Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2014 February 18; 8929: 89290O–. doi:10.1117/12.2045681.

Enhancing the detection of hidden occlusal caries lesions with OCT using high index liquids

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Abstract

In a previous study, we investigated the influence of several high refractive index fluids on the performance of polarization sensitive optical coherence tomography (PS-OCT). That study showed that these liquids can increase the effective imaging depth and lesion contrast. Other *in vitro* and *in vivo* studies have shown that OCT can be used to show whether occlusal lesions have penetrated to the dentinal-enamel junction (DEJ) and spread laterally under the enamel. The purpose of this study was to determine if high index fluids can enhance the ability of OCT to detect hidden occlusal lesions and show if these lesions have penetrated through the enamel into the underlying dentin. Ten extracted teeth with occlusal lesions were imaged using OCT after the application of water, glycerol, BABB (33% Benzyl Alcohol + 67% Benzyl Benzoate) and a Cargille Liquid (Cedar Grove, NJ) (hydrogenated terphenyl 1-bromo-naphthalene) with a refractive index of 1.61. The intensity of the reflectance from the underlying lesion area for each sample was compared with the reflectance of the sound tooth surface for each fluid. The use of high index fluids significantly ($P < 0.0001$) increased the reflectivity of subsurface occlusal lesions under the surrounding sound enamel.

Keywords

optical coherence tomography; tooth demineralization; occlusal caries lesions

1. INTRODUCTION

Occlusal caries lesions are routinely detected in the United States using visual/tactile (explorer) methods coupled with radiography. Radiographic methods have poor sensitivity for occlusal lesions, and by the time the lesions are radiolucent they have typically progressed deep into the dentin¹. Many occlusal caries lesions have spread into the underlying dentin while the enamel surface has remained intact and these lesions are not obvious under visual examination. Some of these “hidden” lesions may show up in radiographs but many do not.^{2–5} Such lesions are more common today with the wide spread use of fluoride. New methods are needed to detect such lesions. The Diagnodent which employs fluorescence from bacteria porphyrin molecules was developed for detecting

hidden lesions, however it suffers from many false positives and it does not measure either the depth or exact position of the lesions⁶⁻⁹.

Optical coherence tomography (OCT) is a noninvasive technique for creating cross-sectional images of internal biological structure¹⁰. Several groups have used OCT and PS-OCT to image dental caries¹¹⁻¹⁵ on both smooth surfaces and occlusal surfaces. We have demonstrated that polarization-sensitivity is invaluable for providing depth-resolved measurements of the severity of demineralization both *in vitro* and *in vivo*¹⁶⁻²⁰.

Quantitative depth resolved measurements are useful for clinical studies and for monitoring the state of early lesions and our studies indicate that polarization sensitivity provides considerable advantages for these types of measurement particularly for early demineralization near tooth surfaces¹⁶⁻²⁰. However, many clinicians are only interested in knowing how deep the occlusal lesions have actually penetrated into the tooth so that they can decide whether a restoration is necessary. The advantage of having polarization sensitivity is less evident for assessing the depth of deeply penetrating caries lesions. The requisite optical penetration/imaging depth for the detection and diagnosis of occlusal lesions is to the dentinal-enamel junction (DEJ).

In previous studies we demonstrated that OCT can be used to determine if occlusal lesions have penetrated to the underlying dentin^{21, 22} by detecting the lateral spread at the DEJ. If extensive demineralization is present from the enamel surface all the way down to the DEJ the results are quite mixed, i.e., sometimes the entire lesion is visible from the enamel surface to the DEJ, while more typically only the outer surface of the lesion is visible or the area where the lesion has reached the DEJ (lower part) can be seen. Most lesions extend laterally along the DEJ upon reaching the underlying dentin, therefore we are able to determine whether most lesions have reached the DEJ. In our previous clinical study, 12 out of 14 of the lesions examined *in vivo* using OCT exhibited increased reflectivity below the DEJ which suggested that the lesions had spread to the dentin, considering that none of the lesions showed up on a radiograph, this is a remarkable improvement in sensitivity over existing technology^{21, 22}. Therefore, it is likely that OCT can be used in a similar fashion as the Diagnodent, namely to show that there is hidden demineralization under the sound enamel and confirm that the lesion has penetrated beyond the DEJ. Moreover, OCT has the added advantage of producing an image showing the spread of demineralization as opposed to a single reading that does not indicate the depth or area of demineralization and stains do not absorb NIR light so there is minimal interference from stain.

We previously demonstrated that index matching agents can be used to enhance the contrast of demineralization and that better images could be acquired in occlusal surfaces by use of index matching agents applied to the fissure areas¹⁹. The higher index agents appeared to increase the optical penetration depth of OCT. The viscosity is also important because penetration of the agent into the lesion pores can decrease the lesion contrast. Even though such penetration is anticipated to lower the contrast of the lesion near the tooth surface it is also expected to increase the optical penetration to deeper layers in the lesion.

The purpose of this study was to use higher index liquids to increase the visibility of subsurface hidden occlusal lesions. We hypothesize that increased optical penetration will increase the reflectivity from demineralized areas near the DEJ.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Teeth extracted from patients in the San Francisco Bay area were collected, cleaned and sterilized with Gamma radiation. Molars and premolars were visually inspected for caries lesions. On extracted molars these lesions are easily identified as white or brown/black (pigmented) spots on the tooth surface and specimens are readily available. Those samples with suspected lesions were further screened using a near-IR transillumination imaging system operating at 1300-nm. In the visible range it is difficult to differentiate between stains and actual decay and many of the teeth selected by visual inspection were only stained without decay. The organic molecules that cause pigmentation apparently do not strongly absorb near-IR light and staining does not interfere in the near-IR^{23, 24}. Ten samples were selected with suspected deep natural existing occlusal decay using this screening technique.

The roots were cut off and the teeth were mounted on 1.2x1.2x3 cm³ rectangular blocks of black orthodontic composite resin with the occlusal surface containing the lesion facing out from the square surface of the block. Each rectangular block fit precisely in an optomechanical assembly that could be positioned with micron accuracy.

Four fluids were used in the study water, glycerol, BABB (33% Benzyl Alcohol + 67% Benzyl Benzoate) and a Cargille Liquid (Cedar Grove, NJ) (hydrogenated terphenyl 1-bromo-naphthalene) with a refractive index of 1.61. The fluids were added to tooth occlusal surfaces prior to OCT imaging in sufficient quantity to fill the pits and fissures.

2.2 Digital Microscopy

Images of the tooth occlusal surfaces were examined using a digital microscopy/3D surface profilometry system, the VHX-1000 from Keyence (Elmwood, NJ) with the VH-Z25 lens with a magnification from 25 to 175x.

2.3 Near-IR Transillumination Imaging

A 150-W fiber-optic illuminator FOI-1 E Licht Company (Denver, CO) with a low profile fiber optic with dual line lights, Model P39-987 (Edmund Scientific, Barrington, NJ) was used with each light line directed at the cemento-enamel junction (CEJ) beneath the crown on the buccal and lingual sides of each tooth. Light leaving the occlusal surface was directed by a right angle prism to an InGaAs camera equipped with a Navitar (Rochester, NY) SWIR-35 lens, a 75-mm plano-convex lens LA1608-C Thorlabs (Newton, NJ) and a 90-nm wide bandpass filter centered at 1300-nm, BP1300-90 Spectrogon, (Parsippany, NJ). A 320 × 240 element InGaAs area camera SU320-KTSX (Wakefield, MA) from Sensors Unlimited (Princeton, NJ) was used with a 25-μm pixel pitch.

2.4 OCT System

A single-mode fiber, autocorrelator-based Optical Coherence Domain Reflectometry (OCDR) system with an integrated fiber probe, high efficiency piezoelectric fiber-stretchers and two balanced InGaAs receivers that was designed and fabricated by Optiphase, Inc. (Van Nuys, CA) was integrated with a broadband high power superluminescent diode (SLD), DL-CS313159A Denselight (Jessup, MD) with an output power of 19-mW and a bandwidth of 83 nm and a high-speed XY-scanning system, ESP 300 controller & 850-HS stages, Newport (Irvine, CA) and used for *in vitro* optical tomography. The fiber probe was configured to provide an axial resolution at 9- μm in air and 6- μm in enamel and a lateral resolution of approximately 50- μm over the depth of focus of 10 mm. The all-fiber OCDR system has been previously described in greater detail^{25, 26}. The OCT system was completely controlled using LabVIEWTM software, National Instruments (Austin TX).

PS-OCT system is completely controlled using LabviewTM software (National Instruments, Austin, TX). Acquired scans are compiled into *b-scan* files. Image processing was carried out using Igor ProTM, data analysis software (Wavemetrics Inc, Lake Oswego, Oregon).

2.5 Image Analysis and Statistics

PS-OCT images were acquired of the tooth occlusal surfaces with each of high index fluids applied to the tooth surfaces. For speckle noise reduction, signals not exceeding four standard deviations from the mean background noise floor were reduced to the mean background value and a Gaussian blur smoothing algorithm was applied using a 5×5 pixel convolution kernel^{27–29}. Selected a-scans were chosen which contained subsurface reflections adjacent to occlusal lesions characteristic of increased reflectivity at the DEJ. The reflectance at the lesion surface in the center of the fissure is very strong and the OCT signal is quickly attenuated. However, lesions that penetrate to the DEJ typically spread laterally in the less acid resistant dentin so adjacent areas of the lesion are located under sound enamel and show up in OCT images as strong reflections well below the tooth surface usually at the position of the DEJ. These b-scans typically have two areas of increased reflectivity corresponding to the tooth surface (position 1) and the DEJ (position 2). These positions can be seen in the b-scan and a-scan images of Fig. 2. The ratio of the magnitude of the initial surface peak over the second 2nd (DEJ) peak was calculated and used as a measure of the visibility of these hidden lesions, i.e, dentinal lesions that have spread under the surrounding sound enamel.

Repeated measures analysis of variance was used to compare the peak intensity ratios for the four liquids with the Tukey-Kramer multiple comparison test. A significance level of 0.05 was used. Analysis was carried out using Graphpad Prism (La Jolla, CA).

3. RESULTS AND DISCUSSION

One of the tooth samples with an occlusal lesion is shown in Figure 1. A depth composition image (visible light) acquired with the digital microscope is shown along with an image acquired with near-IR transillumination. Stains are not visible in the near-IR and the dark areas visible in Fig. 1B suggest deep areas of demineralization in the fissure areas. CP-OCT b-Scans are shown for each of the high index fluids in Fig. 2 taken at the position of the red

dotted line shown in Figure 1. A-scans were extracted at the position shown by the upper and lower red arrows and they are shown on the right side of the figure. Each A-scan shows an initial peak shown at position 1 (black box). The scans with the higher index fluids B-D show a second peak corresponding to the subsurface position of the underlying lesion (see arrows in 2C). The second subsurface peak (lesion) is only visible in this tooth with the aid of the higher index fluids.

A near-IR transillumination image is shown of a second tooth in Figure 3. The B-scans for that tooth are shown in Figure 4. The second peak is clearly visible for all the fluids but the magnitude of the second peak is much larger for Figure 4D.

The mean intensity ratios $\pm$ standard deviation were calculated for all ten samples and are listed in Table I along with the refractive index and viscosity for each liquid. They are also plotted in Fig. 5. Color bars containing the same color are statistically similar ($P > 0.05$). There was a significant increase in the peak intensity ratio for the liquids with higher refractive index ($P < 0.0001$).

This study shows that the use of high index fluids significantly increases the visibility of subsurface lesions located under sound enamel peripheral to pits and fissures in the occlusal surface. One can envision how such a fluid would be utilized clinically. Most lesions are visible as demineralization or staining in the fissures. Demineralization in the fissures typically strongly attenuates the OCT signal preventing an accurate depth determination of the lesion. However the majority of lesions that penetrate to the dentin near the base of the fissure rapidly spread laterally in the dentin under the DEJ. That lateral spread can be detected with OCT. After an initial scan of a suspect fissure using OCT those areas can be rescanned after application of a suitable high index fluid to enhance the ability to detect the subsurface lesion either by revealing a subsurface reflection that was not visible without enhancement by the high index fluid or by increasing the intensity of a very weak reflection for additional confirmation.

These studies indicate that optical coherence tomography has great clinical potential for the nondestructive assessment of the depth of occlusal lesions and for the detection of hidden lesions under the enamel.

The requisite optical penetration/imaging depth for the detection and diagnosis of occlusal lesions is to the DEJ. If the lesion is present in the underlying dentin and the enamel above is sound, OCT works quite well in resolving that lesion and the images confirm penetration to the DEJ. If extensive demineralization is present from the enamel surface all the way down to the DEJ the results are quite mixed, i.e., sometimes the entire lesion is visible from the enamel surface to the DEJ, while more typically only the outer surface of the lesion is visible or the area where the lesion has reached the DEJ (lower part) can be seen. One limitation of radiography is that ionizing radiation is required, however it is even more important to emphasize that radiography is insensitive for the detection of early occlusal lesions and that by the time they show up on a radiograph they have typically spread extensively throughout the dentin and are far too late for non-surgical intervention.

Acknowledgments

This work was supported by NIH/NIDCR Grant R01-DE17869. The authors would like to thank Kenneth Chan, Jacob Simon, Henry Tom, Robert Lee and Michal Staninec for their help with this study.

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Fig. 1.
(A) Visible depth composition image and (B) near-IR transillumination image of tooth.

Fig. 2. (Left) CP-OCT b-scans taken at the position of the dotted line in Fig. 1 for the four liquids, (A) water, (B) glycerol, (C) BABB and (D) Cargille liquid. CP-OCT A-scans extracted at the position of the upper and lower red arrows are shown on the right. The position of the two peaks analyzed are shown in (C) for both the B-scan and A-scan images.

Fig. 3.
Near-IR transillumination image of one of the tooth samples.

Fig. 4. (Left) CP-OCT b-scans taken at the position of the dotted line in Fig. 3 for the four liquids, (A) water, (B) glycerol, (C) BABB and (D) Cargille liquid. CP-OCT A-scans extracted at the position of the upper and lower red arrows are shown on the right.

Fig. 5.

Mean $\pm$ S.D. of the peak intensity ratios of each of the ten liquids for the 10 samples. The values of the refractive index are also listed for each liquid. Groups with the same color are statistically similar ($P > 0.05$).

Table I

The refractive index and viscosity of each fluid along with the mean (sd) of the peak intensity ratio between the surface and subsurface (DEJ) reflections for the ten samples.

	Water	Glycerol	BABB	Cargille
Contrast Ratio	0.287 (0.168)	0.350 (0.258)	0.603 (0.259)	0.820 (0.390)
Refractive Index	1.33	1.47	1.56	1.61
Viscosity (cP)	1.0	1194	8.8	2063