Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2012 February 9; 8208: 82080U-. doi:10.1117/12.914632.

Selective Removal of Demineralization Using Near Infrared Cross Polarization Reflectance and a Carbon Dioxide Laser

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Abstract

Lasers can ablate/remove tissue in a non-contact mode of operation and a pulsed laser beam does not interfere with the ability to image the tooth surface, therefore lasers are ideally suited for integration with imaging devices for image-guided ablation. Laser energy can be rapidly and efficiently delivered to tooth surfaces using a digitally controlled laser beam scanning system for precise and selective laser ablation with minimal loss of healthy tissues. Under the appropriate irradiation conditions such laser energy can induce beneficial chemical and morphological changes in the walls of the drilled cavity that can increase resistance to further dental decay and produce surfaces with enhanced adhesive properties to restorative materials. Previous studies have shown that images acquired using near-IR transillumination, optical coherence tomography and fluorescence can be used to guide the laser for selective removal of demineralized enamel. Recent studies have shown that NIR reflectance measurements at 1470-nm can be used to obtain images of enamel demineralization with very high contrast. The purpose of this study was to demonstrate that image guided ablation of occlusal lesions can be successfully carried out using a NIR reflectance imaging system coupled with a carbon dioxide laser operating at 9.3- μm with high pulse repetition rates.

Keywords

enamel; CO₂ laser; dental caries; demineralization; near-IR imaging; reflectance

1. INTRODUCTION

Several studies have demonstrated that carbon dioxide lasers operating at wavelengths of $\lambda = 9.3$ and $9.6\text{-}\mu\text{m}$ are ideally suited for the efficient ablation of dental caries and for surface treatments to increase the resistance to acid dissolution.¹⁻⁵ CO₂ lasers are capable of operating efficiently at high pulse repetition rates and the laser system can be combined with a laser beam scanning system for high-speed precision removal of dental caries.

New caries diagnostics can be used to identify early caries lesions, before they have spread extensively into the underlying dentin. For lesions of this magnitude, it is too early to use conventional restorations that require the removal of large amounts of healthy tissue. The

laser is ideally suited for selective micropreparation. It can be precisely focused into the carious fissure of a molar to remove any debris and bacteria, ablate away the demineralized enamel and enlarge the narrow neck of the fissure leaving a smooth crater. If the appropriate irradiation conditions are met, the walls will have enhanced resistance to acid dissolution^{6, 7}. A flowable composite can subsequently be applied for a highly conservative restoration. By taking this approach the dentist can intervene in a conservative manner before the lesion has progressed to the point that more invasive surgical intervention is necessary.

For high precision and selectivity, the laser must be controlled by an automated scanning system. Lasers have been used for many years for industrial marking and computer aided design/machining (CAD/CAM) and high-speed scanning systems are in routine use. It is practical to use high-speed computer controlled scanning systems with a compact delivery system to scan a laser over tooth surfaces to selectively remove either dental caries or composite restorative materials. Moreover, rapidly scanning the laser beam increases the ablation efficiency and delocalizes the heat deposition in the tooth to minimize thermal damage.

Selective ablation can be achieved by simply tuning the laser to a wavelength that has a lower ablation threshold for specific tissue components⁸⁻¹⁰. However, the mineral content of demineralized enamel is highly variable and it is often necessary to remove sound enamel to reach the underlying lesion. Therefore a more practical approach is to operate the laser with a wavelength and pulse duration that efficiently removes sound enamel, and employ some form of sensor, either optical, spectral or acoustic in nature that can be used to discriminate between sound and demineralized tooth structure and composite materials. We postulate that image-guided approaches are best suited for the selective removal of demineralized enamel and dentin and that spectral feedback will be most effective for the selective removal of composite^{11, 12}.

For selective removal, low energy pulses must be used to minimize the amount of tissue removed per laser pulse, therefore the laser has to be operated at high pulse repetition rates for practical removal rates. The flash-lamp pumped erbium solid-state lasers presently being used for dental hard tissue ablation are not suitable for this approach since they utilize high energy pulses and relatively low pulse repetition rates. Diode pumped Er:YAG lasers can achieve pulse repetition rates of 1–2 kHz¹³ and they should also work effectively for this approach. Transverse excited atmospheric pressure (TEA) and radiofrequency excited carbon dioxide lasers can be operated efficiently at high repetition rates at wavelengths that are coincident with the strongest absorption of dental hard tissues near $\lambda=9.3$ and $9.6\text{-}\mu\text{m}$ due to the phosphate ion in hydroxyapatite. Therefore, the irradiation intensities required for ablation of dental hard tissue are markedly lower at those wavelengths than for other laser wavelengths and are likely to lead to less accumulation of heat in the tooth for typical irradiation conditions. We have demonstrated that enamel and dentin can be most efficiently ablated using laser pulses of 10–20- μs duration^{5, 14, 15}. Another important advantage of CO₂ laser irradiation is that it also imparts improved morphological and chemical changes to dental hard enamel¹⁶ that increases resistance to acid dissolution and improves its adhesive properties for bonding to composite. Therefore, we chose to utilize a CO₂ laser operating at

9.3- μm with a pulse duration of 10–15- μs and a pulse repetition rate of 100–300-Hz for these studies.

Lasers can ablate/remove tissue in a non-contact mode of operation and a pulsed laser beam does not interfere with the ability to image the tooth surface, therefore lasers are ideally suited for integration with 2D and 3D imaging devices for image-guided ablation. Fluorescence and near-IR imaging systems offer the highest image contrast between sound and demineralized enamel and dentin and they can be readily interfaced with a computer controlled scanning-laser ablation system. Image-guided ablation of caries lesions on extracted teeth will be achieved using a 2D approach in which the laser is scanned over the designated lesion area after each image is acquired to remove the demineralized tissues one layer at a time. Previously we demonstrated that NIR transillumination at 1300-nm can be used to guide the laser for image guided ablation of occlusal caries¹⁷. This approach is appropriate for deeply penetrating lesions that produce high contrast, however occlusal transillumination does not provide sufficient contrast for shallow lesions. Recent studies show that the highest contrast for shallow lesions is provided by NIR reflectance at 1460-nm due to the increased water absorption^{18, 19}. The purpose of this study was to demonstrate image guided ablation using NIR reflectance measurements at 1460-nm.

2. MATERIALS AND METHODS

2.1 Samples

Noncarious, extracted teeth from patients in the San Francisco bay area were collected with approval from the UCSF Committee on Human Research, cleaned, sterilized with gamma radiation, and stored in a 0.1% thymol solution to preserve tissue hydration and to prevent bacterial growth. Teeth with early occlusal demineralization were selected via visual, tactile feedback, and cross polarization optical coherence tomography. Samples were glued down on orthodontic resin blocks for convenience in mounting and scanning. The occlusal demineralization was outlined in a 4 × 4 mm box with fiducial markings with a CO₂ laser, operating with a fluence of 42 J/cm² with a spot size around 300- μm .

2.2 Near Infrared (NIR) Reflectance Imaging

Light from a 1468-nm superluminescent diode with a bandwidth of 40-nm and a peak output of 14-mW, Model 1480 (Exalos, Langhorne, PA) was directed towards the occlusal surface through a broadband fused silica beamsplitter (1200–1600-nm). The reflected NIR light from the tooth was transmitted by the beamsplitter to a 320 × 240 element InGaAs SU320-KTSX camera from Sensors Unlimited (Princeton, NJ) with a Infinimite lens (Infinity, Boulder, Co) for image acquisition. Crossed polarizers were used to remove specular reflection (glare) that interferes with measurements of the lesion contrast.

2.3 Imaging and Laser Scanning

An industrial marking laser, Impact 2500 from GSI Lumonics (Rugby, UK) operating at a wavelength of 9.3 μm was used. The laser was custom modified to produce a Gaussian output beam (single spatial mode) with a pulse duration between 10–15- μs . This laser is capable of high repetition rates up to 500 Hz, and a fixed repetition rate of 200 Hz was used

for these experiments. The laser energy output was monitored using a power/energy meter, ED-200 from Gentec (Quebec, Canada). The laser beam was focused to a spot size of $\sim 300\text{-}\mu\text{m}$ using a planoconvex ZnSe lens of 125-mm focal length. 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 the sample surfaces.

The samples were air-dried for ~ 40 seconds prior to acquisition of NIR images of the occlusal surface of each tooth. During the contrast analysis of the NIR image, a 40 by 40 pixel box highlighting the region of interest (ROI) was positioned over the fiducial markings in the NIR picture; in this square area, the near infrared image contrast was normalized and a threshold value was chosen to demarcate areas of high contrast to be selected for image-guided removal. Threshold values were varied slightly due to the illumination intensity and tooth size and topography. Typical threshold values varied between 20–30% of the normalized contrast selected for removal; once the threshold value was chosen, a look-up table was created to designate areas of demineralization for image guided ablation. Samples were then mounted on a separate system for CO₂ laser ablation, and positioned precisely to match the same mounting orientation as the one used for NIR imaging. An incident fluence of 42 J/cm^2 (30 mJ per pulse) was used for ablation of the demineralized areas of the occlusal tooth surface defined by a lookup table. This tooth surface was scanned 20 times using the same lookup table before acquiring a new image and lookup table. This was repeated for the first five cycles to shorten the time taken to remove the demineralization due to the larger quantity of demineralization that had to be removed initially. After the 5th cycle of image guided ablation, the number of scans was reduced to 5 scans per cycle before acquisition of a new image and lookup table. This was done to enhance the selectivity by decreasing the ablation rate per iteration thereby increasing preservation of the sound tissue. In odd numbered scanning cycles, the beam position was shifted by $100\text{ }\mu\text{m}$ to the top left of the previous scanning cycle for more uniform removal. The process was repeated until the lesion was no longer visible at a threshold of 20%. A flow chart for each scanning cycle is shown in Fig. 1.

2.4 Cross-Polarization Optical Coherence Tomography

The cross-polarization system is Model IVS-3000-CP from Santec (Komaki, Aichi, Japan) and utilizes a swept laser source, Santec Model HSL-200-30, operating with a 30 kHz sweep rate. The Mac-Zehnder interferometer is integrated into the handpiece which also contains the microelectromechanical (MEMS) scanning mirror and the imaging optics. The handpiece body is $7 \times 18\text{ cm}$ 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 $11.4\text{ }\mu\text{m}$ (3 dB). The lateral resolution is $80\text{-}\mu\text{m}$ ($1/e^2$) with a transverse imaging window of $6\text{ mm} \times 6\text{ mm}$ and a measured imaging depth of 7-mm in air. The extinction ratio was measured to be 32 dB.

2.5 Polarized light microscopy

The blocks were serial sectioned to sections $\sim 200\text{-}\mu\text{m}$ thick using a linear precision saw, the IsoMet 5000 (Buehler, Lake Bluff, IL). Polarized light microscopy (PLM) was carried out

using a Meiji Techno RZT microscope (Saitama, Japan) with an integrated digital camera, Canon EOS Digital Rebel XT from Canon Inc. (Tokyo, Japan). The sample sections were imbibed in water and examined in the brightfield mode with cross polarizers and a red I plate with 500-nm retardation.

3. RESULTS AND DISCUSSION

The use of NIR reflective images for guiding ablation is demonstrated in Fig. 2 using 1470-nm illumination. Areas of demineralization appear whiter than the sound areas (Fig. 2b) for NIR reflectance. Areas of higher intensity in the ROI (red box) were identified by threshold and marked for ablation (highlighted white areas in Fig. 2c). The laser was scanned 5 times and the process was repeated until all the demineralization was removed. NIR images were acquired after every 5 scans. This tooth was scanned twenty times. Before and after OCT images show the amount of tissue removed and the PLM image shows that the areas of decay were removed.

More detailed results are provided for a second tooth shown in Figs. 3 to 5 which include the NIR images, areas targeted for ablation, visible images at each stage, OCT images before and after ablation, and PLM images after ablation and sectioning.

This study indicates that the NIR reflectance measurements at (1470-nm) provided high contrast for image-guided ablation of lesions in occlusal surfaces. The results were very promising and serial imaging was successful in guiding ablation for both shallow lesions localized to the outer half of enamel and more severe lesions penetrating to the dentin. One prior concern was that the roughness of the surface and the thermally induced optical changes caused by modification of the mineral phase of enamel by the laser might reduce the contrast of the lesions after the initial iterations of ablation. Thermally induced changes do interfere with OCT imaging²⁰. However, this did not appear to be as significant a problem for reflectance imaging. We did find that the rough edges of the laser incisions did have increased reflectivity which sometimes caused a spread in the area ablated as the depth increased. This phenomenon can be easily accounted for by not increasing the area to be ablated in subsequent images.

Water on the surface of the tooth did appear to reduce the image contrast of demineralization. It is well understood that the presence of water on the tooth surface and the degree of internal hydration of the tooth influence the contrast of caries lesions for most imaging modalities. In this study we addressed this problem by drying the tooth for a fixed time. Such an approach may not be practical if rapid caries removal is desired and additional studies with the drying step removed are warranted. The 1470-nm wavelength specifically targets water absorption and it is likely that this wavelength is particularly sensitive to hydration. This wavelength gave us the best contrast after surface drying but other wavelengths may give higher contrast for a “wet” tooth surface.

It appeared that demineralization was removed remarkably well with minimal residual demineralization in most areas although some issues did become apparent. Most occlusal lesions spread laterally as they progress down into the tooth. Therefore there is the likelihood for demineralized areas to be hidden well below the surface under sound enamel.

Such lesions may not show up well in reflectance images. Such areas should however be visible in NIR occlusal transillumination images. Such an example does appear in the PLM image shown in Fig. 5c(ii) where a small circular dark area appears well below the surface to the left of the ablated area, which is indicative of demineralization. It may be necessary to use both NIR reflectance and transillumination to remove all areas of demineralization.

A major objective of this work was to demonstrate the high selectivity of image-guided ablation. This requires the accurate measurement of the lesion volume before ablation. This is extremely challenging, even though we have demonstrated that OCT images can be used to measure the lesion volume before and after removal, this approach is not likely to be effective for areas of demineralization that penetrate much deeper than one mm. Highly scattering areas near the surface of the lesion can prevent resolution of the deeper layers of the lesion. One possible approach is to take multiple OCT images as ablation proceeds. It may be necessary to use X-ray tomographic imaging technique such as high-resolution μ CT in future studies to accurately measure the lesion volume prior to removal.

ACKNOWLEDGEMENTS

This work was supported by NIH/NIDCR Grants R01DE19631 and R01DE14698. The authors would like to acknowledge Dr. Michal Staninec, Hobin Kang and Cynthia Darling for their contributions.

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Fig. 1.
Flow chart for image guided ablation showing the steps involved in each cycle.

Fig. 2.

A tooth with an occlusal lesion shown before and after removal of demineralized enamel from the ROI outlined by the red box. (A) Visible and (B) NIR reflectance images (1470-nm) before removal. The ROI was analyzed and areas were marked for ablation in (C). After 20 passes the lesion was removed (D). Overlays of the OCT scans along the green dotted line in (A) are shown in (E) before (orange arrow) and after removal (yellow arrow). PLM image along green dotted line is also shown after removal (F).

Fig. 3.
(Top) NIR CP Reflectance images taken at 1470 nm during each ablation scanning cycle;
and (Bottom) the designated lesion area above threshold (yellow) in the ROI (red box) for
the six cycles required for complete removal.

Fig. 4.
Visible image taken after each ablation scanning cycle.

Fig. 5.

(A) Tooth before sectioning along the red (B) and blue (C) dotted lines matching the position of the pre-ablative OCT images (i) and the post-ablative PLM images (ii) and OCT images (iii).