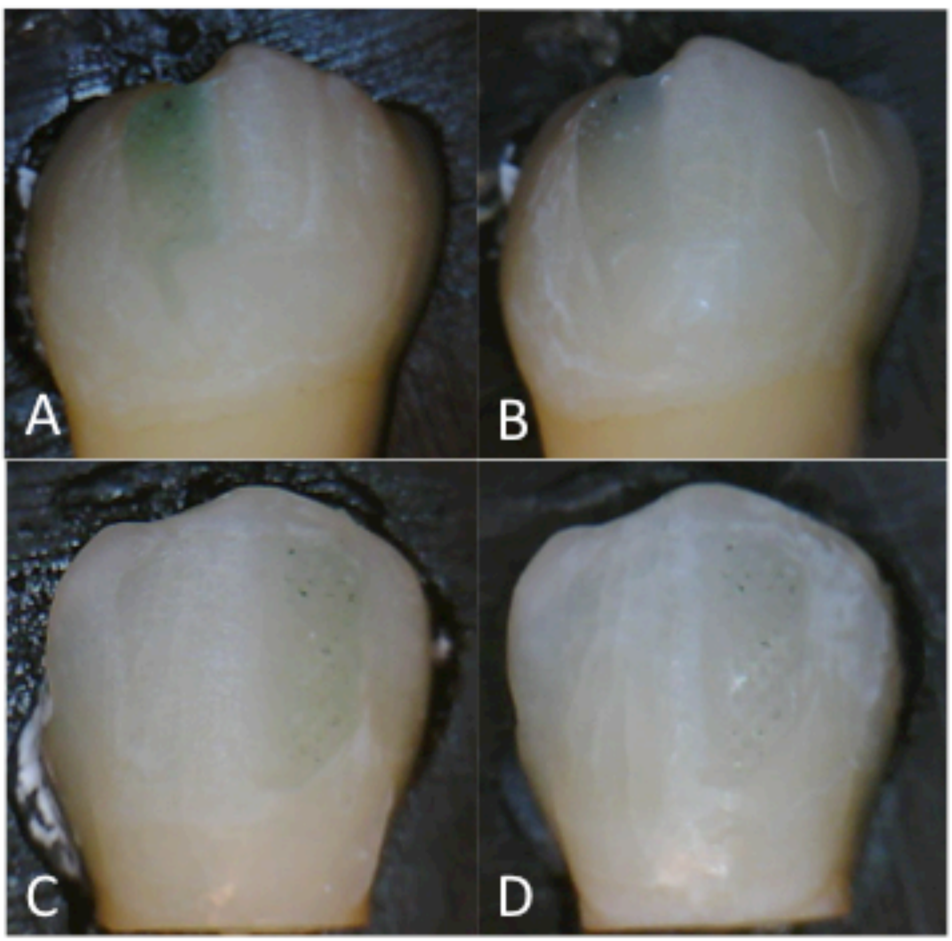

Figure 12: Enamel surface after laser ablation of two teeth (A, C). Enamel surface after polishing with pumice (B) and Reliance polishing tips (D)

Discussion

The selective removal of composite using a CO_2 laser with spectral feedback produced a level of enamel modification that was well within and often below conventional means for removal with dental low-speed and high-speed handpieces. Most debonding techniques result in some loss of enamel. However, the degree of enamel loss varies widely in the literature.[28] Enamel loss at the acid etching stage for 15-30 seconds with 37% phosphoric acid can be 8.8-16.4 µm,[29] but it has also been reported to be as little as 3 µm. [30] Loss after the removal of residual composite with carbide burs can remove as little as 7.4 µm (range 1-52 µm), or a mean around 50 µm. [6,7] In comparison, Pus and Way reported 5 µm of enamel loss with prophylaxis with a rubber cup. [31] The thickness of enamel is usually about 1500-2000 µm, and the loss of 60 µm is not thought to be detrimental to the tooth. [32] However, the surface fluoride layer gradient is very steep, with the highest concentration at the surface and a rapid decline in the first 20 µm of enamel. [28] Therefore, preservation of the fluoride-rich surface layer of enamel should be attempted when removing residual composite. In this study, the amount of enamel loss averaged 22.7 µm ± 5.3 and 25.3 µm ± 5.0 at 3.8 J/cm^2 and 4.2 J/cm^2, respectively. The selective removal of composite with spectral feedback ensures that all composite is removed in a target area, and that a consistent and known amount of underlying enamel is affected.

As the laser hits enamel, melting can also occur, modifying and possibly raising the surface. Therefore, the measured vertical surface deviations or modulation may not represent the actual loss of enamel.

When visually evaluating the tooth surface after irradiation, the surface texture produced by the laser was visible with the naked eye when the surface was completely dry.

There was a range in the amount of surface texture observed even though identical laser parameters were used on all teeth, but after polishing with either the Renew polishing tips or prophy paste, the surface greatly improved, and the surface texture was only apparent under magnification.

There was no statistically significant difference between the two fluence levels (3.8 and 4.2 J/cm^2) for surface roughness. In order to investigate the maximum effects on the enamel surface, five of the deeper areas on the scanned enamel surface were sought. At 200x magnification, it was difficult to mount the sample so that the microscope findings were replicable to the micrometer scale. The five deepest areas may not have been found, but by averaging five of the visually deeper areas, hopefully a general overview of the tooth surface was acquired. A high-resolution optical profilometer or 3D imaging system would better assess the overall affect on the surface from the CO_2 laser.

The time required to remove residual composite with the rapidly scanned CO_2 laser is comparable if not less than conventional methods. Average time to remove all composite in this study was 19.3 ± 4.1 seconds, and polishing all teeth successively would then add a few seconds per tooth. Using conventional methods, total time to remove all residual composite and polish the tooth surface can differ depending on the number of steps included in each clinician's debonding protocol. Ryf et al. also reported a total composite removal time of 65.9±14.0 seconds with two steps and up to 183.5±14.1 seconds per tooth for four step procedures.[1] Composite thickness may have been greater on some sample teeth than others, since the same upper premolar brackets were used on all teeth, creating a longer average time than in clinical settings.

Thermocouple measurements of the pulp chamber indicate that minimal heat accumulation will be produced during laser irradiation when water spray is used. It was important to note that a fully desiccated tooth experienced a rise in temperature above the critical value of 5.5°C, while a tooth that had been soaking in 1% thymol solution and was only removed 10 minutes prior to the thermocouple trial did not approach the critical value. This is obviously not an issue clinically since teeth are well-hydrated *in vivo*.

The greatest challenge in composite removal was avoiding a thin layer of residual composite that was left at the margin between the residual composite and the enamel. It was necessary to develop a "clean-up" algorithm in order to account for overlap at the enamel and composite margins. Another challenge of selective ablation with spectral feedback was balancing the water spray repetition rate with the analysis of the plume, since too much water negated the ability of the spectrometer to capture the plume. In addition, too little water caused charring of the residual composite, slightly altering its plume, and leaving composite on the enamel surface. A light pulsed water spray at a rate of 0.5mL/min, 0.5 Hz, and 0.25 duty cycle was ideal to prevent composite charring and to minimally interfere with analysis of the plume.

Conclusions

Residual orthodontic composite can be selectively removed from the tooth surface using a rapidly scanned CO_2 laser with spectral feedback, with a minimal temperature rise within the pulp and acceptable damage to the underlying enamel surface. Future studies will incorporate a hand-held device that can be used *in vivo* to remove composite restorations or residual orthodontic composite.

References

1. Ryf S, Flury S, Palaniappan S, Lussi A, van Meerbeek B, Zimmerli B. Enamel loss and adhesive remnants following bracket removal and various clean-up procedures *in vitro*. Eur J Orthod 2011.

2. Oliver RG, Griffiths J. Different techniques of residual composite removal following debonding--time taken and surface enamel appearance. Br J Orthod 1992;19(2):131-7.

3. Gwinnett AJ, Gorelick L. Microscopic evaluation of enamel after debonding: clinical application. Am J Orthod 1977;71(6):651-65.

4. Hong YH, Lew KK. Quantitative and qualitative assessment of enamel surface following five composite removal methods after bracket debonding. Eur J Orthod 1995;17(2):121-8.

5. Fitzpatrick DA, Way DC. The effects of wear, acid etching, and bond removal on human enamel. Am J Orthod 1977;72(6):671-81.

6. Tufekci E, Merrill TE, Pintado MR, Beyer JP, Brantley WA. Enamel loss associated with orthodontic adhesive removal on teeth with white spot lesions: an *in vitro* study. Am J Orthod Dentofacial Orthop 2004;125(6):733-9.

7. Al Shamsi AH, Cunningham JL, Lamey PJ, Lynch E. Three-dimensional measurement of residual adhesive and enamel loss on teeth after debonding of orthodontic brackets: an in-vitro study. Am J Orthod Dentofacial Orthop 2007;131(3):301 e9-15.

8. Zach L, Cohen G. Pulp Response to Externally Applied Heat. Oral Surg Oral Med Oral Pathol 1965;19(April):515-30.

9. Uysal T, Eldeniz AU, Usumez S, Usumez A. Thermal changes in the pulp chamber during different adhesive clean-up procedures. Angle Orthod 2005;75(2):220-5.

10. Dumore T, Fried D. Selective ablation of orthodontic composite by using sub-microsecond IR laser pulses with optical feedback. Lasers Surg Med 2000;27(2):103-10.

11. Alexander R, Xie J, Fried D. Selective removal of residual composite from dental enamel surfaces using the third harmonic of a Q-switched Nd:YAG laser. Lasers Surg Med 2002;30(3):240-5.

12. Louie TM, Jones RS, Sarma AV, Fried D. Selective removal of composite sealants with near-ultraviolet laser pulses of nanosecond duration. J Biomed Opt 2005;10(1):14001.

13. Azzeh E, Feldon PJ. Laser debonding of ceramic brackets: a comprehensive review. Am J Orthod Dentofacial Orthop 2003;123(1):79-83.

14. Dostalova T, Jelinkova H, Sulc J, Nemec M, Jelinek M, Fibrich M, et al. Ceramic bracket debonding by Tm:YAP laser irradiation. Photomed Laser Surg 2011;29(7):477-84.

15. Featherstone JD, Barrett-Vespone NA, Fried D, Kantorowitz Z, Seka W. CO2 laser inhibitor of artificial caries-like lesion progression in dental enamel. J Dent Res 1998;77(6):1397-403.

16. Kuroda S, Fowler BO. Compositional, structural, and phase changes in *in vitro* laser-irradiated human tooth enamel. Calcif Tissue Int 1984;36(4):361-9.

17. Featherstone JD, Nelson DG. Laser effects on dental hard tissues. Adv Dent Res 1987;1(1):21-6.

18. Fried D, Featherstone JD, Le CQ, Fan K. Dissolution studies of bovine dental enamel surfaces modified by high-speed scanning ablation with a lambda = 9.3-microm TEA CO(2) laser. Lasers Surg Med 2006;38(9):837-45.

19. Can AM, Darling CL, Ho C, Fried D. Non-destructive assessment of inhibition of demineralization in dental enamel irradiated by a lambda=9.3-microm CO2 laser at ablative irradiation intensities with PS-OCT. Lasers Surg Med 2008;40(5):342-9.

20. Hsu DJ, Darling CL, Lachica MM, Fried D. Nondestructive assessment of the inhibition of enamel demineralization by CO2 laser treatment using polarization sensitive optical coherence tomography. J Biomed Opt 2008;13(5):054027.

21. Zuerlein MJ, Fried D, Featherstone JD. Modeling the modification depth of carbon dioxide laser-treated dental enamel. Lasers Surg Med 1999;25(4):335-47.

22. Zuerlein MJ, Fried D, Featherstone JD, Seka W. Absorption coefficients of dental enamel at CO2 wavelengths Special Topics J Quantum Electronics 1999;5(4):1083-89.

23. Staninec M, Darling CL, Goodis HE, Pierre D, Cox DP, Fan K, et al. Pulpal effects of enamel ablation with a microsecond pulsed lambda = 9.3-microm CO2 laser. Lasers Surg Med 2009;41(4):256-63.

24. Niemz MH. Investigation and spectral analysis of the plasma-induced ablation mechanism of dental hydroxyapatite. Appl Phys B 1994;58:273-81.

25. Striganov AR, Sventitskii NS. Table of spectral lines of neutral and ionized atoms. New York: IFI/Plenum; 1968.

26. Chan KH, Hirasuna K, Fried D. Rapid and selective removal of composite from tooth surfaces with a 9.3 microm CO2 laser using spectral feedback. Lasers Surg Med 2011;43(8):824-32.

27. Cheng JY, Fan K, Fried D. Use of a compact fiber optic spectrometer for spectral feedback during the laser ablation of dental hard tissues and restorative materials. Lasers in Dentistry XII 2006;6137:1-7.

28. Brown CR, Way DC. Enamel loss during orthodontic bonding and subsequent loss during removal of filled and unfilled adhesives. Am J Orthod 1978;74(6):663-71.

29. Legler LR, Retief DH, Bradley EL. Effects of phosphoric acid concentration and etch duration on enamel depth of etch: an *in vitro* study. Am J Orthod Dentofacial Orthop 1990;98(2):154-60.

30. Ireland AJ, Hosein I, Sherriff M. Enamel loss at bond-up, debond and clean-up following the use of a conventional light-cured composite and a resin-modified glass polyalkenoate cement. Eur J Orthod 2005;27(4):413-9.

31. Pus MD, Way DC. Enamel loss due to orthodontic bonding with filled and unfilled resins using various clean-up techniques. Am J Orthod 1980;77(3):269-83.

32. Thompson RE, Way DC. Enamel loss due to prophylaxis and multiple bonding/debonding of orthodontic attachments. Am J Orthod 1981;79(3):282-95.

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