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Imaging Simulated Secondary Caries Lesions with Cross Polarization OCT

Jonathan Stahl, Hobin Kang, and Daniel Fried¹

University of California, San Francisco, San Francisco, CA94143-0758

Abstract

The clinical diagnosis of secondary caries has been found to account for the replacement of the majority of intra-coronal restorations. Current methods to diagnose the presence of these lesions at early stages are considered insufficient due to their low sensitivity. Polarization-sensitive optical coherence tomography (PS-OCT) imaging studies have confirmed its effectiveness for imaging carious subsurface lesions in enamel and dentin. The objective of this study was to determine if PS-OCT can be used to nondestructively image demineralization through resin restorations on extracted teeth with both simulated and natural lesions. Simulated secondary caries lesions were created by exposing cavity preparations made in extracted human teeth to a demineralizing solution for 48 hours and subsequently restoring with resin. Negative control restorations were also prepared on each tooth. Optical changes in demineralized versus control preparations beneath restorations were measured as a function of depth using PS-OCT. PS-OCT images indicated that a significant increase in reflectivity and depth occurred in the simulated lesions compared with the control preparations. This study suggests that PS-OCT is well-suited to nondestructively detect early caries lesions in enamel beneath composite restorations.

Keywords

polarization-sensitive optical coherence tomography; secondary caries; composite resin; caries detection

1. INTRODUCTION

Secondary caries is a primary reason for replacing dental restorations (1). Secondary caries is the lesion at the margin of an existing restoration. Structurally, it is primary caries at the margin of a previously placed restoration and typically presents as an outer lesion and a wall lesion that can progress to a significant depth beneath the restoration. Diagnosis and validation of the presence of these lesions in the early stages can be challenging (2, 3). Methods that would allow for the early detection of secondary caries and institution of preventive strategies have the potential to reduce the need for replacement of restorations or to allow for minimally invasive repairs (4). Clinical signs such as ditching and staining around restorations are often poor predictors of active secondary caries (5, 6). In addition to

visual inspection and tactile examination diagnostic methods to detect early carious lesions include traditional and digital radiography, fiber-optic transillumination (FOTI), digital fiber-optic transillumination (DIFOTI), laser fluorescence (LF), and quantitative light induced fluorescence (QLF). Several of these methods such as traditional radiography cannot detect the lesion until the more advanced stages and other methods such as visual detection produce arbitrary data that does not correlate with actual mineral loss (7). QLF does have the capability of measuring mineral loss in early lesions, but is limited to surface lesions (8, 9). Current *in vivo* methods to detect caries adjacent to existing restorations are considered insufficient due to the low sensitivity (10).

Multiple studies over the past several years have demonstrated the ability of optical coherence tomography (OCT) to be used for the detection of early caries lesions (11–14). Polarization-sensitive OCT (PS-OCT) measures changes in the magnitude of light scattering and changes in polarization of the scattered light due to demineralization (14, 15). PS-OCT is a non-invasive technique for creating cross-sectional images of internal tissue structures. It is a non-destructive and non-ionizing method that has significant potential for imaging *in vivo*. Depth-resolved reflectivity measurements can provide a measure of the severity of demineralization on smooth surfaces and in the occlusal pits and fissures (14–17). The high reflectivity of the tooth surface creates a strong reflection that interferes with the measurement of early demineralization located on the tooth surface. The magnitude of the strong reflection from the surface is reduced by using polarized light (14). The intensity of backscattered light is measured as a function of its axial position in the tissue. Low coherence interferometry is used to selectively remove or gate out the component of backscattered signal that has undergone multiple scattering events, resulting in very high resolution images ($<15\ \mu\text{m}$). Lateral scanning of the probe beam across the biological tissue is then used to generate a two-dimensional intensity plot, similar to ultrasound images, called a b-scan (18). Polarization resolved images using a 1310-nm source are capable of detecting lesions 1–2mm deep in enamel. Highly scattering structures such as carious dentin can be imaged to a depth of 2–3mm beneath sound enamel. OCT systems that function with near-infrared light (1310-nm) have the advantage of improving the axial imaging penetration depth over wavelengths in the visible range since dental enamel is nearly transparent in the near-IR (19, 20).

Studies have shown that OCT can be used to detect composite restorations (11, 21, 22). The penetration depth of PS-OCT through composite has been shown to be sufficient to detect and track early demineralization or secondary caries on the occlusal surface under a sealant or restoration *in vitro* (22). The composite reflectivity, depolarization, and penetration depth are not influenced by the composition of the filler. The reflectivity, however, is markedly increased when an optical pacifier such as titanium dioxide is added (22).

The principal objective of this study was to demonstrate that PS-OCT can be used as a non-destructive means of detecting the severity of demineralization beneath resin composite restorations in a cavity preparation.

2. MATERIALS AND METHODS

2.1 Sample collection and preparation

Teeth extracted from patients in the San Francisco Bay area were collected with University of California Committee on Human Research (CHR) approval, cleaned and sterilized with gamma radiation. The samples were stored in a moist environment to prevent tissue hydration, namely distilled water with 0.1% Thymol added to prevent bacterial and fungal growth. Eleven posterior teeth were inspected to be sound and mounted in acrylic blocks. A preparation of 2 mm $\times$ 1 mm was made to a depth of 1 mm on the facial surface of each tooth utilizing a 330 bur and high speed dental handpiece with water coolant. A thin layer of acid resistant varnish in the form of red nail polish, Revlon (New York, NY) was applied to all areas of the tooth except for the preparation to protect the sound enamel prior to exposure of the teeth to a 4.8 pH demineralization solution composed of a 40-mL aliquot of 2.0 mmol/L calcium, 2.0 mmol/L phosphate, and 0.075 mol/L acetate. Each sample was then placed into the demineralization solution and incubated at 37°C. After a 48 hr period of demineralization, the samples were removed from the demineralization solution and the acid resistant varnish was removed using acetone. Each sample was then stored in 0.1% thymol solution.

A preparation of the same dimensions as previously stated was made on the lingual side of each specimen to serve as the control. Both the demineralized preparations and the control preparations were restored with Filtek Z-250 (A3) composite from 3M ESPE (Minneapolis, MN). Z250 is a hybrid resin filled to 60 percent by volume with zirconia/silica particles having a size range of 0.01 to 3.5 microns and an average size of 0.6 micron. The resin was placed in bulk and cured for 30 seconds at a distance of 3 mm. The restorations were not bonded to the tooth as long-term retention was not expected to be an issue in this in vitro study. The effects of any gap created resin shrinkage would not be expected to influence the results of this study as the shrinkage experienced in the demineralized samples would be equivocal to the control samples.

2.2 Polarization-sensitive optical coherence tomography

Each scan of reflectivity vs. depth from within the tooth is called an a-scan. Adjacent a-scans are compiled into b-scan files. PS-OCT b-scans representing light reflected in the original polarization incident on the tooth manifest high reflectivity across the entire tooth surface due to the refractive index mismatch at the surface. The light reflected from the tooth surface remains parallel to the original polarization and we call this the parallel axis ($\parallel$ -axis) image. The strong specular reflection at the tooth surface masks resolution of the lesion structure near the surface such as the presence of a surface zone that may provide important information about lesion activity. The corresponding image of the light reflected in the polarization perpendicular to the original polarization incident on the tooth surface, the perpendicular axis ($\perp$ -axis) image, provides better resolution of the lesion structure. This image can also be called the cross polarization image since it is analogous to an image through crossed polarizers. There are two mechanisms that produce increased reflectivity in the $\perp$ -axis image. The native birefringence of the tooth enamel can shift or rotate the phase difference between the two orthogonal axes (similar to a wave-plate) as the light propagates

through the enamel without changing the degree of polarization of the light. Complete depolarization, or polarization scrambling, of the incident linearly polarized light leads to an equal distribution of the intensity in both orthogonal axes. Demineralization of the enamel due to dental caries causes an increase in the scattering coefficient by 1 – 2 orders of magnitude, thus demineralized enamel induces a very large increase in the reflectivity in conjunction with depolarization. This causes a concomitant rise in the $\perp$ -axis image. In the $\perp$ -axis image, the lighter areas represent intense reflectivity/scattering and depolarization from the lesion area, allowing better discrimination of the caries lesion that lies well below the surface.

A single-mode fiber autocorrelator-based Optical Coherence Domain Reflectometer (OCDR), HSR-3000-P, custom designed and fabricated by Optiphase, Inc. (Van Nuys, CA) with a polarization switching probe, high efficiency piezoelectric fiber-stretchers and two balanced InGaAs receivers was used for these studies. This OCDR was integrated with a broadband high power superluminescent diode (SLD) (Denselight, Jessup, MD) with a center wavelength of 1314-nm, an output power of 48-mW and a bandwidth of 33-nm. A high-speed XY-scanning system, ESP 300 controller & 850-HS stages, Newport (Irvine, CA) was used for lateral movement of the tooth samples at the focus of the optical probe for in vitro optical tomography. The autocorrelator-based \ OCDR system is described in more detail by Bush et al. (23, 24). A pair of Faraday rotators built into the probe assembly were used to switch the polarization with the sweep rate of 50-Hz. The system was configured to provide a lateral resolution of approximately 50- μ m over a depth of focus of 10-mm and an axial resolution of 15- μ m in enamel. The interferometric signal was electronically demodulated and filtered and processed using LabViewTM software (National Instruments, Austin, TX). An image of the OCT system sample holder and imaging probe along with a tooth with a simulated lesions are displayed in Fig. 1.

2.3 Lesion depth and integrated reflectivity calculations

An automated edge detection program created using Lab ViewTM was used to identify the lesions at the base of the restorations. An initial background subtraction was carried out for each cross polarization OCT scan and a 2×2 convolution filter was applied to remove speckle noise. The enamel edge and the lower lesion boundary were determined by applying an edge locator. Two passes were required for each a-scan to locate each respective boundary with each pass starting from opposite ends of the a-scan and identifying the first pixel that exceeds the threshold of e^{-2} of the maximum value. The minimum threshold value of 4 standard deviations above the background signal intensity was also applied to eliminate weak signals caused by birefringence in sound enamel. Distance (micron) per pixel conversion factor was obtained experimentally by system calibration. The two cutoff points for the lesion surface and endpoint represent the calculated lesion depth. Each scan interval was 50 μ m, an area of 10 $\times$ 20 pixels representing an area of ~ 0.5 mm² was chosen for analysis in the center of the composite restoration for each demineralized and control sample. The reflectivity was integrated over the calculated lesion depth to yield the integrated reflectivity for the simulated lesion. The integration depth is a real depth not an optical depth calculated by dividing the optical path length/optical depth of each PS-OCT a-

scan by the refractive index of enamel ($n=1.6$). Images were imported into IGOR Pro for analysis.

3. RESULTS

Cross polarization OCT b-scan images of the preparation along with an image of the control preparation on the same tooth are shown in Fig. 2. Images of both polarizations ($\parallel$ and $\perp$ -axis) are shown. A red-white-and blue scheme is used for the PS-OCT images with intensity scale in decibel units (dB), where red and white areas have the highest reflectivity. The zone of demineralization was relatively uniform throughout the walls of the preparations as is demonstrated in Fig. 2. Sample groups were compared using a paired t-test. InStatTM from GraphPad software (San Diego, CA) was used for statistical calculations. The mean $\pm$ standard deviation values for the simulated caries lesion depths as measured with PS-OCT were 58 ± 46.7 for the preparation with lesions and 4.3 ± 10.2 for the control preparations. The demineralized preparations also demonstrated a significantly greater mean reflectivity, R , ($\text{dB} \cdot \mu\text{m}$) compared to the control preparations 161 ± 178 vs 11 ± 27 ($p < 0.05$).

4. DISCUSSION

The present study describes an initial investigation to determine the ability for PS-OCT to detect enamel demineralization beneath resin restorations. Despite its relatively small sample size this investigation demonstrated that PS-OCT could detect increases in demineralization beneath resin in enamel. Clinically this technique would offer advantages over other existing optical detection systems such as QLF in that false readings from stain and plaque are not issues of concern. Moreover, OCT provides depth resolved measurements and not a single reading representing lesion severity. One clinical limitation that would exist in employing this technology in the detection of secondary caries is that lesions occur adjacent to a multitude of restorative materials including amalgam and gold. As a consequence of amalgam's metallic composition it completely obscures the tooth's interior beneath it in an OCT image.

Secondary caries occurs in areas of plaque stagnation (25). For this reason, the cervical margins of restorations are commonly affected. It's reported that 80% to 90% of clinically diagnosed secondary caries have been reported to be located gingivally regardless of the restorative material used (26). Similar to other techniques imaging these areas with PS-OCT could prove challenging, however, it is feasible to build a probe that could be inserted sub-gingivally and interproximally to image these areas.

The goal of this study was to show that PS-OCT could detect subsurface caries adjacent to composite. However, OCT can also provide a quantitative measure of the lesion severity and show the lesion depth. It is likely that OCT images of secondary caries would be of great value to help determine whether a restoration warrants replacement. A previous investigation showed that PS-OCT could be utilized to monitor the progression of simulated lesions created on the occlusal surface underneath composite sealant and composite restorative material(22).

PS-OCT is likely to emerge as an exceptional tool for *in vivo* diagnosis of hard to detect early lesions. A more extensive investigation of natural secondary caries lesions is warranted to substantiate these results.

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Fig 1.

The sample holder, scanning stages and the optical probe of the PS-OCT system used to scan the natural and simulated caries lesions. Inset: One of the simulated caries tooth samples still covered with the acid resistance varnish after removal from the demineralizing solution and prior to placement of the composite in the area of the preparation.

Fig 2.

Sample PS-OCT b-scan images of the cross polarization image ($\perp$ -axis) taken of the control restoration (A) and the restoration with the simulated lesion (B). The arrow shows the increased subsurface reflectivity from the zone of demineralization under the composite.