Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2011 January 23; 7884(0): . doi:10.1117/12.878888.

In vivo Near-IR Imaging of Occlusal Lesions at 1310-nm

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Abstract

Several *in vitro* studies have demonstrated the potential for transillumination imaging and optical coherence tomography operating at 1310-nm for imaging caries lesions on tooth proximal and occlusal surfaces. Recently, we demonstrated that lesions on proximal surfaces could be imaged *in vivo* using NIR transillumination and that PS-OCT can be used *in vivo* to measure early demineralization on tooth buccal and occlusal surfaces. In this paper we report the first *in vivo* measurements using OCT and NIR imaging of occlusal lesions that have been scheduled for restoration. Occlusal lesions were chosen that were scheduled for restoration based on conventional diagnosis that consists of visual and tactile examination. Occlusal lesions were visible in the NIR. OCT looks promising for confirming the lateral spread of occlusal caries under the dentinal-enamel junction adjacent to fissures. These studies suggest that both near infrared transillumination imaging at 1310-nm and OCT provide valuable information about the severity of caries lesions.

Keywords

Optical coherence tomography; near-IR imaging; occlusal caries; transillumination

1. INTRODUCTION

Clinicians need new imaging technologies employing non-ionizing radiation to aid in caries management and diagnosis, to reliably track the course of caries lesions over an extended time period in order to determine whether the lesion is active and expanding or whether the lesion has been arrested, and determine if intervention is needed. The principal factor limiting optical transmission through the tooth in the visible range from 400–700-nm is light scattering in sound enamel and dentin. The magnitude of light scattering in dental enamel decreases as $(1/\lambda^3)$, where λ is the wavelength, due to the size of the principal light scatterers in enamel^{1, 2}. Therefore, the near-IR (NIR) region between 1300 and 1700-nm offers the greatest potential for new optical imaging modalities due to the weak scattering and absorption in sound dental hard tissues. Upon demineralization light scattering increases by one to two orders of magnitude which provides high contrast of caries lesions³.

Several studies have demonstrated the potential for optical coherence tomography for imaging dental caries and the best performance is in the NIR at 1310-nm due to the high transparency of the enamel⁴⁻⁷. Several *in vitro* studies have demonstrated that polarization sensitive optical coherence tomography (PS-OCT) can be used to nondestructively measure the severity of early subsurface demineralization in enamel and dentin and is therefore well suited for this role⁸⁻¹⁶. We recently completed the first *in vivo* PS-OCT study demonstrating that it can be used effectively to measure the severity of early demineralization¹⁷. Demineralization that developed under orthodontic bands and in occlusal pits was measured after a period of one month on premolars scheduled for extraction. The integrated reflectivity in the cross polarization (CP) OCT images was compared with microradiography performed after tooth extraction and sectioning. Since the strong specular reflectance at the tooth surface makes it extremely difficult to quantify early demineralization on tooth surfaces, we believe that it is necessary to acquire CP-OCT images in order to reliably quantify demineralization near the tooth surface. We have demonstrated that cross polarization OCT can be effective up to a depth of 500- μ m in the pits and fissures of occlusal surfaces and through composite which does not strongly depolarize the incident polarized light¹⁸. The requisite optical penetration/imaging depth for the detection and diagnosis of occlusal lesions is to the dentin-enamel junction (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 DEJ¹⁹. 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 in the OCT image. However, more frequently only the outer surface of the lesion is visible or the area where the lesion has reached the DEJ (lower part) can be seen outside the fissure area. It has not been established why the optical penetration depth through the lesions is so variable. Most lesions extend outward upon reaching the underlying dentin, therefore we anticipate that OCT should be able to determine whether most lesions have reached the DEJ.

In a study of deep occlusal caries presented at this meeting last year, we compared PS-OCT images of the lesions with polarized light microscopy and transverse microradiography. The correlation of OCT with PLM and TMR was encouraging. Images of the reflected light parallel and orthogonal to the incident polarized light were analyzed for the deeply penetrating occlusal lesions and the parallel image which would be similar to a conventional non-PS-OCT system showed similar correlation with histology to the cross polarization image which suggest that polarization sensitivity is not essential for simply measuring the depth of deep lesions. The utility of PS-OCT for the measurement of early demineralization on tooth surfaces has been clearly established from previous studies^{11, 20-23}. However, if the sole aim is assessing the depth of deeply penetrating caries lesions a conventional OCT system may suffice. The polarization sensitivity does provide an apparent improvement in contrast, but most of the benefit is near the tooth surface. Polarization sensitivity also helps differentiate subsurface artifacts from lesions. However, PS-OCT systems are more complex and that study suggests that it is not absolutely necessary to have polarization sensitivity to detect more severe deeply penetrating occlusal lesions. Therefore we did not employ PS-OCT in this study which focused on deeply penetrating occlusal lesions.

Several studies that have been carried out by our group over the past several years have demonstrated that interproximal caries lesions can be imaged by transillumination of the proximal contact points between teeth and by directing NIR light below the crown while imaging the occlusal surface both *in vitro* and *in vivo*^{24–26}. The same approach can be used to image occlusal lesions with high contrast^{26–31} as can be seen in Fig. 1.

The first *in vivo* NIR imaging study was completed this last year involving radiopositive lesions on proximal surfaces²⁶. Although, radiographs have a poor sensitivity, they have a high specificity for proximal lesions which makes them suitable for comparison with the NIR images. All of the 33 lesions imaged, with the exception of one lesion, were Class II and only one of the lesions imaged was Class III, none of the lesions could be seen by visual examination (visible light) and 32/33 were visible in NIR images. Class III lesions can typically be seen by visual examination which excluded most of them from our study. Most of the lesions were small and confined to the enamel (27/33). Lesions were imaged using the InGaAs focal plane array (FPA) with two probe configurations which were designed for imaging from either the facial to lingual or the lingual to facial orientation and another probe that delivered light to the facial and lingual surfaces near the cementum enamel junction and the camera was placed above the occlusal surface. Most of the lesions were visible with NIR from the occlusal surface (27/33). Many possible lesions were seen in the NIR with high contrast that were not radiopositive, which suggests that the sensitivity of the NIR is likely higher than radiography, however since the teeth were not extracted we could not make that determination from this first study. Analysis of NIR images of occlusal lesions on extracted teeth show that the area and contrast in NIR images correlates with the lesion severity and that the lesions that penetrate into dentin have significantly higher contrast than those limited to enamel^{31–33}.

In this study employing both OCT and NIR imaging systems, we imaged 15 test subjects diagnosed with occlusal lesions that had been scheduled for restoration, to establish that deeply penetrating occlusal lesions can be seen with high contrast in the NIR and determine whether or not OCT can be used to detect if the lesions had penetrated through the enamel to the underlying dentin.

2. MATERIALS AND METHODS

Test Subject Recruitment, Inclusion Criteria and Imaging Procedures

Subjects were recruited from the patient population of the University of California at San Francisco School of Dentistry who had lesions that were scheduled for restoration. Informed consent was obtained in accordance with the protocol approved by the Institutional Committee on Human Research. The occlusal lesions selected were not visible on bitewing radiographs, and were assessed using visual/tactile criteria.

NIR Imaging

An imaging probe was employed to acquire images from the occlusal surface. It consisted of a 25-mm objective lens, a ½ inch in diameter tube 5' long with a relay lens, a mirror and light delivery optics. A high sensitivity InGaAs (Indium gallium arsenide) imaging camera, Model SU320KTSX (Sensors Unlimited, Princeton, NJ) was used to collect all the images.

For comfort and stability, the video camera/handpiece assembly was mounted onto the examiner's forearm as shown in Fig. 2 and the probes were held by the ½ tube of the probe. Since lesions are detected by differences in optical contrast uniform illumination is critical for NIR imaging. The probe shown in Fig. 3 is placed directly over the tooth and optical fibers coupled to Teflon optical diffusers in two arms (A) direct the NIR light to just above the gingival tissues on the facial and lingual side of the tooth and the mirror (C) directs the light to the camera. The system provides uniform illumination of the crown and the sound enamel is visible as a ring of higher intensity around the central dentin core of the tooth as shown in Fig. 4. Occlusal lesions are visible as dark areas in the occlusal pits and fissures. Approximal lesions are also visible from below the contact point on adjacent teeth even though the light has to propagate through several mm of enamel. Light was provided by two 1310-nm superluminescent diodes (SLD) from (Optospeed, Zurich, Switzerland), with an output power of 15 mW and a 35-nm bandwidth. The power was determined empirically by experimenting with various settings and the bandwidth was chosen because the use of broadband SLD's reduce speckle noise and the related image degradation that is common with narrow bandwidth light sources. If it was necessary to remove bubbles on the teeth to be examined, they were gently dried with a stream of air from a dental unit air syringe and video (8-bit) was acquired as the imaging handpiece was passed over the tooth.

OCT Imaging

A single-mode fiber, autocorrelator-based Optical Coherence Domain Reflectometry (OCDR) system with high efficiency piezoelectric fiber-stretchers and a balanced InGaAs receiver that was designed and fabricated by Optiphase, Inc. (Van Nuys, CA) was integrated with a broadband high power superluminescent diode (SLD), Denselight (Jessup, MD) with an output power of 20-mW and a bandwidth of 35-nm. The system was configured to provide an axial resolution at 22-μm in air and 14-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^{34, 35}. The OCT system was completely controlled using LabVIEW™ software, National Instruments (Austin TX). To enable the acquisition of *in vivo* images a low profile scanning stage has been integrated with an optical-fiber probe, Fig. 5. The MM-3M-F-05 mini-stage from National Aperture Inc, was used with a MS-4CA Servo Amplifier system and Labview™ Software and the National Instruments PCI-7344 motion controller. This stage has a lateral scan range of 12.7-mm, sufficient to scan across the entire tooth with a speed of 6 mm/sec to avoid motion artifacts. The scanner has an outer sheath of delrin that is removable and autoclavable. A picture of a subject being scanned using the system is shown in Fig. 6.

Conventional Examination, Impressions and Restoration

Conventional visual/tactile examination was performed and radiographs acquired. Penetration to the dentin typically demarcates the point at which non-cavitated lesions should be restored. After imaging, teeth were prepared conservatively using a combination of tactile feedback and a caries indicator dye. An impression of the cavity was taken to assess the lesion depth and area using a polyvinyl siloxane impression material.

RESULTS AND DISCUSSION

Fifteen lesions in fifteen test subjects were scanned using the occlusal NIR imaging system. All the lesions were visible in the NIR, however in many cases we did have difficulty locating them because the contrast appeared lower than we had observed *in vitro*. A NIR image of one of the lesions is shown in Fig. 7. The approach of delivering the light at the gum line of the tooth and allowing it to diffuse up through the enamel works *in vivo* in vital teeth in a similar fashion to our *in vitro* studies. One concern was that the vital pulp could somehow interfere with the distribution of light under the crown preventing this approach. Occlusal images of both sound teeth and images of teeth with caries do not appear dark over the pulp chamber which would be indicative of high absorption due to the pulp. At NIR wavelengths where water absorption is high the strong absorption in dentin does cause it to appear very dark and reduces contrast of occlusal lesions; see paper 7884–33 in this proceeding. We also had difficulty focusing on the lesions due to the topography of the occlusal surfaces. In our previous study, we had less trouble viewing interproximal lesions from the occlusal surface, therefore we didn't make any modification to our imaging probe to enhance the visibility of occlusal lesions for this study. However, we believe the performance can be increased considerably by using a longer depth of focus and adjustment of the illumination system.

Fourteen of the lesions were scanned using OCT. The scanner malfunctioned with one of the test subjects and we were unable to scan that particular lesion. In 12 out of the 14 test subjects (86%) with occlusal lesions that penetrated to the dentin, one or more of the OCT scans showed an area of high reflectivity at the center of the suspected lesion in the fissure with loss of optical penetration in the OCT image along with a subsurface increase in reflectivity well below the surface to the left or right of the fissure near the location of the dentin-enamel junction (DEJ). This can be seen in the OCT image shown in Fig. 8. There is high reflectivity from the top of the lesion in the fissure at the position of the arrow. The optical penetration is cut off below the lesion. However, there is a distinct rise in reflectivity to the left of the lesion well below the surface at the position of the DEJ. Many occlusal lesions spread laterally under the enamel after reaching the dentin which has a higher permeability and is more susceptible to acid dissolution. In order for this approach to work effectively the enamel above the carious dentin must be sound in order to allow optical penetration. Some teeth have decay or developmental defects that encompass a large area of the occlusal surface and prevent light penetration to the DEJ. 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 it is too late for non-surgical intervention. Therefore, the performance of OCT in this study is a marked improvement over existing technology. Even though we were able to detect the subsurface lateral spread of most of the lesions using a two dimensional scanner that acquired individual b-scans, based on our experience with this small study we believe it will be most advantageous to acquire 3D images of each lesion in order to make a reliable diagnosis.

Acknowledgments

This work was supported by NIH/NIDCR Grant R01-DE14698.

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Fig. 1. Visible and NIR images of occlusal decay. Note how stain in visible image poorly represents the location of the decay. Lesion areas in yellow box.

Fig. 2.
NIR clinical imaging system with InGaAs imager with probe.

Fig. 3.
In vivo NIR imaging probe used to acquire images of lesion on the occlusal surfaces. (A) light source, (B) direction of light propagating in tooth, (C) InGaAs imager.

Fig. 4.
In vivo NIR image taken with the occlusal probe shown in Fig. 3 showing a interproximal lesion in red box.

Fig. 5. PS-OCT hand-piece. (Left) Our handheld scanner with a disposable cylindrical plastic sleeve that fits over the probe assembly that can rest on tooth surfaces. (Right) Sample in vivo scan ($\parallel$) polarization that took 2.2 seconds to scan with no motion artifacts.

Fig. 6.
OCT imaging system Each “b-scan” OCT image is 3.5-mm (depth) by 10-mm. (bottom)
Photograph of the mobile PS-OCT system and handheld scanner.

Fig. 7. Near-IR image of a tooth with an occlusal lesion scheduled for restoration. The lesion is located in the white circle.

Fig. 8. OCT image showing the high reflectivity at the beginning of the lesion, the loss of penetration, and the rise in subsurface reflectance to the left of the lesion near the position of the dentin-enamel junction. The white arrow shows the center of the lesion.