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

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Abstract

Objective—The purpose of this study is to assemble a laser system for the selective removal of dental composite from tooth surfaces that is feasible for clinical use incorporating a spectral feedback system, a scanning system, articulating arm and a clinical hand-piece and evaluate the performance of that system on extracted teeth.

Methods—Ten extracted teeth were collected and small fillings were placed on the occlusal surface of each tooth. A clinical system featuring a CO_2 operating at 50-Hz and spectral optical feedback was scanned across the tooth. Removal was confirmed using a cross polarized optical coherence tomography (CP-OCT) system designed for clinical use.

Results—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.

Conclusion—We have demonstrated that plume emission spectral feedback can be incorporated into an automated system for composite removal by incorporating dual photodiodes and a galvanometer controlled CO_2 laser. Additionally, the use of registered OCT images presents as a viable method for volumetric benchmarking. Overall, this study represents the first implementation of spectral feedback into a clinical hand-piece and serves as a benchmark for a future clinical study.

Keywords

composite; selective laser ablation; spectral feedback; clinical handpiece

1. Introduction

Within dentistry, composite is a popular material of choice for clinicians due to its versatility. It is often color matched and physically bonded to the surrounding tooth structure making it ideal for the esthetic replacement of missing tooth structure and bonding dental appliances. A primary caveat with using dental composite is that the placement procedure for composite is highly technique sensitive and is often incorrectly done, increasing the likelihood of secondary dental caries and need for a replacement filling [1, 2]. When

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replacing and removing unwanted composite, clinicians often have a difficult time visually differentiating composite from healthy enamel, usually resulting in the excessive removal of healthy tooth structure to ensure complete removal of the composite [3, 4]. Therefore, a system that allows a dentist to rapidly remove composite while minimizing the damage to the underlying healthy tooth structure would provide a significant improvement over current methods.

Lasers have been used in dentistry for several treatment modalities including soft/hard dental tissue removal and caries inhibition [5–9]. Studies have shown that CO_2 lasers operating at 9.3 and 9.6-μm wavelengths can be used to efficiently remove enamel and dentin [7–11] with minimal impact on the health of the pulp [12–14]. A clinical study employing the same carbon dioxide laser used for this study demonstrated no pulpal effects for a pulse repetition rate of 50-Hz and an incident fluence of 20-J/cm^2 [15]. Similar to other CO_2 lasers, this laser has been shown to exhibit an inherent selectivity for composite by ablating more composite material per pulse compared to healthy enamel [16–20]. Additionally, the localized ablated particles created from each laser pulse become electronically excited from the laser energy thereby generating a localized luminous plume. The plume contains the emission spectra of the ablation site’s elemental constitutes and can therefore be used to identify and differentiate materials [21, 22]. Spectral analysis of the plume has revealed that the distinctive high intensity calcium emission line at 605-nm found in dental hard tissues can be used to differentiate tissues rich in hydroxyapatite (i.e. dentin and enamel) from composite (Fig. 1) [16, 17, 23]. 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.

We have previously demonstrated that spectral feedback can be used to remove dental composite on an optical bench setup using a spectrometer for optical feedback. This study formed an initial proof of concept for an automated removal of composite at clinically relevant rates using a CO_2 laser operating at 9.3-μm with high pulse repetition rates and also showed that high speed removal can be achieved with minimal heat deposition [16].

This study pursues the next logical step by developing a spectral feedback clinical handpiece system for selective removal that is feasible for use within patients. This is achieved incorporating an articulating arm and a galvanometer into a clinical delivery system. In addition to constructing a handpiece capable of operating within the oral cavity, the clinical system will be benchmarked to determine its efficacy for selective composite removal by using volumetric analysis techniques on 3D images captured with a high-speed optical coherence tomography (OCT) system that is suitable for clinical use.

Within this context of this study, we will test the feasibility of this clinical system through the following objectives: 1) Explore the use of photodiodes for spectral feedback of plume for enamel/composite identification. 2) Fabricate a clinical hand-piece setup small enough for feasible use in a clinical setting. 3) Test the efficacy of the hand-piece with volumetric analysis. This study will serve as the 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) were collected from patients in the San Francisco Bay Area, California, and sterilized with gamma radiation as previously described [24] and stored in a 1% thymol solution. A small pit filling prep 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 laser treated using the experimental clinical handpiece. 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 for volumetric analysis.

2.2 Clinical laser scanning system for composite removal

The clinical system consists of the following components: CO_2 laser, articulating arm, and experimental handpiece (Fig. 2 and 3) including 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 [15]. 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 500 Hz, however for the purposes of this study the rate was 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). An articulating arm from MLS (Novi, MI) was used to couple the laser beam to the scanning hand-piece. 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 hand-piece 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 (Fig. 4).

2.3. Cross Polarization Optical Coherence Tomography (CP-OCT) system

The swept source CP-OCT system used for this study has been previously described by Fried *et al.* [25]. The system is Model IVS-3000-CP from Santec (Komaki, Aichi, Japan) and utilizes a swept laser source from Santec (Komaki, Aichi, Japan), (Model HSL-200-30) operating with a 30-kHz sweep rate. This system is capable of acquiring images *in vivo* and it has been used for clinical imaging studies [26, 27]. The Mach-Zehnder interferometer is integrated into the hand-piece which also contains the microelectromechancial (MEMS) scanning mirror and the imaging optics. The handpiece is shown in Figure 1, the body is 7-cm × 18-cm with an imaging tip that is 4-cm long and 1.5-cm across. This system operates at a wavelength of 1321-nm with a bandwidth of 111-nm with a measured resolution in air of 11.4-μm (3-dB). The lateral resolution is 80-μm ($1/e^2$) with a transverse imaging window of 6-mm × 6-mm and a measured imaging depth of 7-mm in air. The extinction ratio was measured to be 32-dB. Resulting images had a voxel size of 32.5-μm × 24.7-μm × 8.3-μm.

Postprocessing of captured OCT images was done using a program written in MATLAB from Mathworks (Natick, MA) utilizing a median filter and a rotating kernel transformation (RKT) filter [28].

2.4. Volumetric Analysis

Volumetric analysis was carried out using Avizo from FEI (Hillsboro, OR). Correlation based rigid body registration was used to align OCT scans of the tooth in the “cut” and “composite removed” based on the consistent regions of the occlusal surface (e.g. unaltered cusps and grooves of the tooth) using registration techniques previously described [29]. In short, regions of the tooth that were altered by the experiment were excluded from the image registration while consistent regions (e.g. groves and tooth cusps) were used align the surfaces. Each aligned image was then segmented based on intensity to determine the volumetric space of the tooth. From these images, leftover composite (V_{LC}) and excess enamel removed (V_{EER}) was calculated. A voxel which was present in the in the “composite removed” volume but not present in the “cut” volume was defined as V_{LC}. Additionally, a voxel which was present in the “cut” volume but not in the “composite removed” volume was defined as V_{eer}. Volume spaces were then morphologically opened to compensate for slight image registration alignment errors.

3. Results

3.1. Plume emission analysis

Figure 5 shows images of representative plumes generated from a single laser pulse on enamel (Fig. 5a) and GrenGloo composite (Fig. 5b). Plots of the photodiode response are also shown in Figure 5c (enamel) and Figure 5d (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. 5a & 5b).

3.3. Volumetric measurements

OCT scans of a representative specimen can be seen in Figure 6a–c. A combined aligned image using correlative rigid body registration is shown in Figure 6d. Visual representations of extracted surfaces and volumetric measurements from the OCT scans are shown in Figure 6e. Across the ten specimens analyzed the mean±(s.d.) volume of leftover composite (V_{LC}) was 0.011(0.008)-mm^3 and mean±(s.d.) volume of excess enamel removed (V_{EER}) 0.032(0.029)-mm^3. The calculated prep volume was ~ 0.6 mm^3 yielding a two-dimensional area of 1.77 mm^2, therefore the mean depth of the enamel lost is about 18-μm.

3.2. Clinical hand-piece results

The run time for the composite removal program for a 1-mm × 1-mm × 1-mm filling was approximately 30–40 seconds. Representative images of the original, prepped, composite placed, and composite removed states are shown in Figure 7. A video of the laser program operating on a tooth sample can be found in the supplemental video file. Composite was apparently removed without major deviations to the original shape of the tooth preparation.

4. Discussion

The inspiration for this study lies within growing challenge to improve the standards of minimally invasive dentistry. Better shade matched dental composites are being developed each year, which signifies an advancement in esthetic dentistry but also leads to increased difficulty for removal. As more composite fillings and adhesives are being placed in patients, there exists an inherent need to efficiently remove composite while reducing the damage to adjacent tooth structure.

In this study, we have demonstrated that composite can be selectivity 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 demonstrated that a CP-OCT system suitable for clinical use can be used to nondestructively assess the selectivity of removal via analysis of the volumetric removal of composite and loss of healthy tooth structure through rigid body image registration.

Several considerations went into the design of the laser removal system optimized for clinical use. An articulating arm and galvanometers were incorporated to the system in stabilize the position of the handpiece while the laser is scanned over the occlusal surface of the tooth (Fig. 2 and 3). This combined approach allows for the system to achieve clinically acceptable speeds. The pulse repetition rate of (50-Hz) was chosen to match the corresponding pulpal safety study [15]. Faster removal rates can be achieved by using higher pulse repetition rates with the limiting factor being excessive heat accumulation within the pulp. Within the context of future patient studies, the parameters for operating the laser are well within those mentioned defined within the safety study [15]. 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) [16] while generating the smallest possible plume for producing 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 decreasing the overall cost and increasing its feedback reliability. 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. It was noted that emission from the plume produced from the ablation of composite material at 600-nm has a longer lifetime than that for enamel (Fig. 5). This is likely due to increased thermal radiation since the amount of ejected material is higher for composite than enamel [16]. 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.

This study also represents advancements in the ability to use a clinical OCT for high resolution volumetric quantification over existing methods. Previous studies have relied on 3D measurements using techniques including µXCT [30] and physical probe scanning techniques [31] which are not feasible for patient studies. Clinical cone beam CT systems can capture volumetric data within the patient but have large voxel sizes (about 150–200-µm voxel length) for the scale of this study. By comparison, the OCT system used within this study has a higher resolution (32.5-µm × 24.7-µm × 8.3-µm) and can rapidly scan the surface of the tooth with a short scan time (~4 second).

A crucial stage in the volumetric quantification was the registration of images since a minor misalignment between the registered images may result in volumetric inaccuracies. However, the topology of the occlusal surface of the tooth provided many features which increased our confidence in the image registration results. Once image registration was completed, the process of extracting the difference in occupied volume is straightforward.

Overall, the clinical system performed as designed and removed the composite filling within a short period (~30 second). The procedure time can be decreased 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. A possible workaround would include a revised alternating scanning pattern that would decrease localized heating at a specific ablation site. 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. 6d) which does not affect the esthetics of the tooth. From a volumetric perspective, excess enamel removed (0.03-mm^3) is considered comparable to the average amount of enamel lost in an individual (0.04-mm^3) per year [32]. From a depth perspective, previous studies have measured the annual enamel loss on the occlusal surface from chewing behaviors to be from 30-μm [33] to 50-μm [34], and therefore we consider the mean enamel loss from our study (18-μm) to be insignificant. The system was also able to remove the majority of composite leaving behind a minor amount of material that was not visually apparent. 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 a small undercut or due to minor image registration error.

In conclusion, 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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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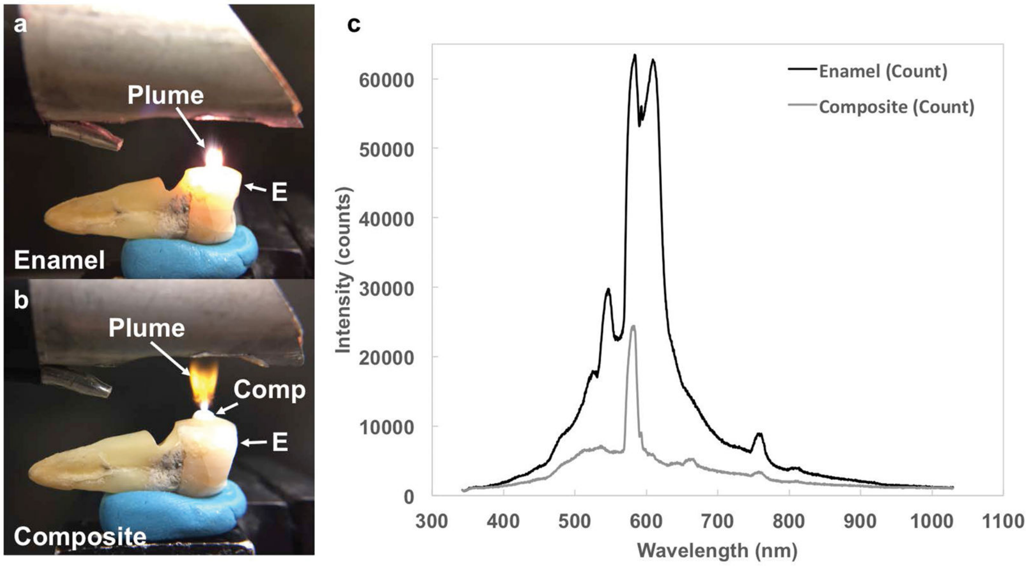

Figure 1.

Differences in plume emission color for (a) enamel and (b) composite can be seen visually. c) Collected spectral data for composite and enamel were plotted to highlight the differences in general intensity as well the strong calcium emission peak (605-nm) in enamel which is not present in composite.

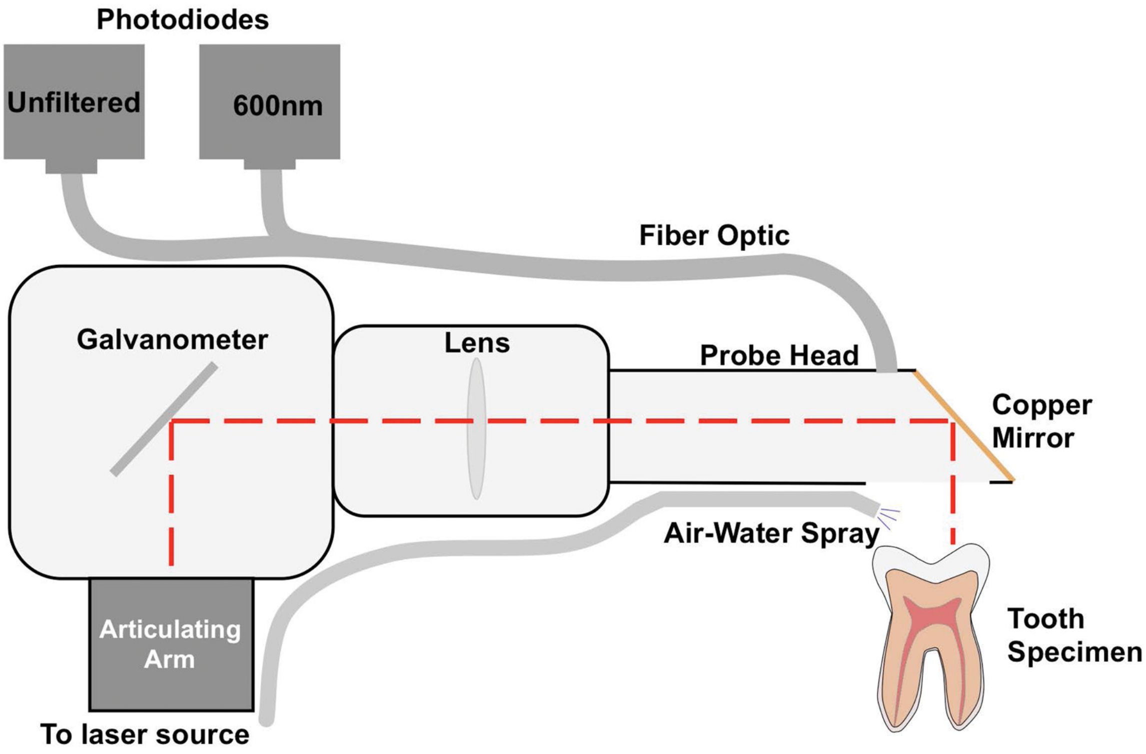

Figure 2.

Schematic diagram of clinical laser hand-piece.

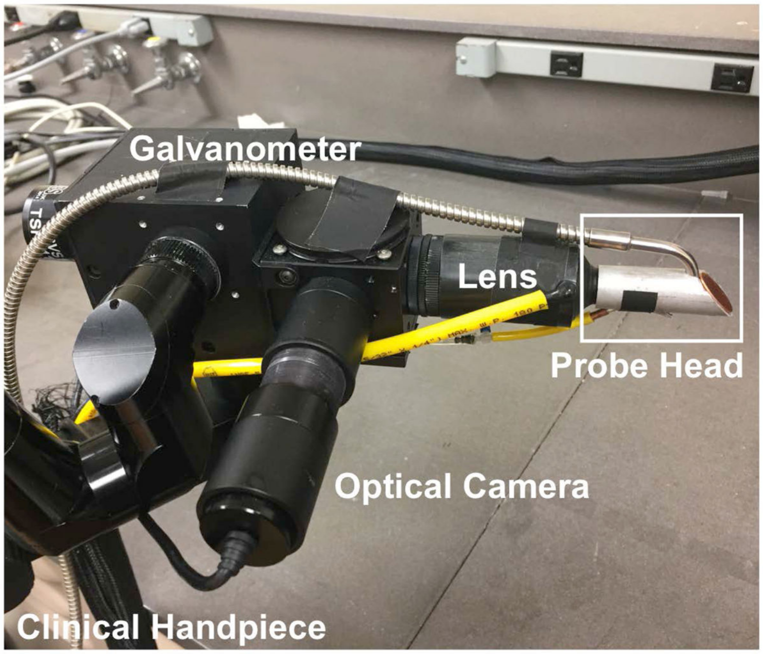

Figure 3.

Images of clinical hand-piece and clinical probe head, which is designed to fit within the patient's mouth.

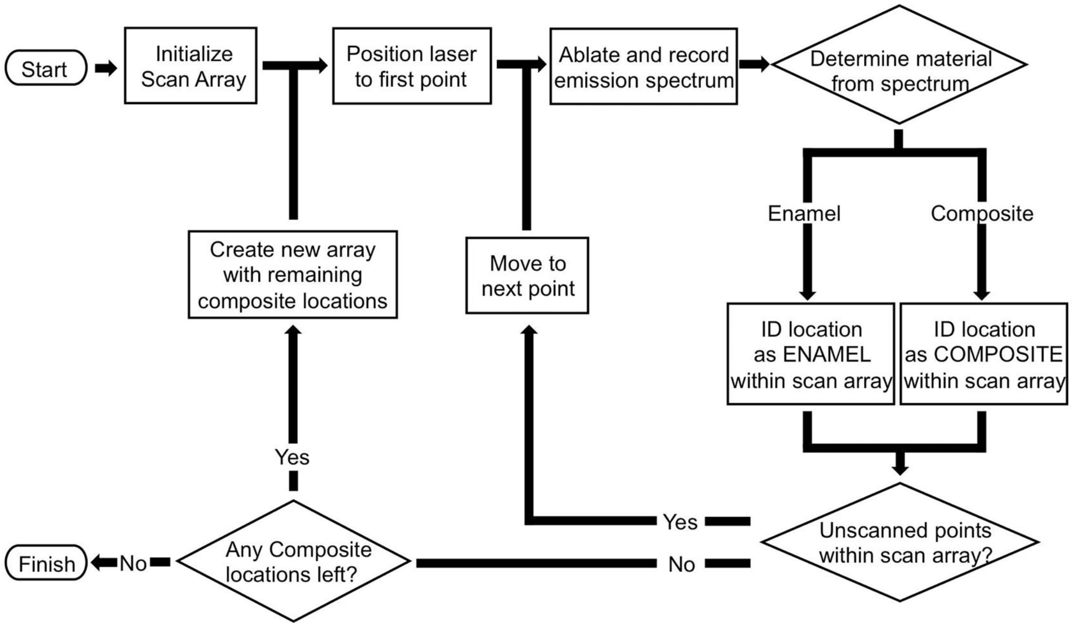

Figure 4.

Flowchart outlining coding logical steps for selective composite ablation.

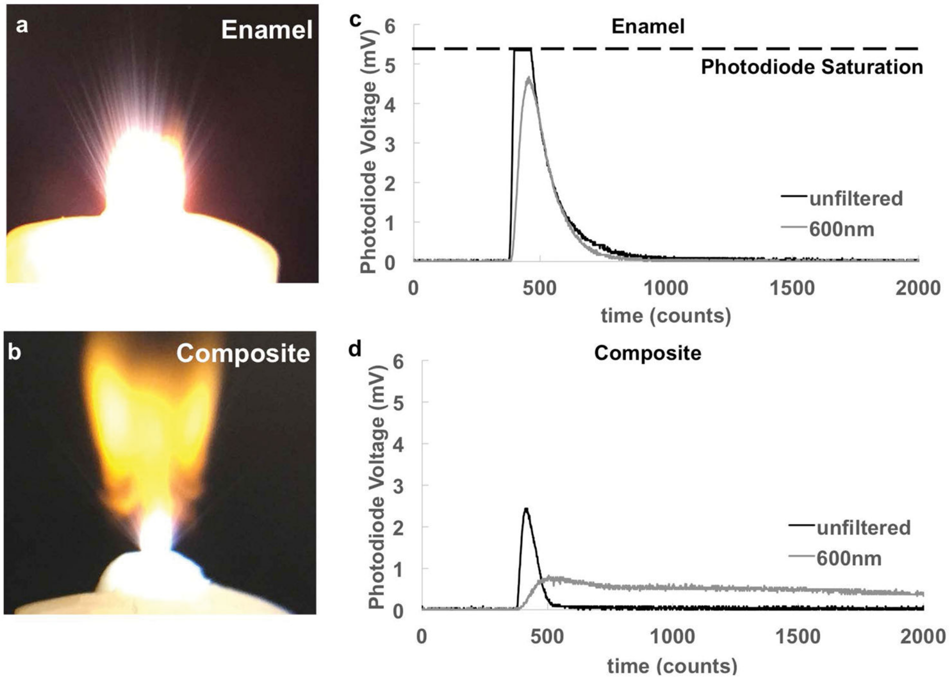

Figure 5.

Photodiode response to emission plumes from (a) enamel and (b) composite.

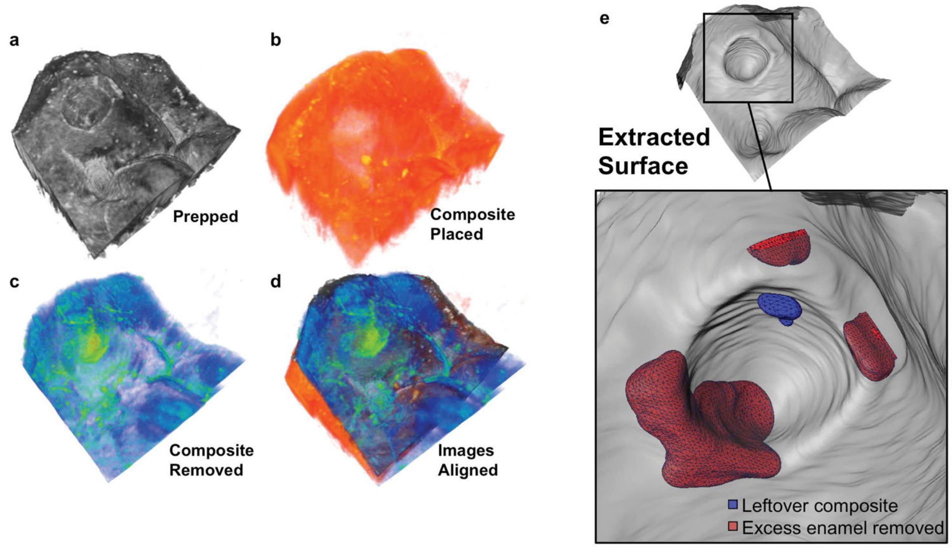

Figure 6.

(a–d) Optical coherence tomography (OCT) scans of tooth occlusal surfaces. Scans were aligned within the same 3D space to generate volumetric measurements. Volumetric regions and surfaces were generated for OCT scans and subtracted from each other to calculate the leftover composite [vol. leftover composite = vol. composite removed – vol. prepped] and excess enamel removed [vol. enamel removed = vol. prepped – vol. composite removed].

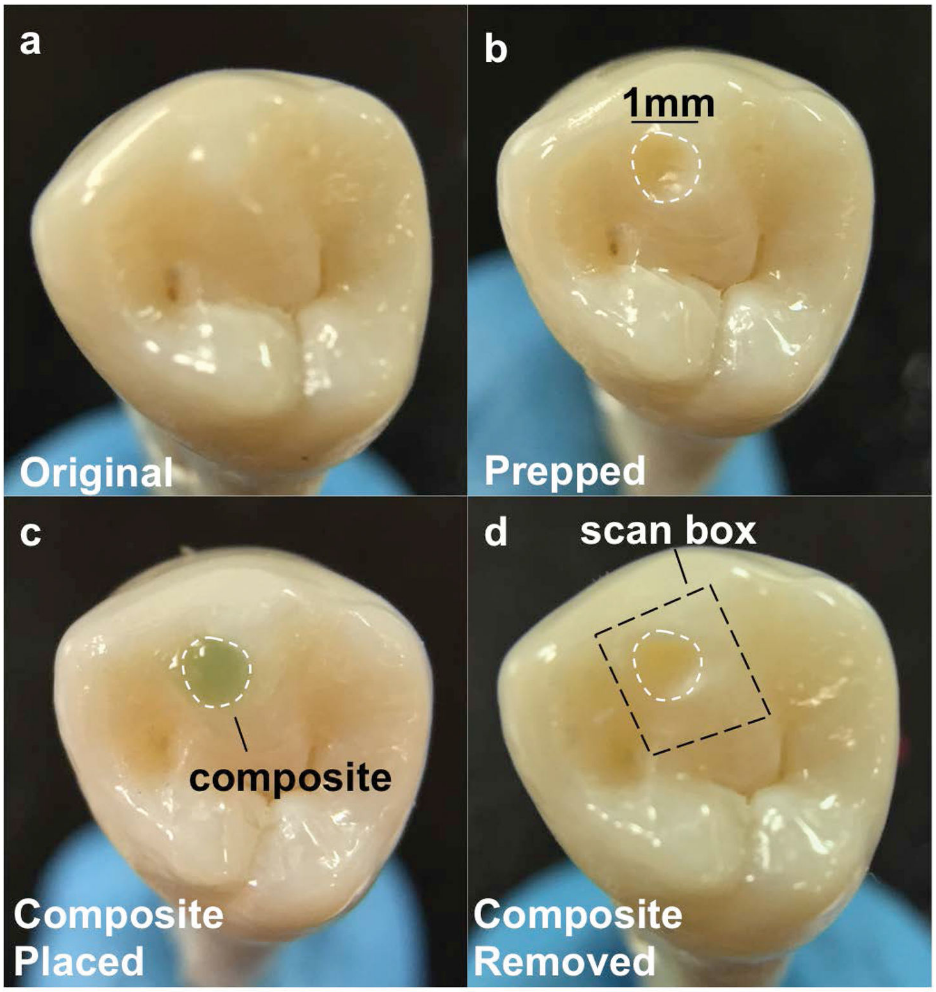

Figure 7.

Images of (a) original tooth (b) prepared tooth (c) tooth with contour restored with Grengloo™ composite (d) tooth with composite removed via selective ablation. Please see supplemental movie of the selective ablation process.