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Selective Removal of Natural Occlusal Caries by Coupling Near-infrared Imaging with a CO₂ Laser

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Abstract

Laser removal of dental hard tissue can be combined with optical, spectral or acoustic feedback systems to selectively ablate dental caries and restorative materials. Near-infrared (NIR) imaging has considerable potential for the optical discrimination of sound and demineralized tissue. Last year we successfully demonstrated that near-IR images can be used to guide a CO₂ laser ablation system for the selective removal of artificial caries lesions on smooth surfaces. The objective of this study was to test the hypothesis that two-dimensional near-infrared images of natural occlusal caries can be used to guide a CO₂ laser for selective removal. Two-dimensional NIR images were acquired at 1310-nm of extracted human molar teeth with occlusal caries. Polarization sensitive optical coherence tomography (PS-OCT) was also used to acquire depth-resolved images of the lesion areas. An imaging processing module was developed to analyze the NIR imaging output and generate optical maps that were used to guide a CO₂ laser to selectively remove the lesions at a uniform depth. Post-ablation NIR images were acquired to verify caries removal. Based on the analysis of the NIR images, caries lesions were selectively removed with a CO₂ laser while sound tissues were conserved. However, the removal rate varied markedly with the severity of decay and multiple passes were required for caries removal. These initial results are promising but indicate that the selective removal of natural caries is more challenging than the selective removal of artificial lesions due to varying tooth geometry, the highly variable organic/mineral ratio in natural lesions and more complicated lesion structure.

Keywords

image-guided laser ablation; near-infrared imaging; CO₂ laser; selective caries removal; polarization sensitive optical coherence tomography

2. INTRODUCTION

New optical caries imaging systems have been recently developed that are ideally suited to interface with lasers for the selective removal of dental caries. The most promising caries imaging systems employ fluorescence and near-IR imaging methods, including quantitative light fluorescence (QLF)¹, near-IR fluorescence², polarization sensitive-optical coherence tomography (PS-OCT)^{3–5} and near-IR (NIR) imaging^{4,6,7}. These imaging systems can be

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used for the acquisition of 2-D or even 3-D images of tooth demineralization on proximal and occlusal surfaces. 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. Other approaches involving acoustic and spectral feedback have already demonstrated that lasers can be scanned over tooth surfaces to remove dental composite and pigmented caries using acoustic and spectral feedback to differentiate these materials from sound enamel^{8,9}. However, these approaches proved to be unsuccessful for non-pigmented caries⁹. In this paper we have coupled NIR and PS-OCT imaging of simulated caries lesions with a high-speed scanning CO₂ laser ablation system to demonstrate that demineralized enamel can be imaged with high contrast and selectively removed by the laser.

Fluorescence based caries imaging and detection methods have been under development for more than 20-years and commercial systems such as QLF and the Diagnodent are readily available. KavoTM (Biberach, Germany) which sells the DiagnodentTM and Er:YAG laser systems has recently introduced an Er:YAG laser hand-piece with an integrated fluorescence feedback system¹⁰. The operator can monitor the fluorescence signal to determine when all the caries have been removed. Although this is a significant step forward, the fluorescence signal is non-localized and can arise from stains in the pits and fissures and does not correlate with the mineral loss. Therefore such an approach is not promising for integration with a scanning system.

At the wavelength of 1300-nm in the near-IR, healthy enamel appears transparent and does not strongly scatter light whereas demineralized enamel and carious lesions manifest reduced transmission and strong light scattering respectively¹¹. Therefore, demineralized enamel can be imaged with high contrast for discrimination from healthy enamel. NIR imaging can be used to acquire 2-D images of demineralized enamel on proximal and occlusal surfaces while PS-OCT is capable of acquiring depth-resolved images of demineralization so that 3-D images can be generated. The polarization sensitivity is necessary to remove the strong surface reflections from tooth surfaces for higher contrast images of demineralized areas³. These near-IR imaging methods can also be used to image demineralized enamel under composite for removal of secondary caries lesions⁵.

Last year we successfully demonstrated that near-IR images can be used to guide a CO₂ laser ablation system for the selective removal of artificial caries lesions on smooth surfaces¹². Patterned artificial lesions were generated with acid resistant varnish protecting the sound tissues before submersion of samples in a demineralization solution for 9 days (see Fig. 1). The image-guided laser ablation process was divided into three phases: image acquisition, analysis and treatment. NIR and PS-OCT images are used to generate optical maps of the caries lesions. In turn, the optical maps translated the NIR images into instructions to implement a computer-controlled CO₂ laser system to selectively remove lesions at a uniform depth. Our pilot study successfully demonstrated that near-IR imaging can be used to guide a CO₂ laser ablation system for the selective removal of dental caries and the next step is to apply this novel approach to natural occlusal lesions and the objective of this study was to test the hypothesis that two- dimensional near-infrared images of natural occlusal caries can be used to guide a CO₂ laser for selective removal.

3. MATERIALS AND METHODS

1.1 Near Infrared Imaging (near-IR)

Each sample was imaged using 1310-nm light using the system described in reference¹³. Light from a single-mode fiber-pigtail coupled to a 1310-nm superluminescent diode (SLD) with an output power of 15-mW and a 35-nm bandwidth, Model SLED1300D20A (Optospeed, Zurich, Switzerland), was coupled to a 20-mm NIR fiber-collimator (μ LS Micro Laser Systems, Garden Grove, CA). Samples were placed in the 20-mm collimated beam between the light source and imaging system with the enamel side facing the camera. We found that broadband SLDs were advantageous to avoid speckle. An InGaAs focal plane array (FPA) (318×252 pixels) the Alpha NIRTM (Indigo Systems, Goleta, CA) with an InfinimiteTM video lens (Infinity, Boulder, CO) was used to acquire all the images. The acquired 12-bit digital images were analyzed using IRVistaTM software (Indigo Systems, Goleta, CA). Areas of demineralization appear opaque in the NIR images.

1.2 Polarization Sensitive Optical Coherence Tomography (PS-OCT) Systems

An all single-mode fiber autocorrelator-based Optical Coherence Domain Reflectometry (OCDR) system with polarization switching probe, high efficiency piezoelectric fiber-stretchers and an InGaAs receiver that was designed and fabricated by Optiphase, Inc., Van Nuys, CA was used for these measurements. A description of the scanning autocorrelator is described in reference¹⁴. The OCDR was integrated with a broadband high power superluminescent diode (SLD) (Denselight, Jessup, MD) with an output power of 45-mW and a bandwidth of 35-nm and a high-speed XY-scanning system (ESP 300 controller & 850G-HS stages, National Instruments, Austin, TX) for in vitro optical tomography. The probe was designed to provide a spot diameter of 50-3m for each scan. Additional details of this system are described in references^{14,15}.

1.3 Ablation apparatus

A transverse excited atmospheric pressure (TEA) CO₂ laser, Impact 2500 (GSI Lumonics, Rugby, United Kingdom) operated at 9.3 μ m, was used to irradiate tooth samples with a fluence of 12 J/cm², and an energy of 14 mJ per pulse and a pulse duration of 16 μ s. The laser energy was calibrated and measured using a laser energy/power meter, EPM 1000, Coherent-Molelectron (Santa Clara, CA) with a ED-200 Joulemeter from Gentec (Quebec, Canada). The laser was focused with a planoconvex ZnSe lens of 100-mm focal length to a beam diameter of approximately 356- μ m. The laser beam diameter ($1/e^2$) at the position of irradiation was determined by scanning with a razor blade across the beam. Two and three dimensional images of the laser spatial profile was acquired using a Spirocon PyrocamTM I pyroelectric array (Logan, UT). Both laser beam profile and spatial profile showed that the laser was operated in a single spatial mode, Gaussian spatial beam. Incisions were produced by scanning the laser in spots spaced at 60- μ m intervals, each spot receiving 20 pulses at a repetition rate of 150-Hz. A computer-controlled stage was used to create controlled movement of the samples for the incisions. 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 enamel surfaces at 2 mL/min.

1.4 Experimental procedures

Selective removal was accomplished in six distinct steps described in the flow chart below in Fig. 2.

Step 1: Select samples with occlusal caries and identify area of interest—

Extracted human molars with occlusal caries were selected. A $3 \times 3 \text{ mm}^2$ area of interest enclosing both carious and sound tissue were identified. The area of interest was outlined on the sample using a CO₂ laser, Fig 3.

Step 2: Capture pre-ablation images—Pre-ablation NIR and PS-OCT images were captured, Fig. 3. In NIR images, lesion areas appeared more opaque than sound tissue due to decreased transmission of light and increased light scattering at the lesion site. Twenty cross-sectional scans of PS-OCT images were acquired across each sample (optical cross-sections) to provide depth-resolved images of lesion areas. In PS-OCT images, lesion areas manifested high reflectivity due to the higher scattering from the porous demineralized lesion areas.

Step 3: Image analysis—An image processing module was developed using Matlab program to analyze the 12-bit NIR images. A gray-scale NIR image with the dimension of $M \times N$ pixels is represented as an M by N matrix containing values from 0 to $2^{12}-1$. The number zero represents black while the number $2^{12}-1$ represents white. Given the matrix representation of the gray-scale image, an NIR output was reconstructed as a 3D graph (Fig. 4) with the x and y coordinates identifying the position of the pixel and the z coordinate representing the gray-scale value of each pixel. An appropriate threshold was set to distinguish between the sound and lesion areas based on the original gray scale values.

Step 4: Generate optical maps—Based on the appropriate threshold, the image processing module traversed through each pixel of the image to identify the pixel as sound or demineralized. When the z value was less than or equal to the threshold, the tissue was classified as part of the lesion (Fig. 4, 5) and was demarcated for selective ablation in the treatment phase. In contrast, when the z value was greater than the threshold, the pixel was marked as sound tissue and would be omitted from ablation. From the initial $M \times N$ matrix of the gray-scale image with values ranging from 0 to $2^{12}-1$, the image processing module translated the NIR image to a binary $M \times N$ matrix, namely the optical map containing either value of 0 or 1. The optical maps provided instructions to the laser ablation system to differentiate between sound and demineralized tissue and, the laser system subsequently utilized this information to achieve selectively removal of the caries tissues, Fig. 5.

Step 5: CO₂ laser programmed to selectively ablate the carious lesions—A Labview™ program (National Instruments, Austin TX) utilized the optical maps as the input parameters, and controlled the laser and scanning system to scan the samples across the laser beam. Depending on the value in the optical maps, the laser would either ablate or take no action at a given pixel. Each pixel position was separated by approximately 50 μm apart. Figure 6 demonstrated the simulated laser ablation generated by the image analysis module and compared simulated ablation to the result of the ablation.

Step 6: Post-ablation NIR images—Post-ablation NIR images were captured to assess the selectivity of caries removal.

4. RESULTS

Visible reflected light images and near-IR images of the three surfaces before and after laser ablation are shown above in Figs. 7 & 8. Comparing the pre-ablation and post-ablation images, the results show that selective removal of occlusal caries by combining NIR imaging with a CO₂ laser ablation system is feasible. Most carious tissue was removed while sound tissues were conserved. Furthermore, this approach can also be used to remove hidden lesions below the sound enamel surface. For example, a large portion of the lesion of sample# 1 was located under sound enamel which was clearly evident from the PS-OCT pre-ablation images (Fig. 3, CS3). The component of the lesion below the sound enamel was also selectively removed as can be seen in the NIR pre-ablation and post-ablation images. We found that multiple passes were required to achieve removal of carious tissue from the designated areas of samples# 2 & 3. This was due to either the pooling of the cooling water in the ablation crater or the highly variable state of mineralization of the enamel in the lesions. However, removal was successfully achieved with only one pass for sample# 1.

5. DISCUSSION

These initial results are promising but indicate that the selective removal of natural caries is more challenging than the selective removal of artificial lesions due to varying tooth geometry, the highly variable organic/mineral ratio in natural lesions and more complicated lesion structure. More work is required to validate this approach and to design a clinically feasible image-guided ablation system. The caries removal rate varied quite markedly with the severity of demineralization, therefore a more iterative approach that employs multiple passes with repeated imaging between passes is likely to be required. We found that one advantage of the image-guided approach employing a CO₂ laser is that it is capable of efficiently ablating sound enamel over other methods that require preferential absorption by caries pigmentation and that caries located below sound enamel can be removed. Further studies will explore this approach and utilize the 3-D imaging capabilities of optical coherence tomography.

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Fig. 1. Artificial lesions on enamel smooth surfaces can be selectively removed by a CO₂ laser through a combination of NIR imaging and a computer controlled scanning system.

Fig. 2.
Flowchart for selective removal.

Fig. 3. Area of interest selection and pre-ablation NIR and selected PS-OCT images of sample #1. Subsurface lesions were observed in PS-OCT cross-section CS3 shown on lower right.

Fig. 4. False color 3-D representation of the gray-scale NIR image and threshold determination based on the gray scale level.

Fig. 5.
Optical maps generation based on an appropriate threshold that are used to distinguish caries from sound tissue.

Fig. 6.
Simulated ablation based on optical maps and comparison with the ablation result.

Fig. 7.

Visible reflected light images of the three surfaces before and after laser ablation.

Fig. 8.
Near-Infrared (NIR) images of the three surfaces before and after laser ablation.