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Remineralization of Root Caries Monitored Using Cross-Polarization Optical Coherence Tomography

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Abstract

Previous studies have demonstrated that polarization sensitive optical coherence tomography (PS-OCT) can be used to image caries lesions in dentin, measure nondestructively the severity of dentin demineralization, and determine the efficacy of intervention with anticaries agents including fluoride and lasers. However, those studies were limited to artificial lesions on dentin and roots surfaces. The objective of this study is to determine if a cross polarization OCT system (CP-OCT) can be used to nondestructively measure a reduction in the reflectivity of natural root caries lesions after exposure to a remineralization solution. CP-OCT images of 11 teeth with existing root lesions were acquired before and after exposure to a remineralizing solution for 20 days. The integrated reflectivity was calculated after integrating to a fixed depth of 200- μ m. There was a significant decrease in the integrated reflectivity after exposure to the remineralizing solution.

Keywords

polarization; optical coherence tomography; dentin; root caries; remineralization; dental hard tissue

1. INTRODUCTION

Several studies over the past few years have demonstrated that optical coherence tomography (OCT) can be used to measure natural and artificial caries lesions on enamel surfaces^{1–13}.

PS-OCT, has been successfully used to acquire images of both artificial and natural caries lesions, assess their severity in depth, assess the remineralization of such lesions on enamel, and determine the efficacy of chemical agents in inhibiting demineralization^{15–19}. Recent studies in our laboratory on dentin and cementum surfaces demonstrate that PS-OCT is also well suited to assess the severity of demineralization on those surfaces, as well as determine the efficacy of anticaries agents such as fluoride and lasers^{20–22}. One of the most promising applications of PS-OCT is the nondestructive measurement of the remineralization of

existing caries lesions. In-vitro measurements of the remineralization of artificial lesions produced on enamel surfaces demonstrated that the thickness of the thin layer of higher mineral content that is typically formed near the lesion surface during the remineralization process can be measured with PS-OCT^{21, 23–26}. This layer is of considerable importance, since the formation of this fluoroapatite rich layer limits diffusion into the lesion leading to the arrest of lesion progression, the lesion becomes inactive and there is no further need for intervention. Polarization-sensitive depth-resolved reflectivity measurements can provide a measure of the severity of natural and artificial caries lesions on smooth surfaces and in occlusal pits and fissures. The high reflectivity of dentin and enamel surfaces produces a very strong reflection that can interfere with the measurement of early demineralization on the surface. This strong reflection can be reduced using polarized light. Moreover, demineralized areas in the tooth depolarize the incident linearly polarized light, and the reflectivity in the orthogonal or perpendicular polarization state to the incident polarization can be directly integrated to provide a measure of the lesion severity. Although the penetration depth of near-IR light is considerably less in dentin than for enamel due to the markedly higher scattering coefficient of dentin, PS-OCT and OCT images of dentin with root caries show that penetration depths of 1 mm can be achieved, demineralized dentin can be discriminated from sound dentin and cementum, and root canal walls and fractures can be imaged^{14, 20–22, 27, 28}. In contrast to sound enamel that is highly transparent in the near IR, sound dentin strongly scatters light in the near-IR and is highly birefringent. Even with this limitation, we have successfully demonstrated that a similar approach to that used to assess the severity of demineralization on enamel surfaces can be applied to the dentin surfaces as well. Amaechi et al. measured the percent reflectivity loss due to demineralization on dentin surfaces, and showed that this correlated well with mineral loss from microradiography¹⁴. However, the validity of an approach that relies on the measurement of reflectivity loss is questionable, since light scattering increases with demineralization for both enamel and dentin, producing an overall increase in reflectivity from the area of the lesion, not a decrease in reflectivity. The approach that we have chosen is to measure the reflectivity from each layer of the lesion and subsequently integrate over a specific depth to yield the integrated reflectivity (R) in units of dB $\times\mu\text{m}$, that is calculated in a similar fashion by integrating the mineral loss over a specific depth. Recently, Natume was able to measure changes in root caries lesions by calculating the integrated reflectivity using an OCT system without polarization sensitivity²⁹. This approach can work for deeper lesions but is problematic for shallow lesions in which the surface reflectivity introduces a proportionally greater interference. The principal objective of this study was to demonstrate that a significant reduction in the reflectivity from the area of natural root caries lesions can be measured using CP-OCT after exposure of those lesions to a remineralization solution.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Extracted teeth with natural root caries lesions were collected from patients in the San Francisco Bay Area. Teeth were sectioned in half and mounted on cylindrical delrin blocks with the exposed root caries lesion facing up to facilitate matching the position of the OCT scans. The dentin root lesion 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 200-μm. The rest of the sample was covered with a thin layer of acid-resistant red nail polish (Revlon, New York). After the initial OCT scans, the samples were placed in a solution for remineralization consisting of 1.5-mmol/L calcium, 0.9-mmol/L phosphate, 150 mmol/L KCl, 2-ppm fluoride and 20-mmol/L cacodylate buffer maintained at pH 7.0 and 37 °C for 20 days and then scanned again.

2.2 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 × 18 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 μm (3 dB). The lateral resolution is 80-μm (1/e²) with a transverse imaging window of 6 mm × 6 mm and a measured imaging depth of 7-mm in air. The extinction ratio was measured to be 32 dB.

2.3 Integrated Reflectivity Calculations

The integrated reflectivity was calculated in each area of interest on the samples. Line profiles were taken from the CP-OCT images to a real depth of 200-μm, yielding the integrated reflectivity, R , of the regions in units of (dB•μm). An area in the center of 4 × 4 mm box that was 1 mm square was integrated for each sample since we had some difficulty demarcating the laser cut for some of the samples. Prior to taking the line profiles for the OCT images, a 10×10 convolution filter was applied to smooth out the images using the Convolution Filtering function from the Image Processing package of Igor Pro. Three dimensional images were calculated using Osirix imaging software which is an open-source DICOM file viewer (<http://www.osirix-viewer.com>). OCT images were converted to DICOM files using MATLAB (Mathworks, Natick, MA).

3. RESULTS AND DISCUSSION

Figure 2 shows tomographic CP-OCT scans of one of the root caries lesions before and after exposure to the remineralization solution. The image shows both c-scans of the surface of the lesions area before and after remineralization (Figs. 2a&b) and b-scans taken in the vertical (V) and horizontal (H) positions of the yellow lines shown in the c-scan images. The OCT images show reduced reflectivity both at the surface of the lesion and within the lesion body. A highly mineralized surface zone is visible both before and after exposure to the remineralization solution. The surface zone is most evident in the vertical b-scan taken after exposure to the solution, it appears quite thick, greater than 100 μm. Another sample is shown in Fig. 3. For this sample the reflectivity also shows reduced reflectivity both at the surface of the lesion and within the lesion body. In this sample surface zones are more visible in the horizontal b-scans. Only on the right side of the horizontal b-scan does a slight surface zone appear in the image which was not visible prior to exposure to the remineralization solution. We did find that it was far more challenging to line up the before

and after images for the root surfaces than it was for enamel lesions. This was probably due to the extensive erosion and cavitation on the more surface root caries lesions along with the susceptibility to shrinkage which is sensitive to the water content on the tooth surfaces. Figure 4 shows surface renderings of the root caries lesions at different viewing angles before and after remineralization. The box demarcating the area to be imaged and exposed to the remineralizing solution can be seen more easily than in either the visible reflectance image or the OCT c-scans of Figs. 2 & 3.

Table I shows the values of the reflectivity before and after exposure to the remineralizing solution for each of the eleven samples integrated to a real depth of 200- μm . The bar graph of Fig. 5 compares the mean reflectivity before and after remineralization. The real depth was calculated by dividing the optical depth by the refractive index of dentin, 1.47. All of the samples manifested a decrease in the integrated reflectivity and surprisingly the magnitude was quite similar varying from 20 to 40%. The mean reflectivity decreased by $\sim 30\%$ which was very similar to what we observed previously for artificial lesions²¹. A two tailed t-test indicated that this difference was significant ($P < 0.05$). However, the formation of a distinct surface zone of higher mineral content was not observed nor was there precipitation of a distinct surface layer evident. The integrated reflectivity was also calculated to a depth of 400- μm which did not result in an increase in percent remineralization, $26.7\% \pm 6.4$. This suggests that the mineral deposition was localized to the outer 200- μm . We plan on sectioning these samples and examining them further using polarized light microscopy and microradiography. One problem with histological techniques is that they require tooth sectioning and can only be performed after remineralization. It would be valuable to repeat this study using a high-resolution x-ray tomographic technique such as μCT that can be used to image the lesions before and after remineralization.

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Fig. 1.
Visible reflectance image of one of the lesions used in this study.

Fig. 2.

Tomographic CP-OCT scans of one of the root caries lesions before and after exposure to the remineralization solution. C-scans of the surface of the lesion area before (A) and after (B) exposure to the remineralization solution. B-scans taken in the vertical (V) and horizontal (H) positions of the yellow lines shown in the respective c-scan images. A red-white-blue color table was used for the decibel intensity scale, red is high reflectivity and blue is low reflectivity.

Fig. 3.

Tomographic CP-OCT scans of one of the root caries lesions before and after exposure to the remineralization solution. C-scans of the surface of the lesion area before (A) and after (B) exposure to the remineralization solution. B-scans taken in the vertical (V) and horizontal (H) positions of the yellow lines shown in the respective c-scan images.

Fig. 4. Surface rendered tomographic CP-OCT scans of one of the root caries lesions shown before and after exposure to the remineralization solution at different viewing angles.

Fig. 5.
The mean integrated reflectivity before and after demineralization for the eleven lesions.

Table I

CP-OCT integrated reflectivity and percent remineralization for natural root lesions before and after twenty days in a remineralizing solution.

Sample	Integrated Reflectivity (R) before (0 days)	Integrated Reflectivity (R) after (20 days)	Percent Remineralization
1	752.4	585.6	22.2
2	722.3	545.2	24.5
3	821.6	603.1	26.6
4	827.0	653.4	21.0
5	833.0	603.3	27.6
6	820.3	579.0	29.4
7	870.4	577.6	33.6
8	1032.4	659.8	36.1
9	1024.7	770.3	24.8
10	1170.5	897.7	23.3
11	907.8	636.1	29.9
Mean±SD	889.3±134.8	646.5±102.8	27.2±4.7