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Selective Removal of Dental Composite using a Rapidly Scanned Carbon Dioxide Laser

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Abstract

Dental restorative materials are color matched to the tooth and are difficult to remove by mechanical means without excessive removal or damage to peripheral enamel and dentin. Lasers are ideally suited for selective ablation to minimize healthy tissue loss when replacing existing restorations, sealants or removing composite adhesives such as residual composite left after debonding orthodontic brackets. In this study a carbon dioxide laser operating at high laser pulse repetition rates integrated with a galvanometer based scanner was used to selectively remove composite from tooth surfaces. A diode array spectrometer was used to measure the plume emission after each laser pulse and determine if the ablated material was tooth mineral or composite. The composite was placed on tooth buccal and occlusal surfaces and the carbon dioxide laser was scanned across the surface to selectively remove the composite without excessive damage to the underlying sound enamel. The residual composite and the damage to the underlying enamel was evaluated using optical microscopy. The laser was able to rapidly remove the composites rapidly from both surfaces with minimal damage to the underlying sound enamel.

Keywords

emission spectroscopy; laser ablation; dental enamel; CO₂ laser; dental composite

1. INTRODUCTION

Multiple studies have shown that emission spectroscopy can be used effectively to discriminate between the ablation of dental composite adhesive/restorative materials and dental hard tissues. During the ablation event there is a distinct luminous emission plume with characteristic atomic and molecular emission lines that can be used to determine the composition of the target material. The plume emission is dominated by calcium atom, ion and molecular emission lines during the ablation of dental hard tissues and bone which can be exploited for selective laser ablation. Composite restorative materials lack calcium and thus lack the calcium emission lines that are very strong between 580 and 650-nm giving the plume a distinct red appearance. Plume emission spectroscopy or laser microprobe emission spectroscopy can be used for the identification of many materials.^{1–3} The method was first used to examine teeth over forty years ago⁴ and has been used to identify calcified plaque in

arteries⁵ and many other organs and tissues. Niemz⁶ and others suggest that this approach can be used to discriminate sound from decayed dental hard tissues, however after extensive studies utilizing several different laser systems we did not find the spectral emission useful for discriminating between sound and demineralized dental hard tissues⁷. Over the past few years very compact fiber-optic spectrometers have become available that are relatively inexpensive and can be readily interfaced with laser ablation systems. Dumore et al.⁸ and Alexander et al.⁹ showed that the spectra of the tooth could be easily discriminated from composite by the strong distinctive calcium emission lines in the tooth that are not present in the composite resin or filler material. One requirement of using plume analysis for laser control is that the ablation pulses do not remove excessive amounts of sound tissue. For example, such an approach would not be suitable for use with the Er:YAG or Er:YSGG lasers that are typically used with fairly high single-pulse energies and irradiation intensities to remove dental hard tissues, namely 100–500 mJ per pulse with incident fluence ranging from 20–100 J/cm². Such pulses can remove up to 50- μ m of enamel and 200- μ m of dentin per shot producing unacceptable damage to the underlying tooth structure. Optical plume analysis is better suited for femto- and pico-second visible laser systems, UV laser systems, and TEA CO₂ laser systems operating at high pulse repetition rates. Such systems remove less than 10–20- μ m of sound tissues per pulse and are capable of operating at repetition rates approaching a kHz for rapid processing of tissue. One can also envision future caries removal systems utilizing these laser systems coupled with robotic control to scan over tooth surfaces to selectively remove only carious tissue or composite restorative material to replace sealants and restorations. Previous measurements in our laboratory have demonstrated that we can use 355-nm and 10.6- μ m laser pulses to remove sealants and residual orthodontic composite from smooth and occlusal surfaces^{9–11}. Louie et al.¹² used optical coherence tomography to show the high selectivity of composite removal. Suri et al.¹³ demonstrated that optical feedback could be used to control the removal of residual composite from tooth surfaces using a 355-nm laser.

CO₂ lasers operating at a 9.3 and 9.6- μ m wavelengths can be used for the efficient ablation of dental hard tissues. Since these lasers can be operated at high pulse repetition rates and they have a high degree of ablation selectivity at low incident fluence 5–10 J/cm², they are well suited for selective ablation of composite using spectral feedback. The purpose of this study was to determine if a rapidly scanned 9.3- μ m CO₂ laser ablation system can be used for the rapid and selective removal of dental composite from enamel surfaces with minimal loss of sound enamel.

2. MATERIALS AND METHODS

Sample Preparation

Sound and carious whole teeth and tooth sections taken from teeth extracted from patients in the San Francisco Bay Area were collected, cleaned, and sterilized with gamma radiation. Teeth were sectioned using a diamond saw to provide transverse sections approximately 1–2-mm thick. Composite disks were prepared from Z-250 composite (3M Minneapolis, MN) and GrenGloo™ composite (Ormco, Orange, CA). The GrenGloo™ composite was green below body temperature which made it easy to identify any residual composite missed by

the laser. The ablation thresholds and ablation rates were similar for both composite materials.

Tissue Irradiation and Laser Parameters

An industrial marking laser, Impact 2500 from GSI Lumonics (Rugby, United Kingdom) operating at a wavelength of 9.3 μm was used. The laser was custom modified to produce a Gaussian output beam (single spatial mode) and a pulse duration of between 10–15- μs . This laser is capable of high repetition rates up to 500 Hz. The laser energy output was monitored using a power meter EPM 1000, Coherent-Moletron (Santa Clara, CA), and the Joulemeter ED-200 from Gentec (Quebec, Canada). A f-theta scanning lens with a focal length of 90-mm from II-VI (Saxonburg, PA) was used to focus the beam onto the tooth surfaces. A razor blade was scanned across the beam to determine the diameter ($1/e^2$) of the laser beam. Computer-controlled XY galvanometers 6200HM series with MicroMax Series 671 from Cambridge Technology, Inc. (Cambridge) were used to scan the laser beam over sample surfaces. A low volume/low pressure air-actuated fluid spray delivery system consisting of a 780S spray valve, a Valvemate 7040 controller, and a fluid reservoir from EFD, Inc. (East Providence, RI) was used to provide a uniform spray of fine water mist onto the tooth surfaces at ~ 2 mL/min. The setup is shown in Fig. 1.

Optical Microscopy

In previous studies we had used optical coherence tomography to assess underlying damage to the enamel surface. However, the 10–20- μm resolution of OCT is too low to measure changes that were typically less than 10–20- μm . Therefore, optical microscopy was used to analyze the samples in this study. After surface ablation, a Leitz Secolux microscope with 5, 10, 20, 50 and 100 $\times$ infinity corrected fluorite objectives and BF/DF/DIC capability with a maximum magnification of 1000 times (10 $\times$ eyepieces) interfaced to a digital firewire camera, and image analysis software was used to acquire images of the underlying enamel after composite removal. Other lower magnification optical scopes were also used.

Optical Feedback and Selective Removal

The laser was scanned from point to point over a 4–5 mm square area with the computer controlled XY Galvanometer scanning system. The flowchart below describes the procedures used for selective ablation.

A laser spot size of 750- μm was used with a spot to spot separation of 150- μm . The entire area was scanned by the laser and the plume produced from each spot was interrogated using a USB2000+ fiber optic spectrometer from Ocean Optics (Dunedin, FL) incorporating a 2048 element CCD detector that was used in conjunction with a 1-mm bare silica-fiber to acquire spectra. The fiber was attached to an XYZ stage and positioned to view the ablation plume. The calcium emission lines were used to identify the enamel surface. After the entire area was scanned, the area was rescanned and only the spots identified as having composite were irradiated in this second iteration and subsequent scans. Scans were repeated until the composite was completely removed from the target area. Excessive heat deposition was avoided by scanning over the target area during each iteration and delivering only a single laser pulse to each spot containing composite as opposed to delivering multiple pulses to each spot without moving until all the composite is removed. This approach also improves efficiency and prevents stalling since deep holes are not being drilled with high aspect ratios. The laser was not operated at a fixed pulse repetition rate and the repetition rate was determined by the rate at which the program analyzed the plume and then subsequently triggered the laser. The number of spots irradiated per second fluctuated slightly and fell between 200–220.

The spectra of dental composite and sealants are markedly different than that of enamel and dentin⁷. The composite spectra produced using the CO₂ laser had only a single strong single peak at around 580 nm, that was identical to the spectrum of glass which we had observed previously⁷. The 580-nm peak is most probably due to sodium emission, which is the main component in glass/silica the filler material of dental composites. This peak is also present in the spectrum of dental hard tissues. The spectral lines were identified using spectral tables¹⁴. Dental hard tissues have much stronger emission with a very strong peak centered at 605-nm. Since the intensity is dependent on the position of the optical fiber we used an imaging system that viewed the entire plume to avoid excessive variation in the spectra. The ratio and intensities of the 580 and 605-nm peaks were used to differentiate between composite and enamel. The sodium line is present in both materials while the strong 605-nm calcium emission line is only present in dental hard tissue.

3. RESULTS AND DISCUSSION

Disks of composite and enamel thin sections were used to determine the ablation rates for varying incident fluence for each material in order to select the initial irradiation intensities for investigation. Several irradiation intensities were empirically investigated for rapid removal of composite with minimal removal of the underlying enamel. Composite applied to smooth buccal surfaces was investigated first since these areas are most sensitive to damage to the enamel and excessive damage would adversely affect the appearance of the tooth. The Grengloo™ composite used in this study is designed as an adhesive for metal orthodontic brackets. After removal of orthodontic brackets it is difficult to see the residual composite left on tooth buccal surfaces and the green coloration is designed to aid mechanical removal. Figure 2 shows a layer of composite approximately 1-mm thick bonded to the enamel of the crown before and after the tooth surface was scanned by the laser over the right half of the composite area. As can be seen in the images the composite is cleanly removed without charring of the composite. If a water spray is not used there is discoloration and thermal

damage to the composite. At a fluence of only 3.2 J/cm^2 , there is minimal removal of sound enamel. High-resolution optical microscopy shows that there is melting and recrystallization of the enamel without ablation in most areas. There were some areas of the treated area where there was some minor enamel removal. This was localized to the center of the individual laser spots where the local fluence was highest due to the Gaussian spatial profile of the laser beam. These areas of localized damage to enamel were limited to a depth of less than $20\text{-}\mu\text{m}$ which has a minimal impact on appearance and is similar in magnitude to that produced during prophylaxis using a brush. Measurements of the enamel loss during a routine brush and cup prophylaxis indicated mean enamel loss ranging from $6\text{--}17\text{-}\mu\text{m}$ depending on the material employed¹⁵. The enamel loss associated with the removal of filled composite after debonding orthodontic brackets was as high as $70\text{-}\mu\text{m}$ after multiple bonding and debonding procedures¹⁵.

After establishing the laser parameters that could be used effectively for composite removal on smooth surfaces we applied composite to the pits and fissures of the occlusal surfaces of molars as shown in Fig. 3. Although this appears far more challenging to remove composite from the highly convoluted topography of these surfaces, it is actually easier than removal from smooth surfaces since damage to the underlying enamel is less critical for cosmetic reasons and higher irradiation intensities are permissible. A higher fluence of 7 J/cm^2 was used for the occlusal surfaces. The higher fluence results in faster composite removal and it compensates for the topography of the fissures which lowers the effective incident fluence in those areas. One advantage of using the $9.3\text{-}\mu\text{m}$ CO_2 laser to remove composite from these areas is that the laser modified surface has an increased resistance to acid dissolution^{16–18}.

Even though ablation is more selective for 355-nm pulses from a frequency tripled Q-switch Nd:YAG laser, the performance of the CO_2 laser compares quite favorably and removed the composite more than an order of magnitude faster and at clinically feasible rates. The composite removal process took from $10\text{--}20$ seconds with the CO_2 laser and that rate could be increased if needed by either decreasing the processing time or by increasing the laser spot size.

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Fig. 1. Setup for composite removal, (A) XY Galvanometers, (B) Scanning lens, (C) water spray and (D) sample embedded in resin block.

Fig. 2.
Composite (green) on tooth buccal surface, (A) before and (B) after scanning half the area of the composite.

Fig. 3. Composite (green) on tooth occlusal surface, (A) before composite placement and (B) after composite placement and after removal by the laser.