Title
Selective removal of residual orthodontic composite using 355 nm nanosecond laser pulses

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Publication Date
2001

Selective Removal of Residual Orthodontic Composite using 355 nm Nanosecond Laser Pulses

by

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

ORAL BIOLOGY

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

San Francisco

[redacted]

Date University Librarian

I. Acknowledgements

I would like to thank the following individuals for their assistance in helping me complete this project:

- Dr. Daniel Fried for his patience and invaluable guidance, not to mention his lessons in history and other interesting stuff. Without him, this project could have never been realized -- thanks Dan.
- John Xie for his priceless help and for knowing where to find things, how to set them up, and most importantly, how to fix them.
- Dr. Karin Vargervik and Dr. Arthur Miller for their time and input. Their efforts are most appreciated.
- Charles Le for his help in preparing samples.
- Dave Nasharr and Ormco for their selfless donations.
- My parents for their years of sacrifice, words of encouragement, and faith in my capabilities.

Most importantly, I would like to thank my wife Robyn, daughter Abby, and son Matthew for their unconditional love and support. They have helped me keep my priorities straight and made life enjoyable during my seven years at UCSF.

II. Abstract

Selective Removal of Residual Orthodontic Composite using 355 nm Nanosecond Laser Pulses

Robert Morgan Alexander, D.D.S.

Background and Objective: Traditional methods of residual composite removal after debonding orthodontic brackets involve the use of abrasives that damage the underlying enamel. The objective of this study was to determine if a laser, operating at 355 nm and a pulse duration of 3-5 ns, can be used for the selective ablation of residual orthodontic resin without damage to the underlying enamel and without excessive accumulation of heat.

Study Design: Ablation rate thresholds for enamel and orthodontic composite were measured. Using 355 nm irradiation fluences below the enamel ablation threshold, residual composite was ablated from the surface of bovine and human enamel samples. Internal temperature changes, during the ablative process, were also measured and photoacoustics were used to characterize the mechanism of absorption and ablation.

Results: Selective ablation of residual orthodontic composite, without enamel damage and without excessive heat accumulation, was demonstrated.

Conclusion: This study demonstrates that 355 nm laser pulses can be used to selectively remove residual orthodontic composite without thermal or mechanical damage to the underlying enamel.

III. Introduction

A. Background

1. Orthodontic bonding and traditional residual composite removal techniques.

The advent of dental adhesive materials has greatly improved the efficacy of orthodontic treatment. Gone are the days of banding every tooth, with its sequelae of uncomfortable spacers, decreased esthetics, increased periodontal irritation, and excessive residual band spaces. Bonding orthodontic brackets to the enamel surfaces of teeth, using bis-gammamethylmethacrylate (bis-GMA) organic resins, has greatly reduced the unwanted aspects of bands and has emerged as the profession's standard of care.

Manufacturers of orthodontic adhesive resins have done a remarkable job of developing quality products that form strong micro-mechanical bonds with etched dental enamel.[1] However, the desire to develop strong bonds between teeth and orthodontic attachments that will withstand an assault by masticatory and mechanical forces must be tempered because every attachment must eventually be removed. In fact, if one considers bracket repositioning during treatment, patient induced bond failures, and debonding at the end of treatment, it is conceivable that the bonding/debonding cycle may take place several times throughout the course of orthodontic treatment.

"Do no harm", a longstanding medical creed adopted by the dental profession, has caused orthodontists to assess the bonding/debonding cycle. In a perfect world, a tooth's enamel surface will be as pristine after the debonding of an orthodontic attachment as it was prior to its application. In an attempt to balance the need for strong resin bonds capable of withstanding heavy forces with the need for safe and efficient destruction of these bonds, when appropriate, unwanted composite is often left on the tooth.

Various methods for the removal of residual composite resin have been developed. Dentistry's need to eliminate carious enamel and dentin, remove calculus, and section tissues and restorations with precision and accuracy, has supplied orthodontists with a vast armamentarium of cutting, scraping, and polishing instruments to employ. Hand scalers, debonding pliers, and ultrasonic scalers have all been utilized for residual composite removal, although the dental drill is probably the most popular.

Countless burs, stones, wheels, and disks have been developed for use with dental drills with the purpose of cutting and polishing teeth as well as dental materials. Stainless steel, tungsten carbide steel, garnet, quartz, diamond, and rubber are just a few of the materials used to manufacture the wide array of dental abrasives and polishing devices.[2] With so many different attachments available for use with dental drills, it is no surprise that countless residual composite removal techniques and protocols have been developed and researched.

2. Assessment of enamel surface changes after residual orthodontic composite removal.

In a comparative study by Retief and Denys[3], the efficacy of residual composite removal was assessed at 700x magnification. Thirty-eight extracted incisors, bonded with a low filler bis-GMA resin, were inspected for gouges and roughness after the use of various finishing techniques. Their findings show that use of debonding pliers, hand scalers, and finishing diamonds produced deep gouges that persisted even after polishing with pumice. They concluded by recommending twelve-fluted carbide steel burs for the bulk removal of residual resin followed by graded finishing and polishing discs.[3]

A comparable study by Rouleau[4], using blinded observers to rank SEM photomicrographs for surface smoothness, determined that pristine enamel controls exhibited significantly smoother surfaces than teeth finished with ultra fine tungsten carbide burs and that the ultra fine tungsten carbide bur's ability to produce a smooth enamel surface was superior to the other burs assessed in the study. In addition, it was determined that hand scalers generated the roughest enamel surface and were least effective at resin removal. It was also shown that pumicing had no significant effect on improving smoothness.[4] Many other researchers, such as Gwinnett[5], Zachrisson[6], Burapavong[7], have also investigated the debonding process. The majority of them have determined that debonding procedures result in enamel loss and that the enamel surfaces are roughened, gouged, and scratched.[5-7] It was also determined that gouges and scratches deeper than 10 – 20 μm cannot be polished away.[7] Therefore, the orthodontic profession, despite decades of research, continues to search for a better method for residual composite removal.

In 1995, Cambell[8] conducted a survey of 72 orthodontists on the prevalence of enamel scarring. Over 80% of the respondents recognized that enamel scarring was a problem following debonding, with 12% acknowledging scarring in over half of their cases.[8] It is possible that Campbell's results under-estimated the extent of enamel scarring, since most orthodontists do not consciously look for scarring after debonding. In addition, pristine enamel was preferred by 52% of the respondents, while 47% felt that the appearance of previously bonded enamel was acceptable.[8] The conclusion is that enamel scarring, as a result of an orthodontic debonding procedure, is a common occurrence that can produce esthetic consequences visible to the naked eye.

The amount of enamel lost during removal is also important due to the fact that it is non-regenerative. Pus and Way[9] determined that a No. 7902 bur in a high-speed drill produced a mean enamel loss of 19.2 μm. They also showed that the pre-bonding prophylaxis, acid-etch, finishing and polishing cycle produced an enamel loss ranging from 29.5 to 41.2 μm.[9] Follow up studies assessing the bonding/debonding cycle, where multiple prophylaxes were done, showed a mean enamel loss of up to 71.5 μm.[10] Therefore, due to the non-regenerative nature of enamel, it is important to use a composite removal technique that minimizes enamel loss and scaring. In an attempt to conserve enamel, from both an esthetic and physiologic standpoint, dental researchers have explored alternative means of adhesive removal. One of these is the use of a dental laser.

3. Ablative removal of residual orthodontic composite using laser irradiation.

Since the development of the ruby laser by Maiman in 1960, there has been great interest among dental practitioners, scientists, and patients to use lasers to make dental treatment more pleasant and efficient. Recently, the use of dental lasers by clinicians has increased. Dental lasers have been used to ablate soft tissue, cure composites, activate bleaching chemicals, clean root surfaces, promote caries resistance in enamel, and perform simple cavity preparations.[11,12] However, use of a laser for specific applications is dictated by its properties, such as wavelength, energy, pulse rate, and spot size. To date, three different lasers have received FDA approval for use on dental hard tissues. They are the Er:YAG, Er:YSGG, and Nd:YAG lasers.

In order to use lasers safely and efficiently, enamel damage such as fractures, scarring, and increased caries susceptibility, must be avoided. Laser light must also be benign to the dental pulp by avoiding heat accumulation, which can cause irreversible pulpal damage or necrosis. Various researchers have investigated the effects of thermal heating on dental pulp[13-16] with more recent investigations assessing pulpal effects associated with the use of dental lasers.[17-19] These studies indicate, overall, that a temperature rise of 5.5°C can cause irreversible pulpal damage and that elevation in excess of 11°C may cause necrosis.[18] Therefore, for the purpose of removing residual orthodontic resin, the ideal laser system is one that can ablate residual resin without excessive accumulation of heat.

Recent studies by Dumore and Fried [20] have demonstrated that lasers operating with sub-microsecond pulse duration are well suited for the removal of dental composite from enamel surfaces through the selective ablation of the composite. The studies indicated that a pulsed CO_2 laser operating at 10.6 μm with pulses of approximately 1 μs in duration is well suited for this application. Spectral analysis of the emission plume created by ablating composite and enamel identified a number of spectral lines that could be used to distinguish between the ablation of enamel and composite. The studies also demonstrated that the CO_2 laser pulses could be used to ablate composite at a rate almost an order of magnitude higher than for enamel. However, some measurable damage to the underlying enamel was still evident. Complete selectivity was not obtained.[20]

In another study, Thomas [21] demonstrated that a combination of 532 nm and 1064 nm laser pulses was capable of degrading the strong resin bonds between ceramic orthodontic brackets and enamel. In his study, a Nd:YAG laser (Kiger, Inc, Hilton Head, SC), which simultaneously emits two wavelengths with energy outputs of 60% 532 nm and 40% 1064 nm, was used to assess laser-aided degradation of composite resin. Using a 300 μm diameter focal spot and various pulse frequencies, he set out to determine the compressive strength of composite resin cylinders after being subjected to laser irradiation at different frequencies and times.[21] His findings showed a significant decrease in the ultimate compressive strength of the irradiated composite cylinders. He also reported that irradiation of the composite resulted in rough damaged surfaces with carbon deposits as well as an odor of burnt plastic. SEM evaluation of enamel controls showed very little change. The perikymata remained visible, but the rod ends seemed more defined.[21] The purpose of his study was to demonstrate that a combination of 532 nm and 1064 nm irradiation could help clinicians debond ceramic brackets and thus reduce enamel "tear outs" or fractured brackets that require removal with course diamond burs. The design and purpose of Thomas' study was not to demonstrate composite removal but composite degradation as to allow easier de-bracketing. Complete resin removal still required traditional removal techniques.

Dental researchers are not the only ones interested in laser ablation of resins materials. High-tech manufacturing companies currently use 355 nm lasers to efficiently ablate conductive and/or insulating resins used in micro-electric circuitry production. The ability to drill holes and cut surface modifications into the resin interconnects has allowed manufacturers to reduce product size and cost.[22-24] 355 nm lasers are also used for CAD/CAM machining of other resin components. Considering the ablative capacity that 355 nm laser pulses' have for various resins, as demonstrated by their high-tech applications, a strong argument can be made for using this wavelength for the ablative removal of residual orthodontic composite.

4. Rationales for using photoacoustics to monitor the selective removal of residual composite.

The present study was designed to investigate the feasibility of using a 355 nm laser to completely remove the residual composite resin from orthodontically bonded teeth without damaging the underlying enamel or pulpal tissues. To investigate the mechanism of absorption and ablation, photoacoutics were used. Photoacoustics probe the acoustic wave generated at the surface of an opaque sample when the absorbed light is converted into heat. The signal generated by the modulated light source is proportional to the incident intensity, absorption coefficient, thermal diffusivity, and modulation frequency. A thermal wave generated by the absorbed laser energy heats the gas above the sample that subsequently causes pressure waves that can be detected by a microphone placed near the sample surface. At the ablation threshold the signal increases by orders of magnitude due to the explosive release of gases and ablated material that directly perturb the surrounding air.[25-32]. Therefore, the photoacoustic method is excellent for determining both the onset of ablation and monitoring the selective removal of tissue. Rechmann and Hennig used [33-36] photoacoustics to demonstrate the selective ablation of protein rich calculus from a tooth's root surface using 377 nm laser pulses from a frequency doubled alexandrite laser. In this study, photoacoustics were be used to demonstrate the mechanism of absorption and ablation during the removal of residual composite resin from orthodontically treated teeth.

B. Overall Hypothesis

The central hypothesis of this research was that ***a laser, operating at 355 nm and a pulse duration of 3-5 ns, can be used for the selective ablation of residual orthodontic resin without damage to underlying enamel and without excessive accumulation of heat.*** Taking into account the morbidity involved with removing residual composite resin from orthodontically treated teeth using traditional methods, the ability to use laser irradiation to restore enamel surfaces to their pristine, pre-treatment condition would be a significant benefit for practitioners. Four specific aims were used to test the central hypothesis.

C. Specific Aims

The overall objective of this study was achieved through the following aims:

Specific Aim #1: To test the hypothesis that 355 nm laser pulses have a significantly lower ablation threshold for composite resins than for enamel.

Specific aim #2: To test the hypothesis that frequency tripled Nd:YAG lasers, operating at 355 nm, can remove residual orthodontic resin from the enamel surfaces of teeth without damaging those surfaces.

Specific Aim #3: To test the hypothesis that heat accumulation within a tooth, as a result of the ablative removal of residual orthodontic resin, is quantifiable and can be maintained within a safe physiological range.

Specific Aim #4: To test the hypothesis that the mechanism of absorption and ablation is the incubation of defect sites leading to a non-linear increase in ablation.

IV. Materials and Methods

A. Specific aim #1: To test the hypothesis that 355 nm laser pulses have a significantly lower ablation threshold for composite resins than for enamel.

1. Ablation rate testing of human enamel and Enlight® composite resin using 355 nm laser pulses.

Enamel sections were prepared from the crowns of extracted third molars with the roots removed. The teeth had previously been sterilized with gamma irradiation to destroy all pathogens. Thin sections were prepared using a hard tissue microtome (Sci-Fab Series 1000 Deluxe, Lafyette, CO) and care was taken to ensure samples were plano-parallel as well as approximately 200 μm in thickness.

To produce composite sections, it was first necessary to prepare a cylinder of Enlight® orthodontic composite (Ormco Co., Glendora, CA). This was accomplished by taking a section of plastic tubing approximately two centimeters long and ten millimeters in diameter, filling it with the composite, and then curing the sample for 15 minutes in a Triad 2000® light cure oven. The cured composite was then sectioned into plano-parallel samples of approximately 200 μm in thickness using the microtome.

A Q-switched Nd:YAG laser (Minilase III system from New Wave; Sunnyvale, CA) operating at a wavelength of 355 nm and a pulse duration (FWHM) of 10 ns, was used to measure the ablation rates of the enamel and composite samples. The Minilase III laser was equipped with a variable beam attenuator incorporating two linear polarizers that were used to vary the incident intensity. The laser beam was down-collimated onto the surfaces of the samples using BaF_2 and fused silica lenses producing spot sizes (e^{-2}) of 200 – 500 μm. A pyroelectric energy meter was placed behind the focusing stage to monitor the beam energy and to detect perforation of the sample, which produced a rise in signal from the detector. The number of pulses needed to perforate the full thickness of the samples was collected at various laser fluences. Initial testing commenced at the laser system's maximum intensity and was then decreased by 10-20% increments until energy levels decreased to levels not capable of sample perforation. A minimum of 5 readings was taken at each energy level.

2. Ablation rate testing of human enamel and Enlight® composite resin using an Er:YAG laser operating at 2.94 μm.

Er:YAG lasers, the first to be approved by the FDA for hard tissue use, are among the most commonly used lasers in dental offices. Therefore, perforation rates of composite and enamel were measured for comparison. A Schwartz Electro-0ptics Model-123 Er:YAG laser system (Schwartz Electro-optics, FL), operating at 2.94 μm with a pulse duration (FWHM) of 100-300 μs, was used to test the ablation rates of composite and enamel samples identical to those used with the 355 nm Nd:YAG laser. The laser beam was down-collimated onto the samples' surfaces using BaF_2 and fused silica lenses producing spot sizes (e^{-2}) of 200 - 500 μm. The intensity of the Er:YAG laser pulses was varied by placing Pyrex slides in the beam's path.

As outlined above with the Nd:YAG laser, a pyroelectric energy meter was used to detect perforation of the sample. The number of pulses needed to perforate the full thickness of the samples was recorded at various fluences. Initial testing commenced at the laser system's maximum intensity and then was decreased by 10-20% increments until perforation was not achieved. A minimum of 5 readings was taken at each energy level.

B. Specific aim #2: To test the hypothesis that frequency tripled Nd:YAG lasers, operating at 355 nm, can remove residual orthodontic resin from the enamel surfaces of teeth without damaging those surfaces.

1. Surface damage assessment of bovine enamel samples.

Gamma sterilized bovine incisors were divided into two groups. Group 1 consisted of five sectioned bovine blocks (5 mm x 5 mm x enamel thickness), highly polished with sequential diamond abrasives, 6 μm, 3 μm and 1 μm. Group 2 consisted of five intact bovine crowns, cleaned with flour of pumice in order to remove the bio-film layer, but not highly polished. Both groups were then bonded with orthodontic brackets using Enlight® orthodontic composite, adhesive, and etchant. Bonding recommendations were followed as specified by the manufacturer. Subsequently, the brackets were then debonded, leaving an adhesive remnant of orthodontic composite bonded to the samples.

Both sample groups, the polished blocks and intact crowns, were irradiated with 355 nm laser pulses at 10 Hz and a fluence of 3 J/cm^2. The laser's 470 μm diameter beam was scanned over the residual composite resin using an ESP3000 motion control system (Newport Electroptics, Irvine, CA) with two 6 mm/sec stages interfaced to a computer at a repetition rate of 10 Hz. The block samples had a 5 mm x 3 mm area scanned, using 30 laser pulses for each 200 μm scan distance. A larger 7 mm x 3 mm scan area was used for the crown samples with 45 pulses per 200 μm scan.

The irradiated bovine enamel samples were then assessed visually using an Olympus BX50 optical microscope with integrated DVC 1300C digital camera and Image Pro Plus® software (Media Cybernetics) and/or a Leica M3Z optical microscope with integrated digital and BioQuant True Color Windows® software. Digital images were captured at magnifications up to 200x.

2. Surface damage assessment of human enamel samples.

Gamma sterilized human bicuspids, extracted for orthodontic purposes, were cleaned and prepared with residual composite resin in the same manner as the bovine enamel samples. Additional procedures to remove the dental pulps and place thermocouples were also performed, details of which will be outlined in the next section on internal temperature increases. The five bicuspids were then irradiated with the 355 nm laser operating at 10 Hz and a fluence of 1.26 J/cm^2. The laser's 522 μm diameter beam was scanned over the residual composite resin using the ESP3000 motion control system. The bicuspids had a 4 mm x 1 mm area scanned, using 100 laser pulses for each 150 μm scan distance. During the irradiation of the samples, concurrent temperature readings were taken. The irradiated human bicuspid samples were then assessed in the same manner as the previous bovine samples. Digital images were captured at magnifications up to 200x.

C. Specific aim #3: To test the hypothesis that heat accumulation within a tooth, as a result of the ablative removal of residual orthodontic resin, is quantifiable and can be maintained within a safe physiological range.

1. Internal temperature assessment during residual composite removal.

The five human bicuspids samples used for surface damage assessment were also used to record internal temperature changes. After they were cleaned and prepared with residual composite resin, the dental pulps were removed from the intact teeth using endodontic broaches and files inserted from the root apex. Prefabricated, insulated thermocouples (type K Chromel-Alumel, 0.005" wire diameter, OMEGA Technologies) were then inserted up through the root apex and attached at the corono-facial aspect of each sample's pulp chamber using thermally conductive epoxy (OMEGABOND® 101, OMEGA Technologies, Stamford, CT) to assure good thermal contact and accurate temperature measurement. A radiographic image was taken to insure proper thermocouple placement , as seen in Figure 1 on the following page.

Figure 1. Radiographic image of extracted human bicuspid with thermocouple inserted up through the apex into the most occluso-facial aspect of the pulp horn.

The five samples were then irradiated with the 355 nm laser operating at 10 Hz and a fluence of 1.26 J/cm^2. The laser's 522 μm diameter beam was scanned over the residual composite resin using the ESP3000 motion control system. The bicuspids had a 4 mm x 1 mm area scanned, using 100 laser pulses for each 150 μm scan distance.

Concurrent with the ablative removal of the residual composite resin, internal temperature readings were recorded at 1 second intervals. Temperatures were collected during the entire scan as well as for an additional five minutes after the irradiation was terminated. Voltage readings were collected using a thermocouple amplifier and a National Instruments A/D board interfaced to a computer. Thermocouple voltages were converted to temperatures using a 7th order polynomial curve-fit.

D. Specific aim #4: To test the hypothesis that the mechanism of absorption and ablation is the incubation of defect sites leading to a non-linear increase in ablation.

1. **Photoacoustic assessment of residual composite removal from bovine enamel samples.**

A sectioned bovine block (5 mm x 5 mm x enamel thickness), highly polished with sequential diamond abrasives (6 μm, 3 μm and 1 μm), was bonded with an orthodontic bracket using Enlight® orthodontic composite, adhesive, and etchant. Bonding recommendations were followed as specified by the manufacturer. The bracket was subsequently debonded, leaving a pad of residual orthodontic composite on the sample.

The 355 nm Nd:YAG laser, operating at a repetition rate of 10 Hz and a fluence of 1.26 J/cm^2, was used to ablate residual composite from the samples. The beam was down-collimated onto the sample surface using a BaF_2 lens to produce a 522 μm spot size. A microphone (Model #4012, ACO Pacific, Belmont CA) was used to record the sound waves produced during laser irradiation of the bovine block with residual composite. The time-resolved waveform was acquired using a digital oscilloscope (Textronix 2440) interfaced to a computer. Two Boxcar Integrator/Averagers SRS 250 (Stanford Research, Stanford, CA) were used to sample and hold the amplitude of the voltage of the first resonance in the detected waveform. The magnitude of that voltage was monitored as a function of the number of pulses incident to the composite layer on a bovine enamel block.

V. Results

A. Specific aim #1: To test the hypothesis that 355 nm laser pulses have a significantly lower ablation threshold for composite resins than for enamel.

1. Ablation rate testing of human enamel and Enlight® composite resin using 355 nm laser pulses.

Ablation of composite and enamel was investigated using 355 nm laser pulses. Ablation rates (μm/pulse) were calculated according to the protocols discussed in the Methods and Materials section. Figure 2, on the following page, shows the recorded ablation rates vs. incident fluence for the enamel and composite samples using 355 nm laser pulses.

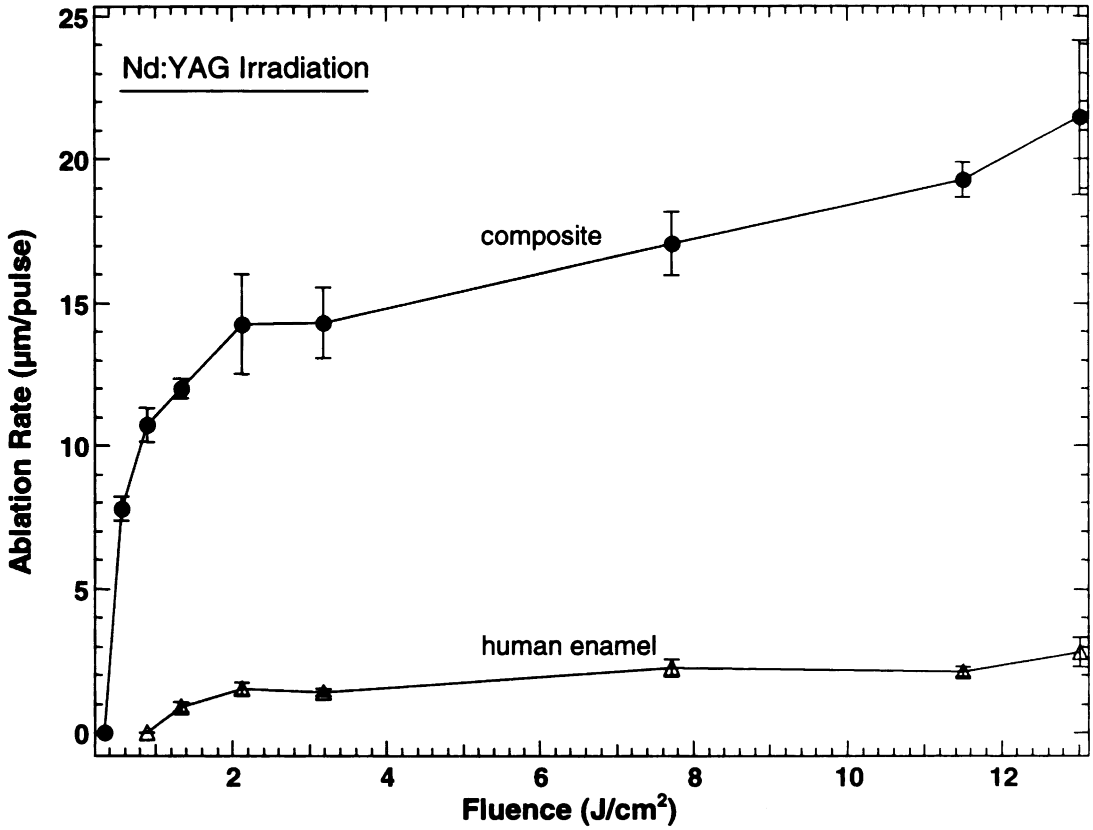

Figure 2. Ablation rate vs. incident fluence for 355 nm irradiation of enamel and composite samples.

Ablation rates for composite and enamel without the use of externally applied water for fluences from 0-12 J/cm^2 are shown. The data show that the ablation threshold for composite ablation is less than 1 J/cm^2. At 1 J/cm^2 the ablation rate exceeds 10 µm/pulse and climbs to 15 µm/pulse at fluences of 2-3 J/cm^2. As irradiation intensities continue to rise, as illustrated by fluences greater than 3 J/cm^2, a gradual increase in the ablation rate is seen until the 20 µm/pulse maximum is reached. This is the ablation rate at maximum energy output.

In contrast, the enamel ablation threshold is at or just above 1 J/cm^2. As the fluence increases, a small rise in the enamel's ablation rate is observed until the fluence reaches 2 J/cm^2. Beyond this intensity, the ablation rate quickly saturates at a level of only 2 μm/pulse. Therefore, the data demonstrate the ability for 355 nm laser pulses of ~1 J/cm^2 to selectively ablate composite resins at a rate of 10 μm/pulse while not removing underlying enamel.

In this experiment, each tested fluence had a sample size of 5 or greater. Statistical analysis of the data presented in Figure 2 showed that our sample size of n=5 has adequate power. Using the largest S.D. from Fig. 2 data, s.d.= 2 for composite at a fluence of 13 J/cm^2 for a conservative estimate, we estimated a power of 95% with n=3 per group to detect a difference of 8 μm/pulse using a 2-sided a=0.5 2 sample *t*-test. Statistical results of an unpaired *t*-test revealed a significant difference ($p < .0001$) between the ablation rate of composite and enamel at all tested fluences.

2. Ablation rate testing of human enamel and Enlight® composite resin using an Er:YAG laser operating at 2.94 μm.

As stated in the Methods and Materials section, comparative ablation rates for 2.94 μm laser pulses were collected in order to compare 355 nm ablation thresholds with that of the FDA approved Er:YAG laser. Ablation rates (μm/pulse) were calculated as outlined above. The ablation rates vs. incident fluence for enamel and composite using 2.94 μm laser pulses are shown below in Figure 3.

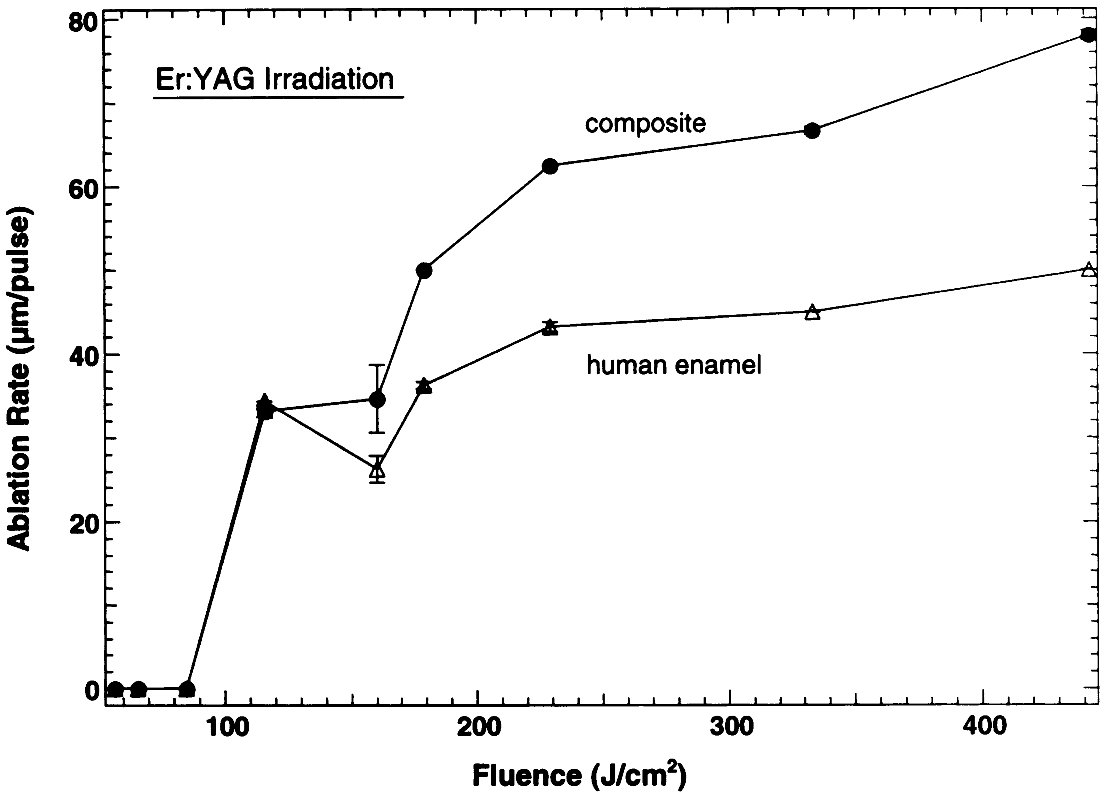

Figure 3. Ablation rate vs. incident fluence for 2.94 µm irradiation of enamel and composite samples.

Ablation rates for composite and enamel without the use of externally applied water for fluences from 0-500 J/cm^2 are shown. The data show that irradiation intensities in excess of 100 J/cm^2 are required for ablation of both enamel and composite and no selectivity is observed until irradiation intensities reached levels of ~200 J/cm^2. Compared to the 355 nm laser pulses, the irradiation intensities required to produce any noticeable ablation selectivity are two orders of magnitude greater for the Er:YAG laser. It must also be remembered that at this fluence, the rate of enamel ablation is ~40 µm/pulse. Therefore, it can be concluded that conventional 2.94 µm laser pulses are not suitable for the ablative removal of residual composite resin from orthodontically treated teeth due to its excessive enamel removal rate and potential for peripheral thermal damage.

B. Specific aim #2: To test the hypothesis that frequency tripled Nd:YAG lasers, operating at 355 nm, can remove residual orthodontic resin from the enamel surfaces of teeth without damaging those surfaces.

1. Surface damage assessment of bovine enamel samples.

Visual observation of the bovine enamel samples shows the effectiveness and selectivity of 355 nm laser pulses at removing residual composite resin. No peripheral enamel damage was seen in these samples. To demonstrate the findings, magnified images have been included. Figure 4 shows the surface of a polished bovine block that has been scanned with 355 nm laser pulses.

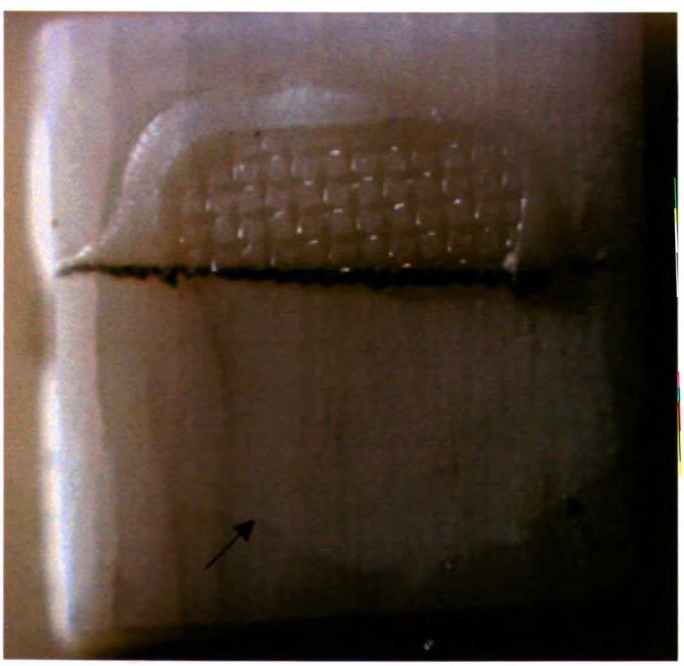

Figure 4. Selective ablation of residual orthodontic composite. ***Note:*** The outline of the acid etching (arrows), produced at the time of bonding, was not removed during the procedure.

The laser was used to remove the lower half of the composite from the surface of the bovine enamel. The remaining composite is visible with a narrow char layer separating the two zones. It is noted that the carbonization of the resin (char layer) occurs at the interface between the irradiated and non-irradiated zones. This result is due to the reduced intensities at the periphery of the laser beam, which are at levels insufficient to fully ablate the resin at the interface. Further discussion of the beam's intensity distribution will be addressed in the Discussion section. Also of note is that the frosted surface, produced by etching the surface with 37% phosphoric acid as required with orthodontic bonding, was not altered by the 355 nm irradiation. Thirty-second acid etching of enamel has been shown to remove < 7 μm of tooth structure[9], meaning that the 355 nm enamel removal was most likely less than 7 μm, if any at all.

Figures 5 and 6, on the following page, show the enamel surface of an intact bovine incisor after removal of residual resin.

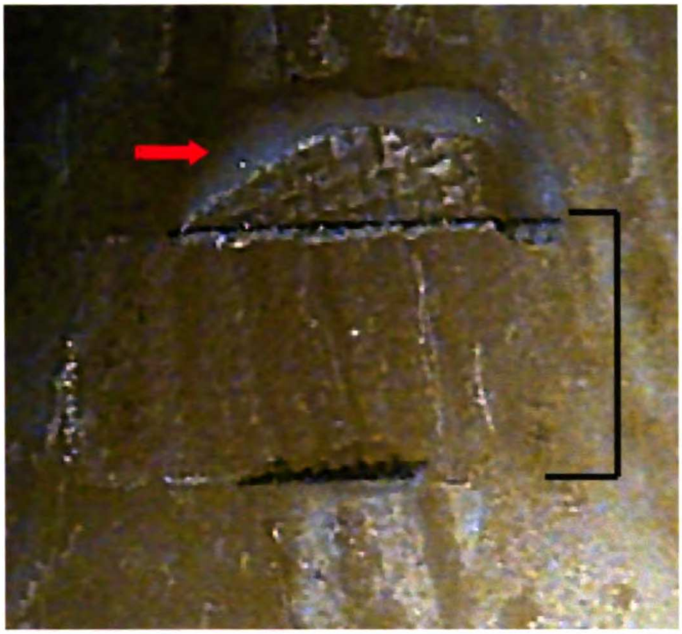

Figure 5. Residual composite removal from a bovine incisor using 355 nm laser pulses. The black bracket indicates the height of the scan area. The red arrow points to the top portion of residual composite that was not irradiated.

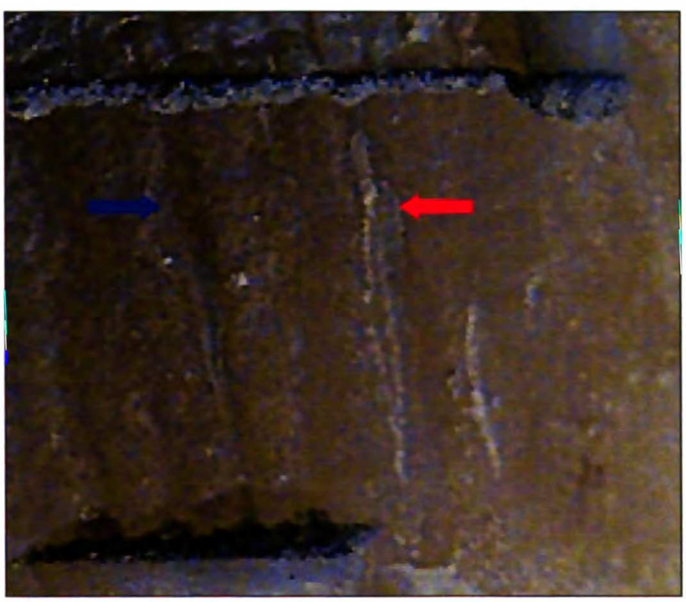

Figure 6. Increased magnify-cation of the bovine incisor seen in Fig. 5 reveals that the perikymata (blue arrow) were not destroyed by the 355 nm irradiation. The red arrow points to resin not removed by the laser.

Magnified images show that the perikymata, or enamel ridges, were unchanged by treatment with the 355 nm laser pulses. This supports the idea that the amount of enamel loss, if any at all, is not clinically significant. In fact, no enamel damage was visually detected on any of the bovine samples assessed at magnifications up to 200x. However, with the unpolished bovine incisors, some islands of residual composite remained within the deepest troughs of the perikymata. Inability to completely remove the resin from the deepest troughs is most likely due to diminished irradiation intensity at distances outside the beam's focal length. Controlling focal length and insuring adequate intensities on irregular and curved surfaces will be addressed in the Discussion section.

2. Surface damage assessment of human enamel samples.

The surfaces of the five human enamel samples were also visually assessed under magnifications up to 200x. At 150 μm scan intervals, 100 laser pulses were fired at the surface. The 522 μm diameter beam delivered a fluence of 1.26 J/cm^2. Microscopic assessment of the samples revealed obvious enamel damage. The distinct pattern of six scanning rows is seen in Figure 7.

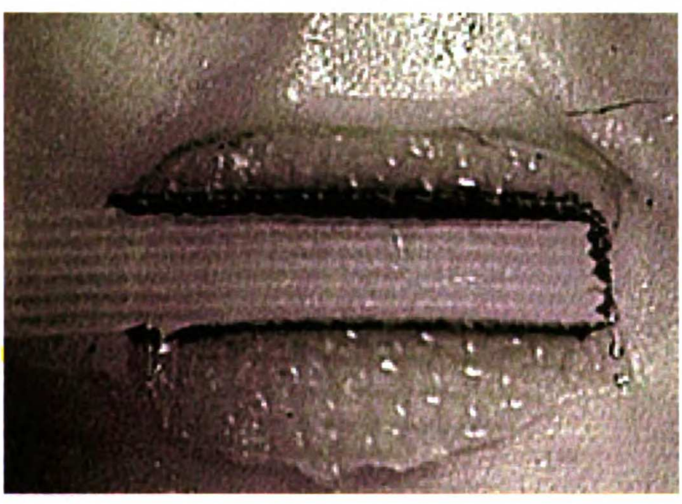

Figure 7. Composite removal from a human bicuspid using 355 nm pulses. Enamel damage, showing a distinct pattern of six scanning rows, is observed.

Extrapolating the data presented in Figure 2, the human enamel ablation rate for a fluence of 1.26 J/cm^2 is approximately 1 μm/pulse. Therefore, since each 150 μm scan interval received 100 laser pulses, enamel ablation was estimated at ~100 μm. In hope of demonstrating successful composite ablation from the enamel surfaces of human teeth, two additional samples were treated using a reduced fluence of 1.0 J/cm^2.

Microscopic evaluation of the additional samples revealed that 355 nm laser pulses were capable of completely removing the residual composite resin without any discernable damage to the human enamel surfaces. By lowering the fluence, as was indicated by the calculated ablation rates found in Figure 2, the residual resin pads could be completely removed without discernable enamel damage. Figures 8-11 show microscopic images of a sample.

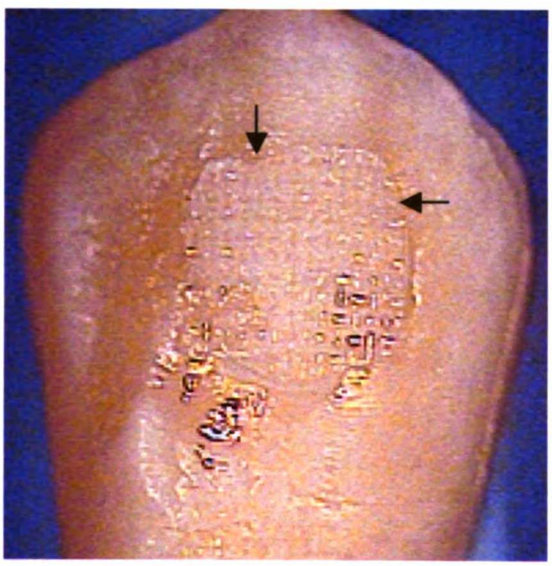

Figure 8. Pre-treatment photo showing residual composite pad (black arrows).

Figure 9. Post-treatment photo. Note the glossy appearance of the unfilled resin primer outlining the boarders of the scan area (black arrows).

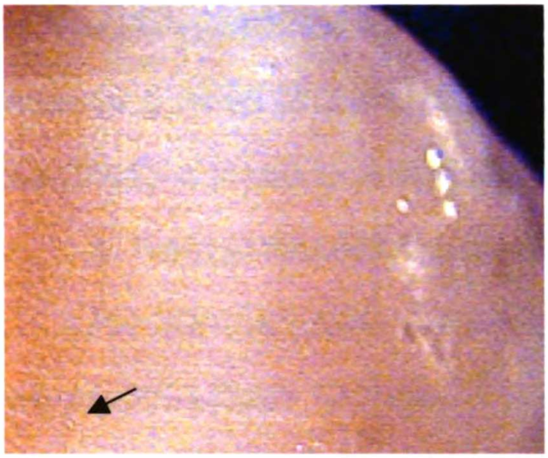

Figure 10. Post-treatment photo magnified at 38x. The black arrow points to a small resin remnant.

Figure 11. Post-treatment photo showing the same small resin remnant (black arrow) magnified at 60x. Note the smooth enamel surface.

Microscopic evaluation of the samples showed no enamel ablation, however additional pulses were required to remove the thicker areas of composite that are commonly seen adjacent to the edges of the bracket's pad. The microscopic assessment unmistakably showed that 355 nm laser pulses can selectively ablate composite resin from human enamel surfaces when operating at fluences less than or equal to 1 J/cm^2. However the time required to do so, using our current equipment, makes clinical application impractical. Possible methods for reducing time requirements will be addressed in the Discussion section.

C. Specific aim #3: To test the hypothesis that heat accumulation within a tooth, as a result of the ablative removal of residual orthodontic resin, is quantifiable and can be maintained within a safe physiological range.

1. Internal temperature assessment during residual resin removal.

The data collected from the internal temperature measurements have been plotted in Figure 12 below.

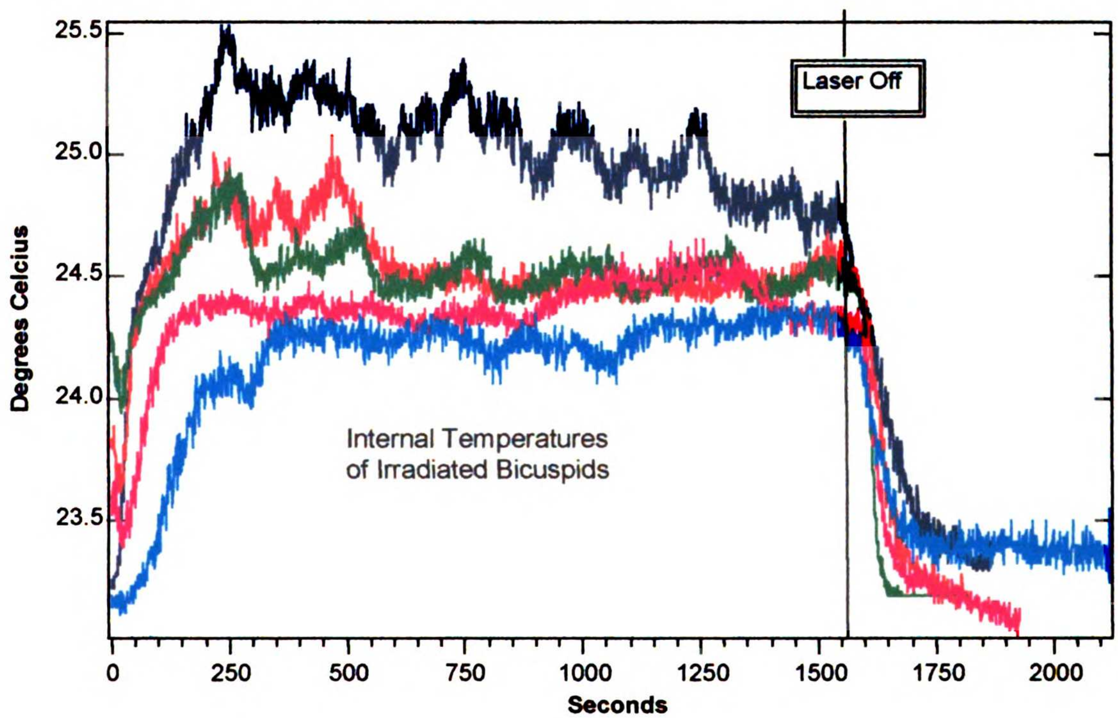

Figure 12. Internal temperature vs. time recorded during the ablative removal of composite from the enamel surfaces of human bicuspids.

The graph shows that internal temperature increased when the laser pulses began to irradiate the sample. However, the temperature rise quickly saturated as the energy being deposited into the tooth equilibrated with the heat

lost by conduction, convection and thermal radiation from the tooth. The achieved equilibrium was represented by the characteristic plateau of the graph's plotted temperatures. The data showed an average temperature rise of 1.53 °C ± 0.52.

Further analysis revealed that a sufficient baseline temperature might not have been recorded prior to initiating laser irradiation. In doing so, the average increase in temperature may have been over-estimated. Therefore, a second plot of the data, seen below in Figure 13, was performed in which a "tail end" baseline was used.

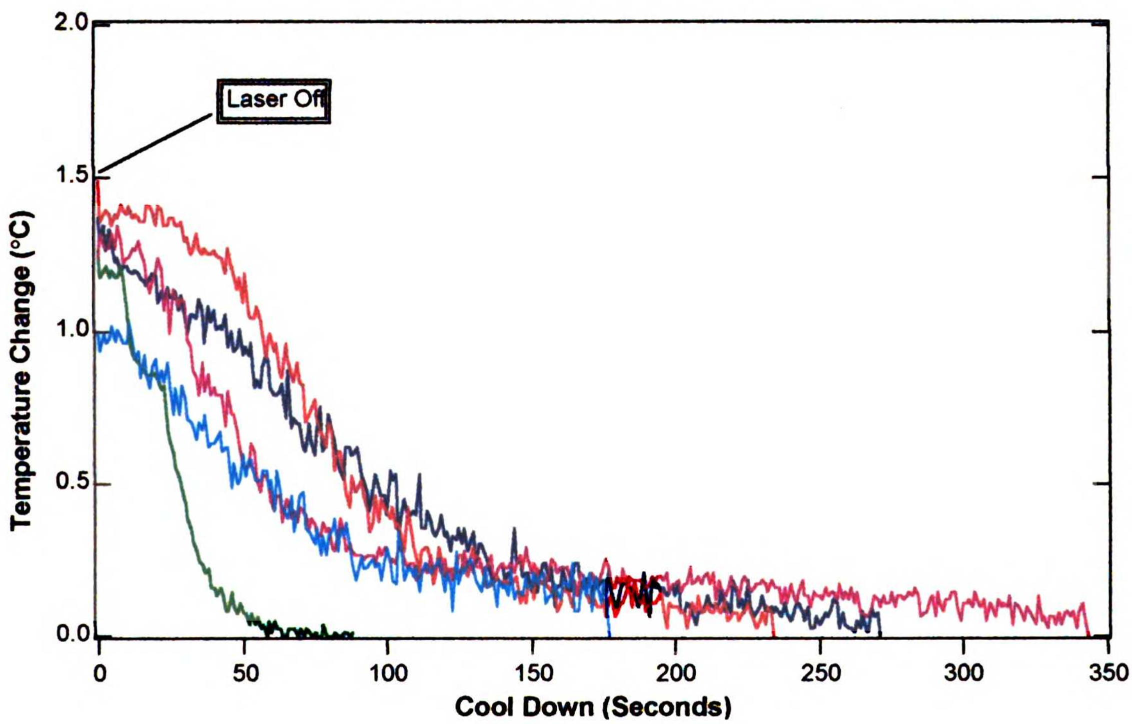

Figure 13. Internal temperature vs. time recorded during the cooling down phase.

This graph starts with the internal temperature recorded just prior to the time that laser scanning was terminated. This is the point when the entire amount of energy delivered by the laser has been deposited onto the sample. It can therefore be argued that this temperature represents the most accurate representation of true internal temperature change. Subsequent temperature readings recorded the time it took for each sample to reach its minimum temperature during a cooling down phase (the tail end baseline). The data were normalized by setting each samples' minimum value to 0 °C. The difference between the samples' maximum value just prior to turning off the laser and its minimum value was then calculated. Using the "tail end" baseline, the average temperature change was calculated to be 1.30 °C ± 0.16, which is 0.23 °C less than the original calculations. Either way, taking the "worst case" scenario, the maximum temperature rise was ~2 °C, which is well below the 5.5 °C threshold where irreversible pulpal damage begins to occur.[14,17,18] In addition, it is quite possible that *in vivo* conditions would allow for better heat dissipation and that actual temperature increases would be even less than those recorded in these experiments. This topic will be explored in the Discussion section.

D. Specific aim #4: To test the hypothesis that the mechanism of absorption and ablation is the incubation of defect sites leading to a non-linear increase in ablation.

1. Photoacoustic assessment of residual composite removal from bovine enamel samples.

Photoacoustic monitoring of the ablative process during multiple pulse irradiation revealed the mechanism of interaction between the 355 nm laser pulses and dental composite. Figure 14 shows the magnitude of the sound waves produced during absorption and ablation for each laser pulse incident on the residual composite of ~200-μm thickness.

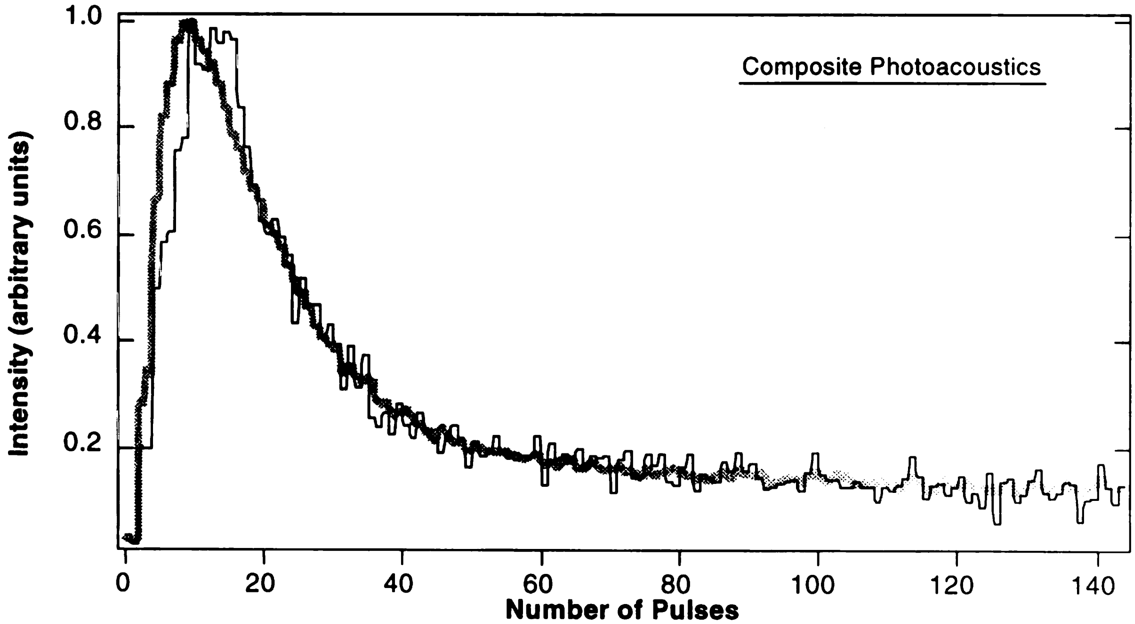

Figure 14. Number of pulses vs. sound wave intensity recorded during the ablation of composite from the surface of bovine enamel using 355 nm laser pulses. The black line represents the intensity reading of an individual test. The thick gray line represents the average of 16 individual tests.

The magnitude of the sound waves during the first few laser pulses was low, however, the sound intensity level increased markedly with the increasing number of laser pulses incident on the same site. After 20 - 30 laser pulses, the sound intensity level peaked, most likely signifying that the ablative pulses had removed the composite down to the underlying enamel. The magnitude of the sound waves continued to decrease until the entire composite had been removed. At this point, the magnitude of the sound waves reached a steady state or baseline. This increase in recorded photoacoustic intensity suggests that absorption and ablation is due to an incubation of defect sites leading to a non-linear increase in ablation. It is likely that increasing temperature induces changes in internal bonds, leading to the charring that enables the subsequent laser pulses to be absorbed more efficiently. Further commentary about charring will be addressed in the Discussion section.

To further illustrate the difference between the photoacoustic signals of composite and enamel at selective intensity levels, a second graph was plotted. Figure 15, on the following page, shows the sound wave magnitudes of composite and enamel recorded over time.

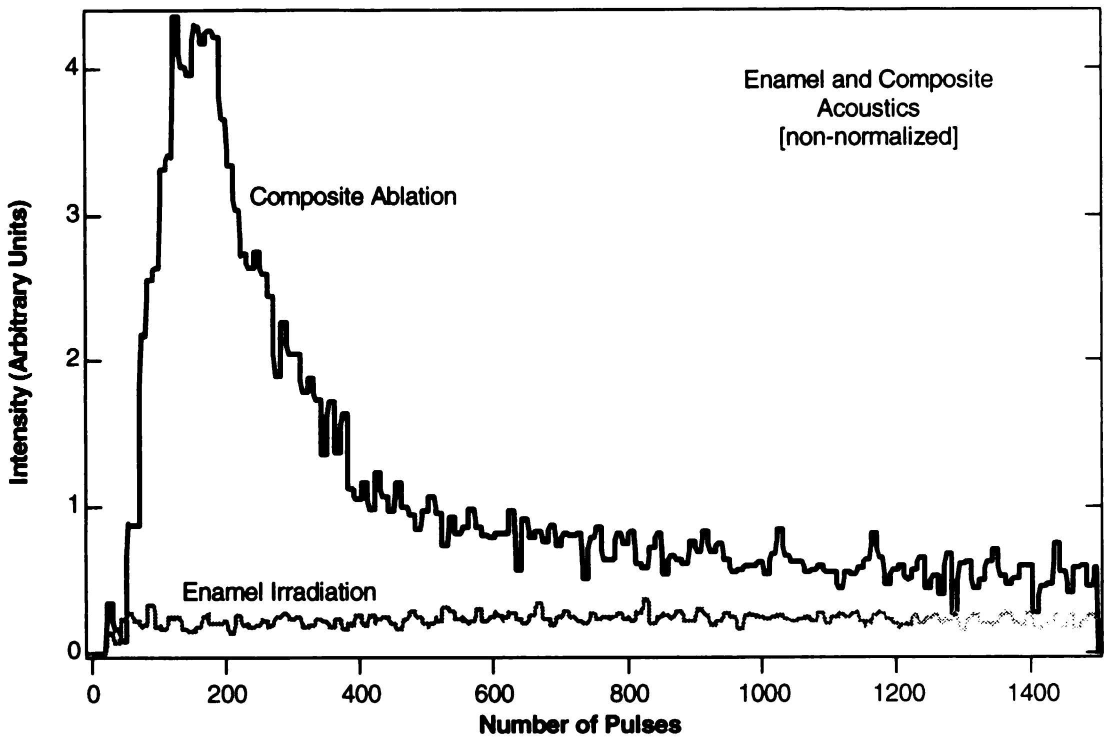

Figure 15. Number of pulses vs. sound wave intensity recorded during the ablation of composite from the surface of bovine enamel using 355 nm laser pulses. The black line represents the composite photoacoustic recording seen in Fig. 14. The gray line represents the average of 5 enamel tests conducted under the same parameters as the composite tests.

The average of five photoacoustic recordings derived from the enamel controls was plotted against the composite photoacoustic recording used in Figure 14. The photoacoustic recordings of the enamel controls showed no initial rise, peak, and decrease in sound wave intensity, as was seen with the composite samples. The steady state of their photoacoustic recordings suggested a lack of enamel ablation. Microscopic evaluation of the enamel controls confirmed the absence of ablation. Also of note was the difference in magnitude displayed by the two groups' baseline readings. This difference will also be addressed in the Discussion section.

VI. Discussion

To emphasize the need for improved methods of residual composite removal, samples exhibiting enamel damage incurred by traditional removal techniques are presented for comparison. The following digital images, captured with a high-powered optical microscope, demonstrate the enamel damage produced by removing residual orthodontic resin using a 12-fluted carbide bur (No. 7902) and a high-speed dental drill. Care was taken to use light pressure and gently "paint" the surface with broad sweeping motions, not holding the bur in any one location in order to avoid gouging. This is the adhesive removal technique currently taught by the UCSF orthodontic division as well as advocated in the literature.[3,9] Figures 16-19 show the pre and post-treatment images.

Figure 16. Pre-treatment photo showing residual composite pad.

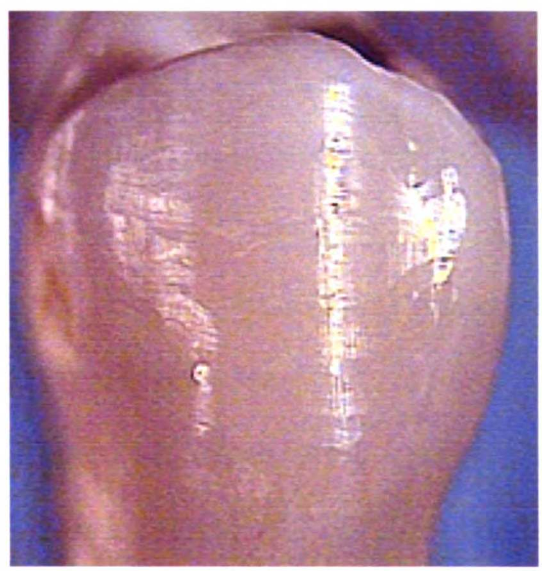

Figure 17. Post-treatment photo. Note the altered enamel appearance.

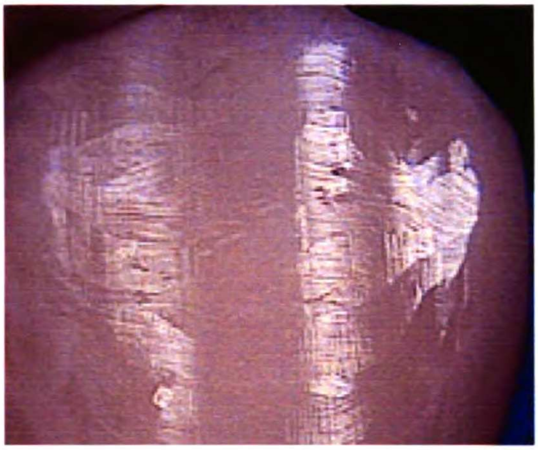

Figure 18. Post-treatment photo magnified at 24x.

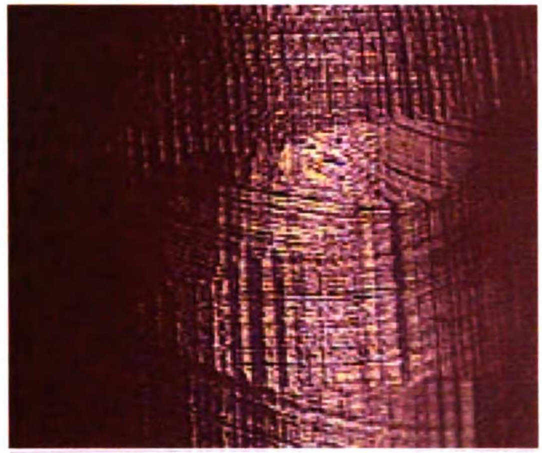

Figure 19. Post-treatment photo captured at 38x. Note the rough and gouged enamel surface.

Of note was the flattening of the tooth's surface, as well as the deep scratches. This technique is quite possibly the profession's current standard of care for residual composite removal. However, most of the time teeth are bathed in saliva that fills these gouges and deep scratches. The layer of saliva masks the enamel damage much like wax on the paint of an automobile. The wetting characteristics of saliva allow it to fill the iatrogenic defects and allows for an even reflectance of light from the tooth's surface. However, it must be remembered that irreversible damage has occurred and that enamel scarring is often evident during smiling when anterior teeth become dry.

In contrast Figures 20-23, as previously seen in the result section, were shown again to illustrate the quality of the enamel surface after laser removal of the residual composite resin. After comparing the selective laser ablation images

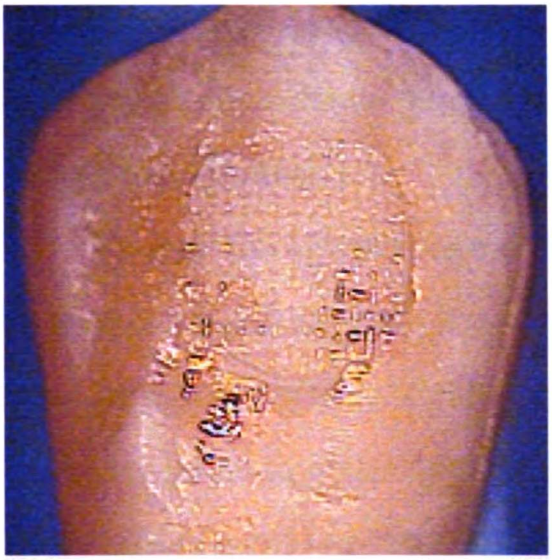

Figure 20. Pre-treatment photo showing residual composite pad.

Figure 21. Post-treatment photo. Note the glossy appearance of the unfilled resin primer outlining the boarders of the scan area (black arrows).

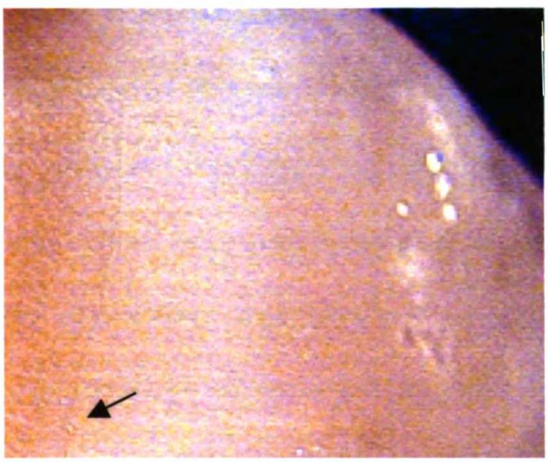

Figure 22. Post-treatment photo magnified at 38x. The black arrow points to a small resin remnant.

Figure 23. Post-treatment photo showing the small resin remnant (black arrow) magnified at 60x. Note smooth enamel surface.

(Figures 20-23) with the dental drill images (Figures 16-19), it is easy to appreciate the smooth surface produced by selective ablation as opposed to composite removal using a dental drill and bur. Arguably, selective laser ablation returns the orthodontically bonded tooth to a condition that rivals its pristine, pretreatment condition.

Despite the positive outcomes of surface damage evaluations, laser removal of residual adhesive cannot become a viable treatment option unless it is benign to pulpal tissues. The results of the temperature tests revealed that the average internal increase was 1.53 °C ± 0.52. According to the literature, temperature increases of this magnitude do not induce irreversible damage to pulpal tissues.[14, 17, 18] This study however, was not reflective of *in vivo* conditions. Healthy teeth with capillary flow would possibly dissipate heat more quickly than the extracted teeth used in our tests by transporting the heated fluids out of the pulp chamber and replacing them with cooler, 37 °C fluids from neighboring tissues. The thermal interaction between laser irradiation and tissue is outlined in greater detail by Katzir.[37] Suffice it to say, it can be speculated that actual temperature rises produced by 355 nm irradiation of vital teeth would be significantly less than that which was seen *in vitro*. However, the design of this study did not allow for testing *in vivo*.

As both internal and external damage has been demonstrated to be negligible, the last issue to solve is that of clinical practicality. Being able to use a fiber optic hand-piece to deliver the laser pulses would help to make composite ablation more clinically applicable. Collimating and focusing the laser beam so that the beam's focal length extends just beyond the tip of the fiber optic would allow for good operator control. The fiber optic hand-piece could be used much like a traditional dental drill, giving the operator versatility and a sense of familiarity. A fiber optic delivery system would allow the clinician to follow the curvatures and contours of the enamel surfaces so that the laser beam contacts the sample at the distance where the beam is focused, thus delivering a maximized intensity.

Visual and acoustic feedback would also give the operator sensory feedback to help give a clinical “feel” to the ablative process. In turn, the clinician could treat thicker areas of residual composite with more laser pulses and the thinner areas with less. Automated scanning devices, as were used in this study, do not allow for this control. Each section of the scan area received the same number of pulses, regardless if it was indicated or not. As a result, the time required to remove all residual composite was unduly increased because differentiating thick from thin areas of residual composite cannot be done within the programmed scan area.

It was stated above that photoacoustics could help give a clinical “feel” to the ablative process. Further investigation of the photoacoustic data revealed that the intensity baselines, collected from the samples and controls, were not equivalent. As was seen in figure 15, the composite samples’ baseline was greater than that of the enamel controls.

One explanation for the difference in the acoustic baseline intensity levels resides with the fact that the laser beam had a Gaussian distribution in intensity, as do most medical lasers.[37] The significance of this point is that intensity distribution within the beam is not equally distributed. More energy or intensity exists at the center of the beam than at its peripheries.

Since the greatest intensity is found at the center of the beam, it is easily understood why composite ablation is greatest at the center. As you move from the center, the rate and efficiency of the ablation decreases due to a reduction in intensity. Figure 24 illustrates intensity distributions of a Gaussian laser beam.[37]

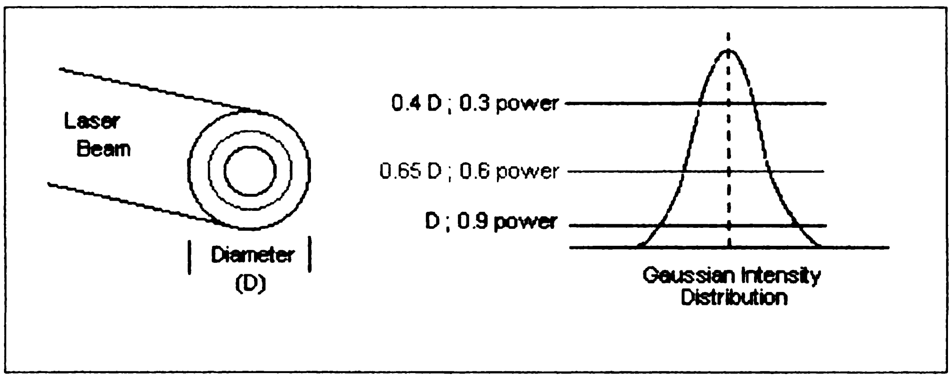

Figure 24. Intensity distribution of a Gaussian laser beam.

Taking the beam characteristics into account, the difference in baseline sound levels between the photoacoustic samples and controls was most likely the result of continued ablation at the periphery of the beam. The lower intensity levels at the periphery were still adequate to ablate composite resin, but at a greatly reduced rate. Due to this reduced rate, the peripheral regions of the beam would continue to contact residual resin long after the higher intensities at the beam's center had removed composite and uncovered the underling enamel. The minimal ablation at the periphery would continue to produce an elevated magnitude of sound waves when compared to the controls. However, this minor difference may be clinically indistinguishable as opposed to the initial rise in magnitude that is easily discernable to the human ear.

Evidence of the different ablation rates, due to the different intensities at specific areas of the beam, was also evident by the crater formation within the sample's composite layer. If the intensity distribution was uniform throughout the beam, one would expect the shape of the voided composite to resemble a cylinder. The beam's Gaussian distribution should therefore create a void that is parabolic in shape, which it did.

Understanding the intensity distribution of the Nd:YAG's Gaussian beam also helps to explain composite charring. As explained above, the reduced intensities located at the periphery of the beam were at times insufficient to thoroughly ablate the incident composite. Laser-induced degradation of composite has been hypothesized to take place as a result of: (1) thermal softening, (2) thermal ablation, which comes about when heating is fast enough to vaporize the resin, or (3) photoablation, which occurs when laser energy, being absorbed by the resin, increases molecular vibration causing chemical bonds to disassociate.[21] In the case of charring, it was hypothesized that sub-ablative intensities are sufficient to carbonize the incident composite but not disassociate its bonds or vaporize it. It was also speculated that further irradiation of charred composite will better absorb light, due to its darkened surface, and thus ablate more efficiently.

The reduced intensities explain why charring was observed at the periphery of the beam's spot. To compensate for the reduced ablative capacities at the beam's periphery, the scan distance used with the ESP3000 motion control system was less than the diameter of the beam. Beam spots were overlapped so that charred peripheries would be incident to ablative intensities during subsequent irradiation. Charring, therefore, was mainly seen at composite-enamel interfaces where no overlapping took place.

Besides darkening composite and increasing its light absorption, charring also enables clinicians to better differentiate between enamel and composite that are often very similar in color. Unlike composite, enamel does not char. Therefore, charring can give useful visual feedback for the clinician.

A major drawback with the 355 nm laser used in these experiments is that complete ablation of residual orthodontic resin was too slow to be clinically practical. For laser ablation to be practical, the time necessary to completely remove residual resin should approximate that of traditional techniques. Developing a fiber optic hand-piece will reduce treatment times by delivering optimally focused beams as well as eliminating unnecessary rescans of cleared areas. Other ways to speed up the process would be to increase the diameter of the beam, perform beam shaping, and/or increase the repetition rate.

A repetition rate of 10 Hz was used in this study, however, there are Nd:YAG lasers capable of repetition rates up to 10,000 Hz. This study has shown that 355 nm laser irradiation can selectively ablate composite resin, but refining beam diameter, repetition rates, and delivery systems in order to make it clinically practical still needs to be explored. The technology to do so currently exists, but just how expensive this would be is not known.

The Nd:YAG Minilase III system from New Wave (Sunnyvale, CA) that was used in this research sells for approximately $30,000. However, lasers continue to become more technologically advanced while decreasing in price. Development of a multipurpose dental and/or orthodontic laser would make them more cost effective. It is possible that a single Nd:YAG laser could be developed that can selectively ablate composite, etch enamel, promote caries resistance, bleach teeth, cure composites, perform gingivectomies, and cut simple cavity preparations by varying emitted wavelengths and fluences. Arguably, a laser with multiple applications would be a cost effective investment for dental practitioners.

VII. Conclusions and clinical significance.

In this study, 355 nm laser pulses were shown to selectively ablate composite resin from the enamel surfaces of orthodontically bonded teeth with no detectable damage when operating at a fluence of ~1 J/cm^2. It was also demonstrated that intemal temperature increases were keep at levels less than or equal to 2 °C, which is well within the safety limits determined by dental research.[14,17,18] However, the speed at which composite was removed in these studies was too slow to be clinically effective. Future investigations to develop a more efficient delivery system while increasing beam diameter and repetition rates will make clinical applications practical. The future for ablative removal of residual composite following orthodontic treatment may someday be realized.

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Table 1. 355 nm ablation rates for composite and human enamel used in Fig. 2.

Fluence (J/cm^2)	Composite Ablation Rate (μm/pulse)	SD of Rate Composite	Enamel Ablation Rate (μm/pulse)	SD of Rate Enamel
0.339	0	0	0	0
0.557	7.799	0.443	0	0
0.884	10.752	0.583	0	0
1.332	12.001	0.352	0.895	0.176
2.119	14.27	1.765	1.523	0.205
3.178	14.319	1.219	1.409	0.115
7.718	17.098	1.113	2.277	0.286
11.501	19.282	0.615	2.158	0.179
13.014	21.464	2.661	2.831	0.525

Table 2. 2.94μm ablation rates for composite and human enamel used in Fig. 3.

Fluence (J/cm^2)	Composite Ablation Rate (μm/pulse)	SD of Rate Composite	Enamel Ablation Rate (μm/pulse)	SD of Rate Enamel
56.6	0	0	0	0
65.6	0	0	0	0
84.7	0	0	0	0
116	33.13	0.71	34.3	0
160	34.64	4.1	26.2	1.64
179	50	0	36.2	0.45
229	62.5	0	43.2	0.55
333	66.67	0.45	45	0
442	78	0.55	50	0