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Removal of orthodontic composite with a laser

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Removal of Orthodontic Composite with a Laser

by

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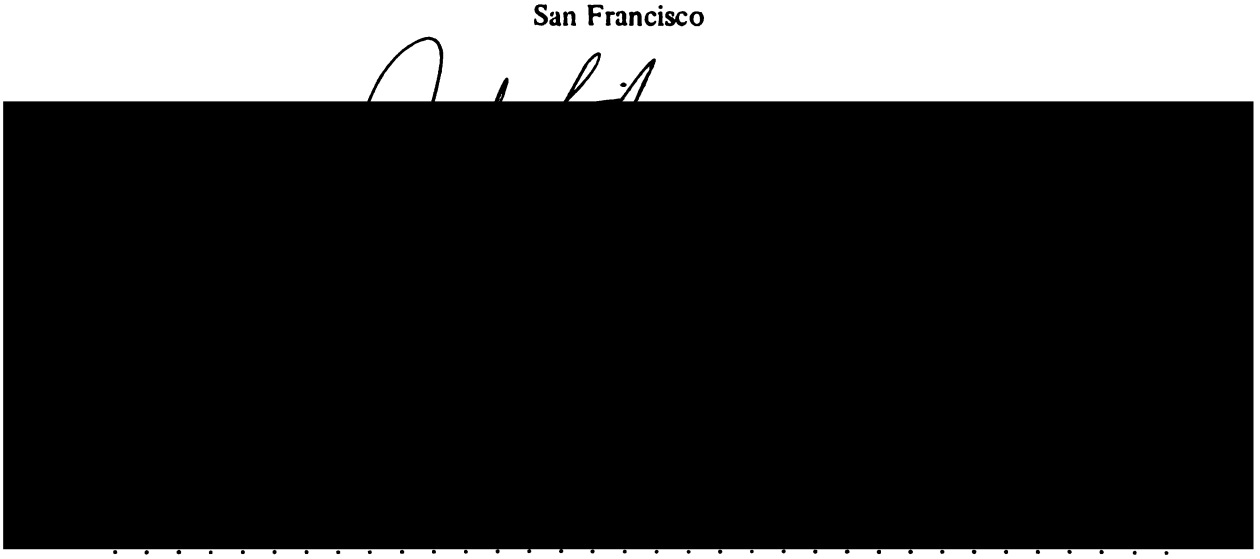

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I. Acknowledgements

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II. Abstract

Laser Ablation of Orthodontic Composite

Tim Dumore, D.M.D., B.Sc.

Traditional techniques used to remove composite from enamel after debonding orthodontic brackets involve the use of burs, stones, discs, and polishing cups, which typically result in microscopic damage to the enamel and loss of tooth structure. It is hypothesized that given the correct conditions, it should be possible to remove composite from enamel with a laser either through an ablative process or by disruption at the composite/enamel interface, without negative effects on the underlying enamel. The objective of this study was to characterize the infrared spectrum of an orthodontic adhesive and then use this information to aid in the selection of parameters for surface ablation of composite. Alternatively, the spectral information could be used to determine parameters that might allow for deposition of energy at the enamel/composite interface, which could disrupt the adhesive bond. A further aim was to characterize the ablation emission spectra of composite and enamel so that these could be used to differentiate between the ablation of the two materials and therefore prevent removal of enamel. Based on the infrared spectra that were produced for specific orthodontic composites, long pulse CO_2, TEA CO_2, Er:YAG, and Q-switched Er:YAG lasers were evaluated for their ability to ablate the composite material. It was found that the TEA CO_2 laser selectively ablated composite with minimal peripheral thermal damage. The 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 results of this project suggest that a TEA CO_2 laser operating at 10.6μm could be used in conjunction with a method of spectral analysis to selectively ablate composite and minimize inadvertent removal of enamel.

III. Introduction

A. Background

Every orthodontic bracket that is bonded to a tooth is eventually removed. Obviously, brackets are removed at the end of treatment, but debonding also occurs when bracket repositioning is required and when the patient inadvertently debonds or "breaks" a bracket between appointments. If one considers repositioning of brackets during treatment, patient induced debonding, and final debonding, it is conceivable that a particular tooth could undergo the bonding/debonding cycle a significant number of times over the entire course of orthodontic therapy. The distribution of rebonding frequency is likely skewed so that while the typical tooth would likely be debonded only once or twice, on occasion, a tooth might be debonded ten times. The net effect of this on a patient's enamel is a concern to the orthodontist and dentist, as well as the patient.[1]

According to Zachrisson, the objective of debonding is "to remove the attachment and all the adhesive resin from the tooth and to restore the surface as closely as possible to its pretreatment condition without inducing iatrogenic damage"[2]. The manner in which brackets are removed from the tooth and in which residual composite adhesive is subsequently removed is important since different techniques can produce very different effects on the enamel surface. [3] Regardless of the technique used, however, the process can be difficult for both operator and patient. To ensure that excess composite flash around the bracket

is not an esthetic liability for the patient during treatment, bracket adhesives are made so that their color blends with the underlying enamel surface. This benefit becomes a liability when it is required to remove the adhesive since it maybe difficult to visually discriminate between composite and enamel, thus hindering safe removal of the adhesive. The result is that adhesive removal can often become a time consuming procedure. From the patient's perspective, removal of the adhesive remnant can be messy, uncomfortable, and time consuming. Composite dust and debris produced from rotary instruments may cover the patient's face and mouth. These rotary instruments are sometimes difficult to use around hypertrophic gingiva without inflicting trauma to these tissues. However, the use of hand instruments to scrape composite from mobile teeth can be quite uncomfortable. Small amounts of composite left on the tooth generally are not a significant problem though one cannot expect composite to wear off in a short period of time.[4] However, the composite can become an esthetic liability and can interfere with the resolution of gingival inflammation following treatment should it be located close to the gingival tissues. Any improved technique that aids in restoring the tooth to its pretreatment appearance would undoubtedly be welcomed by patient and orthodontist alike.

A review of the various techniques that have been used to remove brackets and the adhesive remnant is warranted. Ideal bracket removal leaves an adhesive remnant on the tooth since attempts to directly remove composite from enamel may produce iatrogenic sequelae such as enamel tear outs and cracks [3]. Oliver compared various direct mechanical methods of removing the

bracket from the tooth surface and concluded that one should not attempt to debond at the enamel/composite interface due to a concern over damage to the enamel.[5] Thus, the safest debonding technique leaves an adhesive remnant on the tooth surface. However, selective removal of the residual adhesive is a difficult task and may result in damage to the surface of the tooth. As a result, it is not unusual for the clinician to either remove some of the enamel structure or to leave the tooth with some residual adhesive, which can subsequently stain. The large number of studies that address the issue of debonding and refinishing techniques points to the importance of this issue for the orthodontist.

In the late 1970's after the introduction of composite for bonding of orthodontic brackets, numerous studies were carried out to assess techniques used to remove brackets and the adhesive remnant. One of the earliest studies evaluating techniques for the removal of orthodontic adhesive was by Burapavong et al who compared a hand scaler, a low-speed green stone, or an ultrasonic scaler.[6] All three methods left appreciable amounts of adhesive on the enamel surface (20-60%) and roughened the surface somewhat, especially the green stone technique. The majority of scratches were removed with pumicing, though some deep gouges, in the 10-20μm range, could not be removed.[6] However, a more recent study found that an ultrasonic scaler could be used to remove brackets and composite in a safe manner which was faster than conventional methods.[7] The authors preface the concept of using an ultrasonic scaler by stating that "'gentler' methods for bracket removal are needed". Brown and Way later attempted to quantify *in vivo* total enamel loss

during bonding and debonding techniques and the *in vitro* enamel loss during polishing, etching, final debonding and clean-up.[8] Their study suggested that approximately 50μm of enamel is lost during the refinishing process, less if unfilled resins are used. Of that amount, one could expect 10 to 40 μm to be lost from 15 seconds of prophylaxis with zirconium silicate or 3-4μm from 30 seconds of rubber cup/pumice use. In a study assessing the removal of a low filler content bis-GMA resin, Retief and Denys compared a number of finishing techniques in the restoration of the enamel surface of 38 teeth bonded with brackets.[9] Among their findings was the fact that while debonding pliers were effective in removing brackets, they should not be used to remove composite since they produced gouges which persisted after polishing with pumice. They found similar results for hand scaling and diamond finishing burs, which also were not recommended. Twelve-bladed carbide burs were recommended for bulk removal followed by graded finishing and polishing discs. This study was observational using SEM images and did not attempt to quantify enamel loss because of the finishing process. A comparable study using blinded observers to assess surface smoothness as seen on SEM photographs found that controls were smoother than teeth finished with a tungsten carbide ultrafine bur. These were followed by twelve-fluted carbide burs, then hand scalers.[10] As in previous studies, they also found that pumicing smoothed rough surfaces and reduced regions of residual resin, but was insufficient to remove deep scratches or gouges. In a similar study, Hong and Lew found that high-speed ultra fine diamonds were unacceptable for removing composite since they left huge

surface scratches. [11] They suggested the use of a Jet high speed tungsten carbide bur and a debonding plier for gross removal of composite followed by a Komet slow speed tungsten carbide bur as the ideal clinical method for most thoroughly removing the majority of the composite from the tooth while producing the smoothest surface. Zachrisson has written extensively on the subject of the effects of debonding techniques.[2, 12, 13] Using direct and replicating stereomicroscope and SEM analysis, he first appraised the enamel surface appearance after a number of debonding techniques in a manner similar to Retief. For that study, an enamel surface index (ESI) was designed which rated the treated surface based on the number and size of scratches and gouges and the presence or absence of perikymata. As has been noted in previous studies, diamond burs were not recommended since they produced deep grooves. The use of a sandpaper disc or a green rubber wheel followed by polishing was deemed an improvement over the previous two methods though the green rubber wheel did not produce an acceptable surface. A tungsten carbide bur at low speed followed by polishing was deemed to produce the best surface finish. Given that some finished teeth displayed perikymata, Zachrisson suggested that enamel loss might be in the 5-10μm range. This last finding has been disputed, however.[14] Pus and Way found that perikymata were a poor estimator of enamel loss and suggested that even in teeth with perikymata present, as much as 29μm of enamel had been lost. They also quantified the amount of tooth structure lost during each step of the bonding and debonding procedure for 100 premolars using steel reference markers in enamel. In their study, they found

that pretreatment prophylaxis removed between 5 and 10μm of enamel, which differs somewhat from earlier studies.[8] While etching times today are in the 20 second range, they found that a 90 second phosphoric etch removed 6.9μm of enamel. Loss of enamel when removing unfilled and filled resin equaled 8 and 17μm respectively, while rubber cup polish removed a further 6μm. In a study of the effects of acid etching and bracket removal, Diedrich found that enamel loss due to tear outs during debonding alone could reach 100μm.[15] To investigate the possibility that debonding might produce cracks in teeth, Zachrisson compared the prevalence and appearance of enamel cracks in two post-orthodontic groups (one bonded, one banded) and in a matching group of untreated adolescents. Using a fiber optic light for transillumination, teeth were assessed over their entire surface for horizontal, vertical, and oblique cracks. Somewhat surprisingly, cracks were found to a high degree in all teeth though there were more cracks in the treated groups. In their conclusions, the authors stressed the need for careful debonding technique to minimize the introduction of cracks. The most recent study of finishing techniques by Campbell suggested that enamel scarring after removal of brackets cannot be avoided.[16] However, he suggested that proper finishing techniques can restore the tooth surface to its natural appearance. This SEM study strongly advised against using greenstones, finishing diamonds, and scraping instruments and suggested a routine of a No. 30 tungsten carbide bur at high speed, Enhance cups/points, water slurry of pumice, then brown and green cups. This paper also reported on the responses of 62 orthodontists who responded to a survey. The results

indicated that over 80% of respondents recognize scarring following debonding as a problem. Approximately 55% used a ligature cutter or band slitter while 32% used a scraping instrument to remove composite from the enamel, despite the fact that these methods have been shown more likely to damage enamel. Finally, only 47% of respondents felt that enamel that had been bonded looked as good as virgin enamel. This survey confirmed that debonding is an issue that still concerns orthodontists, despite years of research into this issue. Given the difficulties in removing orthodontic adhesive, any new method, which made this procedure easier for the patient and practitioner, would be welcomed by both.

Laser research in the dental field began in the early 1960's and has progressed to the point where many practical and promising applications exist for the practitioner. There have been several dental laser studies relevant to orthodontics. Treatment of the enamel surface with a CO_2 laser has been shown to have a caries inhibiting effect, which could potentially aid in preventing decalcification in the orthodontic patient.[17] Additionally, it has been shown that an Nd:YAG laser can prepare the enamel surface for bonding of orthodontic brackets, though the results have not yet been compared with conventional acid etching.[18, 19] KrF(248nm), XeCl(308nm), and Nd:YAG(1060nm) lasers have also been used to successfully debond "esthetic" brackets without risk of enamel fracture as can occur using conventional debonding techniques, by melting the composite and allowing the bracket to be easily sheared off the tooth.[20] The study showed that brackets could be removed from the tooth surface with no damage occurring on any of the teeth tested.

Laser irradiation of dental hard tissues has been studied extensively. However, as the first clinical laser systems became available for clinical trials, it became apparent that while a significant amount was known about the effects of lasers on hard tissues, nothing was know about the effects of the same lasers on restorative materials. Some of the first researchers to address the issue of the removal of dental filling materials with a laser were Hibst and Keller who assessed the ability of the Er:YAG laser (Aesculap Meditec) to ablate a number of filling materials including composite.[21] Their conclusion was that the restorative materials that were studied could be removed in a clinically sufficient manner under the tested conditions. However, an analysis of the crater wall morphology suggested greater thermal side effects within the filling material than is typically seen within enamel. Other researchers have also evaluated the effect of the Nd:YAG laser on amalgams and composites. [22, 23]It has been shown that a XeCl 308 nm excimer laser, a 2.94μm Er:YAG laser, and a 10.6μm CO_2 can be used by orthopedic surgeons to remove methylmethacrylate from bone when performing hip revision surgery.[24-26] Few other references exist in the health sciences literature reporting to ablate methacrylate polymers. Polymethylmethacrylate (PMMA) is used extensively in orthopedics as bone cement to fixate prosthetic joints. Since joint replacements are not always successful, the orthopedic surgeon is often called upon to replace the failing prosthesis and this requires the removal of bone and PMMA. In 1988, Nelson et al used an Er:YAG laser to ablate methacrylate and rabbit femur bone. [26] Their findings indicated that over the entire energy range tested, minimal thermal

damage occurred in bone or polymer. As fluence increased over a range of fluences (5.7-11.3J/mm^2), the size of the ablation crater increased, accompanied by a proportionately greater increase in thermal damage for the methacrylate than for the bone. In a similar study, individuals from the previous group used an XeCl (308nm) excimer laser to ablate bone and PMMA.[25] Using a 1mm-diameter fiber, 40 Hz, and fluences ranging from 20-80J/cm^2, they were able to show that bone could be ablated with a thermal damage zone of only 2 or 3μm, and that the corresponding value for PMMA was between 10-40μm. In a paper reminiscent of the previous group's work, Sherk et al used a super-pulsed CO_2 laser to remove PMMA. [24] While it is not possible to evaluate the exact parameters that were used in this study, it was found that using 15-35W of power, PMMA could be removed with the laser with clinically insignificant heating of the bone. Conceivably, in a similar manner, one might suppose suitable that laser parameters could be found for the preferential removal of orthodontic adhesive from enamel after bracket removal.

Hypothesis and Goals

The central hypothesis of this research is that given the correct conditions, it should be possible to remove composite from enamel either through an ablative process or by disruption at the composite/enamel interface, without negative effects on the underlying enamel. Given the previously mentioned difficulties that exist with the orthodontic composite removal process, the ability to use a laser to restore the tooth surface to its pretreatment condition would be a significant benefit to the orthodontic field. Recently, it has been shown that

exposing composite to specific laser conditions (Nd:YAG dual wavelength 532/1064nm, 100Hz, 3sec) can degrade the compressive strength of composite resin by 75 percent, thereby facilitating removal of residual composite.[27] We suggest that by elucidating the mechanism of interaction of laser radiation with enamel and composite with enamel and composite, it will be possible to select the conditions that will make it possible to ablate composite without significantly ablating enamel. The infrared spectra will first be determined for selected composite materials so that their optical properties can be compared to enamel. The identification of regions of the spectrum where the composites preferentially absorb IR laser energy will make it possible to select lasers that will operate at those wavelengths. Having determined wavelengths that are suitable for testing with composite and enamel, it will then be necessary to determine the relative ablation rates for the two materials. It is important that composite be ablated significantly more efficiently than enamel in order to minimize enamel damage. An alternative hypothesis is that if the material is transparent at a certain region of the spectrum, one could add absorbers to the unfilled bonding resin that is applied directly to the enamel surface. Then, laser energy would travel through the bulk of the material and would be absorbed at the enamel/composite interface. The result is that the adhesive remnant will catastrophically fail at its junction with the tooth or significantly weaken it so that removal is facilitated. It is known that a luminous emission plume is seen above materials ablated with laser energy. If the spectrum of the emission is analyzed, characteristic species will be seen that are unique to the material. By comparing these spectra to

elemental spectra, the species represented by the specific peaks are identified. Once this process is completed for enamel and composite, it should be possible to provide feedback to an operator identifying the material that is being ablated. In this way, undesirable removal of enamel will be significantly minimized.

B. Specific Aims

The above stated hypotheses will be tested through the following specific aims:

Specific aim #1: Test the hypothesis that orthodontic composite has a characteristic infrared transmission/absorption spectrum that can be determined using infrared spectroscopy.

Specific aim #2: Using the information derived from specific aim #1, evaluate the hypothesis that the ablation efficiency and etch rate is greater for composite than for enamel, and that these rates are a function of incident fluence.

Specific aim #3: To test the hypothesis that adhesive remnants can be removed by depositing laser energy at the enamel composite interface.

Specific aim #4: To test the hypothesis that he emission spectra of the ablation plume of enamel and composite differ such that they can be used to discriminate between the ablation of the two materials, to prevent the ablation of enamel.

IV. Materials and Methods

A. Specific aim #1: Determine the infrared spectrum of orthodontic composite.

1. Infrared analysis of Concise and Transbond XT composites.

Characteristic absorption/transmission spectra of the composites were identified for comparison with known spectra for enamel. Optimum laser parameters to be used to ablate composite can be determined by identifying wavelength regions of the spectrum where the light absorption of composite greatly exceeds that of enamel. Lasers that emit light in the identified regions of the spectrum would then be expected to differentially ablate composite versus enamel. The transmission spectra were determined using the RFX-30 FTIR spectrometer (Laser Precision Analytical, Irvine, CA).

Samples of composite were prepared from both Transbond XT and Concise orthodontic bracket adhesives (3M Unitek Corporation, Monrovia, CA). These materials were selected because they represent commonly used materials used in orthodontic practice. Light cured and chemically cured materials were selected to allow for the possibility that the optical properties of light and chemically cured materials differ. Both materials are highly filled (~75% Quartz) Bis-GMA based resins. Transbond XT is a light cured material whereas Concise is a chemically cured two-paste system. Samples measuring 5x5x1mm were produced for both materials to allow for the production of composite shavings. For the preparation of Transbond XT samples, material was placed in molds,

covered with a clear template, and cured according to the manufacturer's instructions for 20 seconds. Since the absence of a bracket allows for direct light curing of composite, 20 seconds might allow for a greater degree of cure that is experienced clinically. For the preparation of Concise samples, equal amounts of material were spatulated according to the manufacturer's instructions for 20 seconds, placed into molds, covered with a clear template, and allowed to cure for 24 hours. Separate molds were used for each material to avoid contamination. Cured samples were then used to prepare composite dust to be analyzed with the FTIR. Each material was shaved using separate acrylic burs on a straight slow speed dental handpiece to produce a fine dust, which was subsequently collected for analysis. The composites were thinned with their respective bonding agents so that a thin film could be directly applied between two salt plates. The conventional "Nujol mull" method failed to produce spectra of sufficient resolution. A sample spectrum of each composite material was acquired and stored. To verify the results obtained with the previous method, thin discs of each composite were prepared and spectra acquired in the FTIR without the use of salt plates. Samples of Transbond XT and Concise approximately 15mm in diameter and 0.5mm in thickness were prepared by placing material in a mold and curing the material. After allowing at least 24 hours for more complete curing, spectra of each material were acquired in the FTIR for subsequent analysis.

B. Specific aim #2: Evaluate the ablation efficiency and etch rates of enamel and composite as a function of incident fluence for relevant wavelengths determined in specific aim #1.

1. Ablation of Transbond XT and Concise composites with a long pulse CO_2 laser.

It is desirable to have as high an absorption coefficient as possible at the laser wavelength of interest for efficient ablation. The spectra obtained using the FTIR spectrometer indicated strong (almost complete) absorption of light in the IR region greater than λ=5μm for both composite materials as shown in Figure 2. Therefore, the absorption coefficient must be at least 1000cm^{-1} between 9-11μm, which would indicate very strong absorption. Based on this calculation, a long pulse CO_2 laser was selected for trial ablation of composite samples since it produces radiation at wavelengths between 9.3-10.6μm, which corresponds with the region of low transmission shown in the FTIR spectra. A Pulse Systems CO_2 laser (Los Alamos, NM) tuned to a wavelength of 9.3μm, a pulse duration of 100μs, and a repetition rate of 1Hz was initially used to perforate sections of composite. The only exception to this wavelength use was for the 20J/cm^2 samples, which were treated at 10.6μm. Given the weak transmission throughout this region as shown on the spectra in Figure 2, it was expected that similar results would be produced at 9.6μm and 10.6μm. At the 10.6 μm wavelength, one sample of each material was treated dry and one was treated after being rehydrated to assess any effects due to the hydration status of the sample on ablation. On each sample at 10.6μm, five separate spots were

irradiated until an energy rise was detected, indicating that the laser had perforated the material. Overall, for the Transbond XT samples, the incident fluences employed were 0.1-1.5J, 2, 5, and 20 J/cm^2. The Concise samples were ablated at 1.0, 1.5, 5.0, 8.4, and 10 J/cm^2. At each fluence, the number of pulses applied ranged from 1-50. For fluences other than 2,5, and 10J/cm^2, thin samples of material were used. For 2,5, and 10J/cm^2 fluences, adhesive remnants on extracted third molars were used with approximately one half of the remnant irradiated for each sample. One of these teeth was sectioned and viewed under the light microscope to assess irradiation effects. The initial attempts to ablate composite with the long pulse CO_2 laser at the lowest fluence had proved ineffective and it was possible that the energies used were below the ablation threshold of the material. Therefore, it was thought that ablation might occur more readily at much higher fluences, >10J/cm^2, which were therefore assessed.

2. Er:YAG ablation of adhesive remnants.

The FTIR spectra of Transbond XT and Concise composites identified the region of the Er:YAG laser, 2.94μm, as one of low transmission, though two large peaks of high transmission bracket this wavelength. The strong absorption of light energy at this wavelength is consistent with the strong absorption that occurs due to water. Additionally, it should be noted that ablation of composite with the Er:YAG laser has been reported.[21] With this knowledge, an attempt was made to use a clinical Er:YAG laser to remove adhesive remnant samples

(Incisive Technologies, San Carlos, CA). Extracted third molars were prepared for bonding according to the manufacturer's instructions. Selected samples were bonded using unfilled resin mixed with India Ink or 12.5μm Al_2O_3. The rationale for this was to concentrate energy that may have been transmitted through the composite at the enamel/composite interface and thereby disrupt this bond. Brackets were then bonded with Transbond XT according to the manufacturer's instructions. Brackets were debonded by squeezing the mesial and distal wings of the bracket then the laser was then used to ablate adhesive remnants under a variety of conditions, with each sample being treated for approximately one minute, which was estimated to be a clinically relevant time frame. Parameters were selected to assess the range of output available for this laser and are listed in Table 1.

Table 1. Er:YAG laser ablation of adhesive remnants with an Continuum Er:YAG laser.

Sample	Bonding material	Rep rate (pps)	Energy (mJ)	Fluence (J/cm^2)
1	Transbond XT	5	200	55
2	Transbond XT	5	200	55
3	Transbond XT	10	200	55
4	Transbond XT	1	375	104
5	Transbond XT + ink	Not treated		
6	Concise	5	251	69
7	Transbond XT	5	251	69

8	Transbond XT	Not treated		
9	Transbond XT + Al_2O_3	5	251	69
10	Transbond XT + Al_2O_3	3	350	97
11	Transbond XT	3	350	97
12	Transbond XT	3	350	97
13	Transbond XT	5	350	97
14	Concise + ink	3	350	97

3. Er:YAG thermocouple measurements.

Thermocouples were used to measure temperature rise in the pulp chamber adjacent to adhesive remnant ablation with an Er:YAG laser (Continuum, Santa Clara, CA).

SAMPLE PREPARATION. Orthodontic brackets were bonded with Transbond XT to the labial and lingual surfaces of extracted third molars according to a standardized protocol. Sample teeth were sectioned in a mesial-distal direction using a slow speed lab saw (Buehler, Lake Bluff, IL). Using a high-speed handpiece, dentin was removed to fully expose the pulp chamber and to allow removal of its contents. The pulpal wall was dried before bonding a precision fine wire thermocouple (Type K, Dia=0.005, Insulation=Teflon/Teflon, Omega Engineering, Stamford, CT) to the surface directly adjacent to the adhesive remnant. Omega 100 epoxy resin cement was used to bond the thermocouples. Teeth were stored in a moistened paper towel to keep the composite hydrated

since Er:YAG radiation is absorbed strongly by water, and clinically, the composite would also be hydrated. Just prior to testing, brackets were removed from the teeth by squeezing the mesial and distal wings of the brackets thereby leaving an adhesive remnant on the tooth surface.

THERMOCOUPLE MEASUREMENTS. Precalibrated thermocouples supplied by Omega Engineering (Stamford, CT) were used for these measurements. Recording voltages in ice water at 0oC and boiling water at 100oC with a Fluke 83 multimeter (Fluke Corporation, Everett, WA) confirmed the calibration. The thermocouples were then connected to a Tektronix 2440 oscilloscope with a thermocouple amplifier and a cold junction compensator to record the time versus temperature evolution during laser irradiation. Thermocouples work on the principle that an electrical potential exists between two differing metals and that it varies according to the temperature of the metals. This effect can manifest itself in the connections made between thermocouples and other equipment, which may be of differing metal types, thus necessitating the cold junction compensator. Temperature changes in the pulp chamber in the region adjacent to the ablation site were measured using this apparatus. The distance from the thermocouple to the adhesive surface was not measured but was estimated to be approximately three millimeters. Parameters were varied to assess thermal effects at through the range of the laser's operating ability. Refer to Table 2. Water was used to cool the majority of the samples for this experiment since clinically, water is typically used when operating this laser. Some samples were irradiated without the benefit of water to assess the potential rise in pulpal

temperature without cooling. For this study, six samples were prepared and treated. Treatment time varied between 30 to 60 seconds, which corresponds to a clinically relevant time frame.

Table 2. Er:YAG laser thermocouple measurements.

Sample	Repetition rate (Hz)	Energy (mJ)	Fluence (J/cm^2)	Water
1	10	350	97	Spray
2	10	200	56	Drops
3	10	200	56	No
4	10	100	28	Drops
5	10	200	56	Drops
6	10	200	56	Drops

4. TEA laser ablation of enamel and composite.

The TEA laser (Transverse Excited Atmospheric Pressure) is a CO_2 laser that differs from the long pulse version in that its pulse duration is much shorter, in the 1μsec range versus 100μsec. That difference might allow the TEA laser to be used effectively to remove composite by producing less peripheral thermal damage and by disruption of the composite matrix through laser generated stress waves. This is because the shorter pulse duration results in a greater power density as the energy is delivered over a much shorter period of time. This fact results in an increased time interval between pulses so that thermal energy has a greater time to dissipate between pulses. Depending on the thermal relaxation

time of the material being ablated, a shorter pulse means that heat accumulation within the material can be minimized. Therefore, the ability of the TEA laser to ablate this material at 9.6μm and 10.6μm was investigated.

The laser used for this study was an Argus Photonics TEA short pulse CO_2 laser (Jupiter, FL) that can operate at 9.6μm and 10.6μm. This laser fires at a fixed rate of one pulse per second, with a pulse duration of approximately 1μsec. Using a series of mirrors and lenses (1.5"BaF, 3"ZnSe, and 65mm ZnSe), the laser beam was down collimated onto the sample surface. The spot diameters were 386μm, 695μm, and 640μm respectively. Placing CaF_2 and Silicon attenuators of various thickness in the beam path changes the energy level of the beam, which allows the fluence to be varied. A Gentec energy detector was placed behind the focusing stage in the beam path to allow the beam energy to be detected. The energy detector was connected to a Tektronix 2440 oscilloscope from which peak energy levels were recorded. Prior to ablating a sample at a particular fluence, an energy reading was taken. A sample was then placed in the beam path using Helium Neon aiming lasers to reproducibly select a particular spot for testing. Ablation of a sample was then initiated and the number of pulses required for sample perforation was measured. Ablation was stopped when a sample was perforated by the beam as indicated by a rise in energy at the detector and the total number of pulses recorded using a computerized data acquisition system (Lab Windows, National Instruments Corporation, Austin, TX.)

PREPARATION OF SAMPLES. Thin sections of enamel and composite were prepared using a hard tissue microtome (Sci-Fab Series 1000 Deluxe, Lafyette, CO). Enamel sections were prepared by sectioning the roots from extracted third molars and mounting the crown in the microtome. The teeth had previously been sterilized by Gamma sterilization to destroy all pathogens. An attempt was made to ensure samples were approximately 150-200μm in thickness. To produce composite sections, it was first necessary to prepare a cylinder of Transbond XT composite. This was accomplished by taking a section of a drinking straw approximately two centimeters long and five millimeters in diameter, filling it with the composite, and then curing each area of the surface for 20 seconds. The cured composite was then cut to fit in the microtome and sections of the same dimensions as the enamel sections were produced. Enamel and composite samples were stored in containers with moist paper towels to ensure the samples remained hydrated.

MEASUREMENT OF CRATERS. Craters were visualized on an Olympus BX50 microscope (Olympus, Melville, NY) using Bioquant imaging software (R&M Biometrics, Incorporated-BIOQUANT, Nashville, TN). The microscope was used to focus on the top surface of each crater using the most powerful objective that would allow for complete visualization of the crater. Initially linear measurements were made using the Bioquant program at the greatest vertical and horizontal dimensions of the hole. However, it was noted that the shape of the ablation crater was often irregular and not always circular. Therefore using diameters to

assess the size of the ablation crater was somewhat arbitrary. However, the Bioquant program allows one to trace the periphery of objects. It then automatically calculates the area of the traced shape, which can be used in the formula to calculate the volume of the crater. It was thought that this method would improve the accuracy of the measurements so all subsequent measurement of craters were made in this fashion. Having been previously zeroed, the focusing knob was then used to bring the crater into focus 100μm down from the surface, which is approximately half way through the sample. The perimeter of the hole at this depth was again traced. Finally, the microscope was focused down until the exit hole of the crater was brought into focus and the perimeter traced a third time. The total depth of the crater from surface to exit hole was recorded from the focusing knob to the nearest 5μm.

ANALYSIS OF DATA. Data from the measurement of the craters and the number of pulses recorded to perforate the samples was analyzed using the data analysis program Igor Pro 3.1 (WaveMetrics, Inc., Lake Oswego, OR). The volume of a conic section can be calculated using the equation

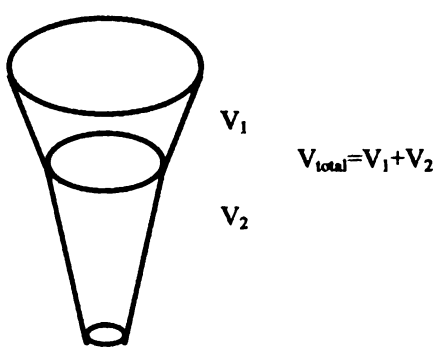


Figure 1. Calculation of crater volume.

$$V = \frac{\pi h(r_1^2 + r_1 r_2 + r_2^2)}{3}$$

where r_1 and r_2 are the radii of the top and bottom of the conic sections and h is the height. The ablation crater was divided into upper and lower sections at the

middle measurement, which was 100μm from the surface. Volumes were calculated for both sections and then added to create the total volume of the ablation crater. Incident energy was divided by area of the focal spot to calculate fluence (J/cm^2). Efficiency was then calculated by dividing total volume of the crater by the single pulse energy. Etch rate is the depth removed in μm per laser pulse and is calculated by dividing total thickness of the sample by the total number of pulses required to penetrate the sample.

COMPOSITE ABLATION. Composite and enamel samples were ablated with the TEA laser at 9.6m using the protocol described above. For this experiment, at each fluence, each Transbond XT sample was ablated eight times and each enamel section was ablated six times. Data obtained was entered into Igor Pro 3.1 and efficiency and etch rates calculated.

Given that the absorption spectra of enamel and composite differ at 9.6μm and 10.6μm, it was necessary repeat the previous experiments at 10.6μm to determine any difference in ablation characteristics for the two wavelengths. Additionally, while the FTIR spectra initially produced did not clearly indicate a difference between Transbond XT and Concise, it was considered important to confirm that the ablation characteristics of the two materials were in fact the same. Thus, for this experiment, both composite materials were irradiated. Again, all craters were measured with the Bioquant system and data analyzed using Igor Pro 3.1.

5. Assessment of method error of crater measurement technique.

The reported values for ablation efficiency and etch rate depend on the accuracy of the measurements of the ablation craters. Of primary importance in the accurate measurement of ablation craters is reliable and repeatable identification of the margins of the crater when making the measurements. A number of factors combine to make this task difficult. With the top surface of the crater in focus, it is often difficult to identify what defines the perimeter of the crater. The middle measurement taken 100μm from the surface seems somewhat easier to make. Determining when the bottom of the crater is in focus and hence determining the thickness of the sample is also difficult. This in turn affects apparent size of the exit hole since as you focus above or below the exit hole the size of the observed hole appears to increase. Thus, considering these difficulties, one might reasonably question the error associated with this measurement method. Therefore, an attempt was made to quantify the method error for measuring ablation craters.

It was necessary to perform repeated measures of systematically selected holes in order to assess method error. Holes were selected from samples ablated with the TEA laser operating at 9.6μm and using a 25mm BaF_2 lens. Three fluences, low (7.61J/cm^2), medium (18.3 J/cm^2), and high (52.1 J/cm^2), were selected to allow for the possibility that fluence might be associated with measurement error. At each fluence, three holes were randomly selected for both enamel and composite materials by drawing hole numbers placed on pieces of paper. The same operator then remeasured selected holes on three

occasions on different days. Given that the reproducibility of the measurements was expected to be reasonably high, a total of four replicates was assumed to be sufficient to give an accurate indication of the variance or reproducibility of the measurement of the craters.[28] Measurements were entered into a spreadsheet and statistically analyzed. For each measurement on each selected sample, means and standard deviations were calculated. Additionally, using measurements from the individually repeated measurement, the total volume of the crater was calculated and the mean and standard deviation for this value was also calculated. Note that since the ablation efficiency is the total volume of the crater divided by the energy used to create the hole, the variance of the volume of the crater is the variance of the efficiency because the energy used is constant for these calculations. Similarly, since the etch rate is the quotient of the depth and the number of pulses used to perforate the sample and the number of pulses used is constant for a particular hole, the variance of the depth is the variance of the etch rate. The Coefficient of Variance (CV) is calculated by dividing the standard deviation by the mean and it gives an indication of the size of variance relative to the size of the mean. The CV was calculated for each measurement and as well as for each material at each fluence, materials alone, and fluence alone.

6. Q-Switched Er:YAG laser ablation of composite and enamel.

In light of the success of the TEA CO_2 laser studies, the short pulse Er:YAG laser was investigated. Q-switching allows a laser to deliver very high

energy levels in pulses of very short duration, in the nanosecond range. The Q-switched Er:YAG laser operates at 2.94μm. The FTIR spectra produced previously in this project indicate that at this wavelength, transmission through composite is very low at approximately 5-15 percent. This wavelength also corresponds to a strong absorption peak of water. Thus, it might be expected that the Q-switched Er:YAG laser could be used to effectively ablate composite. Information obtained in this manner could then be compared to available data concerning enamel ablation.

Perforation studies similar to those performed with the TEA laser were completed. Thin samples approximately 200μm thick were prepared using a Scifab Series 1000 Deluxe hard tissue microtome as previously described, then stored in 100% humidity to keep samples hydrated. For this study a Shiva Systems Q-switched Er:YAG laser (Orlando, FL) operating at 2.94μm, two pulses per second, and 150ns pulse duration was used. Using a series of mirrors and lens, the laser beam was transmitted to a focussing lens, which focussed the beam on a sample target. A Gentec ED 200 joulemeter (Sainte-Foy, Québec) was placed behind the target and was used to measure beam energy and to detect when samples had been perforated. The joulemeter was connected to a Tektronix TDS 210 oscilloscope (Wilsonville, OR) from which energy level measurements could be made. The beam energy was varied by placing glass slides in a holder in the beam path between the focusing lens and the sample. The initial sample was treated with no attenuation of the beam and then for subsequent samples, beam energy was progressively decreased until ablation of

the material was no longer obvious. At each fluence, approximately eight craters were produced. Prior to ablation, water was not applied to the surface of the sample, though samples had been stored in humid conditions.

Measurement of ablation craters was performed in the same manner as for TEA samples using the perimeter tracing method that had been adopted for improved accuracy. Measurements of top, middle, and bottom areas of the crater, depth of the crater, number of pulses to perforation, and fluence information were imported into Igor Pro 3.1 and analyzed. Ablation efficiency and etch rate were plotted against fluence.

Initially it had been intended to compare the results of the previous study with available data on enamel ablation with the same Er:YAG laser. However, after reviewing the enamel data, it became apparent that the two studies followed different protocols and the results were therefore not easily comparable. Thus, the previous composite ablation study was repeated, this time running enamel sections parallel to the composite sections. All parameters and procedures were identical to the previous work with the exception that prior to ablating a spot on a sample, a thin film of water was placed on the surface with a saturated cotton swab. Ten fluences were assessed starting at 93.3J/cm^2 and progressively decreasing the fluence to 12.1 J/cm^2. While the laser continued to perforate the samples at a reasonably rapid rate (approximately 15μm/pulse for enamel and composite), it became extremely difficult to detect the energy rise that occurs when the beam perforates the sample, above the background noise inherent in the system. Thus, the trial was stopped at this point.

Craters were measured and analyzed as described previously for the Er:YAG treatment of composite samples alone.

7. Assessment of adhesive remnant thickness

Information regarding the thickness of the adhesive remnant remaining on the tooth surface following bracket removal could not be found in the published literature. If the typical adhesive remnant thickness was known, the volume of composite on the surface of a tooth could be calculated. Knowing the efficiency of laser ablation of composite, it would then be possible to calculate the amount of energy that would be required to remove the entire remnant. We can then decide if this quantity of energy could be applied to a tooth without expecting thermal injury to the enamel or pulp. An additional purpose for assessing remnant thickness is so that samples used in perforation studies would be of clinically relevant thickness.

SAMPLE PREPARATION. Ten extracted noncarious third molars that had been previously Gamma sterilized, were cleaned to remove soft tissue debris. Brackets were then bonded according to the manufacturer's instructions. The labial surface was polished with a slurry of fine pumice then rinsed for 10 seconds then dried for 10 seconds. Liquid acid etch (37% Phosphoric acid) was applied to the labial surface for 20 seconds then rinsed and dried for 10 seconds each. A thin coat of Transbond XT adhesive was painted onto the etched surface and cured for 10 seconds. Transbond XT orthodontic adhesive was applied to the base of a bicuspid bracket, the bracket positioned on the mesial

facial prominence of the tooth, and then the bracket placed firmly onto the tooth surface. Excess composite expressed around the edges of the bracket was carefully removed with an orthodontic scaler. The adhesive was then cured for 20 seconds with a curing light. Brackets were then removed by gently squeezing the mesial and distal wings of the bracket with a Weinguart plier, leaving an adhesive remnant on the tooth surface.

The roots were then removed from the teeth with a Buehler slow speed lab saw. Crowns were then mounted for sectioning with a Scifab Series 1000 Deluxe hard tissue microtome. An attempt was made to the position the crown so that the blade cut through the remnant perpendicular to the tooth/remnant surface through the middle of the remnant.

MEASUREMENT OF REMNANT THICKNESS. Sections were viewed using an Olympus BX50 microscope and Bioquant imaging software. Remnants were viewed at 10X magnification on the monitor and the image related along the horizontal plane, which allowed for complete visualization of the remnant. The thickness of the remnant from surface of the composite to the enamel surface, perpendicular to the enamel surface, was then measured at six predetermined points. Points were selected by arbitrarily placing a ruler on the monitor along the surface of the remnant and then taking measurements at one-inch intervals.

C. Specific aim #3: Attempt to remove adhesive remnants by depositing laser energy at the enamel composite interface.

1. Nd:YAG ablation of adhesive remnants.

A Pulse Master Nd:YAG laser (Incisive Technologies, San Carlos, CA) was used to remove orthodontic adhesive from the tooth surface by depositing laser energy at the enamel/composite interface. The transmission spectra generated previously did not extend to the region of the spectrum covered by the Nd:YAG laser. However, since there are no characteristic absorbers present in the composite that are opaque at 1μm it was assumed that the composite was transparent to light at the 1.064μm wavelength produced by Nd:YAG lasers (Dr. D. Fried, personal communication, 1998). Thus, the laser energy can be delivered to the enamel/composite interface by adding an absorbing or scattering material to the unfilled resin that is applied to the tooth surface prior to bonding the bracket. The laser energy transmitted through the bulk of the composite and focused on the absorber added to the unfilled resin to disrupt the composite/enamel bond. In a previously reported study laser enhancing dye was used in conjunction with a dual wavelength pulsed Nd:YAG laser system to ablate orthodontic adhesive[27]. In that study however, a red dye was added to the surface of the composite in order to enhance ablation of the composite itself. For the purposes of this study, India Ink and 12.5μm Al_2O_3 were added to the unfilled resin to accomplish the above stated goal. Both of these materials would be expected to absorb or strongly scatter laser light at the enamel/resin interface due to their opaque nature. A limited number of samples were irradiated in order

to establish the feasibility of this procedure. Given the limited success at removing composite in this manner, a larger study was not undertaken.

Four extracted third molars were polished with a slurry of fine pumice, etched, and dried according to the previously described protocol. Two teeth were treated as follows: 12.5μm Al_2O_3 was mixed with Transbond XT bonding resin such that the viscosity was not excessively increased to minimize any effects on the ability of the resin to bond to enamel. A thin coat was applied to the surface of the teeth. Bicuspid brackets were then bonded to facial surface of the teeth with Transbond XT composite according to the previously described protocol. One tooth was treated as follows: one drop of India ink was thoroughly mixed with two drops of Transbond XT bonding resin. A thin coat of the mixture was then applied to the facial and lingual surfaces of the tooth. Bicuspid brackets were then bonded to facial and lingual surfaces of the tooth with Transbond XT composite according to the previously described protocol. One tooth was treated as follows: one drop of India ink was thoroughly mixed with one drop of A and B bonding resin, then a thin coat of the mixture applied to the facial and lingual surfaces of the tooth. Bicuspid brackets were then bonded to facial and lingual surfaces of the tooth with Concise composite according to the previously described protocol. All teeth were then stored in tap water. Prior to laser treatment, brackets were removed from all teeth by gently squeezing the mesial and distal wings of the bracket, leaving the adhesive remnant on the surface of the tooth. The Pulse Master Nd:YAG laser was then used to treat the adhesive remnant under a variety of parameters as listed in Table 3. These

parameters were selected to assess the ability of the laser to remove composite at the extremes of its operating range.

Table 3. Nd:YAG laser ablation of adhesive remnants. Parameters are listed for the ablation of individual samples.

Sample	Material	Energy/Repetition rate	Fluence (J/cm^2)	Note
1 Labial	Transbond with ink	320mJ/pulse, 10 Hz/ 240 mJ/pulse,10 Hz	800/600	High power, low repetition rate.
1 Lingual	Transbond with ink	180 mJ/pulse, 30 Hz	450	Low power, high repetition rate.
2 Labial	Concise with ink	100 mJ/pulse, 10 Hz	250	Low power, low repetition rate
2 Lingual	Concise with ink	960 mJ/pulse, 30 Hz	2400	High power, high repetition rate
3 Labial	Transbond with Al_2O_3	180 mJ/pulse, 30Hz	450	Low power, high repetition rate.
4 Labial	Transbond with Al_2O_3	300 mJ/pulse, 100 Hz	750	High power, high repetition rate.

2. Nd:YAG thermocouple measurements.

For any laser to be safely used to remove orthodontic composite from enamel, it is imperative that the pulp not receive an excessive thermal insult from the procedure. An experiment was devised to assess the thermal effects on the pulp that occur when using an Nd:YAG laser to remove composite from the tooth surface. The protocol used was identical to that used for the similar study of the Er:YAG laser ablation of adhesive remnants. Using the Pulse Master Nd:YAG laser, adhesive was ablated for approximately one minute for each tooth to simulate an amount of time for removal that would be clinically acceptable. The first sample was initially ablated at 140mJ, 10Hz, and 1.4W but switched to

320mJ, 10 Hz, and 3.2W when it became apparent that composite removal was inefficient from a clinical perspective at the lower energy level. All subsequent samples were ablated at this higher energy level. The fourth sample was cooled with water drops every 5-10 seconds during the ablation period while ablation of the fifth sample was initiated in this manner then switched to near continuous cooling toward the end of its ablation period to assess the effect of varying the rate of coolant application.

D. Specific aim #4: Develop a method for detecting the fulfillment of the treatment objective, removal of composite.

1. Ablation spectroscopy.

The ablation of materials with laser energy produces a luminous emission plume above the samples. Spectra of that emission show peaks characteristic of the species produced as a result of the ablation process. Distinct emission lines are produced that are unique to a particular material. Species produced are characteristic of the elemental composition of the ablated material. Spectra obtained can be compared to elemental spectra and are used to identify species represented by the individual peaks. Using this rationale, it is possible to identify characteristic spectra from enamel and composite and use that information to differentiate between the different materials being ablated. Thus, the initial goal of this section of the study was to separately ablate enamel and composite samples and collect the resulting spectra.

SETUP. The same Er:YAG laser previously used to determine ablation rates and efficiencies was used to ablate samples in this section. Either the TEA CO_2 laser or the Er:YAG could have been used for this study and similar results would be expected since similar ablation species would be produced. A sample of either enamel or composite was placed at the focal spot and ablated at approximately 60J/cm^2. Lenses were used to reflect light resulting from the ablation to a Jarrell-Ash Monospec 27 monochromator/spectrograph (Franklin, MA). The system was calibrated by collecting spectra from a mercury vapor lamp which produces spectra with easily identifiable, characteristic peaks. In order to obtain the maximum spectral resolution, a data were recorded for single pulses of ablation. It would have been possible to average the spectra over a number of pulses but the resolution would be expected to decrease somewhat. Data obtained were imported into Igor Pro 3.1 to allow display of the spectra. This system made it possible to collect information from selected regions of the spectrum from which composite spectra from 360-687nm were obtained.

V. RESULTS

A. Specific aim #1: Determine the infrared spectrum of orthodontic composite.

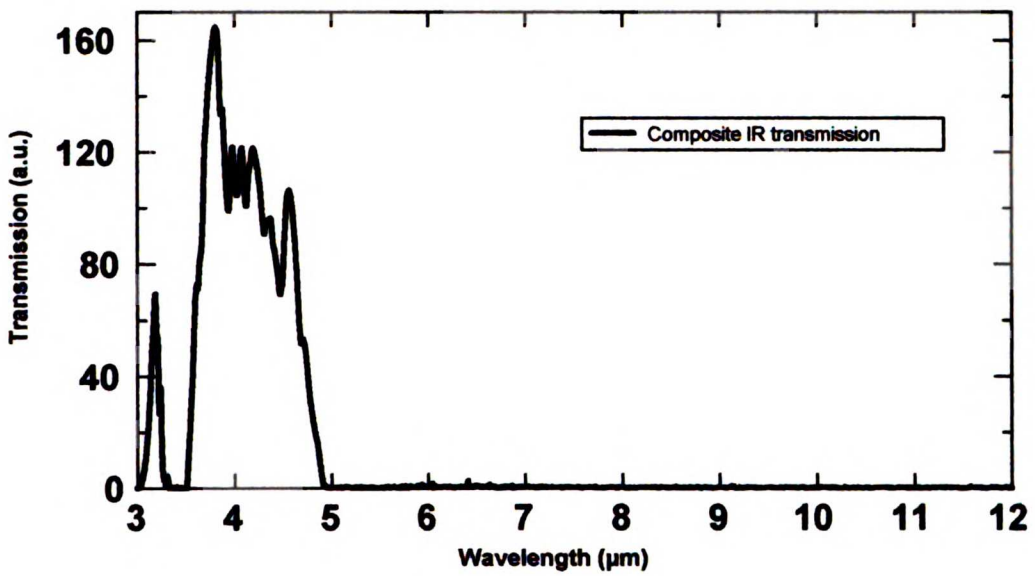
1. Infrared analysis of Concise and Transbond XT composites.

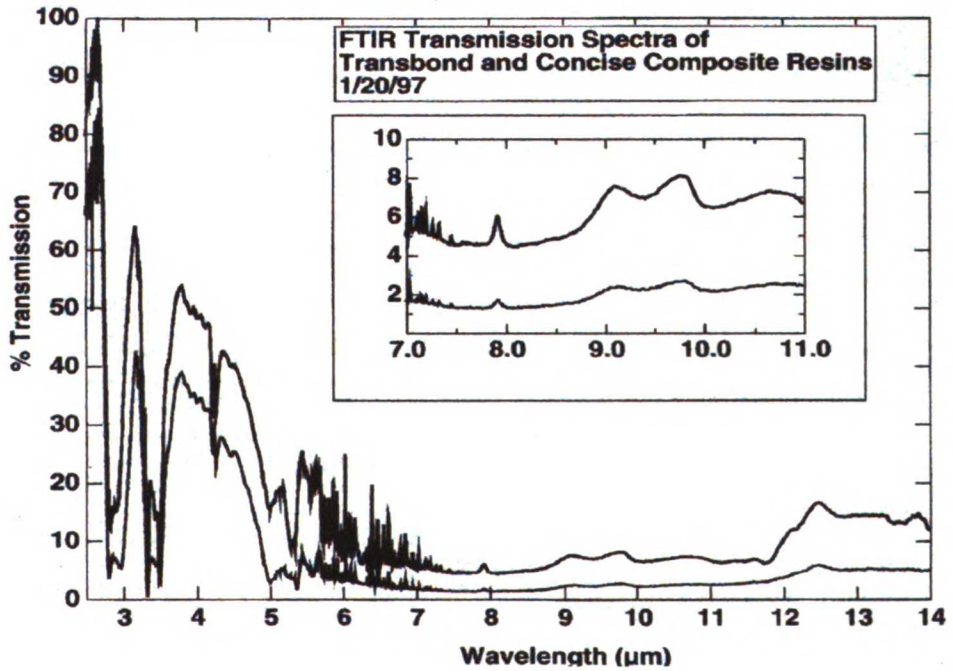
The spectra produced from the infrared analysis of the orthodontic composite revealed useful information about its light transmission properties. The two spectra shown in Figure 2 reveal similar, complementary information. First, note

that in the region beyond approximately 5μm, there is a relative minimum of light transmission. The region between 2.5 and 5μm indicates a number of regions where light is able to penetrate the composite to a significant degree. Between about 3.5-5μm, a broad zone of transmission exists preceded by a stronger peak at about 3μm. The second spectrum also displays the strongest peak of transmission at about 2.5μm.

These spectra cover the regions spanned by Er:YAG and CO_2 laser output and are therefore useful in discussing the applicability of using either of these lasers to ablate composite.

Figure 2. The first spectrum was produced from a Transbond XT composite disc; thickness of the sample limited transmission through the sample. In the second figure the upper data represent Transbond XT while the lower data represent Concise. Note that both figures show complementary information. Transmission between ~5-12um is minimal. Note absorption band near 3μm.





B. Specific aim #2: Evaluate the ablation efficiency and etch rates of enamel and composite as a function of incident fluence for relevant wavelengths determined in specific aim #1.

1. Ablation of Transbond XT and Concise composites with a long pulse CO_2 laser.

The long pulse CO_2 laser (100μs pulse) was operated at 9.3μm and 1 Hz to ablate orthodontic composite samples at relatively low fluence. The fluence ranged between 0.1-1.5J/cm^2 with the number of pulses ranging from one to fifty per spot. Observation of the sample surface indicated that at the fluences used, there was no visible change apparent on the material even on spots that received a higher number of pulses. No charring or cratering could be seen on the material surface. Therefore, at this range of fluences, the long pulse CO_2 laser is unable to effectively ablate orthodontic composite. However, when the fluence was increased some changes were noted in the material as shown in Table 4.

Table 4. Ablation of composite with a long pulse CO_2 laser. Increasing fluence within this range produces progressively greater effects.

Material	Fluence	Pulses	Notes
Transbond #1	2 J/cm^2	10/spot	Some charring, minimal removal
Concise #1	5 J/cm^2	10/spot	Smoke, large plume, charred surface (mild)
Transbond #2	5 J/cm^2	200/	Initial smoke and large plume which stalled out.
Concise #2	10 J/cm^2	100/	Greatest plume, most obvious surface changes.

A few generalizations can be made with respect to this CO_2 laser and its ability to ablate the adhesive remnant within this fluence range. Note that the laser energy striking the adhesive generates a large plume and produces a loud acoustic effect. The plume and the sound that is produced decrease with increasing number of pulses, indicating that the removal of material ceases after a finite number of pulses. The surface of the composite becomes charred to a significant degree and this charring appeared to increase with increasing energy. However, the total amount of material removed by the laser during the irradiation appeared to be minimal. Actual measurement of the remaining remnant thickness was not performed. A fourth tooth, bonded with Concise, was sectioned across the area of ablation using a slow speed lab saw. The sectioned surface was then viewed under a light microscope. It was apparent that there was minimal change to the composite material and that there was minimal difference in the thickness of the adhesive between irradiated and unirradiated sections. It appeared as though some surface charring had occurred with perhaps melting of the composite throughout. The long pulse CO_2 laser was then used to ablate composite under a narrow set of parameters: wavelength of 10.6μm, fluence of 20J/cm^2, and pulse duration of 100 μs. At this energy level, which was significantly higher than previous fluences used with this laser, laser pulses perforated the composite samples. Given that the samples were approximately one millimeter thick and that the average number pulses required to perforate this thickness was close to 40 pulses, the estimated etch rate was

nearly 25μm/pulse (Table 5). There was no apparent reduction in the ablation rate (stall out) as the beam perforated the samples as was observed for fluences in the range of 2-10J/cm^2 and the plume and acoustics produced by the pulse were in fact larger. Note that the ablated surface of the hole was black from charring, indicative of thermal effects on the composite. Given the small sample size and the single fluence used for this trial, statistical tests were not performed to compare neither the two materials used nor their status as either dry or hydrated.

Table 5. Number of pulses required to perforate 1mm thick samples of composite with a long pulse CO_2 laser at fluence equal to 20J/cm^2.

Hole	TB dry	Concise dry	Transbond hydrated	Concise hydrated
1	44	37	40	44
2	40	37	39	42
3	43	35	35	47
4	43	38	35	47
5	42	37	34	39
AVE	42.4	36.8	36.6	43.8
SD	1.5	1.1	2.7	3.4

2. Er:YAG ablation of adhesive remnants.

Adhesive remnants were irradiated with a Continuum Er:YAG laser under a range of fluences and repetition rates extending over the operating extremes of the unit (Table 1). This laser did not appear to efficiently remove composite. Samples were typically treated for approximately one minute at which point a small proportion of the composite had been removed. The strength of the

remnant was then tested in a somewhat arbitrary manner by scraping at its edge with a razor blade in a manner similar to that used to scrape off remnants in vivo. Observations for individual samples are reported.

Sample one was bonded with Transbond XT and was irradiated at 5pps and 200mJ. Minimal effect was noted, though the surface of the appeared more opaque after treatment than before. For sample two (Transbond XT, 5pps, 200mJ), irradiation of the enamel surface under these conditions altered the enamel surface to a small degree making it more opaque. When a razor blade was applied to the edge of the composite, the remnant easily scraped off the enamel surface. This might be interpreted as a weakening of the adhesive bond or it could have resulted from a poor bond. Sample three (Transbond XT, 10pps, 200mJ) showed that with an increased repetition rate, more composite was removed than under the previous conditions, though the apparent effect on the enamel was also increased. The fourth sample (Transbond XT, 1pps, 375mJ) showed that composite was removed or softened, but left tooth surface white and somewhat rough. Sample five was bonded with Transbond XT with India Ink mixed with unfilled resin and treated at 1pps and 375mJ. The remnant debonded at the enamel-resin interface, bringing into question the potential effects of the ink on the bond strength. Sample six (Concise, 5pps, 251mJ) was lightly irradiated over the entire remnant, then an attempt was made to scrape it off with a razor blade. The material flaked off more easily than might have been expected with a typical remnant but it had been noted prior to bonding that the tooth was mildly fluorotic in appearance, which might have affected the bond

quality. The seventh sample (Transbond, 5pps, 251mJ) was treated in the same fashion as sample six but this tooth was free of any fluorosis and in this case the remnant also flaked off easily. Sample eight was untreated. An attempt was made to scrape off remnant but it behaved as untreated remnants typically do and did not come off without a large amount of force. The ninth sample included Al_2O_3 mixed into unfilled resin prior to bonding with Transbond XT. It was then treated at 251mJ and 5pps. Treated minimally, the remnant scraped off easily. No observations were made for sample number ten as the remnant debonded when the bracket was removed (Transbond XT with Al_2O_3 mixed into unfilled resin, 3pps, 350mJ). Sample 11 (Transbond XT, 3pps, 350mJ) partially debonded with some composite remaining on the bracket so the sample was not treated. The treated remnant of sample 12 (Transbond XT, 3pps, 350mJ) scraped off easily. For sample 13, (Transbond XT, 5pps, 350mJ) the remnant scraped off easily but a slight opaqueness was noted on any enamel that was treated. Sample 14 was bonded with Concise with ink combined in unfilled resin and was treated at 3pps and 350mJ and no observation made as the composite was removed when the bracket was debonded.

3. Er:YAG thermocouple measurements

Six samples were irradiated with a Continuum Er:YAG laser and thermocouple measurements were recorded for five of the samples. The laser fiber was swept across the surface of the remnant and an attempt was made to

evenly cover the entire surface. Technical difficulties prevented the recording of the readings for the first sample.

The following observation were made for sample two (10pps, 200mJ). During the irradiation of this sample, the surface of the adhesive was cooled with water from a squirt bottle containing water that had been maintained at room temperature. The remnant was treated for approximately one minute during which time it was noted that the temperature rose approximately 5°C. It was also noted that the enamel was etched by the laser as well as the composite. The third sample was treated with 10pps, 200mJ and no water during ablation. It was noted that this sample exhibited the largest temperature rise of any of the samples as the temperature rose from an initial reading of 25°C to 40 °C. From a clinical perspective, it was noted that the composite scraped off easily and crumbled. However, the irradiation of the enamel appeared to soften the tooth surface. Sample four (10pps, 100mJ, with water-cooling) was subjected to a pre-rinse of 20 seconds prior to irradiation to observe the effects of cooling on the pulpal readings. In this case the temperature reading dropped approximately 5°C (22.5→17°C) before the treatment was initiated. The sample was treated for 30 seconds during which time the temperature only rose two degrees. While the amount of composite removed was minimal, the composite was easily scraped off with a razor blade. Sample five (10pps, 200mJ, water) was treated for approximately 45 seconds. During this time, the temperature recorded by the thermocouple rose from 20°C to 28°C. Significantly, the remnant was scraped off in a single piece when force was applied at its edge with a razor blade. The

final sample partially debonded during the debonding process. The remaining remnant was irradiated for 45 seconds (10pps, 200mJ, water). The composite debonded very easily when subjected to force at its edge though the bond may have been partially weakened when the initial bracket debonding force was applied.

Confirming the results of the earlier trial with the clinical Er:YAG laser, the results of this trial showed that the erbium laser removed adhesive but not in a clinically efficient manner. Attempts to remove the treated remnants with force showed that it could be removed in an easy fashion, suggesting that the enamel/composite bond had been weakened. However, this assessment is highly subjective, lacks proper control teeth, and is therefore speculative. A standardized protocol might be able to elucidate what effect the laser has on the bond strength of the adhesive remnant.

4. TEA laser ablation of enamel and composite.

Ablation of composite and enamel was carried out using the TEA laser at 9.6μm. A range of fluences was assessed starting at the highest achievable fluence and progressively decreasing the fluence with attenuators until it became difficult to distinguish the energy rise after perforation from the background noise seen on the oscilloscope. The results are shown in Figures 3-4.

Figure 2. TEA laser ablation of enamel at 9.6μm wavelength

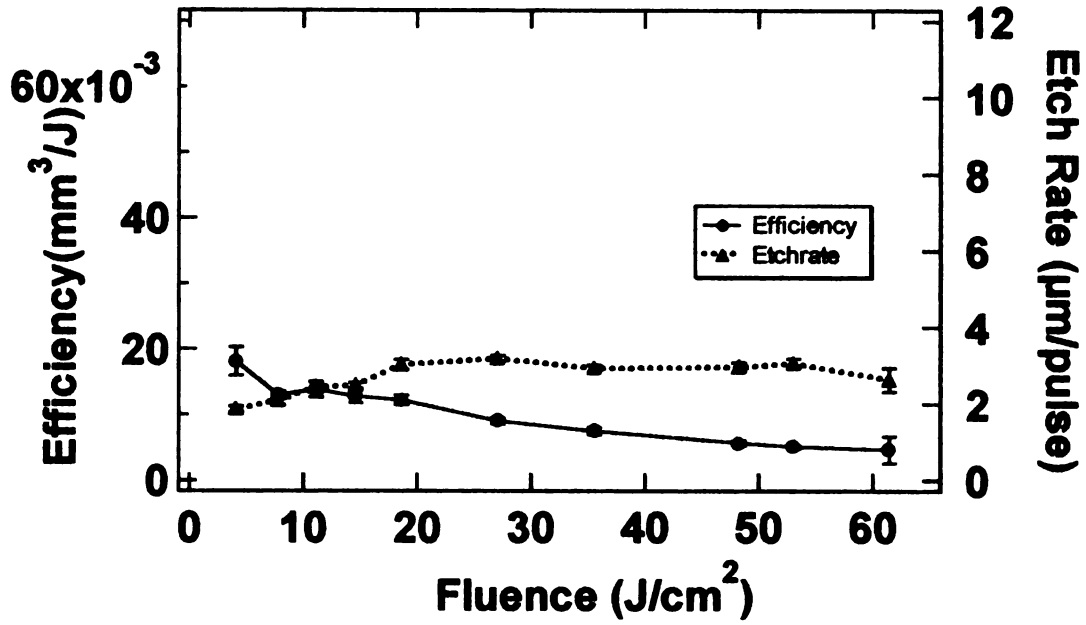
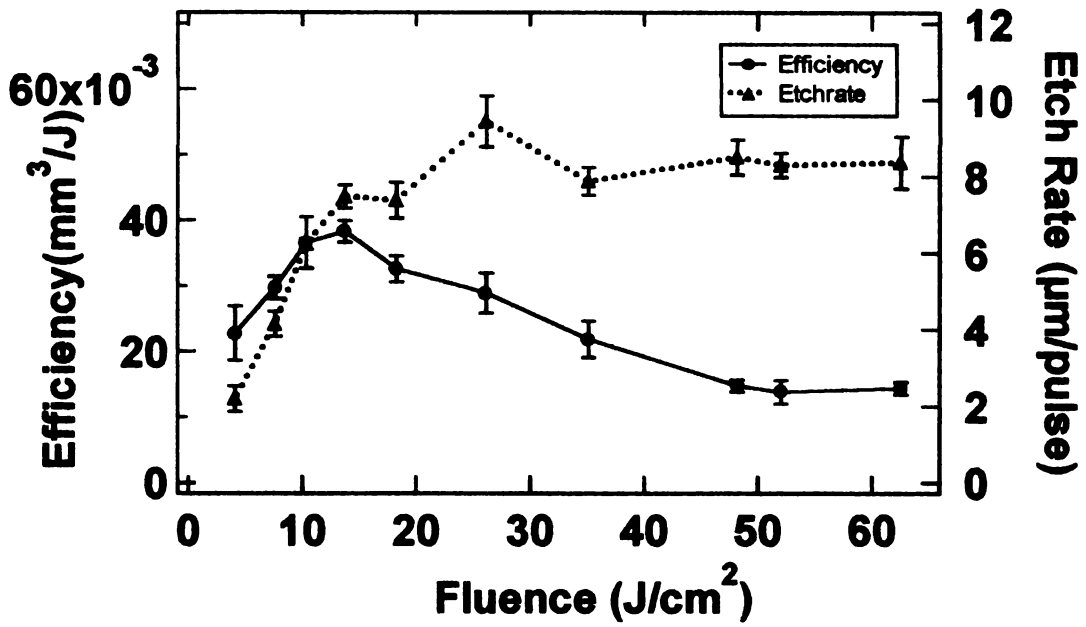


Figure 3. TEA laser ablation of composite at 9.6μm wavelength.



The graphs have been presented with identical scaling to make comparisons of the data easier. At the lowest fluence, the ablation efficiency and etch rate of the two materials appears to be comparable. As fluence increases the efficiency of enamel ablation slowly decreases while the etch rate for enamel rises slightly then reaches a plateau at approximately 3μm/pulse. Composite ablation efficiency is somewhat different from enamel in that there is an increase in efficiency up to about 15J/cm^2 after which it decreases in a manner similar to that seen for enamel. Similar to enamel, the etch rate for composite increases then plateaus; however, the composite plateaus at a much higher rate than enamel. For reference, relative efficiency and etch rate for composite and enamel have been calculated and are presented in the Appendix, Table 1. Note that the ratio of composite to enamel ablation efficiency and etch rate reaches its maximum of just over 3:1 at approximately 13J/cm^2 and persists at that level through to the highest fluences. These values are intended to aid in the comparison of the respective figures and do not imply statistical significance. The difference between the ablation rates of enamel and Transbond XT at the highest fluence (61.5 J/cm^2 for enamel and 62.6J/cm^2 for Transbond XT) was analyzed. This fluence was selected because it is at this point that the ratio between the ablation rates is greatest and where composite ablation would occur at the greatest rate. An unpaired t-Test showed that the difference in efficiency and in etch rate between the two points was statistically significant, $p<0.0000091$ and $p<0.0000034$, respectively. The TEA laser was used similarly to ablate composite and enamel samples at 10.6μm. For this aspect of the study, two

different orthodontic adhesives were used, namely Transbond XT and Concise. Figures 5-7 depict the results achieved with the TEA laser at these parameters.

Figure 4. TEA 10.6μm wavelength ablation of enamel.

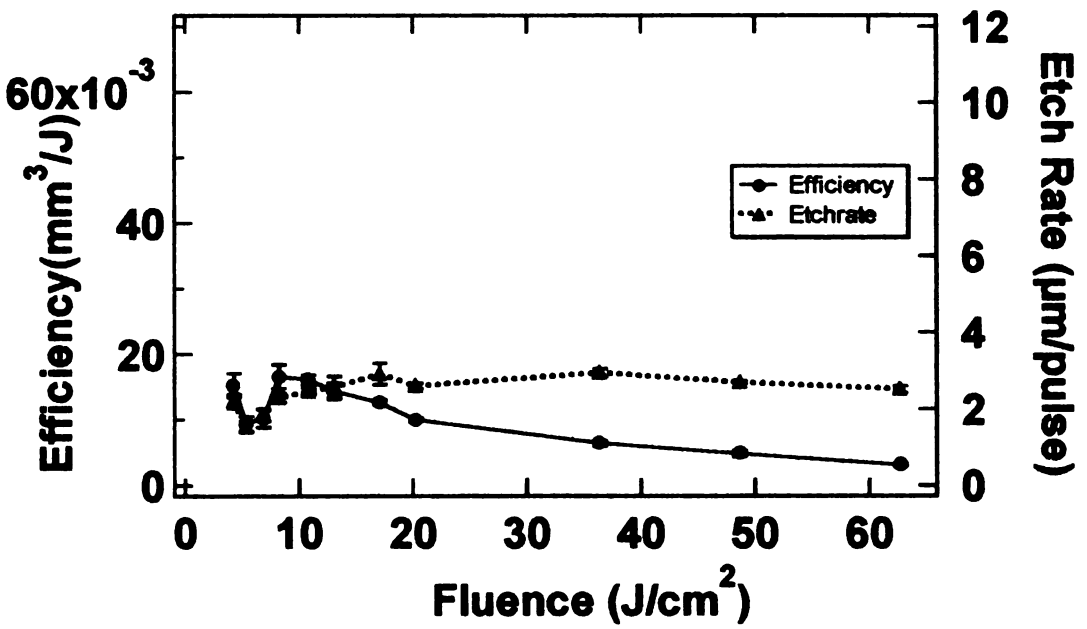


Figure 5. TEA 10.6μm wavelength ablation of Concise.

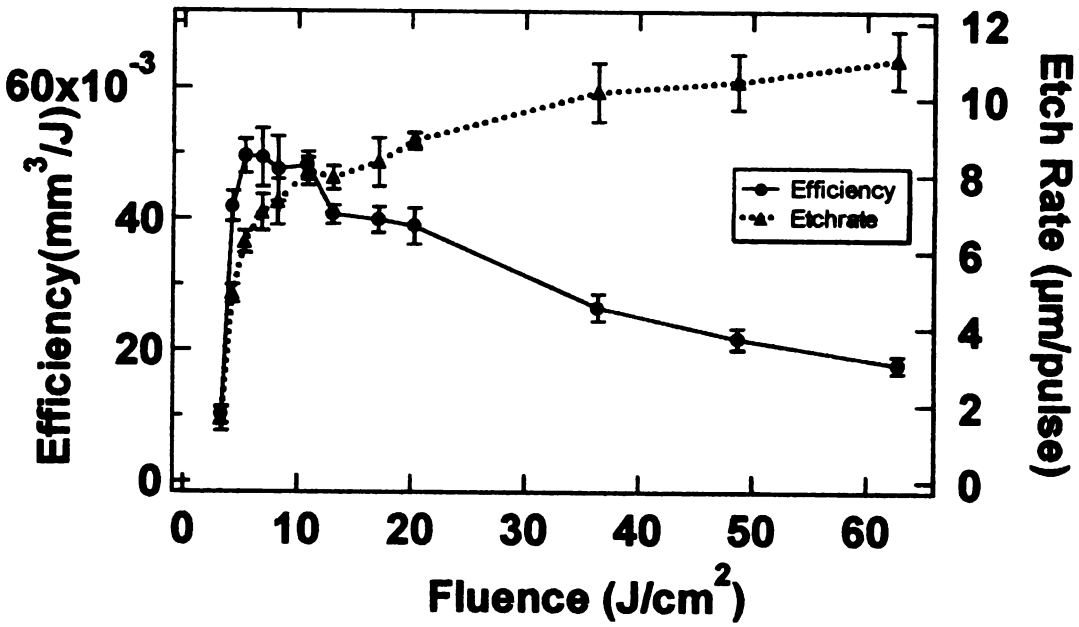
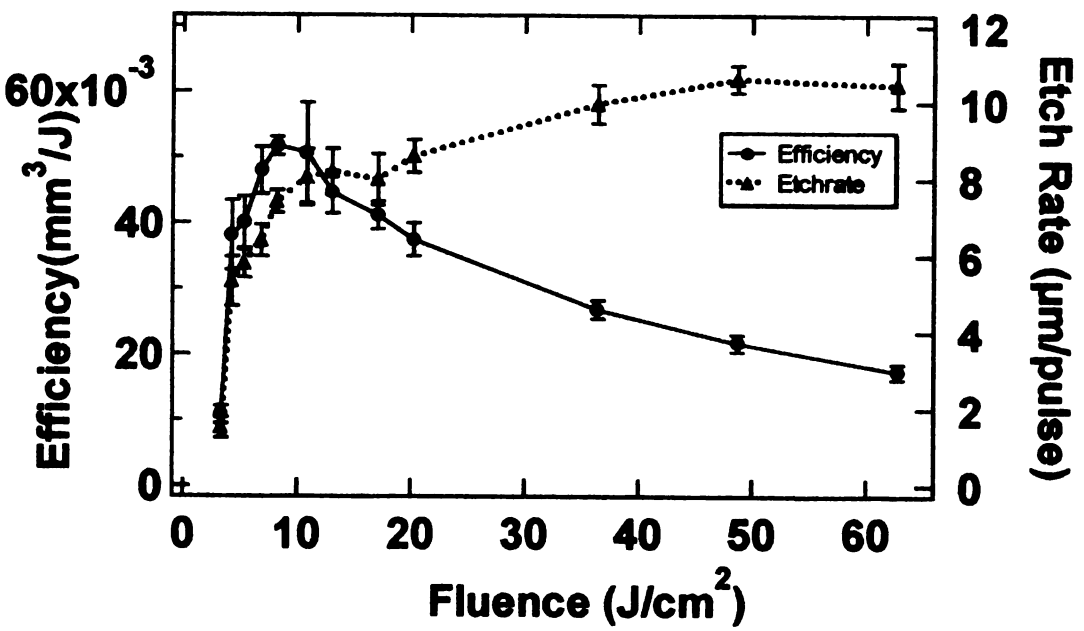


Figure 6. TEA 2 10.6μm wavelength ablation of Transbond XT.

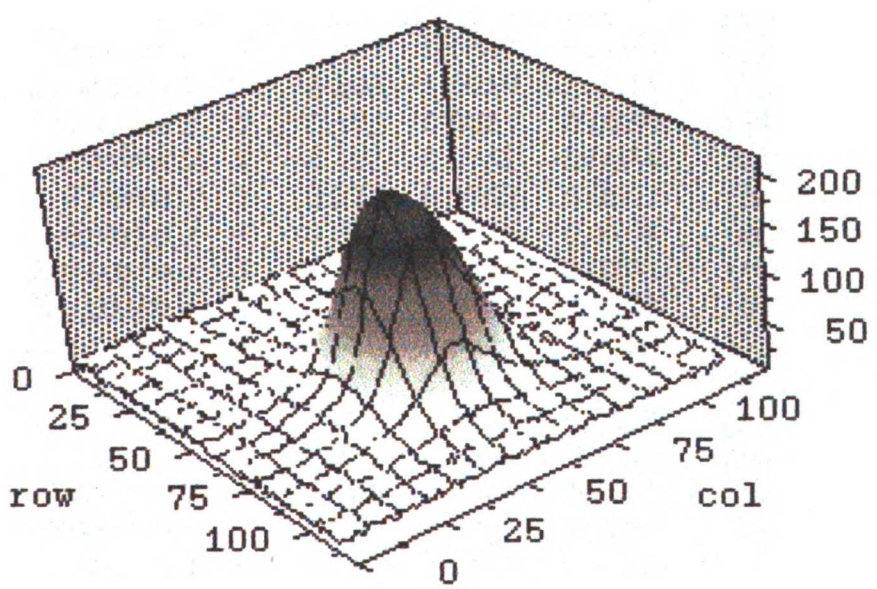


Appearing to confirm the results obtained with the TEA laser at 9.6μm, these results from the 10.6μm wavelength ablation show a large difference in ablation efficiency and etch rate when comparing composite and enamel. The curves for Concise and Transbond XT appear to have the same shape. For all materials, the efficiency increased from initially low levels, peaked, then gradually declined. This phenomenon is due to the initiation of a plasma above the sample that shields the surface from the laser pulse reducing the ablation rate and efficiency. In a similar manner to the 9.6μm wavelength trials, the etch rate increased from initially low levels then appeared to reach a plateau. A comparison of Transbond XT and Concise showed that their ablation rates were almost identical with the ablation ratio of both materials very nearly 1:1. The composites were ablated approximately 3-5.5 times more efficiently than enamel with the greatest differential occurring at the highest fluence. Etch rates were in the range of 3-4 times greater for composite than for enamel (Appendix, Tables 2-3). As was done for the 9.6μm wavelength, the rates at the highest fluence at the 10.6μm wavelength (62.7 J/cm^2) were compared for statistical significance. The differences here were also statistically significant (efficiency $p<0.0000164$, etch rate $p<0.0000155$). By selecting similar fluences at 9.6μm and 10.6μm, some comparisons can be made between the ablation rates of enamel and composite at these two wavelengths. While fluences do not match exactly, they are close enough to allow for an acceptable approximation of the rates at the respective wavelengths. Looking in the Appendix, Tables 4-5, it can be seen that while there are some values that appear to differ from a 1:1 ratio, the numbers for

enamel ablation generally correspond to one another, especially for the etch rate ratio (Efficiency $p<0.096$, Etch rate $p<0.39$). However, it is apparent that a statistically significant difference exists between the ablation rates for composite for the 9.6μm and 10.6μm wavelengths (Efficiency $p<0.00049$, Etch rate $p<0.00019$). In this case, it appears as though composite ablates only ~60-80% as efficiently using the 9.6μm wavelength laser energy.

A beam profile was obtained by the use of a Spirocon detector and is reproduced below (Figure 7). Note the good spatial arrangement of beam energy with only a slight skewing of the energy distribution.

Figure 7. TEA CO_2 beam profile obtained with a Spirocon. Units are arbitrary units. Note the spatial distribution of beam energy is a Gaussian distribution indicating a single mode laser beam.



5. Assessment of method error of crater measurement technique.

In order to assess the method error associated with the measurement of ablation craters, the repeated measurement of randomly selected holes was carried out. Ablation craters were created with the TEA laser (9.6μm, 25mm BaF_2 lens). Three craters were randomly selected from low, medium, and high fluences for both enamel and composite. Craters were measured as discuss previously a total of four times. Values are reported in Table 6. A table listing Coefficient of Variance values is also included in Table 7.

Table 6. Values for repeated measurements of ablation craters with means and standard deviations.

Replicate 1

Sample	Hole	Top (mm^2)	Middle (mm^2)	Bottom (mm^2)	Depth (μm)	Total Vol. (mm^3)
Composite 2	2	0.223	0.0643	0.0403	160	0.0167
Composite 2	7	0.209	0.0610	0.0315	155	0.0153
Composite 2	8	0.181	0.0531	0.0366	140	0.0128
Enamel 2	2	0.197	0.0757	0.0374	180	0.0176
Enamel 2	5	0.231	0.0769	0.0317	180	0.0189
Enamel 2	4	0.226	0.0775	0.0374	180	0.0190
Composite 5	8	0.194	0.0675	0.0361	115	0.0133
Composite 5	3	0.190	0.0478	0.0288	130	0.0122
Composite 5	4	0.200	0.0647	0.0385	115	0.0142
Enamel 5	1	0.167	0.0852	0.0245	205	0.0139
Enamel 5	2	0.177	0.0852	0.0257	205	0.0144
Enamel 5	3	0.197	0.0830	0.0164	205	0.0149
Composite 8	4	0.153	0.0430	0.0179	175	0.0101
Composite 8	7	0.155	0.0485	0.0215	170	0.0107
Composite 8	8	0.147	0.0569	0.0183	180	0.0109
Enamel 8	5	0.126	0.0469	0.0167	190	0.00923
Enamel 8	4	0.137	0.0476	0.0170	235	0.00977
Enamel 8	6	0.134	0.0462	0.0227	180	0.00965

Replicate 2

Sample	Hole	Top (mm^2)	Middle (mm^2)	Bottom (mm^2)	Depth (μm)	Total Vol. (mm^3)
Composite 2	2	0.258	0.0588	0.0387	135	0.0163
Composite 2	7	0.242	0.0654	0.0288	150	0.0167
Composite 2	8	0.245	0.0642	0.0349	145	0.0167
Enamel 2	2	0.217	0.0801	0.0335	170	0.0181
Enamel 2	5	0.246	0.0841	0.0298	170	0.0196
Enamel 2	4	0.275	0.0967	0.0352	185	0.0232
Composite 5	8	0.252	0.0740	0.0369	125	0.0168
Composite 5	3	0.255	0.0582	0.0278	130	0.0157
Composite 5	4	0.235	0.0675	0.0400	105	0.0159
Enamel 5	1	0.194	0.0900	0.0237	210	0.0155
Enamel 5	2	0.184	0.0883	0.0258	205	0.0149
Enamel 5	3	0.211	0.0852	0.0153	205	0.0157
Composite 8	4	0.165	0.0517	0.0190	180	0.0113
Composite 8	7	0.168	0.0479	0.0203	165	0.0112
Composite 8	8	0.155	0.0471	0.0182	165	0.0105
Enamel 8	5	0.140	0.0485	0.0166	200	0.0100
Enamel 8	4	0.149	0.0550	0.0169	230	0.0108
Enamel 8	6	0.150	0.0502	0.0206	190	0.0106

Replicate 3

Sample	Hole	Top (mm^2)	Middle (mm^2)	Bottom (mm^2)	Depth (μm)	Total Vol. (mm^3)
Composite 2	2	0.280	0.0684	0.0377	145	0.0186
Composite 2	7	0.291	0.0751	0.0293	160	0.0201
Composite 2	8	0.222	0.0593	0.0320	135	0.0148
Enamel 2	2	0.244	0.0859	0.0309	185	0.0206
Enamel 2	5	0.250	0.0831	0.0303	180	0.0203
Enamel 2	4	0.260	0.0882	0.0365	185	0.0218
Composite 5	8	0.243	0.0810	0.0379	125	0.0169
Composite 5	3	0.243	0.0564	0.0269	125	0.0149
Composite 5	4	0.219	0.0710	0.0386	105	0.0152
Enamel 5	1	0.189	0.0882	0.0253	210	0.0149
Enamel 5	2	0.204	0.0888	0.0264	210	0.0156
Enamel 5	3	0.223	0.0833	0.0150	205	0.0159
Composite 8	4	0.165	0.0511	0.0185	170	0.0111
Composite 8	7	0.177	0.0544	0.0199	180	0.0119
Composite 8	8	0.172	0.0562	0.0185	170	0.0118
Enamel 8	5	0.156	0.0532	0.0148	200	0.0108
Enamel 8	4	0.163	0.0557	0.0156	230	0.0113
Enamel 8	6	0.151	0.0532	0.0214	185	0.0107

Replicate 4

Sample	Hole	Top (mm^2)	Middle (mm^2)	Bottom (mm^2)	Depth (μm)	Total Vol. (mm^3)
Composite 2	2	0.274	0.0825	0.0361	150	0.0198
Composite 2	7	0.284	0.0963	0.0267	155	0.0214
Composite 2	8	0.274	0.0848	0.0299	140	0.0192
Enamel 2	2	0.258	0.1132	0.0354	185	0.0241
Enamel 2	5	0.265	0.1178	0.0313	185	0.0246
Enamel 2	4	0.262	0.1062	0.0386	185	0.0238
Composite 5	8	0.287	0.0978	0.0373	125	0.0200
Composite 5	3	0.291	0.0815	0.0283	125	0.0188
Composite 5	4	0.286	0.0798	0.0357	115	0.0187
Enamel 5	1	0.222	0.0952	0.0231	205	0.0168
Enamel 5	2	0.243	0.1016	0.0244	205	0.0182
Enamel 5	3	0.237	0.1030	0.0158	215	0.0179
Composite 8	4	0.174	0.0607	0.0182	180	0.0122
Composite 8	7	0.189	0.0565	0.0208	175	0.0126
Composite 8	8	0.178	0.0633	0.0197	175	0.0126
Enamel 8	5	0.174	0.0565	0.0168	225	0.0118
Enamel 8	4	0.173	0.0636	0.0165	225	0.0123
Enamel 8	6	0.170	0.0588	0.0210	190	0.0119

MEAN	Hole	Top (mm^2)	Middle (mm^2)	Bottom (mm^2)	Depth (μm)	Total Vol. (mm^3)
Composite 2	2	0.259	0.0685	0.0382	147.5	0.0178
Composite 2	7	0.257	0.0744	0.0291	155.0	0.0184
Composite 2	8	0.230	0.0654	0.0333	140.0	0.0159
Enamel 2	2	0.229	0.0887	0.0343	180.0	0.0201
Enamel 2	5	0.248	0.0905	0.0308	178.8	0.0208
Enamel 2	4	0.256	0.0921	0.0369	183.8	0.0220
Composite 5	8	0.244	0.0801	0.0371	122.5	0.0168
Composite 5	3	0.245	0.0610	0.0279	127.5	0.0154
Composite 5	4	0.235	0.0708	0.0382	110.0	0.0160
Enamel 5	1	0.193	0.0897	0.0241	207.5	0.0153
Enamel 5	2	0.202	0.0910	0.0256	206.3	0.0158
Enamel 5	3	0.217	0.0886	0.0156	207.5	0.0161
Composite 8	4	0.164	0.0516	0.0184	176.3	0.0112
Composite 8	7	0.172	0.0518	0.0206	172.5	0.0116
Composite 8	8	0.163	0.0559	0.0187	172.5	0.0114
Enamel 8	5	0.149	0.0513	0.0162	203.8	0.0105
Enamel 8	4	0.155	0.0555	0.0165	230.0	0.0111
Enamel 8	6	0.151	0.0521	0.0214	186.3	0.0107

Standard Deviation	Hole	Top (mm^2)	Middle (mm^2)	Bottom (mm^2)	Depth (μm)	Total Vol. (mm^3)
Composite 2	2	0.0254	0.01012	0.001786	10.408	0.001613
Composite 2	7	0.0381	0.01570	0.001957	4.082	0.002848
Composite 2	8	0.0395	0.01375	0.002997	4.082	0.002740
Enamel 2	2	0.0273	0.01685	0.002795	7.071	0.002949
Enamel 2	5	0.0141	0.01851	0.000881	6.292	0.002560
Enamel 2	4	0.0209	0.01225	0.001472	2.500	0.002116
Composite 5	8	0.0381	0.01306	0.000771	5.000	0.002748
Composite 5	3	0.0418	0.01442	0.000816	2.887	0.002729
Composite 5	4	0.0370	0.00657	0.001827	5.774	0.001928
Enamel 5	1	0.0227	0.00422	0.000934	2.887	0.001203
Enamel 5	2	0.0297	0.00727	0.000835	2.500	0.001675
Enamel 5	3	0.0171	0.00962	0.000646	5.000	0.001249
Composite 8	4	0.0084	0.00726	0.000437	4.787	0.000841
Composite 8	7	0.0143	0.00427	0.000664	6.455	0.000809
Composite 8	8	0.0144	0.00666	0.000703	6.455	0.000905
Enamel 8	5	0.0205	0.00438	0.000971	14.930	0.001117
Enamel 8	4	0.0157	0.00654	0.000656	4.082	0.001057
Enamel 8	6	0.0149	0.00532	0.000948	4.787	0.000940

Table 7. Coefficient of Variance (Standard deviation/mean) expressed as a percentage for each measurement, for each material at a particular fluence, for each material, and for each fluence.

CV%	Hole	Top	Middle	Bottom	Thickness	Total Vol.
Composite 2	2	9.83	14.78	4.68	7.06	9.04
Composite 2	7	14.84	21.10	6.73	2.63	15.50
Composite 2	8	17.15	21.04	8.99	2.92	17.25
Enamel 2	2	11.92	18.99	8.15	3.93	14.68
Enamel 2	5	5.67	20.46	2.86	3.52	12.28
Enamel 2	4	8.15	13.29	3.99	1.36	9.64
Composite 5	8	15.64	16.31	2.08	4.08	16.40
Composite 5	3	17.09	23.66	2.92	2.26	17.68
Composite 5	4	15.75	9.29	4.78	5.25	12.08
Enamel 5	1	11.76	4.70	3.87	1.39	7.87
Enamel 5	2	14.68	7.99	3.27	1.21	10.61
Enamel 5	3	7.90	10.86	4.14	2.41	7.76
Composite 8	4	5.14	14.07	2.37	2.72	7.52
Composite 8	7	8.30	8.24	3.22	3.74	6.99
Composite 8	8	8.86	11.92	3.76	3.74	7.90
Enamel 8	5	13.79	8.54	5.99	7.33	10.68
Enamel 8	4	10.12	11.80	3.98	1.77	9.56
Enamel 8	6	9.83	10.20	4.43	2.57	8.77
Ave		11.47	13.74	4.46	3.33	11.23

CV Mat/Flu	Hole	Top	Middle	Bottom	Thickness	Total Vol.
Composite 2	all 3	13.94	18.97	6.80	4.20	13.93
Enamel 2	all 3	8.58	17.58	5.00	2.94	12.20
Composite 5	all 3	16.16	16.42	3.26	3.86	15.39
Enamel 5	all 3	11.45	7.85	3.76	1.67	8.75
Composite 8	all 3	7.43	11.41	3.12	3.40	7.47
Enamel 8	all 3	11.25	10.18	4.80	3.89	9.67

CV Mat	Hole	Top	Middle	Bottom	Thickness	Total Vol.
Composite	all	12.51	15.60	4.39	3.82	12.26
Enamel	all	10.43	11.87	4.52	2.83	10.20

CV Fluence	Hole	Top	Middle	Bottom	Thickness	Total Vol.
2	all	11.26	18.27	5.90	3.57	13.06
5	all	13.80	12.13	3.51	2.77	12.07
8	all	9.34	10.80	3.96	3.65	8.57

The greatest variation occurs in the middle measurement of the crater 100μm from the surface followed closely by the measurement of the entrance hole (Table 7). Both measures however, generally show minimal variation though measurement of some samples did display significant variability; the Coefficient of Variance values varied between 5-21% and 5-17% respectively. Similar values for the exit hole measurement and thickness measurement are even lower than the previously mentioned values (2-9% and 1-7% respectively). Measurements from individual replicates were used to calculate the volume of each replicate hole. Variation in these volumes most closely reflects the variation in the measured area of the entrance hole and perhaps the 100μm depth measurements. An apparent difference does not exist between measurement of composite versus enamel craters nor does fluence appear to be a factor though these differences were not tested statistically. A brief discussion of the assessment of the reproducibility of the crater measurement technique is warranted since the validity of our ablation studies is somewhat dependent on this technique. The initial method of measuring ablation craters involved taking vertical and horizontal diameters across the crater and then averaging the measurements to provide a mean diameter. Values for the entrance hole, the plane 100μm from the surface, and exit holes could then be used to calculate the volume of the ablation crater. However, given that the perimeter of many of the craters is somewhat irregular, the measurement technique was switched to a potentially more accurate method of tracing the circumference of the crater shape and allowing Bioquant to calculate the area (all craters were measured

using the perimeter measuring technique). Since measurement of the ablation craters involves some judgement on the part of the operator, one might question the reliability and reproducibility of the measurements. For this reason, an analysis of the reproducibility of the measurement technique was done as was described earlier. The Coefficient of Variance was calculated by dividing the standard by the mean for a particular measurement that was repeatedly measured. A standard deviation of the same magnitude as the mean is a sign of poor reproducibility. Thus, a small value is desirable for this measure of reproducibility of measurements. For this study, values are reported for the measurement of the entrance hole, 100μm depth area, exit hole, and the depth measurement (Table 6). As was shown, all measures show good reproducibility (Table 7). The greatest variation occurs for the measurement taken at 100μm, then for the entrance hole measurement. Both the exit hole and depth measurements fall within a narrow range. When the total volume measurement was calculated based on the repeated measure sessions, the CV is approximately 11%, which most closely mirrors the values seen for the top measurement. Thus, while there was initially some concern that the measurement technique was not reliable, the reproducibility study showed that the craters could be measured with good precision. For future studies, assessment of the reproducibility of the entrance hole measurements would provide a reasonable indicator of the total volume measurement error and therefore an indicator of the uncertainty associated with the reported efficiency values. There are a number of sources for the error that are present in these

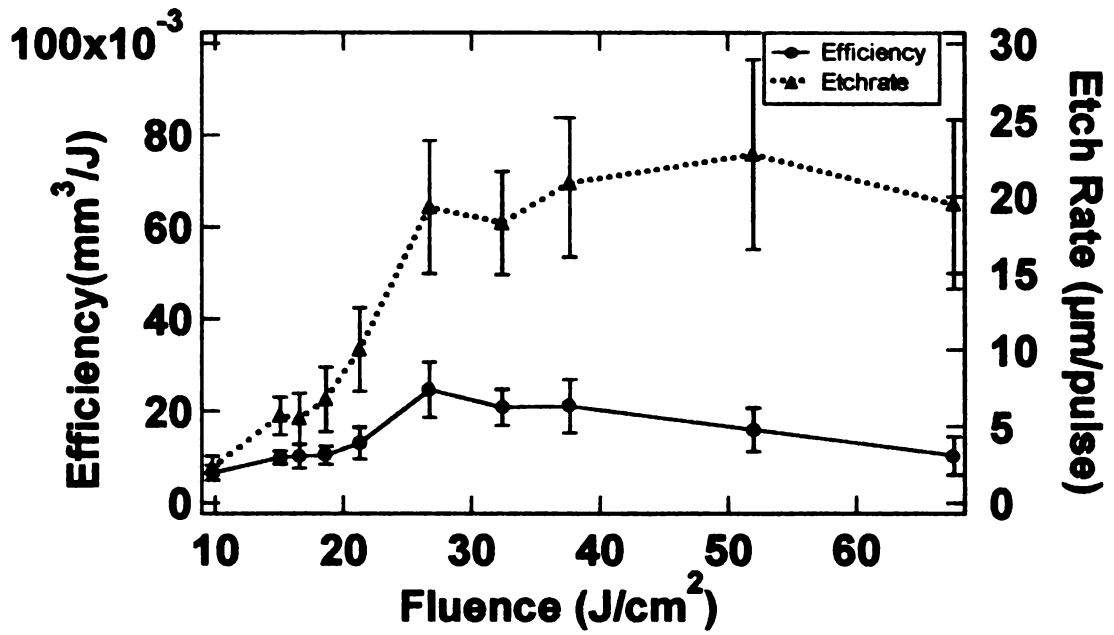
measurements. The circumference of the crater at the three levels that are measured is often irregular. Due to the presence of quartz filler particles jutting out of the resin matrix, or irregular ablation of enamel, defining the margins of the circle can be somewhat arbitrary. Given that fact, some error undoubtedly results in the act of tracing itself. Important in the measurement process is bringing the surface of the sample into focus. Errors at this stage will affect what is in focus and therefore measured as the circumference of the entrance hole. It will also affect the measured thickness of the sample. Regarding the measurement of the exit hole, it should be noted that the edges of hole are not always in the same plane. Thus, it is occasionally difficult to confidently establish when the exit hole is in focus and hence the depth of the crater. Note that as one move past the focus, the apparent size of the hole will appear to increase artificially making the volume of the crater increase. Being the smallest dimension of the cone, error in this measurement would not be expected to contribute as much to the total error as would the top surface measurement. Other errors, inherent in this method are not associated with measurement of the holes. For instance, a sample is deemed to have been perforated by the beam when the detector indicates a rise in energy on the oscilloscope. While the energy rise is dramatic for some samples, especially at higher fluences, it can be a very slow rise at lower fluences making it difficult to detect above the noise inherent in the system. This would lead to an error in the number of pulses recorded which would affect the etch rate and efficiency values. Given these potential sources of error, it should be reemphasized that the Coefficient of

Variance values fall into a very acceptable range. Additionally, the standard deviations shown on the efficiency/etch rate graphs generally indicate low variance. Note that this reproducibility study was done on samples treated with the TEA CO_2 laser at 10.6μm and should be expected to be relevant to all measurements of holes created with the TEA laser. However, the assessment may not be transferable to the Er:YAG measurements.

6. Q-Switched Er:YAG laser ablation of composite and enamel.

The Q-switched Er:YAG laser was used to ablate composite samples in a similar manner to that used with the TEA laser. The first trial was on composite material alone and approximately eight craters were produced on each sample at each fluence in the range used. Figure 8 shows how the ablation efficiency rises slowly up to approximately 30J/cm^2 then shows a slow decline. The etch rate also rises up to approximately 30J/cm^2, then appears to plateau between 20-25μm/pulse. Note that the standard deviations for the etch rate are large in comparison to those seen for the TEA laser. The etch rate is dependent on the measured thickness of a crater. It was noted that due to the particular shape of the crater produced with the Er:YAG laser, precisely identifying the exit hole was difficult. Thus, the measured thickness and hence, the reported etch rate appear to show more variance than was seen previously.

Figure 8. Initial Er:YAG ablation of composite. Note that the efficiency standard deviation is greater than that which was seen with the TEA CO_2 laser ablation.



No data were available that allowed direct comparison between enamel and the Er:YAG composite data shown above. Thus, the previous study was repeated with composite and enamel samples. In this trial, an effort was made to maintain a thin film of water on the surface of the samples prior to ablating; in the previous trial of composite alone, samples were stored in humidity but water was not placed on the surface prior to ablating. The graphs for composite and enamel ablation with the Er:YAG laser show some similarities (Fig. 10-11). The efficiency of enamel ablation compared to composite ablation is higher at the lowest fluence and lower at the maximum fluences tested, but are generally close to a 1:1 ratio. Additionally, the etch rate for both materials appear to follow a similar plateau. While the composite is perforated approximately 3.5 times as

rapidly as enamel at the highest fluence, it should be noted once again that the standard deviations, especially for etch rate measurements, are large. The fluences used for the first and second trials do not allow direct comparison of the experiments. However, selected fluences have been tabled to allow for some analysis of the relative rates. Note that the majority of etch rate values appear to fall within the same range so that the two trials on composite seem complimentary. Initial ablation efficiency values differ somewhat, but again, they generally mirror each other. See Appendix, Table 6 for values comparing rates. Statistical tests have not been performed on this data and the table is not intended to imply statistical significance.

Figure 9. Q-switched Er:YAG ablation of enamel.

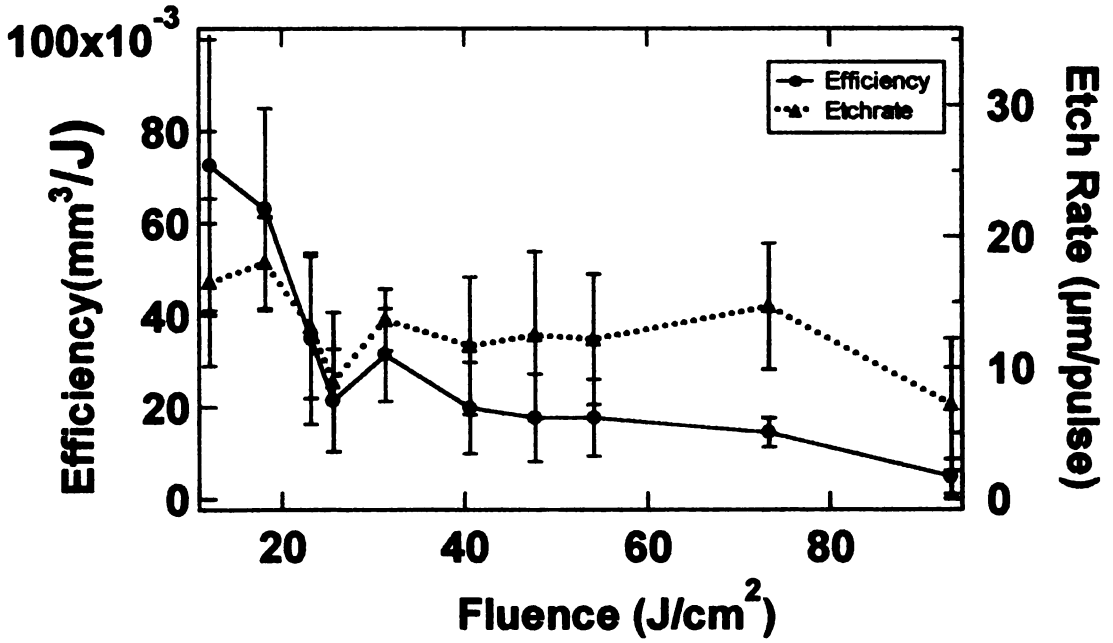
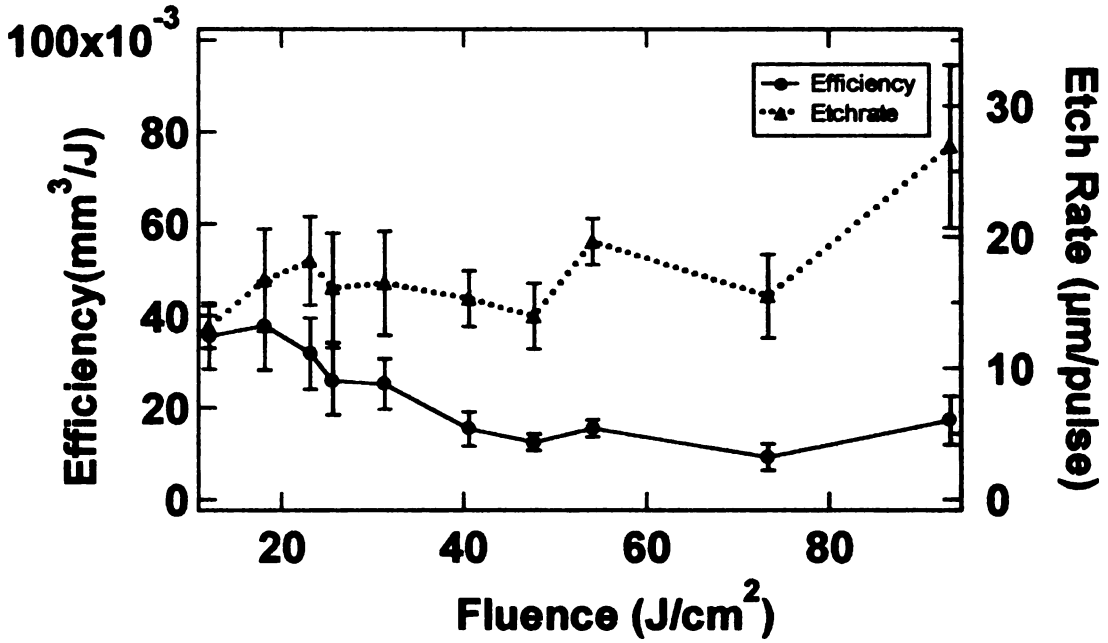


Figure 10. The second experiment with Q-switched Er:YAG ablation of Composite. Compare to the previous ablation of composite with the same laser Figure 8.



7. Assessment of adhesive remnant thickness.

In order to obtain an estimate of the thickness of the adhesive between the bracket and tooth, molars were sectioned through the adhesive remnant, perpendicular to the surface. The cut surface was then viewed with an Olympus BX50 microscope and Bioquant imaging software. Care was taken to make the cut as close to perpendicular to the surface as possible. Cutting the surface at an angle other than 90^0 will produce an apparent increase in remnant thickness. Six predetermined points were selected for each remnant and were averaged to give a mean thickness. The mean thickness was 192.5µm with a standard

deviation of 96.4μm. One remnant stood out since it was nearly three times thicker than the remaining five remnants, all of which fell within a narrow range. Thus, the mean was also calculated having discarded the extreme value. Without this remnant in the calculation, the mean was 154.5±27.6μm. Values are listed in Table 8.

Table 8. Values for adhesive remnant thickness measurements, in micrometers (μm). The first series includes all measurements. The second series of measurements excludes sample 2, which was an extreme value.

Sample	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Ave.	SD
1	95.8	106	110	144	157	85.6	116.4	28.0
2	369	362	397	407	389	373	382.8	17.6
3	136	109	116	164	184	186	149.2	33.7
4	178	164	154	134	123	157	151.7	20.1
5	191	148	164	133	181	154	161.8	21.5
6	215	195	188	205	182	175	193.3	14.8
					Total Ave	**/Total SD**	**192.5**	**96.4**

Sample	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Ave.	SD
1	95.8	106	110	144	157	85.6	116.4	28.0
3	136	109	116	164	184	186	149.2	33.7
4	178	164	154	134	123	157	151.7	20.1
5	191	148	164	133	181	154	161.8	21.5
6	215	195	188	205	182	175	193.3	14.8
					Total Ave	**/Total SD**	**154.5**	**27.6**

C. Specific aim #3: Attempt to remove adhesive remnants by depositing laser energy at the enamel composite interface.

1. Nd:YAG ablation of adhesive remnants.

In general, it was found that the Nd:YAG laser could remove the composite effectively. However, at lower power and repetition rates, the laser seemed somewhat slow in its ability to remove the composite. While faster at higher power and frequency settings, it appeared that such conditions had the potential for generating significant amounts of heat. In fact, one tooth became somewhat hot to touch. Additionally, while it was apparent that composite was being removed, the appearance of the enamel surface after irradiation was unsatisfactory with an opaque, rough surface apparent in some cases. This indicates that at parameters capable of ablating composite, the Nd:YAG laser radiation adversely affected the enamel. While the number of teeth treated was small (six), the results produced strongly suggested that this laser was incapable of selectively removing orthodontic composite from the tooth surface.

2. Nd:YAG thermocouple measurements

The Pulse Master Nd:YAG laser was used to ablate adhesive remnants while measuring the temperature response at the pulpal wall adjacent to the adhesive remnant with thermocouples. Some general trends can be discussed which are useful in describing the thermal effects of the Nd:YAG laser used in this fashion, though the small sample size prevents drawing definitive conclusions. For all teeth, the baseline temperature was approximately 22°C, or room temperature. For the first two teeth treated, it was noted that the maximum

temperature detected by the thermocouple was 41°C and 42°C respectively, a temperature rise of approximately 20°C. Note that these samples were irradiated without the benefit of water-cooling. The fourth sample had the benefit of periodic water-cooling supplied from water drops every five to ten seconds during the ablation process. Note that there was a marked fluctuation in temperature during the procedure. This sample also displayed less charring than the previous two samples. For the final sample, the water-cooling was periodic, similar to the preceding sample, then was switched to continuous cooling toward the end of the process. Consequently, the amount of temperature rise was less than was seen for previous samples though it was still likely to have harmed the pulp. However, it is worth noting that despite efforts to reduce the thermal effects of the laser on the tooth, the actual tooth surface was roughened as a result of the ablation process. It is certain that the temperature rise seen in these samples would have damaged the pulp.

D. Specific aim #4: Develop a method for detecting the fulfillment of the treatment objective, removal of composite.

I. Ablation spectroscopy

Composite and enamel samples were ablated with a Shiva Systems Q-switched Er:YAG laser operating at 2.94μm, 2Hz, with a 150ns pulse duration. The resultant luminous emission plume above the samples was reflected to a Jarrell-Ash Monospec 27 monochromator/spectrograph (Franklin, MA). The collected data was imported into Igor Pro 3.1 for analysis. The spectra that were

produced display peaks that could be useful in distinguishing enamel and composite ablation. Generally, the enamel spectra produced the greatest number of distinct emission lines. Distinct peaks were compared to a reference of elemental spectra in order to identify species represented by the individual peaks. Figures 13 through 17 show the spectra obtained at specific wavelength ranges for both composite and enamel. The wavelength of characteristic peaks that distinguish one material from the other and the responsible elemental species are presented in Table 9.

Figure 11. Combined enamel and composite spectra 360-492nm. Characteristic maxima are present for both materials between 366-377nm.

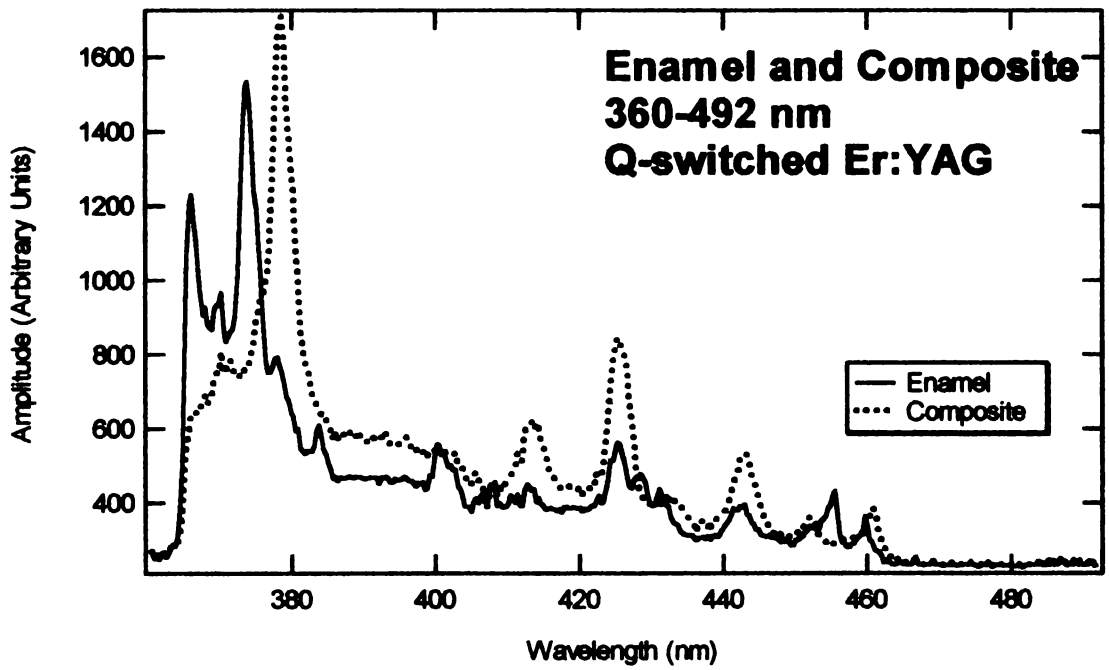


Figure 12. Combined enamel and composite spectra 369-448nm. Note the two distinct emission peaks at 397nm and 399nm.

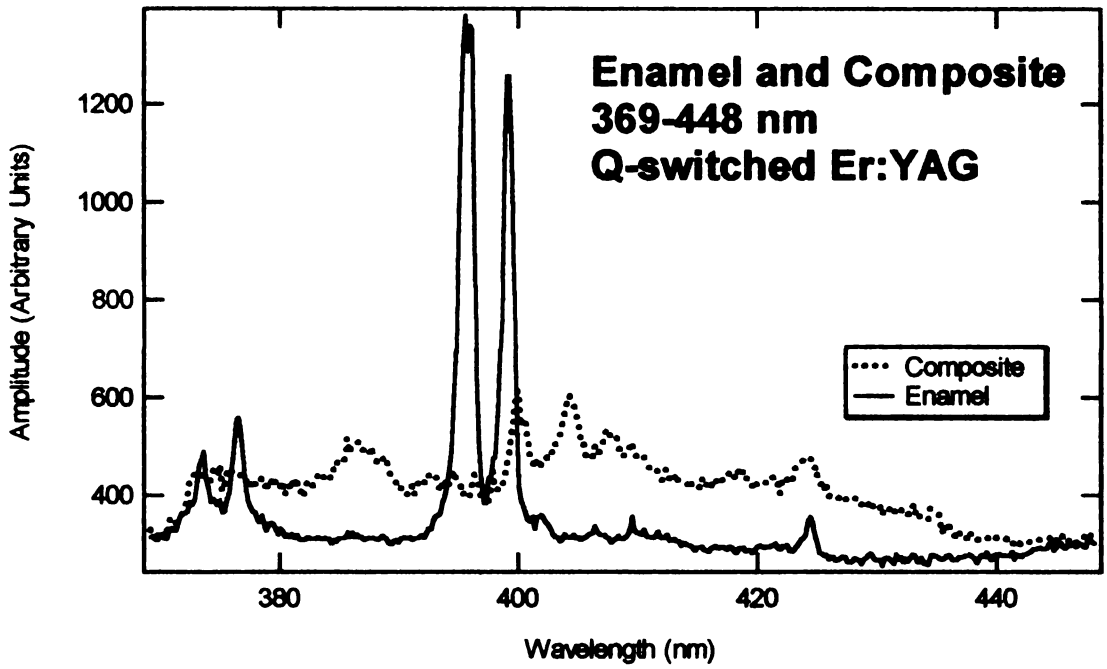


Figure 13. Combined enamel and composite spectra 506-583nm. Distinguishing enamel emission peaks are present throughout this region of the spectrum.

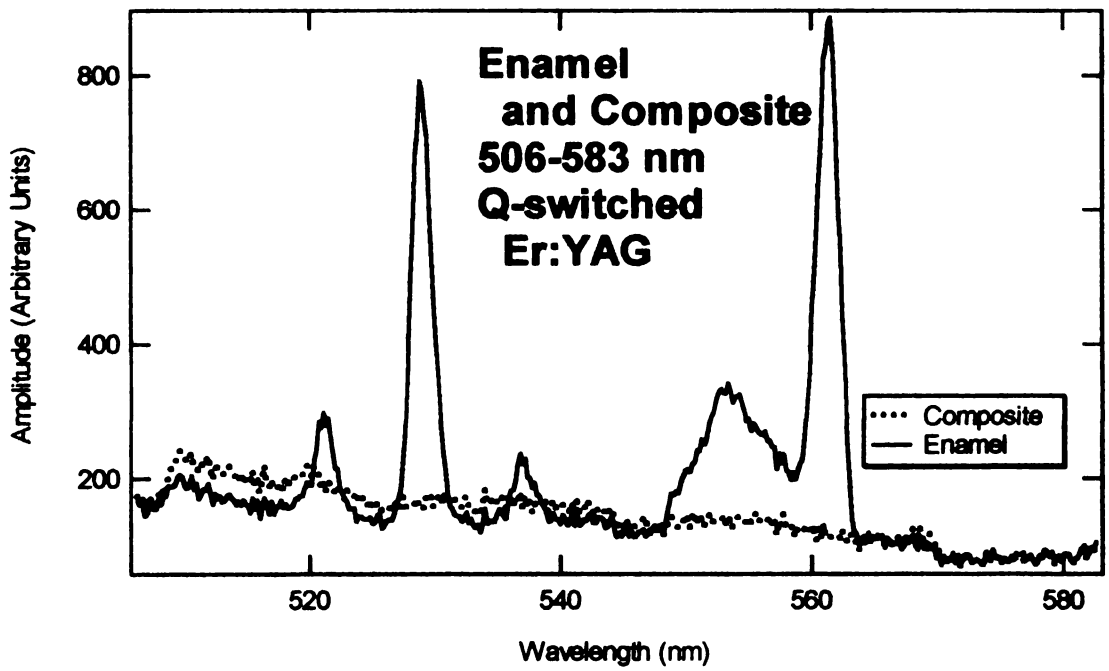


Figure 14. Combined enamel and composite spectra 562-636nm. A distinct emission peak is present at 590nm and a broad emission band is present between 600-618nm.

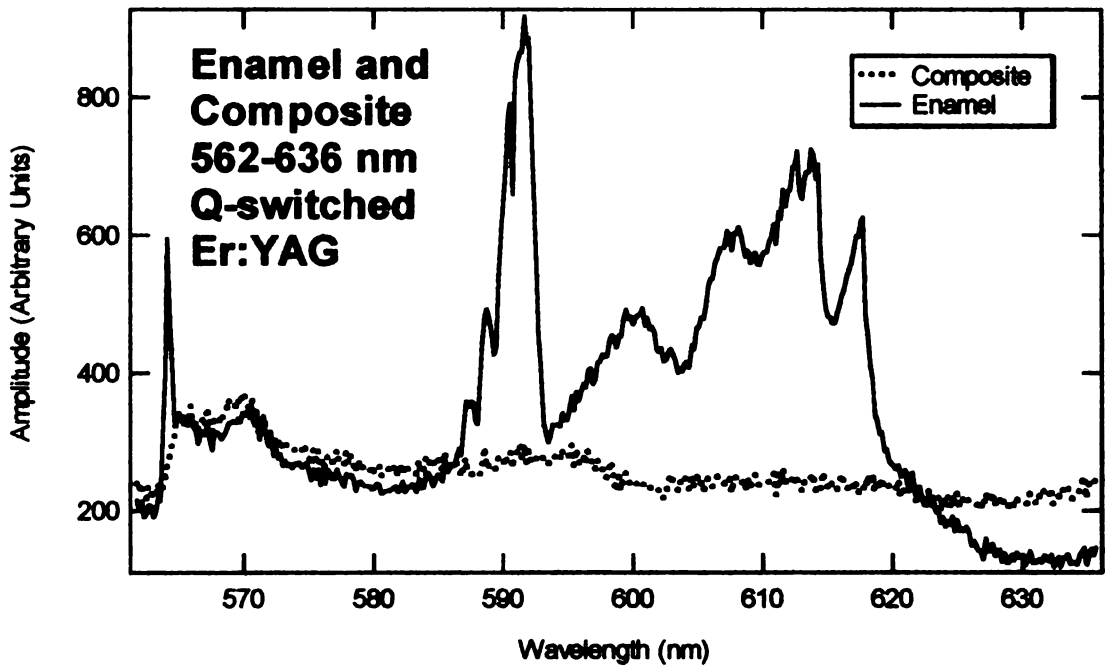


Figure 15. Combined enamel and composite spectra 610-687nm. Peaks near 620nm confirming those seen in Figure 20 and showing moderate size peak centered around 640nm.

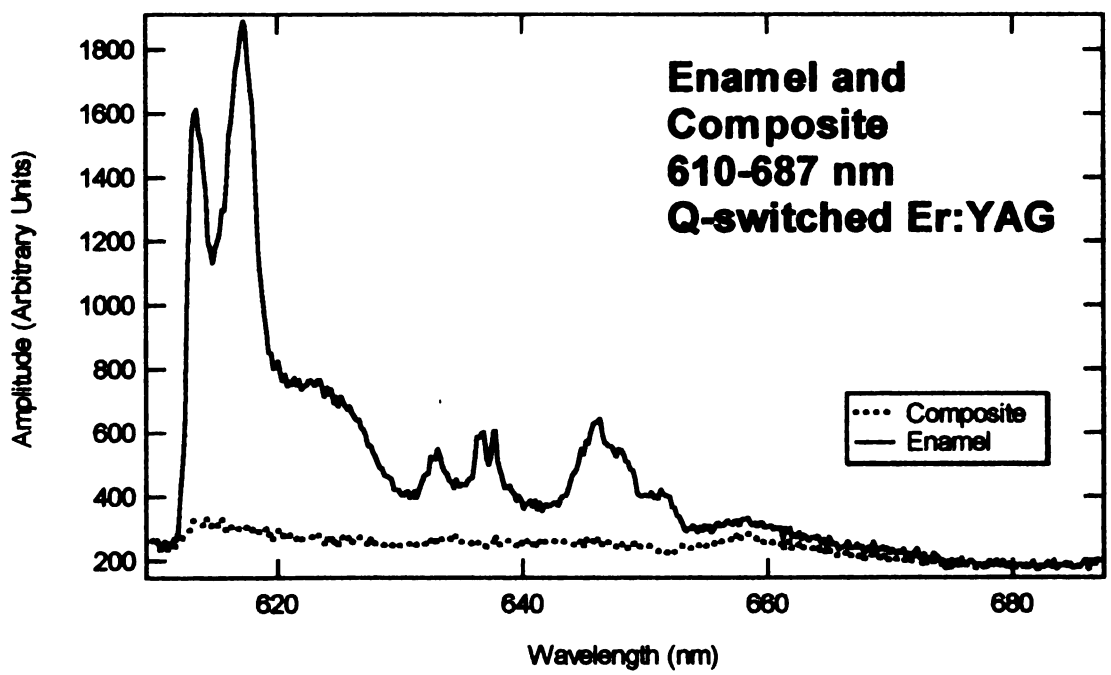


Table 9. Characteristic ablation spectra peaks with responsible chemical species indicated.

Wavelength (nm)	Material	Species
366,374,377	Enamel	Ca(I)
379	Composite	Unidentified
397,399	Enamel	Ca(II)
522	Enamel	Ca(I)
529	Enamel	Ca(I)
553,562	Enamel	Ca(I)
592	Enamel	-
600	Enamel	
613,618	Enamel	Ca(I)
696	Enamel	Ca(I)

V. Discussion.

An important first step in determining the feasibility of ablating orthodontic adhesive with a laser was the acquisition of infrared spectra of the composite material. The two FTIR spectra that were obtained were useful in identifying the light properties of the composite in the infrared region of the spectrum (Figure 2). It is known that enamel strongly absorbs IR radiation in the 9-11μm region of the spectrum.[29] Absorption of IR radiation by composite is a pre-requisite for ablation of the material. The spectra that were obtained in this study showed that

very little transmission occurs through the material beyond about 5μm. Between approximately 2-5μm, regions of strong absorption and almost complete transmission exist. Silicon dioxide, SiO_2, strongly absorbs light between 8-10μm as shown in the reference spectrum in the Appendix, Figure 1.[30]. Roughly three quarters of the composite material is quartz filler (SiO_2). Given the strong absorption of light in the region of the spectrum between 8-11μm, one must consider the CO_2 laser as a potential laser wavelength to ablate quartz-filled composite material. Since both enamel and the composite material absorb light energy here, it was therefore necessary to determine the relative ablation efficiency and etch rate for these two materials. It was found that composite ablates much more easily than enamel. Thus, one could reasonably expect that a CO_2 laser system could be used to remove orthodontic adhesive remnants. The spectra that were obtained also cover the region of the infrared spectrum that includes the Er:YAG laser (2.94μm). The spectra showed that at this wavelength, only approximately 5-15% of incident light is transmitted through the sample. This wavelength also corresponds to a strong absorption peak for water and the strong absorption in the composite may in fact be due to water. Thus, using similar rationale as that used for the CO_2 laser, the Er:YAG laser was selected as a candidate system to ablate orthodontic composite.

Initial attempts to ablate composite focused on the use of the long pulse (100μs) CO_2 laser. Minimum parameters were initially selected to aid in determining the minimum ablation threshold for the material. Later, higher fluences were assessed to determine if the long pulse CO_2 laser could ablate

composite material. The system used was a Pulse Systems CO_2 laser (Los Alamos, NM) and it was operated at 9.3μm with a pulse duration of 100μs and a repetition rate of 1 Hz. Initially very low fluences were used (0.1-1.5J/cm^2) but it was found that essentially no ablation of material occurred at this energy range. At fluences of 2-10J/cm^2, it was noted that while minimal removal of material occurred, the composite appeared to undergo some melting of the resin matrix. Light microscopic observation of a sectioned remnant confirmed this observation. The fluence was further increased to 20J/cm^2 to assess the effect of doubling the fluence, and samples of composite were ablated with the laser operating at 10.6μm for this experiment. It may have been preferable to conduct this ablation at the same 9.6μm wavelength as the previous two experiments. However, it was felt that based on the previously discussed FTIR composite spectra, any difference in ablation rates between the two wavelengths should be minimal and the goal was simply to prove the principle that the material could be ablated. At this higher fluence, the beam perforated the one millimeter samples in about 40 pulses indicating an etch rate of approximately 25μm per pulse. This suggests that the threshold for this laser system at which significant ablation of composite begins is somewhere between 10-20J/cm^2. Note, however, that at the highest fluence, the ablation craters exhibited severe charring. Moreover, at the higher fluences deleterious effects were noted when irradiating enamel.[31] These findings suggest that the long pulse CO_2 would not be suitable for ablation of composite due to the likelihood of thermal damage to the tooth.

The TEA CO_2 laser also emits radiation in the 9.6-10.6μm wavelength range of the infrared spectrum. It differs from the long pulse CO_2 laser in that its pulse duration is much shorter (range= 100ns-10μs).[32] As a result a TEA laser produces much less of a thermal effect and therefore much less carbonization and heating of the target. Thus, given that the composite material absorbs light energy produced by CO_2 lasers and that the TEA laser would be expected to have less of a thermal effect on enamel, the ability of the TEA laser to ablate orthodontic composite was assessed.

The data from the first experiment using the TEA laser at 9.6μm wavelength are presented in Figures 4 and 5, and in the Appendix (Table 1). From this data, it can be seen that using the TEA laser at the 9.6μm wavelength produces very different ablation efficiencies and etch rates for enamel and composite. The difference in rates is less at the lowest fluences but reaches a three to one ratio of composite to enamel at about 15J/cm^2 and persists at this ratio to the highest fluence. Given that some differences exit in the spectra of enamel and composite within the range of CO_2 lasers, the TEA laser was also tested at the 10.6μm wavelength. Repeating the 10.6μm wavelength experiment over a larger range of fluences confirmed the results of the previous trial (Figures 9-11). Looking at the relative ablation, it can be seen that the efficiency and etch rates for the two composite materials appear to be nearly identical (Appendix, Tables 2-3). The difference seen between the materials at the lowest fluences was not shown. When comparing the ablation efficiency of enamel and

composite materials over the range of fluences, the rate was initially 2.5-3 times greater for composite and the ratio increased to 5-6 times at the highest fluence. The difference in etch rate is not quite as dramatic but still is about 3-4 times greater for composite over enamel over the range of fluences tested. Comparisons were made between the ablation rates for enamel and composite at the two tested wavelengths (Appendix, Table 4). It was shown that there was little apparent difference between the enamel ablation efficiency and etch rate measurements between 9.6μm and 10.6μm. However, when we look at the composite ablation rates between the two wavelengths, it was shown that Transbond XT appears to ablate approximately 60 to 80% less efficient at 9.6μm than it does at 10.6μm (Appendix, Table 5). Considering all of the TEA laser ablation data that has been presented, the greatest composite etch rate occurs at 10.6μm with the highest fluences that were used ($63J/cm^2$). These parameters also correspond to the greatest difference in ablation efficiency and etch rate between enamel and composite. This difference was found to be statistically significant (other values were not tested for statistical significance). One goal of this study was to determine parameters that maximized composite ablation while minimizing enamel ablation. Thus, if one required a CO_2 laser to remove composite from the surface of a tooth, the TEA CO_2 laser operating at 10.6μm and high fluence would be the most logical choice given the data that has been presented. Pulpal effects are an important consideration. As has been previously mentioned, the TEA CO_2 laser has a shorter pulse duration, which produces a greater power density. Thus, the shorter laser pulses heat the

composite to a higher temperature with less energy than the longer CO_2 pulses, thus reducing the total energy deposited in the tooth and minimizing the risk of pulpal overheating. The low repetition rate and short pulse duration result in a greater time interval between pulses during which thermal energy deposited in the material can dissipate. Given this property and the results of the previously mentioned study, one might expect that thermal effects would be minimal. However, at the high fluence and energy density used in this study, enamel was ablated. Thus, further study is required before the TEA CO_2 laser can be considered for the removal of orthodontic composite from enamel.

Ablation of composite and enamel was also investigated using a Shiva Systems Q-switched Er:YAG laser operating at 2.94μm. Maximum etch rates for this laser system were approximately twice the maximum rate seen for the TEA laser experimentation, while efficiencies were comparable. Another significant difference between the two systems was the fact that the variation seen within each sample was much greater for the Q-switched Er:YAG laser than for the TEA CO_2 laser. This effect was greater for etch rates than for efficiency plots. It is suspected that this variation stems from the fact that the geometry of the exit hole of Er:YAG craters was more irregular and more difficult to identify than were the TEA craters. This likely led to some error in the thickness measurement, which directly affects the reported etch rate, and the efficiency measurement to a lesser extent. While the ablation rates seen with the TEA laser for enamel and composite varied by a large margin, the same cannot be said of the Er:YAG results. While the relative ablation efficiency and etch rate was approximately

3.5 times greater for composite at the highest fluence, this value appears somewhat anomalous since all other values are much closer to a one to one ratio. When comparing the ablation curves of enamel and composite, there appears to be little difference between them with the Er:YAG laser, especially given the large variation that is present. Thus, while the TEA laser appears to be a rational choice of lasers to preferentially remove composite, the same cannot be said of the Q-switched Er:YAG laser; with the erbium laser, the etch rate and efficiency for enamel and composite are of the same magnitude.

Prior to the experimentation with the TEA CO_2 and Q-switched Er:YAG lasers described above, work was completed with currently available clinical Er:YAG and Nd:YAG lasers. This work was partly inspired by the inability of the long pulse CO_2 laser to efficiently remove composite. Since it was suspected that the composite was transparent to Nd:YAG radiation due to a lack of characteristic absorbers, India ink or 12.5μm Al_2O_3 was added to the unfilled bonding resin. These additives would be expected to absorb or strongly scatter energy at the enamel/resin interface. Using this method, it was found that while composite removal did occur, it was either too slow or if energy levels were sufficient to remove material quickly, the tooth became warm or hot to touch. Given that even small increases in pulp temperature can kill the pulp, this method does not seem viable. Additionally, at higher power and repetition rate settings, enamel was roughened and opaque which would not be clinically acceptable.

Assuming that energy was concentrated at the tooth surface by the ink or aluminum oxide, it is possible that the bond strength would be decreased making

removal of the adhesive remnant greatly easier. To assess this possibility, a study of bond strength of the remnants would need to be conducted. This concept was informally tested when the Continuum Er:YAG laser was used to ablate adhesive remnants. Generally, it was found that this laser was less efficient in removing composite than was the Nd:YAG laser previously mentioned. Similarly, it was noted that treated enamel on some samples had acquired an opaque appearance and some surface roughness. A number of samples were treated minimally and the bond strength tested by placing a hand instrument at the edge of the remnant and applying force. Untreated samples were used as a reference for remnant bond strength. While this test was highly subjective, it did seem to demonstrate a clear reduction of the shear bond strength of the treated samples. A more controlled study of this effect could answer doubts more conclusively.

Any time a laser is used to treat dental hard tissue, one must be aware of potential thermal effects on the pulp. This concern became obvious for the teeth previously treated with Nd:YAG radiation that became hot to the touch. Thus, the thermocouple measurements that were completed using the clinical lasers discussed in the preceding paragraph were done to assess the thermal effects of the two laser systems. From these experiments, it was noted that the temperature rise seen with the Nd:YAG laser was approximately 20°C without water cooling and somewhat less with water cooling. By comparison, Er:YAG thermocouple measurements showed that the temperature rise seen with this laser was less than 10°C with water cooling. This amount of temperature rise is

excessive.[32] The findings of the thermocouple studies performed should be viewed cautiously since a very small number of teeth were treated with each laser system. However, the findings do give a good indication of the magnitude of the temperature rise that might be expected if either of the systems were to be used to remove adhesive remnants. The results also indicate that some manner of water cooling would be required if either of these lasers was used to ablate composite. With the Er:YAG laser at least, this should not significantly affect the ablation efficiency.[33] Similar thermocouple experiments were not completed with the TEA laser. This was because the repetition rate of 1 Hz would not easily allow for a meaningful assessment of the anticipated heat deposition that might occur with a clinical laser operating at a higher repetition rate. In an attempt to determine the typical thickness of composite between the bracket and the tooth, teeth were sectioned through the adhesive remnants and the thickness of the composite was measured at regular points along the cut surface. The mean thickness of composite on the surface of the tooth was 193 μm ±96 μm. While the thickness of most of the remnants fell within a small range, one remnant was different in that it was approximately three times thicker than the others. Thus, the measurements were not normally distributed and the standard deviation does not reflect the true variance of the sample. Clinically, one sometimes will find brackets that have an excessive amount of composite beneath the base so in a sense, the extreme value may not be unrepresentative. However, in order to obtain an estimate of a more ideal sample, the mean was also calculated having discarded the extreme value. Without this remnant in the calculation, the mean

was 155±28 μm. Note that for this experiment, bicuspid brackets were bonded to the prominence of the mesial buccal cusp. While the brackets adapted to the tooth in a manner that would have been clinically acceptable, it would be expected that the surface used would be slightly less convex than the prominence of a bicuspid. Thus, the brackets may not have adapted to the surface as well as they would have on a bicuspid, and the values reported may be slightly elevated. This information is valuable since it validated the chosen thickness of the enamel and composite samples that were used in the perforation studies, which were of the same magnitude as the samples that were used in the ablation studies. With knowledge of the mean thickness of the adhesive remnant and the area of the bracket base, it is then possible to determine the volume of composite on the tooth surface. Using the efficiency and etch rate data that were obtained, it should then be possible to estimate the amount of energy and the length of time that would be required to remove the orthodontic composite from the surface of a tooth.

It has been shown that the use of the TEA CO_2 laser operating at 10.6μm may be a viable alternative to conventional adhesive remnant removal techniques. The ability to remove composite up to six times more efficiently than enamel suggests that minimal removal of tooth structure should occur during composite ablation. However, to ensure that enamel loss is kept to an absolute minimum, the TEA laser would have to be used in conjunction with some form of spectral analyzer. The results of the ablation spectroscopy experiments showed that distinct emission lines exist that could indicate to the operator that the laser

is no longer ablating composite and had started to ablate surface enamel. A signal would be given to the operator in the form of a light or sound cue, or the laser might be inhibited from firing. One would then move the beam to a fresh area of composite. Clearly, however, this concept requires the development of a clinical system and *in vitro* testing prior to attempting to remove adhesive remnants in vivo.

Perhaps more likely, is the ability to use a system of this type to remove composite restorations in patients requiring the replacement of failing restorations. Wigdor showed that an Er:YAG laser could effectively remove a range of dental materials in the lab.[33, 34]. In the current study, the Er:YAG was shown to be unsuitable for composite removal since it appeared to remove enamel nearly as well. It would be expected that an Er:YAG laser would remove dentin more efficiently either composite or enamel, which would be a problem clinically. It is reasonable to think that the TEA CO_2 laser might make a superior choice given its preference for composite over enamel. However, if one intends to use the proposed system to remove restorations, the ablation characteristics of dentin with this system need to be investigated first.

Future studies

Some effort was made to quantify the thermal effects produced with specific Er:YAG and Nd:YAG lasers by ablating composite in conjunction with thermocouple measurements at the pulpal wall. While some useful data were obtained, lack of familiarity with this protocol and small numbers of samples for which adequate readings were obtained (5 and 3 respectively) were problems.

Thus, to be able to draw firm conclusions from this aspect of the study would necessitate repeating the experiments with larger sample sizes. If this were to be done, it would also be useful to do similar measurements while using the TEA CO_2 laser to ablate composite. Given the inability of the currently available version of this laser to fire at a rate greater than 1 Hz, thermocouple measurements might not be meaningful. However, as a TEA CO_2 laser becomes available that is capable of firing at a greater rate, thermocouple measurements should be completed for ablation of adhesive remnants.

Another aspect of this study that suggests further experimentation relates to the ablation spectroscopy work that was done. The ablation spectroscopy was completed using a Q-switched Er:YAG laser to ablate composite and enamel samples. Given that the TEA CO_2 laser proved itself to be a more likely candidate for the purpose of composite removal, it would be prudent to complete spectroscopic measurements using the TEA CO_2 laser as the radiation source to confirm that the ablation species are the same.

Another interesting finding that might warrant investigation relates to the subjective finding that irradiation of adhesive remnants with an Er:YAG radiation seemed to weaken the adhesive bond and decrease the effort required to remove the remnant by scraping. It is hypothesized that irradiation of the remnant either before or after debonding might weaken the bond of the remnant to the enamel sufficiently so that it could be easily removed with hand instruments. To complete such a study, it would be necessary to establish a standardized protocol for irradiating the adhesive and then applying a force to

remove the remnant. If this technique were successful, it might reduce the time required to remove composite from the tooth surface and at the same time decrease the risk of enamel damage.

VI. Conclusions and clinical significance.

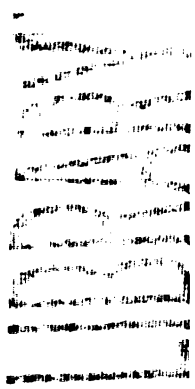
1. The infrared spectrum of the orthodontic adhesives that were tested identified regions where IR radiation is strongly absorbed. This information can be and was used to make rational choices for the selection of lasers to ablate composites of similar composition.
2. The relative efficiency and etch rates at which the TEA CO_2 and Q-switched Er:YAG lasers ablate composite and enamel is dependent on the fluence used and the wavelength that is selected. To achieve the greatest differential between composite and enamel ablation, the TEA CO_2 laser should be used at the 10.6μm wavelength and at a fluence greater than 30-40J/cm^2.
3. The emission spectra from composite and enamel ablation indicate that numerous characteristic peaks exist which can be used to distinguish ablation of the two materials. The peaks at 397, 399, 529, and 562μm appear to be particularly distinct and are especially promising in this respect. This information can be used to minimize the ablation of enamel when removing composite from the surface of a tooth. The goal of this work was to improve the method by which the orthodontic adhesive remnant is removed from the tooth, and while some progress has been made, more work is required before this concept can be recommended to orthodontists.

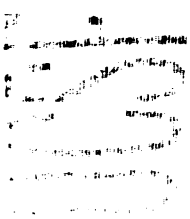
The ability to selectively ablate composite over enamel may ultimately have broader applications however. As an increasing number of composite restorations are placed in teeth and as an increasing number of dentists begin using lasers to prepare cavities, dentists will be faced with the issue of how to remove preexisting composite restorations. Information presented in this thesis may ultimately answer some of their questions.

VII. References.

1. Turpin, D.L., *The return of tooth surface luster following bracket removal [editorial; comment].* Angle Orthod, 1995. **65**(2): p. 83.
2. Zachrisson, B.U., *Bonding in Orthodontics*, in *Orthodontics: Current Principles and Techniques*, T.M. Graber and J. Robert L. Vanarsdall, Editors. 1994, Mosby: St. Louis. p. 542-626.
3. Zarrinnia, K., N.M. Eid, and M.J. Kehoe, *The effect of different debonding techniques on the enamel surface: An in vitro qualitative study.* American Journal of Orthodontics and Dentofacial Orthopedics, 1995. **108**(3): p. 284-293.
4. Brobakken, B.O. and B.U. Zachrisson, *Abrasive wear of bonding adhesives: studies during treatment and after bracket removal.* Am J Orthod, 1981. **79**(2): p. 134-47.
5. Oliver, R.G., *The effect of different methods of bracket removal on the amount of residual adhesive.* Am J Orthod Dentofacial Orthop, 1988. **93**(3): p. 196-200.
6. Burapavong, V., G.W. Marshall, D.A. Apfel, and H.T. Perry, *Enamel surface characteristics on removal of bonded orthodontic brackets.* Am J Orthod, 1978. **74**(2): p. 176-87.
7. Krell, K.V., J.M. Courey, and S.E. Bishara, *Orthodontic bracket removal using conventional and ultrasonic debonding techniques, enamel loss, and time requirements.* Am J Orthod Dentofacial Orthop, 1993. **103**(3): p. 258-66.
8. Brown, C.R. and D.C. Way, *Enamel loss during orthodontic bonding and subsequent loss during removal of filled and unfilled adhesives.* Am J Orthod, 1978. **74**(6): p. 663-71.
9. Retief, D.H. and F.R. Denys, *Finishing of enamel surfaces after debonding of orthodontic attachments.* Angle Orthod, 1979. **49**(1): p. 1-10.
10. Rouleau, B.D., Jr., G.W. Marshall, Jr., and R.O. Cooley, *Enamel surface evaluations after clinical treatment and removal of orthodontic brackets.* Am J Orthod, 1982. **81**(5): p. 423-6.
11. Hong, Y.H. and K.K. Lew, *Quantitative and qualitative assessment of enamel surface following five composite removal methods after bracket debonding.* Eur J Orthod, 1995. **17**(2): p. 121-8.
12. Zachrisson, B.U. and J. Artun, *Enamel surface appearance after various debonding techniques.* American Journal of Orthodontics, 1979. **75**: p. 121-37.
13. Zachrisson, B.U., S. Oystein, and S. Hoymyhr, *Enamel cracks in debonded, debanded, and orthodontically untreated teeth.* American Journal of Orthodontics, 1980. **77**: p. 307-19.
14. Pus, M.D. and D.C. Way, *Enamel loss due to orthodontic bonding with filled and unfilled resins using various clean-up techniques.* American Journal of Orthodotics, 1980. **77**: p. 269-83.

15. Diedrich, P., *Enamel alterations from bracket bonding and debonding. A study with the scanning electron microscope.* American Journal of Orthodontics, 1981. **79**: p. 500-22.
16. Campbell, P.M., *Enamel surfaces after orthodontic bracket debonding [see comments].* Angle Orthod, 1995. **65**(2): p. 103-10.
17. Featherstone, J.D.B., N.A. Barrett-Vespone, D. Fried, Z. Kantorowitz, J. Lofthouse, and W. Seka, eds. *Rational choice of laser conditions for inhibition of caries progression.* Lasers in Dentistry. Vol. 2394. 1995, Society of Photo-Optical Instrumentation Engineers: San Jose. 57-67.
18. Midda, M. and P. Renton-Harper, *Re: Roberts-Harry D., laser etching of teeth for orthodontic bracket placement: a preliminary clinical study. Lasers in Surg & Med 12:467-470 (1992) [letter; comment].* Lasers in Surgery and Medicine, 1993. **13**(3): p. 379-80.
19. Roberts, H.D.P., *Laser etching of teeth for orthodontic bracket placement: a preliminary clinical study [see comments].* Lasers in Surgery and Medicine, 1992. **12**(5): p. 467-70.
20. Tocchio, R.M., P.T. Williams, F.J. Mayer, and K.G. Standing, *Laser debonding of ceramic orthodontic brackets.* Am J Orthod Dentofacial Orthop, 1993. **103**(2): p. 155-62.
21. Hibst, R. and U. Keller, *Removal of dental filling materials by Er:YAG laser radiation.* SPIE, 1991. **1424**: p. 120-126.
22. Chu, R., L. Watanabe, J. White, S. Marshall, G. Marshall, and J. Hutton, *Temperature rise and surface modification of lased titanium cylinders.* Journal of Dental Research, 1992. **71**(Spec Iss 144, #312).
23. Marshall, S., G. Marshall, L. Watanabe, and J. White, *Effects of the Nd:YAG laser on amalgams and composites.* Trans Acad Dent Mater, 1989(2): p. 297-298.
24. Sherk, H.H., G. Lane, A. Rhodes, and J. Black, *Carbon dioxide laser removal of polymethylmethacrylate.* Clinical Orthopaedics and Related Research, 1995(310): p. 67-71.
25. Yow, L., J.S. Nelson, and M.W. Berns, *Ablation of bone and polymethylmethacrylate by an XeCl 308 nm excimer laser.* Lasers Surg Med, 1989. **9**(2): p. 141-7.
26. Nelson, J.S., L. Yow, L.H. Liaw, L. Macleay, R.B. Zavar, A. Orenstein, W.H. Wright, J.J. Andrews, and M.W. Berns, *Ablation of bone and methacrylate by a prototype mid-infrared erbium:YAG laser.* Lasers Surg Med, 1988. **8**(5): p. 494-500.
27. Thomas, B.W., C.R. Hook, and R.A. Draughn, *Laser-aided degradation of composite resin.* Angle Orthod, 1996. **66**(4): p. 281-6.
28. Walter, S.D., M. Eliasziw, and A. Donner, *Sample size and optimal designs for reliability studies.* Stat Med, 1998. **17**(1): p. 101-10.
29. Fried, D., R. Glena, J.D.B. Featherstone, and W. Seka, *Nature of light scattering in dental enamel and dentin at visible and near-infrared wavelengths.* Applied Optics, 1995. **34**(7): p. 1278-85.
30. Pouchert, C.J., *The Aldrich library of infrared spectra.* 3rd ed, ed. C.J. Pouchert. 1981, Milwaukee, WI: Aldrich Chemical Company.





31. Jeffrey, I.W., B. Lawrenson, C. Longbottom, and E.M. Saunders, *CO2 laser application to the mineralized dental tissues--the possibility of iatrogenic sequelae.* J Dent, 1990. **18**(1): p. 24-30.
32. Miserendino, L.J. and R.M. Pick, eds. *Lasers in Dentistry.* . 1995, Quintessence Books: Carol Stream. 341.
33. Wigdor, H.A., J.T. Walsh, and S.R. Visuri. *Effect of water on dental material ablation of the Er:YAG laser.* in *Lasers in Surgery: Advanced Characterization, Therapeutics, and Systems IV.* 1994: SPIE.
34. Wigdor, H.A., J.T. Walsh, and S.R. Visuri. *Effect of water on hard dental tissue ablation of the Er:YAG laser.* in *SPIE.* 1994. Los Angeles: SPIE.

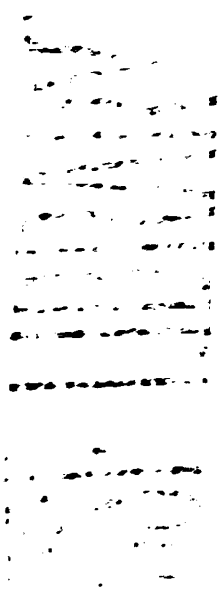
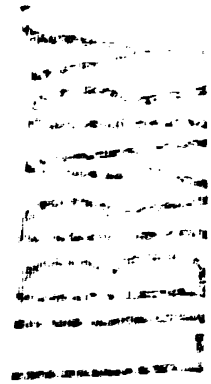


Table 1. Ratio of composite and enamel ablation efficiency and etch rate for the TEA CO_2 laser at 9.6μm. Efficiency and etch rate values are determined by dividing the composite value by the enamel value to give a relative ablation rate.

Fluence (J/cm^2)	Efficiency	Etch rate
4.1	1.25	1.18
7.6	2.28	1.99
10.3	2.64	2.56
13.8	3.00	3.01
18.3	2.66	2.44
26.2	3.19	2.96
35.1	2.91	2.69
48.2	2.60	2.86
52.0	2.71	2.71
62.6	3.07	3.18



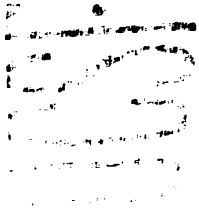


Table 2. Ablation rates for enamel, Concise, and Transbond for the TEA CO_2 laser at the 10.6μm wavelength.

Enamel		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
3.3	-	-
4.3	0.0153	2.20
5.3	0.0094	1.53
6.9	0.0103	1.83
8.2	0.0166	2.30
10.9	0.0161	2.46
13.1	0.0144	2.58
17.1	0.0126	2.92
20.3	0.0101	2.60
36.4	0.0064	2.95
48.7	0.0048	2.70
62.7	0.0031	2.51
Concise		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
3.3	0.01012	1.625
4.3	0.0419	4.90
5.3	0.0495	6.25
6.9	0.0493	7.02
8.2	0.0476	7.29
10.9	0.0481	8.09
13.1	0.0406	7.92
17.1	0.0398	8.33
20.3	0.0389	8.89
36.4	0.0265	10.17
48.7	0.0218	10.45
62.7	0.0179	11.03
Transbond XT		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
3.3	0.01078	1.511
4.3	0.0381	5.33
5.3	0.0401	5.79
6.9	0.0479	6.39
8.2	0.0517	7.41
10.9	0.0506	8.04
13.1	0.0447	8.19
17.1	0.0411	7.99
20.3	0.0375	8.60
36.4	0.0269	9.96
48.7	0.0217	10.62
62.7	0.0174	10.46

Table 3. Comparison of efficiency and etch rates for the TEA CO_2 laser at the 10.6μm wavelength. Values are relative.

Transbond vs. Concise Relative Ablation Rates		
Fluence (J/cm^2)	Efficiency	Etch Rate
3.3	1.06	0.929
4.3	0.910	1.08
5.3	0.809	0.926
6.9	0.971	0.911
8.2	1.08	1.01
10.9	1.05	0.994
13.1	1.09	1.03
17.1	1.03	0.958
20.3	0.963	0.967
36.4	1.01	0.979
48.7	0.998	1.01
62.7	0.970	0.948
Transbond vs. Enamel Relative Ablation Rates		
Fluence (J/cm^2)	Efficiency	Etch Rate
3.3	-	-
4.3	2.49	2.41
5.3	4.26	3.77
6.9	4.66	3.48
8.2	3.10	3.22
10.9	3.15	3.27
13.1	3.10	3.17
17.1	3.25	2.73
20.3	3.72	3.30
36.4	4.17	3.37
48.7	4.50	3.93
62.7	5.53	4.16
Concise vs. Enamel Relative Ablation Rates		
Fluence (J/cm^2)	Efficiency	Etch Rate
3.3	-	-
4.3	2.73	2.22
5.3	5.26	4.07
6.9	4.79	3.82
8.2	2.86	3.17
10.9	2.99	3.29
13.1	2.82	3.07
17.1	3.15	2.85
20.3	3.86	3.42
36.4	4.12	3.44
48.7	4.51	3.87
62.7	5.70	4.39

Table 4. Ablation rates for enamel and composite at 9.6μm and 10.6μm wavelengths at selected similar fluences.

Enamel 9.6μm			Enamel 10.6μm		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)	Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
4.1	0.0181	1.86	4.3	0.0153	2.20
7.8	0.0130	2.08	8.2	0.0166	2.30
11.1	0.0138	2.43	10.9	0.0161	2.46
14.6	0.0128	2.48	13.1	0.0144	2.58
18.6	0.0122	3.02	17.1	0.0126	2.92
35.6	0.0075	2.93	36.4	0.0064	2.95
48.3	0.0057	2.96	48.7	0.0048	2.70
61.5	0.0047	2.63	62.7	0.0031	2.51

Transbond XT 9.6μm			Transbond XT 10.6μm		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)	Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
4.1	0.0228	2.19	4.3	0.0381	5.33
7.6	0.0297	4.15	8.2	0.0517	7.41
10.3	0.0366	6.23	10.9	0.0506	8.04
13.8	0.0383	7.47	13.1	0.0447	8.19
18.3	0.0326	7.38	17.1	0.0411	7.99
35.1	0.0219	7.88	36.4	0.0269	9.96
48.2	0.0148	8.50	48.7	0.0217	10.62
62.6	0.0144	8.36	62.7	0.0174	10.46

Table 5. Comparison of efficiency and etch rates for the TEA CO_2 laser at the 9.6 and 10.6μm wavelengths. Values are relative.

Enamel 9.6μm/10.6μm			
Fluence 9.6μm (J/cm^2)	Fluence 10.6μm (J/cm^2)	Efficiency Ratio	Etch rate Ratio
4.1	4.3	1.18	0.84
7.8	8.2	0.78	0.91
11.1	10.9	0.86	0.99
14.6	13.1	0.89	0.96
18.6	17.1	0.97	1.04
35.6	36.4	1.17	0.99
48.3	48.7	1.18	1.10
61.5	62.7	1.49	1.05

Transbond XT 9.6μm/10.6μm			
Fluence 9.6μm (J/cm^2)	Fluence 10.6μm (J/cm^2)	Efficiency Ratio	Etch rate Ratio
4.1	4.3	0.60	0.41
7.8	8.2	0.58	0.56
11.1	10.9	0.72	0.77
14.6	13.1	0.86	0.91
18.6	17.1	0.79	0.92
35.6	36.4	0.81	0.79
48.3	48.7	0.68	0.80
61.5	62.7	0.83	0.80

Table 6. Er:YAG ablation data for enamel and Transbond XT from two experiments. Enamel and composite ablation rates are compared from the second experiment. Values are also compared between the two composite results.

Er:YAG composite ablation rates for first trial.		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
9.8	0.0066	2.3
15.1	0.0099	5.7
16.6	0.0101	5.5
18.6	0.0104	6.8
21.3	0.0130	10.0
26.7	0.0246	19.3
32.4	0.0208	18.3
37.7	0.0211	20.9
52.0	0.0159	22.8
67.6	0.0103	19.5

Er:YAG enamel ablation rates.		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
12.1	0.0726	16.5
18.2	0.0630	18.0
23.1	0.0349	13.1
25.6	0.0215	8.9
31.3	0.0314	13.7
40.6	0.0198	11.7
47.7	0.0177	12.5
54.1	0.0177	12.2
73.3	0.0145	14.7
93.3	0.0049	7.2
Er:YAG composite ablation rates for second trial.		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
12.1	0.0356	13.2
18.2	0.0378	16.7
23.1	0.0318	18.2
25.6	0.0257	16.1
31.3	0.0252	16.5
40.6	0.0154	15.3
47.7	0.0125	14.0
54.1	0.0155	19.6
73.3	0.0092	15.5
93.3	0.0173	26.9

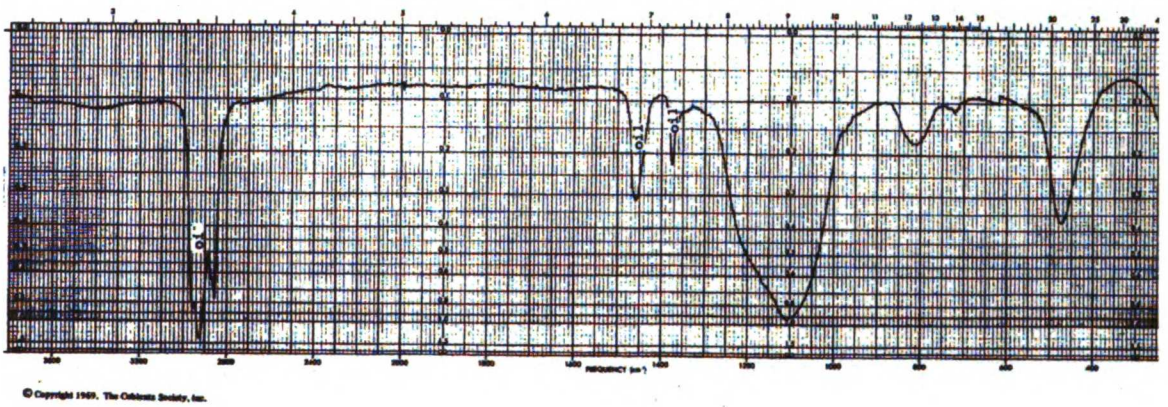
Er:YAG Composite (second trial) vs. enamel: relative ablation rates.		
Fluence (J/cm^2	Efficiency	Etch Rate
12.1	0.490	0.797
18.2	0.600	0.928
23.1	0.910	1.39
25.6	1.19	1.80
31.3	0.801	1.21
40.6	0.775	1.31
47.7	0.702	1.12
54.1	0.875	1.61
73.3	0.638	1.05
93.3	3.523	3.73

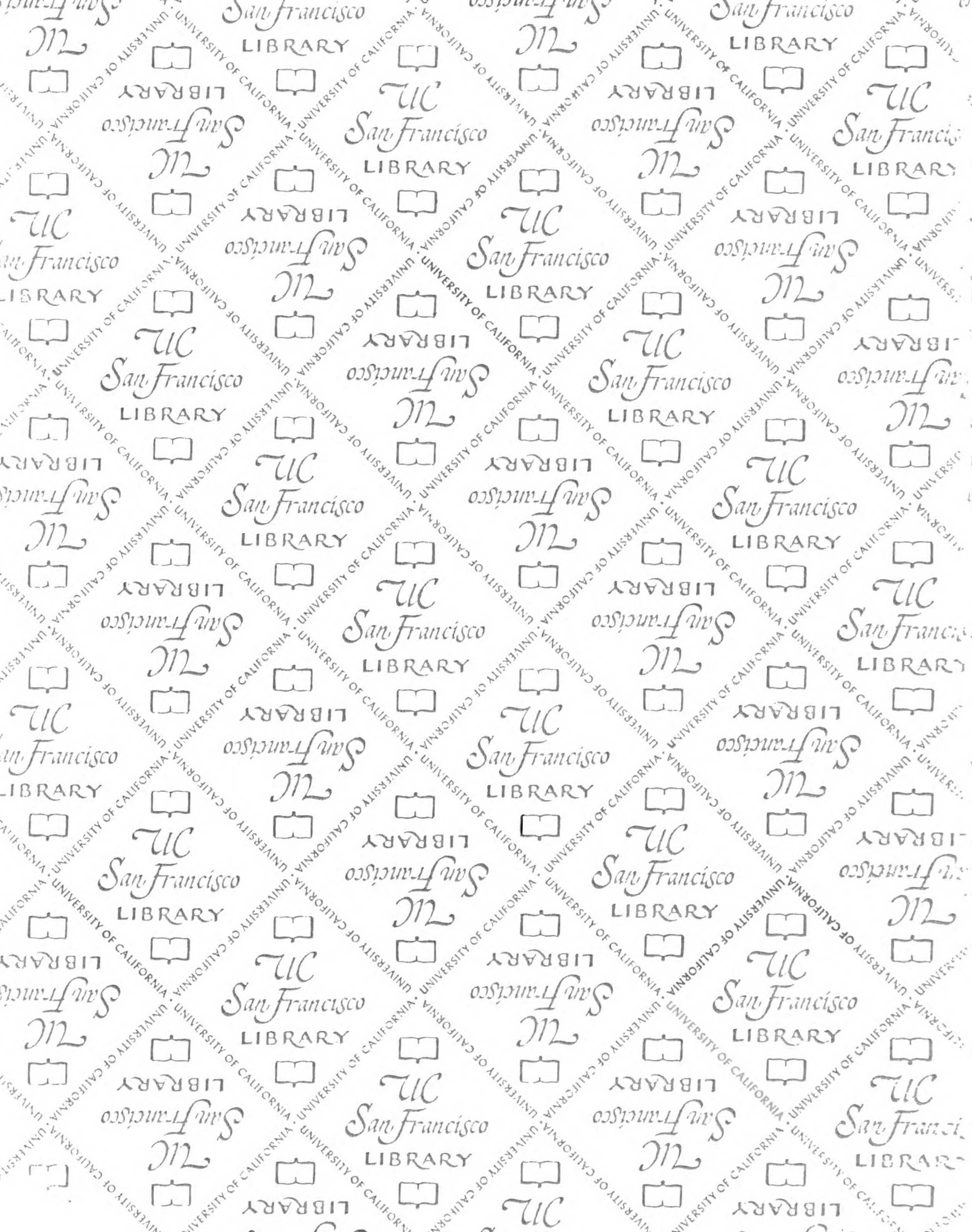
Er:YAG Composite 1			*Er:YAG Composite 2*		
Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)	Fluence (J/cm^2)	Efficiency (mm^3/J)	Etch Rate (μm/pulse)
18.6	0.0104	6.8	18.2	0.0378	16.7
26.7	0.0246	19.3	25.6	0.0257	16.1
32.4	0.0208	18.3	31.3	0.0252	16.5
37.7	0.0211	20.9	40.6	0.0154	15.3
52	0.0159	22.8	54.1	0.0155	19.6
67.6	0.0103	19.5	73.3	0.0092	15.5

Figure 1. SiO_2 reference spectrum. [30]

JOINT COMMITTEE ON ATOMIC AND MOLECULAR PHYSICAL DATA
EVALUATED INFRARED REFERENCE SPECTRUM

Silicon dioxide		5585
Si O_2	SAMPLE PREP. mull PATH REGION SOLVENT	NSRDS - COBLENTZ CLASS III STRUCTURE VERIFIED
SiO_2 See 4662 for KBr disc		STATE solid M.P. B.P.
	SPECTROMETER MAKE + MODEL Perkin-Elmer 521. Filters at 3150, 2500, 2000, 1150, 700, 410 Grating changes: 2000, 630	CONTRIBUTING LAB. Dow Corning Corp. DATE RECORDED 2.4.66

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