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Serial removal of caries lesions from tooth occlusal surfaces using near-IR image-guided IR laser ablation

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Abstract

Previous studies have established that caries lesions can be imaged with high contrast without the interference of stains at near-IR wavelengths greater than 1300-nm. It has been demonstrated that computer controlled laser scanning systems utilizing IR lasers operating at high pulse repetition rates can be used for serial imaging and selective removal of caries lesions. In this study, we report our progress towards the development of algorithms for generating rasterized ablation maps from near-IR reflectance images for the removal of natural lesions from tooth occlusal surfaces. An InGaAs camera and a filtered tungsten-halogen lamp producing near-IR light in the range of 1500–1700-nm were used to collect crosspolarization reflectance images of tooth occlusal surfaces. A CO₂ laser operating at a wavelength of 9.3- μ m with a pulse duration of 10–15- μ s was used for image-guided ablation.

Keywords

light scattering; enamel; near-IR imaging; selective laser ablation

1. INTRODUCTION

Recent studies have shown that near-IR (NIR) reflectance imaging at 1450-nm and 1500–1700-nm can be used to acquire images of enamel demineralization with very high contrast [1, 2]. NIR reflectance is a new caries detection technique that has considerable advantages over conventional caries detection methods, namely it is non-invasive (it uses harmless NIR light), has greater sensitivity in elucidating demineralization, and lacks interference from stain [3–5]. Stains often interfere with visible reflectance and QLF assessment of demineralization, but are not visible in the NIR since pigmented organic molecules poorly absorb NIR light. Therefore, NIR reflectance can generate high contrast images that can delineate sound tissue from demineralization. NIR imaging not only facilitates caries diagnosis, but could also be developed into a computer automation system for caries removal.

Lasers can be operated at high pulse repetition rates and scanned at high speeds using micro-electromechanical system (MEMS) mirrors and miniature galvanometer based scanners.

Lasers can ablate tissue in a non-contact mode of operation and a pulsed laser beam does not interfere with the ability to image the tooth surface nor significantly distort the contrast between sound and demineralized dental hard tissues. Thus, an integrated system combining a rapid laser scanner with a caries lesion detection imaging modality, for instance NIR reflectance, is feasible for removing demineralization in a highly conservative manner at clinically applicable rates.

Lasers have been previously integrated with caries detection technologies including fluorescence [6–8] and near-IR transillumination [9]. In an earlier study, we imaged carious teeth with NIR reflectance and used a CO₂ laser system to remove naturally occurring caries lesions on the occlusal surfaces of teeth *in vitro* [10]. CO₂ lasers ($\lambda = 9.3\text{-}\mu\text{m}$) operating with laser pulses 10–15- μs are well suited for caries removal [9, 11–13]. A major factor contributing to the subjectivity of automated image-guided removal of caries heavily relies on the operator's caries assessment of the NIR image. Previous NIR reflectance caries removal studies have relied on manual caries segmentation in each NIR image acquisition [10, 14]. New NIR reflectance imaging analysis protocols are required before an integrated caries removal system will be acceptable for clinical use. There are several challenges in creating maps of demineralization for guiding the laser from NIR reflectance images. Teeth have highly convoluted topography particularly in the occlusal surfaces and caries lesions lack any distinguishable shape or contour to be processed using conventional pattern recognition algorithms. Demineralization can encompass an entire occlusal surface of the tooth, be localized to a single spot, or hidden well below the surface. There is also considerable interference from developmental defects which are almost indistinguishable from demineralization due to caries. In this study we focused on the algorithm used for the segmentation of NIR images used to guide an IR laser for the removal of natural occlusal lesions.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Extracted teeth from patients in the San Francisco bay area were collected, cleaned, sterilized with gamma radiation, and stored in a 0.1% thymol solution to preserve tissue hydration and to prevent bacterial growth. Teeth with carious lesions were selected via visual inspection, tactile feedback, and cross-polarized near-infrared reflectance. Tooth samples were attached to orthodontic resin blocks for convenience. The occlusal demineralization was demarcated within a $5 \times 5\text{-mm}$ fiduciary box was cut using a CO₂ laser around selected pits and fissures with suspected lesions. The laser beam was focused to a spot size around 200- μm and an incident fluence of 20 J/cm² was used.

2.2 Laser Irradiation

An industrial marking laser, Impact 2500 from GSI Lumonics (Rugby, UK) operating at a wavelength of 9.3- μm was used to ablate lesion areas. 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 100 Hz was used for the following experiments. The laser beam was focused to a spot size

of ~350- μm using a planoconvex ZnSe scanning 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. 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 onto the tooth surfaces. Samples were held in place using exchangeable magnetic mounts which aided in maintaining the sample's positioning between the ablation and imaging systems.

2.3 Cross Polarization Reflectance Images (NIR)

In order to acquire reflected light images, linearly polarized, collimated light from a 150-W fiber-optic illuminator, Model FOI-150 from the E. Light Company (Denver, Colorado) was used to illuminate the samples at an incident angle of 30° . Polarizers were placed after the light source and before the detector to remove specular reflection (glare) that interferes with measurements of the lesion contrast. The NIR reflectance images were captured using a 12-bit 320×240 element InGaAs area camera SU320-KTSX from Sensors Unlimited (Princeton, NJ) sensitive from 900–1700-nm with a 25- μm pixel pitch. The camera was equipped with a Model SWIR-35 lens from Navitar, Inc. (Rochester, NY). Reflectance measurements were taken with a 1500-nm long-pass filter, Model FEL 1500 from Thorlabs (Newton, NJ). Samples were set onto exchangeable magnetic mounts to ease its transition between imaging and ablation systems, and eliminate user-error.

2.4 Digital Microscopy

Tooth surfaces were examined after laser irradiation using an optical microscopy/3D surface profilometry system, the VHX-1000 from Keyence (Elmwood, NJ) with a VH-Z25 magnification lens. Depth composition digital microscopy images (DCDM) were acquired by scanning the image plane of the microscope and reconstructing a depth composition image with all points at optimum focus displayed in a 2D image. 3D images of the samples were acquired before and after ablation at $50\times$. The Keyence 3-D shape measurement software, VHX-H3M, was used to correct the tilt of the sample.

2.5 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 *in vitro* optical coherence tomography. 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 [15]. The PS-OCT, specifically cross-polarization scans, were used to confirm the presence of the occlusal lesions.

2.6 Imaging, Processing, and Caries Removal

A summary of the steps of the proposed algorithm is shown in Fig. 1. Each step of the algorithm is discussed below.

Samples were air-dried for ~20 seconds prior to acquisition of NIR images of the occlusal surface of each tooth. During the image processing analysis of the NIR image, a 103 by 103 pixel box highlighting the region of interest (ROI) was positioned over the fiducial box in the NIR image.

Prior to image acquisition, NIR reflectance images of a barium sulfate reference (99% reflectivity) were taken to produce a suitable reference for non-uniformity correction of the illumination source. The reference image A was normalized under its maximum value to a double float precision decimal between 0 and 1. Then the original image B was divided by the normalized reference image A' to produce an amended NIR reflectance image B'.

$$A' = A / A_{\text{MAX}}$$

$$B' = B / A'$$

In the next step, a contrast map was constructed using the corrected NIR image described above. The determination of the contrast is calculated through a semi-automatic process. Intensity values from the initial scan were collected and reused throughout the caries removal process to maintain repeatability in lesion segmentation.

The mean intensity of sound enamel I_S was calculated over a region of sound enamel outside the ROI and the maximum intensity of the demineralization I_D was calculated inside the ROI. The pixel contrast C was computed by subtracting the intensity of the image pixel I_P with the mean intensity of sound enamel and the minimum value I_{MIN} in each image and dividing this difference over the maximum intensity. An image ablation map or lookup table (LUT) was generated by comparing the pixel contrast to a specified threshold over the enhanced NIR image.

$$\text{If } C = (I_P - I_{\text{MIN}} - I_S) / I_D > \text{TT}; \text{add pixel to LUT}$$

Samples were mounted on a separate system for CO₂ laser ablation, and positioned precisely to match the identical orientation used for NIR imaging. Using the LUT, computer controlled galvanometers scanned the laser point to point over targeted demineralized enamel areas inside the fiducial box. Repeated serial NIR images and LUTs were taken (Fig. 2) and generated with the same threshold values. Teeth were ablated until the lesion was no longer detected by the proposed thresholding segmentation. All image analysis was carried out using Labview (National Instruments) and Igor pro software (Wavemetrics, Lake Oswego, OR).

3. RESULTS AND DISCUSSION

Serial NIR reflectance images and LUTs of the ablation process are shown in Fig. 2. Previous literature has shown that demineralization is significantly less structured and scatters light more than sound enamel. As a result, demineralization appears with higher intensity than sound enamel in NIR reflectance images. A set of NIR reflectance images and LUT overlay images were taken prior to ablation and are shown in Fig. 2. After three iterations of image-guided demineralization removal, demineralization (in white) was no longer visible (Fig. 2D).

In addition, 2-D and 3-D digital microscopy images of the occlusal surface pre- and post-ablation are shown in images A-D in Fig. 3 and indicate no sign of thermal or mechanical damage after ablation. Cross-polarized OCT (CP-OCT) was used to evaluate the removal process. CP-OCT scans E-H taken at the red/green-dashed lines in A-B show lesions corresponding to the high reflectivity areas in the NIR reflectance images. Post-ablative CPOCT images in G-H show depth of ablation. These results suggest that the proposed threshold segmentation of caries lesions is a suitable technique and that serial NIR reflectance images have great potential for image-guided ablation and lesion presence.

This *in-vitro* study used exchangeable magnetic mounts for precise sample positioning, which removed some repositioning errors. An integrated image-guided removal system should avoid such positioning errors.

Furthermore, the angled alignment of the illumination source over the convoluted topography of the tooth surface may cause uneven lighting in the fissures and cracks of the occlusal surfaces. A ring illumination source around the lens of the NIR camera should help distribute the light evenly over the occlusal surface.

In order to increase the contrast of the NIR reflectance image, further contrast enhancement methods can be explored. The robustness of the threshold segmentation algorithm can likely be enhanced if the threshold value was computationally generated and did not rely on the operator positioning over sound enamel regions. Another approach is to use the image histogram to produce adaptive threshold values that can be used in NIR reflectance demineralization segmentation.

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Fig. 1.
Flow-chart of image-guided ablation protocol.

Fig. 2.

(A–D) Left column, serial near-infrared (NIR) reflectance image-guided ablation. (A'–D') Right column, Look-up table (in red) overlaid on top of NIR reflectance images (fiduciary ROI outlined in yellow). (A) Initial NIR images of sample. (D) Final NIR reflectance image of sample. After 3 iterations, contrast between sound and demineralization can no longer be differentiated with thresholding segmentation, suggesting demineralization was removed from the ROI.

Fig. 3.

(A) Initial 2D microscopy image. (B) Final 2D microscopy image. (C) Initial 3D microscopy image. (D) Final 3D microscopy image. (E) Initial OCT B-scan slice taken at the red-dashed line in A. (F) Initial OCT B-scan slice taken at the green dashed line in A. (G) Post-ablated OCT B-scan slice taken at the red dashed line in B. (H) Post-ablated OCT B-scan slice taken at the green dashed line in B.