Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2018 ; 10473: . doi:10.1117/12.2296028.

Image-guided Removal of Interproximal Lesions with a CO₂ Laser

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Abstract

Recent studies have shown that near-IR (NIR) imaging methods such as NIR reflectance can be used to image lesions on proximal surfaces, and optical coherence tomography (OCT) can be used to measure the depth of those lesions below the tooth surface. These imaging modalities can be used to acquire high contrast images of demineralized tooth surfaces, and 2-D and 3-D images can be extracted from this data. At NIR wavelengths longer than 1200-nm, there is no interference from stains and the contrast is only due to the increased light scattering of the demineralization. Previous studies have shown that image-guided laser ablation can be used to remove occlusal lesions, but its use for the removal of subsurface lesions on proximal surfaces has not been investigated. The objective of this study is to demonstrate that simultaneously scanned NIR and CO₂ lasers can be used to selectively remove natural and artificial interproximal caries lesions with minimal damage to sound tooth structure. In this study, images of simulated and natural interproximal lesions on extracted teeth were imaged using a digital microscope, a scanned 1460-nm superluminescent laser diode with an InGaAs detector and a cross polarization OCT system operating at 1300-nm. The lesions were subsequently removed with a CO₂ laser operating at 9.3- μ m and the dental handpiece and the volume of sound tissue removed was compared.

Keywords

caries removal; near-IR reflectance imaging; image-guided laser ablation

1. INTRODUCTION

Recent studies have demonstrated that in addition to being able to acquire high contrast images of occlusal demineralization with extremely high contrast [1, 2], interproximal lesions well below the surface can be imaged *in vivo*[3]. Therefore, NIR imaging can be potentially used to guide lasers for the removal of lesions on tooth proximal surfaces. This technology holds considerable advantages over conventional caries detection methods, namely it produces images with greater contrast for differentiating demineralization from sound tissue. In addition, stains do not interfere at NIR wavelengths beyond 1200-nm so that only demineralization can be targeted [4, 5]. In visible reflectance and quantitative light fluorescence, stains often mask demineralization. In the NIR, the large conjugated molecules associated with stains do not absorb light. Thus, NIR reflectance is capable of rendering high contrast images of demineralization even in the presence of stains. In combination with computer-controlled laser scanning systems, NIR reflectance images can be transcribed into ablation maps for precise demineralization removal and in a previous paper presented last

year NIR light at 1450-nm was used to guide the removal of lesions from tooth occlusal surfaces [6].

Lasers are well suited for minimally invasive dental hard-tissue treatments. They can achieve precise removal with small laser pulse spot sizes to reach demineralization localized on tooth pits and fissures. CO₂ lasers ($\lambda = 9.3\text{--}9.6\text{-}\mu\text{m}$) have been shown to be well suited for caries removal and CO₂ laser pulses can be used to render dental enamel to be more resistant to further decay [7]. Previous work was done to show that the laser irradiated enamel does not interfere with the ability to image the tooth surface at near-IR wavelengths nor significantly distort the contrast between sound and demineralized dental hard tissues [8]. Typical dental lasers are operated by hand, which nullifies their capacity for high precision and selectivity. Therefore, it is advantageous to employ a computer controlled scanning system to control the laser. High speed scanning systems using micro-electro-mechanical system (MEMS) mirrors and miniature galvanometer based scanners coupled with high repetition rate lasers can reach feasible removal rates. Thus, it is practical to employ a high-speed computer-controlled laser scanning system with a non-invasive caries lesion detection for removing demineralization in a highly conservative manner. Prior studies demonstrated the feasibility of removing demineralization by sequentially imaging carious teeth with an NIR InGaAs camera as the CO₂ laser removes the lesion layer by layer [9, 10].

Previous NIR reflectance caries removal studies have relied on using expensive InGaAs cameras for imaging, however, lower cost laser diodes and photodetectors are now available at most wavelengths in the NIR and these can be used with laser scanners to produce similar NIR images. A point-to-point NIR scanner can be integrated with a CO₂ laser into a combined real-time image-guided system as a cheaper alternative for selective caries removal. This integrated system is particularly advantageous as it overcomes the challenges of aligning the imaging and laser ablation systems. In this study, we developed an integrated point-to-point scanning system to simultaneously identify and remove caries lesions.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Posterior teeth with sound interproximal surfaces were selected for participation in this study. Teeth were collected from patients in the San Francisco Bay area with approval from the UCSF Committee on Human Research. The teeth were sterilized using gamma radiation and stored in 0.1% thymol solution to maintain tissue hydration and prevent bacterial growth. A high-speed dental hand piece and #34D diamond burr was used to drill an artificial cavitated lesion into the interproximal surface of ten samples at the mesial or distal contacts. Cavities were subsequently filled with powdered hydroxyapatite and sealed with cyanoacrylate adhesive Loctite (Rocky Hill, CT) to create simulated lesions. The grain boundaries of the hydroxyapatite powder highly scatter light in a similar fashion to the porosities in caries lesions.

Three teeth with natural interproximal lesions were also selected via visual inspection, tactile feedback, and cross-polarized near-infrared reflectance at 1500–1700-nm. Tooth

samples were attached to orthodontic resin blocks for convenience in mounting and scanning.

2.2 Integrated CO₂ Laser and Near-IR Point-to-Point Imaging System

A diagram of the system is shown in Fig. 1. An RF-excited laser, Diamond J5-V from Coherent (Santa Clara, CA) operating at a wavelength of 9.3- μm was used with a pulse duration of 26- μs and a pulse repetition rate of 100-Hz. The laser had a Gaussian output beam. The laser energy output was monitored using a power/energy meter, ED-200 from Gentec (Quebec, Canada). The beam profile was imaged using a Pyrocam Beam profilometer from Ophir-Spiricon (Logan, UT). A room temperature HgCdTe detector Boston Electronics PD-10.6-3 (Boston, MA) with a response time of a few nanoseconds was used to measure the laser pulse temporal profile. The laser beam was focused to a beam diameter of 200- μm using a ZnSe lens of 100-mm focal length. A razor blade was scanned across the beam to determine the diameter ($1/e^2$) of the laser beam. The incident fluence was 30 J/cm², which removes ~30- μm of sound enamel per pulse. Computer-controlled XY motion control system ESP-301 and UTM150 stages from Newport (Irvine, CA) were used to create controlled movements of the samples during laser irradiation. A pressure air-actuated fluid spray delivery system consisting of a 780S spray valve, a Valvemate 7040 controller, and a water reservoir from EFD, Inc. (East Providence, RI) was used to provide a uniform spray of fine water mist (5 ml/mm) onto the tooth surfaces.

Linearly polarized and collimated 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 combined with the CO₂ laser beam using a beamsplitter and focused with the same 100-mm focal length ZnSe lens onto the occlusal tooth surface. A near-IR InGaAs photodiode detector (Thorlabs, Newton, NJ) was used to collect backscattered NIR light from the occlusal surface. A near-IR polarizer was placed before the detector to remove specular reflection that interferes with the measurements of the lesion contrast.

2.3 PS-OCT System (OCT)

An all-fiber-based optical coherence domain reflectometry (OCDR) system with polarization maintaining (PM) optical fiber, high-speed piezoelectric fiber-stretchers and two balanced InGaAs receivers was designed and fabricated by Optiphase, Inc., Van Nuys, CA. This two-channel system was integrated with a broadband superluminescent diode (SLD) Denselight (Jessup, MD) and a high-speed XY-scanning system (ESP 300 controller and 850G-HS stages, National Instruments, Austin, TX) for rapid *in vitro* optical coherence tomography acquisition. The spectral output of the 15-mW SLD was centered at 1317 nm with a spectral bandwidth full-width at half-maximum (FWHM) of 84 nm. This configuration provided a lateral resolution of approximately 20 μm and an axial resolution of 10 μm in air. The system is described in greater detail in reference [11]. PS-OCT, specifically cross-polarization scans, were used to assess the presence of occlusal lesions and volume of tissue removed by the laser.

2.4 Imaging, Processing, and Lesion Removal

Initial NIR images and OCT images were acquired of the simulated lesions. The depth from the occlusal surface of the interproximal lesion could be clearly seen in the initial OCT images (see Figs. 2C and 3C). That depth indicates how deep to cut through the enamel to reach the subsurface lesion. NIR images were acquired over an area 10×10-mm with a 50-μm pixel pitch. The backscattered NIR intensity at each point was averaged over 10 acquisitions to eliminate noisy data. Points were rasterized into an 8-bit near-IR image. Highly scattering demineralized surfaces appear brighter in the NIR reflectance images, while sound tissues appear dark. Lesion pixels were designated for removal by analysis of the image histogram and the distribution of intensities as described in our previous paper presented last year [6]. Examples of designated pixel areas are shown outlined in red in Figs. 2B and 3B. Initially iterations of 8 laser ablation scans followed by repeated NIR image acquisition were carried out until reaching the lesion. After reaching the lesion a 2nd OCT scan was taken and iterations of 4 laser ablation scans were applied followed by repeated NIR image acquisition until the lesion was removed. Then a final OCT scan was taken upon lesion removal. Visible images were taken of the exposed proximal surfaces before and after removal.

In order to replicate the clinical environment during the removal of the simulated lesions using the handpiece, an adjacent tooth was positioned at the contact so that the proximal surface was not visible. NIR, Visible, and OCT images were taken before and after removal. Radiographs were taken prior to removal and the clinician was only given access to the radiographs prior to removal and was not shown the NIR or OCT images.

The same iterative process that was used for the simulated lesions was used for removal of the three natural lesions by the laser system.

The volume of enamel lost during the removal process and the residual lesion volume remaining was calculated by comparing the before and after volumetric OCT scans using Avizo (FEI, Hillsboro, OR) software. Avizo was also used for registration of the before and after images using the surface topography of the tooth. The mean volume of enamel lost and the residual volume of lesion remaining were compared using a paired t-test.

3. RESULTS AND DISCUSSION

The first group of ten samples investigated contained simulated lesions. Five samples were removed using the laser system and five were removed using the dental handpiece. Figure 2 shows visible, NIR and CPOCT images taken before and after removal for two examples, the first using the handpiece and the second with the laser. Visible images of the exposed proximal surface are shown in A and A', before and after removal of the lesion. For laser removal samples, all traces of the lesion have been removed; however, for the handpiece samples, part of the lesion (hydroxyapatite) is still present. NIR reflectance images taken from the occlusal surface are shown in B and B' before and after removal of the lesion. The red highlighted area represents the area designated for laser removal. A comparison of the B' images for the handpiece and laser removal also shows that a large portion of the lesion remains for the handpiece samples while the lesion has been completely removed during the

laser procedure. CP-OCT b-scan images are shown in C and C' while surface rendering of the 3D CP-OCT scans are shown in D and D' before and after removal of the lesion. The position of the lesion below the occlusal surface can be clearly seen in the OCT scans and the before and after scans in C and C' best show how complete lesion removal is. The C' image for the handpiece indicates that about half the lesion remains after removal while there is no residual reflectivity evident in the C' image for laser removal.

The second group of samples investigated contained natural lesions. Three samples were removed using the laser system. Figure 3 shows visible, NIR and CP-OCT images taken before and after removal for one of the samples. The interproximal lesion can be clearly seen in B and the area designated for laser removal is highlighted in red. There is also a large occlusal lesion visible on this tooth that was not removed in this study. The CP-OCT images indicate that the interproximal lesion was completely removed. The volume of enamel removed and the volume of the residual lesion remaining after removal is plotted in Fig. 4 for comparison for the ten simulated lesions samples, Group 1. The volume of enamel removed was higher for the handpiece compared to the laser, $5.94 \pm$ vs. $4.29 \pm \text{mm}^3$, but the difference was not significant ($P>0.05$). The volume of the lesion remaining after removal was significantly higher for the handpiece compared to the laser, $0.99 \pm$ vs. $0.21 \pm \text{mm}^3$, ($P<0.05$).

We had anticipated that the volume of enamel removed would be significantly higher for the handpiece vs. the laser since the operator of the handpiece has only seen the radiograph and does not have specific knowledge of the margins of the lesion before drilling. In contrast, the laser process is automated so that only the enamel that is directly above the lesion is removed to reach the underlying lesion. We did not anticipate that the volume of the lesion remaining with the handpiece would be significantly larger than for laser removal. This obviously skewed the results for the comparison of the volume of enamel removed. It is likely that if one takes into account the additional volume of enamel that needs to be removed to reach the remaining lesion areas not removed for the handpiece, the volume of enamel removed would be significantly larger for the handpiece.

The NIR reflectance images were only used for automated removal by the laser but it would be interesting to explore how useful they could be for improving the selectivity of removal with the handpiece. In summary, the image-guided laser ablation was more efficient in removing the lesions than the traditional dental handpiece. This pilot study clearly shows that NIR image-guided ablation has potential for improving the selectivity of removal of lesions on proximal surfaces.

Acknowledgments

This work was supported by NIH/NIDCR Grants R01-DE019631 and F31-DE026350.

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Fig. 1.

Combined point-to-point NIR image-guided caries ablation system: (A) CO₂ laser; (B) beam dump; (C) near-IR diode (1450-nm) w/ collimator & polarizer; (D) beamsplitter; (E) ZnSe focusing lens; (F) NIR InGaAs photodiode w/ polarizer; (G) tooth sample; (H) XY motion stages; (I) water-/air-spray; (Blue line) CO₂ laser; (Red line) NIR light.

Fig. 2.

Visible images before (A) and after (A') removal of the simulated interproximal lesions, NIR reflectance images at 1450-nm before (B) and after (B') removal, and CP-OCT b-scans (C) and rendered 3D images (D) before and after removal. The top eight images were removed with the handpiece and the bottom eight images were automatically removed with the laser. The red highlighted area in the NIR image in (B) for laser removal is the area designated for removal.

Fig. 3.

Visible images (A), NIR reflectance images at 1460-nm (B), CP-OCT b-scans (C) and rendered 3D CP-OCT images (D) of a natural interproximal lesion before and after removal with the CO₂ laser. The red highlighted area in the NIR image in (B) for laser removal is the area designated for removal.

Fig. 4.
 (top) The mean volume of enamel lost and (bottom) the residual lesion volume remaining after the removal of the simulated lesions, n=4 per group. Bars of same color are statistically similar, $P > 0.05$.