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Authors
Jang, Andrew T
Chan, Kenneth H
Fried, Daniel

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Automated ablation of dental composite using an IR pulsed laser coupled to a plume emission spectral feedback system

Andrew T. Jang, **Kenneth H. Chan**, and **Daniel Fried**
University of California, San Francisco, San Francisco, CA 94143-0758

Abstract

Dental composites are used as restorative materials for filling cavities, shaping, and covering teeth for esthetic purposes, and as adhesives. Dentists spend more time replacing existing restorations that fail than they do placing new restorations. Tooth colored restorations are difficult to differentiate from the surrounding tooth structure making them challenging to remove without damaging healthy tooth structure. Previous studies have demonstrated that CO_2 lasers in conjunction with spectral feedback can be used to selectively remove composite from tooth surfaces. The purpose of this study is to assemble a system that is feasible for clinical use incorporating a spectral feedback system, a scanning system, articulating arm and a clinical handpiece and then evaluate the performance of that system on extracted teeth. In addition, the selectivity of composite removal was analyzed using a high-speed optical coherence tomography system that is suitable for clinical use. The system was capable of rapidly removing composite from small preparations on tooth occlusal surfaces with a mean loss of enamel of less than 20-μm.

Keywords

composite; selective laser ablation; spectral feedback; clinical handpiece

1. INTRODUCTION

Dental composites are a popular choice for replacing missing tooth structure and bonding intraoral appliances. The material is often color matched and bonded to the surrounding tooth structure, making it difficult to remove when necessary and often leads to excessive removal of healthy tooth structure. Laser ablation generates a luminous plume which contains the emission spectra of the ablation site's elemental constitutes (Fig 1). Analysis of this plume has been used in the past to differentiate materials in the dental field [1]–[3] and has identified the calcium emission line at 605-nm as a significant marker for differentiating the hydroxyapatite rich tissues (i.e. dentin and enamel) from composite [2]–[4]. Since the calcium emission line is primarily used for spectral differentiation, it is hypothesized that similar results can be achieved faster and cheaper by substituting the spectrometer with a pair of filtered photodiodes.

In a previous study, we have demonstrated the capacity to selectively remove composite from enamel specimens at clinically relevant rates using a CO_2 laser operating at 9.3-μm with high pulse repetition rates with minimal heat deposition [3]. The next step is to develop a spectral feedback system for selective removal that is feasible for use *in vivo* by incorporating an articulating arm and a galvanometer into a clinical handpiece. The objective of this study was to test the feasibility of this clinical system through the following objectives: 1) Explore the use of photodiodes for spectral feedback through the plume for enamel/composite identification; 2) Fabricate a clinical handpiece setup small enough for use in a clinical setting. This study will serve as an initial preliminary test to ensure proper composite selectivity and removal prior to moving forward with a clinical study.

2. MATERIALS AND METHODS

2.1. Tooth Samples

Mandibular premolars (n=10) with an unmodified occlusal tooth surface were collected from patients in the San Francisco Bay Area, California, sterilized with gamma radiation as previously described [5] and stored in a 1% thymol solution. An occlusal small filling preparation was placed entirely within enamel with a True Speed Elite handpiece from Darby Dental (Jericho, NY) and 2 mm round bur. GrenGloo™ from Ormco, (Orange, CA) composite was placed to restore the tooth to its original contour. Following composite placement, the sample was treated with the experimental clinical handpiece (see section 2.1–2.2). At each stage (original tooth, cut tooth, tooth with composite, and tooth with composite removed), the sample was scanned with a cross-polarization optical coherence tomography system (CP-OCT) system (see section 2.3) for volumetric analysis.

2.2. Clinical Laser scanning system for composite removal

The clinical system (Fig. 2) consists of the following components: CO_2 laser, articulating arm, galvanometer, lens, handpiece head, fiber optic, photodiodes, and air water spray. The laser used was an industrial marking laser, Impact 2500 from GSI Lumonics (Rugby, United Kingdom) operating at a wavelength of 9.3-μm. A previous study within our group has confirmed the safety of using this laser within our operating parameters [6]. 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 pulse repetition rates up to limited to 50 Hz. The laser energy output was monitored using a power meter EPM 1000 from Coherent-Molectron (Santa Clara, CA), and the Joulemeter ED-200 from Gentec (Quebec, Canada). Laser pulses from the source were fed into an articulating arm from MLS (Novi, MI) to allow for proper positioning of the laser handpiece. Computer-controlled XY galvanometers 6200HM series with MicroMax Series 671 from Cambridge Technology, Inc. (Cambridge, UK) were used to scan the laser beam over sample surfaces. An 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. The laser spot size and energy employed was 433-μm and 12.8-mJ, respectively (fluence = 8.6-J/cm^2).

The clinical handpiece head was custom designed in Fusion 360 from Autodesk (San Rafael, CA) and machined out of aluminum using a personal CNC machine from Tormach (Waunakee, WI) (Model PCNC-440). Copper mirrors were polished using a Pro Grinder Polisher from Buehler (Lake Bluff, IL) (Model EcoMet 250) and placed at the end of the clinical head. A bifurcated fiber optic from Banner Engineering (Minneapolis, MN), (Model

BA23S) was used to collect and feed the plume emission into two photodiodes from Thorlabs (Newton, NJ), (Model PDA100a Si Amplified detector), one of which contained a 600-nm FWHM 40 filter from Thorlabs (Newton, NJ), (Model FB600-400), and another which was unfiltered. The signal from the unfiltered photodiode was amplified with a 30-db gain while a gain of 70-db was used for the photodiode with the 600nm filter. A custom fabricated low volume/low pressure air-actuated fluid spray delivery system was used to continuously deliver a 0.5-mL/min water spray over the tooth surface during the laser treatment. A program written in LabVIEW from National Instruments (Austin, TX) was used to control the air water spray, scan the laser over the tooth, and ensure complete removal of the composite.

3. RESULTS AND DISCUSSION

Overall, the clinical system performed as designed and removed the composite filling within a short period. Representative images of the original, prepped, composite placed, and composite removed states are shown in Figure 3. The clinical laser handpiece removed the composite from a 1-mm × 1-mm × 1-mm filling in about 30–40 seconds without major deviations to the original shape of the tooth preparation. Reduction of the procedure time can be one by increasing the pulse repetition rate of the laser, however precautions must be taken to prevent peripheral thermal damage and excessive heating of the dental pulp. Following the scanning procedure, a small 3-mm × 3-mm box representing the laser scanning window was visible on the occlusal surface of the enamel (Fig. 3) which does not affect the overall esthetics of the tooth.

There were several design considerations to prepare the laser removal system for clinical use. An articulating arm and galvanometers were incorporated to the system in stabilize the position of the handpiece to the patient while the laser is scanned over the occlusal surface of the tooth. The pulse repetition rate of (50-Hz) was chosen to match the corresponding pulpal safety study [6]. This combined approach allows for the system to achieve clinically acceptable speeds with minimal operator input. Within the context of future patient studies, the parameters for operating the laser system are well within those defined within the safety study [6]. While it is possible to achieve faster removal rates by using higher pulse repetition rates, the primary limiting factor of heat accumulation within the pulp must be considered. A fluence of 8.6 J/cm^2 was chosen in order to maximize the ratio of selectivity for composite (60-µm composite/pulse vs. 20-µm enamel/pulse) [3] while generating a reliable optical signal. The water flow rate was also adjusted to improve the spectral feedback loop. Too little water would cause the formation of a carbonized layer of composite at the ablation site while too much water attenuates the laser beam reducing the ablation rate and the plume intensity.

Replacing the spectrometer with a pair of photodiodes increases the overall clinical feasibility of the system by increasing its feedback reliability and decreasing the overall cost. Spectrometers are not only many times more expensive than individual photodiodes, they are less sensitive requiring more light for proper spectral analysis. It should be noted that while a single photodiode setup would further increase the sensitivity, it was found that a normalized ratio produced from two photodiodes produced better analytical performance as it was less influenced by variation in the plume size and intensity. Figure 1 shows images of representative plumes generated from a single laser pulse on enamel and GrenGloo™ composite. Overall, the intensity of the plume from enamel was greater than the emission plume from the composite. This was due to the higher content of calcium within the enamel. However, the plume for composite ablation was physically larger and lasted longer than the enamel plume (Fig 1). This is likely due to increased thermal radiation since the amount of ejected material is higher for composite than enamel [3]. This phenomenon may be useful for calculating the total amount of material ablated, however it was not implemented in our differentiation algorithm since the water spray significantly decreases this effect.

Overall, the system was also able to remove most composite leaving behind a minor amount of material that was not visually apparent. A more complete study involving 3D volumetric analysis using CP-OCT will be completed in the near future. It is understood that a major limitation of this system is that the handpiece can only ablate material within its direct line of site and is therefore unable to remove composite within undercuts. Therefore, it is hypothesized that the leftover composite was either due to small undercuts in the filling shape.

In conclusion, we have demonstrated that composite can be selectively removed from tooth surfaces using a computer controlled carbon dioxide laser scanning system with integrated spectral feedback at clinically relevant rates. This study has successfully achieved several milestones needed to proceed to the clinic. Namely, we have successfully integrated the selective ablation system into a hand-piece feasible for clinical use, developed a fast and inexpensive spectral feedback system utilizing two photodiodes, and tested for speed and accuracy. Initial results are promising but will require future testing.

This study serves as an *in vitro* benchmark to test the performance of the clinical handpiece prior its use in a clinical study. Our results have demonstrated that spectral feedback methods can be implemented to selectively remove composite with minimal damage to healthy tooth structure and represents a potential advantage over the current standard of care. The next planned stage for this project is a clinical study in which we will design and fabricate a custom bite block for our handpiece for additional stability within the patient’s mouth.

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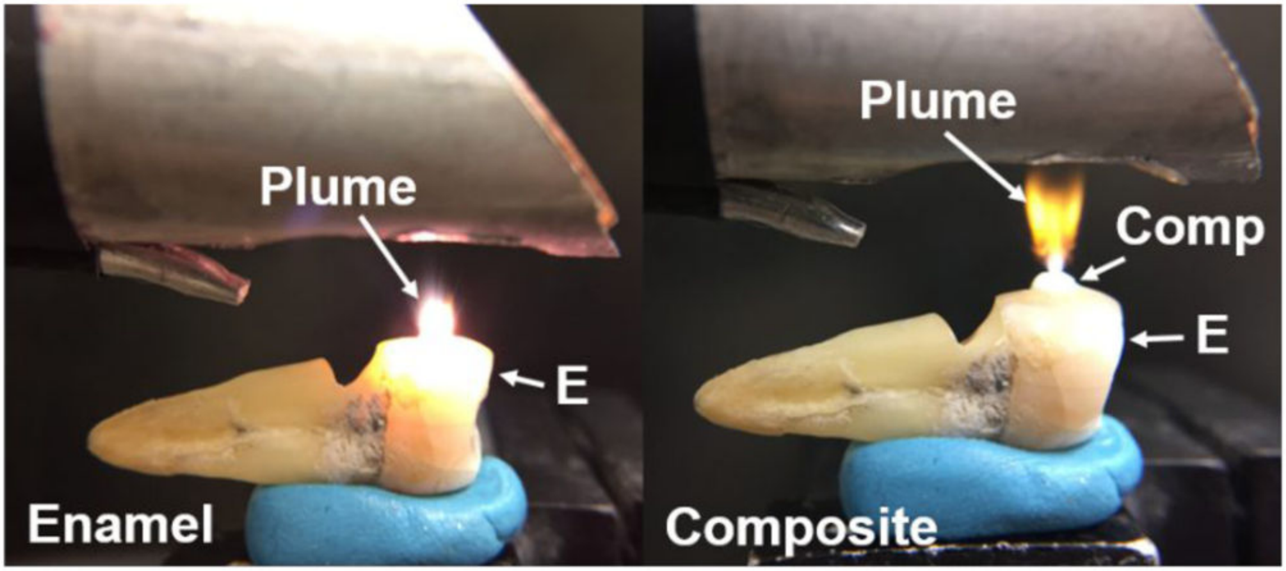

Fig 1.
Plume size and color difference between enamel (E) and composite (Comp).

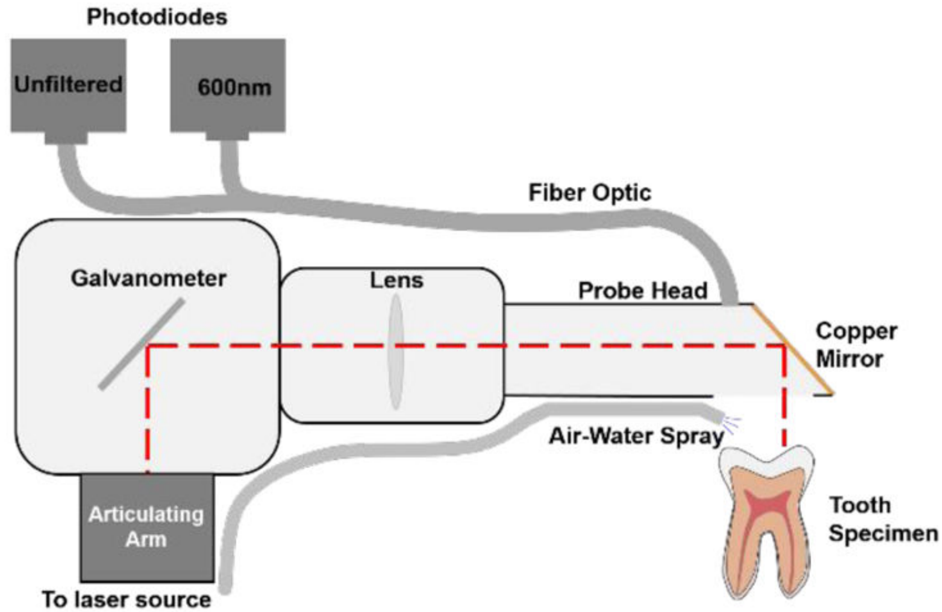

Fig. 2.
Schematic diagram and image of clinical laser handpiece.

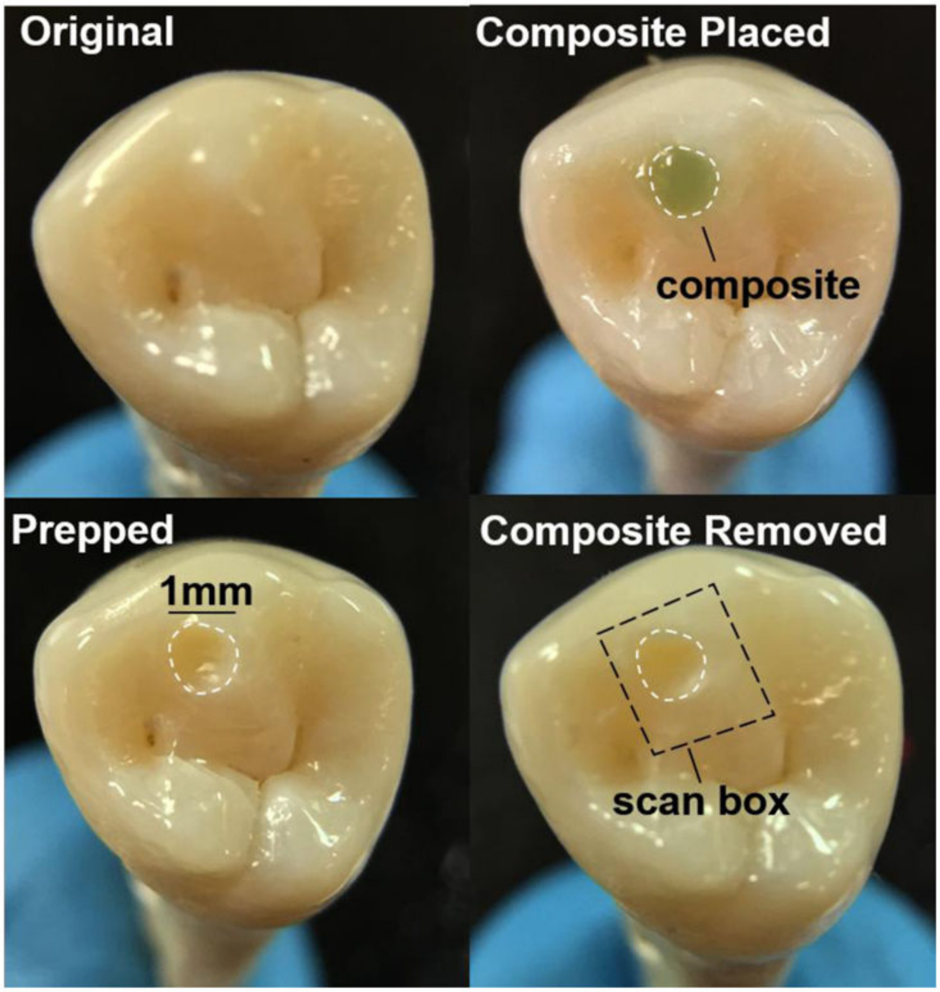

Fig 3.
Image of tooth specimen throughout experimental process