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Rapid and Selective Removal of Composite From Tooth Surfaces With a 9.3 μm CO₂ Laser Using Spectral Feedback

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Abstract

Objective—Dental composite 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.

Methods—In this study, a carbon dioxide laser operating at 9.3- μm with a pulse duration of 10–20-microsecond and a pulse repetition rate of ~200 Hz was integrated with a galvanometer based scanner and used to selectively remove composite from tooth surfaces. Spectra of the plume emission were acquired after each laser pulse and used to differentiate between the ablation of dental enamel or composite. Microthermocouples were used to monitor the temperature rise in the pulp chamber during composite removal. The composite was placed on tooth buccal and occlusal surfaces and the carbon dioxide laser beam 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.

Results—The laser was able to rapidly remove composite from tooth buccal and occlusal surfaces with minimal damage to the underlying sound enamel and without excessive heat accumulation in the tooth.

Conclusion—This study demonstrated that composite can be selectively removed from tooth surfaces at clinically relevant rates using a CO₂ laser operating at 9.3- μm with high pulse repetition rates with minimal heat deposition and damage to the underlying enamel.

Keywords

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

INTRODUCTION

Dental composites are typically color matched to the tooth for esthetic reasons 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

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loss when replacing failed restorations and sealants, removing composite adhesives such as residual composite left after debonding orthodontic brackets, and for the repair of esthetic bonding.

High ablation selectivity can be achieved by operating at laser wavelengths that ablate composite at lower ablation thresholds than dental hard tissues. Previous studies have shown that high selectivity can be achieved for short nanosecond lasers pulses at 355-nm and for CO₂ laser pulses at 10.6- μ m [1–3]. Another approach is to use image guided ablation which has been carried out for selective removal of dental caries using near-IR imaging [4] and fluorescence [5] to demarcate areas of decay. Dynamic methods employing acoustic and spectral feedback are also feasible and these approaches have been demonstrated to remove both caries and dental calculus [6–11].

Multiple studies have shown that spectral feedback or emission spectroscopy can be used effectively to discriminate between the ablation of dental composite adhesive/restorative materials and dental hard tissues [12–16]. 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 which gives the plume a distinct red appearance. Plume emission spectroscopy or laser microprobe emission spectroscopy can be used for the identification of many materials [17–19]. The method was first used to examine teeth over 40 years ago [20] and has been used to identify calcified plaque in arteries [21]. 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 and Fried [13] and Alexander and Alexander [10,12] 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.

We have focused our efforts on the selective removal of composite on two laser systems, the frequency tripled Nd:YAG laser operating at 355-nm and the CO₂ laser that can be operated at several wavelengths between 9.2 and 10.6- μ m [1–3]. Short nanosecond lasers pulses at 355-nm are well suited for selective ablation of composite from enamel surfaces and spectral feedback can be used to control the removal of residual composite [2,15,22]. However, the concern of UV exposure, limited usefulness for other dental laser procedures and the high cost of diode-pumped systems that can be operated at higher pulse repetition rates has tempered enthusiasm for this laser system.

Alexander and Alexander [1] and Cheng et al. [10] showed that a transverse excited atmospheric pressure (TEA) operating at 10.6- μ m can be used for selective removal of composite and that spectral feedback can be used to control removal from the occlusal surfaces. One problem with the shorter TEA CO₂ laser pulses is that the high peak power in the initial gain switched spike which is 500-ns in duration generates a plasma which shields the tail end of the laser pulse. This limits the ablation rate of dental hard tissues to a few

microns per pulse severely limiting their utility for caries removal. Moreover, the laser wavelengths of 9.3 and 9.6- μm are more strongly absorbed by carbonated hydroxyapatite for more efficient coupling to dental hard tissues [23,24]. Recent studies have shown that CO_2 lasers operating at 9.3 and 9.6- μm wavelengths with longer pulse durations of 10–20-microsecond are ideally suited for the efficient ablation of dental hard tissues and for caries removal [25,26]. The longer laser pulse durations reduce the effects of plasma shielding and allow the removal of 10–20- μm per laser pulse at relatively low incident fluence, 5–10 J/cm^2 and these lasers can be operated at high pulse repetition rates.

The purpose of this study was to determine if a rapidly scanned 9.3- μm CO_2 laser ablation system with laser pulses of 10–20-microsecond duration can safely be used for the rapid and selective removal of dental composite from enamel surfaces with minimal loss of sound enamel.

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- μm thick. Composite disks were prepared from Z-250 composite (3M Minneapolis, MN) and Grengloo™ composite (Ormco, Orange, CA). 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. 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-microsecond. 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. The setup is shown in Figure 1. The water spray was pulsed with a frequency of 0.5 Hz for a delivery rate of 10 $\mu\text{l}/\text{second}$ over an area of 5 cm^2 .

Plume Emission Spectroscopy

A USB2000+ fiber optic spectrometer from Ocean Optics (Dunedin, FL) incorporating a 2048 element CCD detector was used to acquire spectra. The spectrometer is equipped with a 600 g/mm grating with a blaze wavelength of 500-nm designed for 350–850-nm. No slit was used and the L2 cylindrical collection lens was installed. A 1" lens with a focal length of 50-mm positioned 6" from the plume was used to focus the plume emission into a 1-mm in diameter optical fiber. The spectra of dental composite and sealants are markedly different than that of enamel and dentin [10]. Spectra of dental enamel and composite are shown in Figure 2. The composite spectra produced using the CO₂ laser had only a single strong peak at around 580 nm, that was identical to the spectrum of glass which we had observed previously [10]. The 580-nm peak is most probably due to sodium emission from glass/silica particles, the filler material of dental composites. This peak is also present in the spectrum of dental hard tissues which also contain some sodium. The spectral lines were identified using spectral tables [28]. 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.

Ablation Rate Measurements

The rate of enamel and composite removal was measured as a function of the incident fluence to determine the optimum laser irradiation intensity to be used for removal of composite. Disks of Grengloo™ and Z250 composites were prepared along with tooth sections approximately half a millimeter thick. The laser spot size was maintained at 450-μm and the laser beam was scanned in a rectangular pattern over an area roughly 3.6 × 1.5 ml with each laser spot separated by 150-μm apart with a high degree of overlap over the samples. After scanning the depth was measured using an optical coherence tomography (OCT) system. The time-domain OCT system is described in reference 27. A high power (15-mW) polarized superluminescent diode source was used with a center wavelength of 1,317 nm and a spectral bandwidth FWHM of 84 nm to provide an axial resolution of 9-μm in air. The laser energy/fluence was varied using CaF₂ attenuators of varying thickness. Two composite materials were explored: Z250 is a filled general purpose composite that best represents the bulk of composite materials that are likely to be encountered and Grengloo™ is also a filled orthodontic composite that expressed similar ablation rates.

Heat Accumulation Measurements

Type K, 36 gauge, 0.13 mm diameter, one meter length thermocouples, Omega Engineering Inc. (Stamford, Connecticut) were placed coronally inside the pulp chamber of extracted human teeth to measure the temperatures in the pulp chamber. Thermally conductive paste was used to adhere the thermocouples to the inside of the pulp chamber and maintain thermal contact with the coronal surface of the pulp chamber wall. Radiographs were used to confirm accurate placement of thermocouples. A thermocouple controller, Stanford Research SR630 (Stanford, CA), and Labview software (National Instruments, Austin, TX)

were used to record the thermal data. The cooling water was at room temperature. The time required for composite removal was also recorded. Ten samples were measured. The temperature rise in the pulp chamber of each tooth was monitored until complete removal of the composite. A temperature rise of 5.5°C was considered indicative of excessive heat accumulation.

Optical Microscopy

In previous studies we had used OCT 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 1,000 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

In order to selectively remove composite, the laser beam was scanned over the area of interest while the plume was monitored with the spectrometer to differentiate between composite and enamel. The laser spot size was 750- μm and the area to be irradiated was divided into a 4–5 mm square grid with each spot on the grid separated by 150- μm .

The algorithm used for selective removal of composite is derived from a closed loop feedback system. The system has a set of input variables and when the system encounters a difference in the output from a controlled variable, the system changes the input variables and reiterates through the process again until the system does not provide any new input variables. For selective removal, the laser beam was scanned across a user constructed area of interest coordinate grid, designated as a primary storage array, with one laser pulse delivered to each grid coordinate. The plume was acquired by the spectrometer at each coordinate and analyzed to determine if composite or enamel was ablated. The plume spectra for enamel and composite are shown in Figure 2. The spectral lines located at 580 and 605-nm were used to demarcate between composite and enamel. The spectra of ablated enamel was more intense than composite and exhibited a strong peak at approximately 605-nm, whereas both enamel and composite exhibited a less intense peak at roughly 580-nm, as shown, respectively, as [E] and [C]. The program utilized the difference in plume emission at these two wavelengths to differentiate between composite and enamel. If the plume emission spectrum indicated composite the grid coordinate was recorded in a secondary storage array and only the coordinates stored in that array were targeted on the next pass. This process was repeated until the program had scanned all the points in the primary array. The program then checked if the secondary storage array contained any more points, if so, the program replaced the primary storage array with the secondary array and repeated the process until the subsequent iteration's secondary array was empty and all the composite was removed. This selective ablation algorithm is shown in the flowchart of Figure 3.

The optimum fluence for composite removal is dependent on the location of the composite on the tooth. On tooth facial surfaces the amount of enamel removed must be minimized since it is desirable to avoid changing the appearance of the enamel. Several irradiation intensities were empirically investigated to determine the maximum fluence that could be used without varying the appearance of the enamel. We chose a fluence of 3.2 J/cm^2 for which visual changes were only visible upon close inspection.

By scanning over the entire area during the initial pass, as opposed to removing composite from each individual location with multiple laser pulses, localized heat deposition is minimized. The ablation efficiency is higher since deep holes are not being drilled in the composite. The ablation rate and efficiency decreases for subsequent laser pulses as an ablation crater develops and the fluence decreases as the incident laser energy is spread over a larger area. In many cases stalling can occur, therefore it is advantageous to scan the laser beam over adjacent spots to minimize crater/hole formation. The laser was externally triggered by the computer after analysis of each laser spot, therefore the pulse repetition rate was limited by the software and processing time. The number of spots irradiated per second fluctuated slightly between 200 and 220.

RESULTS

Figure 4 shows a graph of ablation rate of human enamel and Z250 dental composite for varying incident fluence. The ablation rate for composite ranged from just below $10\text{-}\mu\text{m}$ per pass at 1 J/cm^2 to $90\text{-}\mu\text{m}$ at 18 J/cm^2 . The ablation rate for enamel increased more slowly from $10\text{-}\mu\text{m}/\text{scan}$ at $4\text{--}5 \text{ J/cm}^2$ to around $20\text{-}\mu\text{m}/\text{scan}$ at 18 J/cm^2 . The respective removal rates for the Grengloo™ composite and enamel were 12 and $8\text{-}\mu\text{m}/\text{scan}$ at this fluence. In the occlusal surfaces damage to the underlying enamel is less critical and higher fluence rates can be used for more rapid removal of the composite.

Composite applied to tooth 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. Figure 5 shows two samples in which a layer of composite approximately 1-mm thick was 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. The zone of laser-irradiated enamel is shown in more detail in Figure 6. It is difficult to resolve changes in the irradiated enamel and at higher magnification it can be seen that there were some regions 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 $20\text{-}\mu\text{m}$. This depth was determined by scanning the image plane of the microscope to focus on both the surface and base of the craters using a calibrated micrometer. The average of two sites examined on each of the 10 teeth scanned by the laser indicated a mean depth of 16.3 ± 3.02 at the center of the Gaussian shaped laser spots. At higher magnification, Figure 7, it is obvious that the enamel irradiated by the laser has also undergone melting and

recrystallization without ablation in most areas. The characteristic worm like structures indicative of laser melting and recrystallization are clearly visible [29].

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 Figure 8. 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/cm² 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.

Composite was placed in the occlusal surfaces of 10 teeth and the temperature rise in the pulp chamber was monitored during composite removal. The mean temperature rise during the removal process for nine samples was $2.1 \pm 1.4^{\circ}\text{C}$ with a mean removal time of 21.6 ± 6.4 seconds. The maximum temperature rise measured was 3.5°C . One of the samples was rejected because the removal process was interrupted before complete removal was achieved. A second pass was carried out and the composite was completely removed.

DISCUSSION

In this study we demonstrated that composite could be rapidly removed from tooth surfaces with a high degree of selectivity with minimal heat deposition in the tooth. In previous studies we demonstrated that CO₂ lasers are promising for selective removal of composite from tooth surfaces; however, this is the first study to show that a CO₂ laser optimized for the efficient removal of dental hard tissue and caries, namely operating at a wavelength of 9.3- μm with a pulse duration between 10 and 20-microsecond could be used for the selective removal of composite. Moreover, this is the first study to show that composite could be removed safely at rates fast enough to be feasible for clinical use. In this study the laser was operated at approximately 200 Hz. This rate was limited by the processing time for analyzing the plume and higher removal rates are certainly feasible. It is likely that it will not be necessary to use a spectrometer for plume analysis. A much faster and more simplistic system involving two or three photodiodes should be suitable.

At an incident fluence of 3.2 J/cm² which we found optimal for smooth surfaces, removal was highly selective and damage to sound enamel 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- μm 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 to 17- μm depending on the material employed [30]. The enamel loss associated with the removal of filled composite after debonding orthodontic brackets was as high as 70- μm after multiple bonding and debonding procedures [30]. High-resolution optical microscopy showed that the underlying enamel had undergone melting and recrystallization. This surface

modification is advantageous since the modified enamel has an increased resistance to acid dissolution [31–33]. This surface layer with enhanced resistance to acid dissolution is also created at higher incident fluence as well [33,34]. This is an additional advantage of using the CO₂ laser for composite removal over other lasers systems such as the Er:YAG, Er:YSGG and the Frequency tripled Nd:YAG laser at 355-nm.

One disadvantage of employing a CO₂ laser for this procedure is that this laser has yet to receive FDA approval for hard tissue use, however systems are under development and it is anticipated that such approval may come in the near future.

Selective laser ablation is particularly advantageous for composite removal from the occlusal surfaces where the convoluted topography of the pits and fissures poses a challenge for composite removal by mechanical means. The occlusal pits and fissures are considered high risk surfaces for dental caries and the thermal modification of those surfaces by the CO₂ laser is desirable to render those sites more resistant to acid dissolution. One approach is to scan the CO₂ laser over the pits and fissures of the occlusal surface prior to placing sealants to further enhance the resistance to caries. If the sealants need to be removed due to failure, the same CO₂ laser can be used to remove the sealant and any decay that needs to be removed.

In addition to the removal of composite-based adhesives used for the bonding of orthodontic brackets and dental sealants and restorations, selective laser ablation is likely to work well for the repair of esthetic restorations.

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 [13,14,35,36]. Such pulses can remove up to 50-μm of enamel and 200-μm of dentin per shot [37] producing excessive damage to the underlying tooth structure [38]. Moreover, ablation is not selective at erbium wavelengths [13]. Optical plume analysis is better suited for femto-second and pico-second visible laser systems, UV laser systems, and TEA CO₂ laser systems operating at high pulse repetition rates with low or moderate rates of ablation. Such systems can be operated efficiently at repetition rates approaching a kHz with low ablation thresholds on composite.

We have shown in prior studies that composite ablation is more selective for 355-nm pulses from a frequency tripled Q-switch Nd:YAG laser than for the CO₂ laser and that composite can be removed with minimal damage to sound enamel without the need for spectral feedback at 355-nm [2,15,22]. However, a feedback mechanism is still needed to determine whether the composite has been completely removed and spectral feedback ensures that the minimal number of laser pulses are employed to remove the composite thus minimizing the heat deposition and the time needed for removal. In addition, the CO₂ laser can be used for several applications in dentistry including hard tissue ablation, caries ablative treatments and soft tissue surgery while it has not been established that a laser operating at 355-nm can be

used for any other important dental procedures. Moreover, a diode pumped solid state laser operating at 355-nm with high pulse repetition rates is expensive to manufacture and the 355-nm photons are in the UV and they are considered ionizing radiation.

The heat accumulation measurements taken using microthermocouples suggest that composite can be removed rapidly without excessive heat accumulation. The mean temperature rise was less than half the 5.5°C temperature rise that is considered excessive according to the Zach and Cohen study [39]. It is also important to note that the teeth were isolated so that there was poor heat flow from the tooth and there was no pulpal blood flow to cool the pulp. Therefore the measured temperature rise would be expected to be less *in vivo* for vital teeth. Moreover, the cooling water was at room temperature and the tap water typically used in the dental office is significantly cooler than room temperature which would further limit temperature excursions.

Niemz [6] suggests that spectral feedback can also be used to discriminate sound from decayed dental hard tissues; however, after extensive investigation of this approach utilizing several different laser systems we did not find spectral emission useful for discriminating between sound and demineralized dental hard tissues [10]. Hard tissue spectra are dominated by calcium emission lines and there is little difference in the chemical content between sound and demineralized dental hard tissues. There are differences in the mineral density, however this only influences the overall intensity of the emission. Image guided ablation is more feasible using near-IR imaging [4] and fluorescence [5] to demarcate areas of decay. In conclusion, this study has demonstrated that composite can be selectively removed from tooth surfaces at clinically relevant rates using a CO₂ laser operating at 9.3-μm with high pulse repetition rates with minimal heat deposition and damage to the underlying enamel.

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Fig. 1.

The experimental setup for selective ablation consists of (A) two galvanometers (XY axes), (B) water spray, (C) microthermocouples, (D) CO₂ laser beam, (E) tooth, (F) delrin sample mount, (G) ZnSe f-theta scanning lens, and (H) imaging optics for spectrometer.

Fig. 2. Plume emission spectra of dental enamel [E] and composite [C]. Note the higher intensity of emission from enamel, the common sodium emission line at 589-nm in both spectra and the strong calcium emission line at 605-nm in the enamel spectrum.

Fig. 3.
Flowchart outlining the sequence of steps required for selective ablation.

Fig. 4. Plot of the mean ablation rate ($\pm$ s.d.) for enamel (black squares) and composite (red circles) as a function of the incident fluence.

Fig. 5. Images of two tooth samples with GrenglooTM composite placed on the smooth buccal surfaces. The right half of the composite was removed via selective laser ablation. Images are shown before (A) and after laser irradiation (B).

Fig. 6. Optical micrographs of the enamel surface after composite removal at two magnifications. The bar in the top image is 1-mm and the bar in the lower image represents 250- μ m.

Fig. 7. Optical micrographs of the enamel surface after composite removal at 100 $\times$ magnification. The enamel surfaces irradiated by the laser appear glassy with worm-like structures that are indicative of melting and recrystallization.

Fig. 8. Images of two tooth occlusal surfaces taken before placement of composite (A), after placement of Grengloo™ composite (B), and after selective removal of the composite by the laser (C).