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Enhancement of OCT images with vinyl polysiloxane (VPS)

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Abstract

Several studies have shown that optical coherence tomography (OCT) can be used to measure the remaining enamel thickness and detect the location of subsurface lesions hidden under the sound enamel. Moreover studies have shown that high refractive index liquids can be used to improve the visibility of subsurface lesions in OCT images. In this study, we demonstrate that vinyl polysiloxane (VPS) impression materials which are routinely used in dentistry can be used to enhance the detection of dentinal lesions on tooth occlusal surfaces. Lesion presence was confirmed with polarized light microscopy and microradiography.

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 dentin [1]. 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, 3] Such lesions are more common today with the wide spread use of fluoride and 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 lesions [4, 5]. Optical coherence tomography (OCT) is a noninvasive technique for creating cross-sectional images of internal biological structure [6]. Several groups have used OCT to image dental caries [7–10] on both smooth surfaces and occlusal surfaces.

In previous studies, we demonstrated that OCT can be used to determine if occlusal lesions have penetrated to the underlying dentin by detecting the lateral spread across the dentinal-enamel junction (DEJ) [11, 12]. 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

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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. Since none of the lesions were visible on a radiograph, this is a remarkable improvement in sensitivity over existing technology [11, 12]. 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 areas [13]. 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. Two years ago we demonstrated that higher refractive index (RI) liquids can be used to increase the visibility of subsurface hidden occlusal lesions. Ten teeth were investigated and there was a significant increase in the subsurface lesion visibility with the added high RI fluids. This was defined as the ratio of the magnitude of the initial surface peak over the second 2^{nd} (DEJ) peak. Various imaging analysis methods have been developed for enhancing structures and edges, speckle reduction and denoising OCT images [14–16]. Last year we demonstrated that image processing methods can further improve the visibility of subsurface occlusal lesions [17].

Unfortunately, the high RI fluids employed in our previous studies are not biocompatible and cannot be employed in vivo. In this study a transparent vinyl polysiloxane (VPS) impression material was used which is routinely used clinically in dentistry. The impression material is also designed to make intimate contact with tooth structure for accurate impressions.

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. 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 [18, 19]. 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 $1.2\times1.2\times3$ cm^3 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 fits precisely in an optomechanical assembly that could be positioned with micron accuracy.

A vinyl polysiloxane (VPS) impression material, StartVPS Clear Bite from Danville Materials (San Ramon, CA) that is currently being used clinically to take impressions for restorations was added to tooth occlusal surfaces prior to OCT imaging in sufficient quantity to fill the pits and fissues.

2.2 OCT System

An 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) with an output power of 19-mW and a bandwidth of 83 nm, Model DL-CS313159A Denselight (Jessup, MD) 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 [20]. The OCT system is completely controlled using Labview™ software from National Instruments (Austin, TX). Acquired scans are compiled into *b-scan* files.

2.3 Light Microscopy

After sample imaging was completed, approximately 200 μm thick serial sections were cut using an Isomet 5000 saw (Buehler, IL), for polarized light microscopy (PLM). PLM was carried out using a Meiji Techno RZT microscope (Meiji Techno Co., LTD, Saitama, Japan) with an integrated digital camera, Canon EOS Digital Rebel XT (Canon Inc., Tokyo, Japan). The sample sections were imbibed in water and examined in the brightfield mode with crossed polarizers and a red I plate with 500-nm retardation. Non-polarized images were also acquired.

2.4 Image Analysis and Statistics

Image processing was carried out using Igor Pro™, data analysis software from Wavemetrics Inc. (Lake Oswego, OR). A reference a-scan was acquired from a mirror prior to scanning the samples. The reference a-scan contains several weak artifact signals along with the primary reflection. The reference array was normalized to the intensity of the point of interest and subtracted to selectively remove the artifacts and reduce noise. Background subtraction was carried out by subtracting the mean reflectivity of 5000 data points measured in air from the top 100 pixels of the 50 unprocessed a-scans outside the sample area. Tomographic images of the sample were reconstructed from the parallel b-scans. The images were convolved with a Gaussian filter (3×3 filter, sigma=4) to reduce speckle noise. The 5×5 rotating kernel transformation (RKT) technique was applied to each b-scan to emphasize thin edges while further suppressing speckle noise. [21–24]

OCT images were acquired of the suspect occlusal surfaces with and without VPS applied to the tooth surfaces. Selected a-scans were chosen from acquired b-scans which contained subsurface reflections 2–3 mm below the surface adjacent to the fissures with 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 and the position of the dentin or DEJ. These positions can be seen in the a-scan images of Fig. 1.

3. RESULTS AND DISCUSSION

Figure 1 shows one sample lesion, for which the subsurface lesion/peak was not visible in OCT images without the VPS impression material, Fig. 1A. The b-scan OCT image taken after application of VPS, Fig. 1B, clearly shows the subsurface lesion beneath the surface near the DEJ with an intensity approaching the magnitude of the reflectivity of the surface. The demineralization is so strong at the center of the fissure at the position of the green arrow, that it completely blocks light penetration even with the addition of the VPS. The surface of the VPS layer is also visible at this position as the thin meniscus located above the center of the fissure. The sample was sectioned and polarized and non-polarized microscope images were acquired. The microscope image of the histological section and the OCT scan are shown in Fig. 2. Fig. 2A shows the areas of decay in the enamel and dentin. This image shows a dark pigmented area in the dentin localized to the center and expanding to the left along the DEJ. Microradiography, the gold standard, which directly measures changes in mineral content was used to confirm the presence of decay in the dentin. There is also some demineralization expanding slightly to the right halfway through the enamel. These features are clearly visible in the enhanced OCT image of Fig. 2B. Both the strong reflection from the subsurface lesion near the DEJ at the position of the red arrow and the demineralization in the enamel slightly to the right of the central fissure where optical penetration is completely blocked at the position of the yellow arrow is visible. A complete analysis was carried out for all ten samples and we plan to publish those results in the near future.

The excellent performance of the VPS impression material is particularly exciting because these impression materials have been used clinically for many years and they are transparent, odorless and tasteless. Therefore, they can be used immediately as optical clearing agents for clinical OCT imaging.

Polysiloxanes are used for intraocular lenses and dental impression materials and the refractive index (RI) can be varied from 1.4 to 1.6 with RI increasing with the phenyl concentration. Commercially available diphenyl methyl siloxane copolymer has an RI close to that of dental enamel [25, 26]. Our results with a common dental transparent vinyl polysiloxane (VPS) impression material (RI=1.4) show remarkable improvement in visibility of subsurface structures around the fissure. The higher performance of the lower refractive index VPS impression material (RI=1.4) suggests that index matching is not the most important criterion for increasing optical penetration. Vinyl polysiloxane impression materials are designed for intimate contact with tooth surfaces for accurate impressions, therefore they are hydrophilic and have a low enough viscosity to penetrate tooth fissures. The good wetting properties of these materials is also advantageous for retention to the occlusal surfaces of upper teeth so that VPS can be applied to all teeth and special measures will not be necessary for use on the upper teeth. With application of any agent with a refractive index greater than unity there is some distortion of the image since the optical path length is modified. One change was that the separation of the surface and subsurface peaks contracted somewhat. This can be explained by the optical distortion of the image by the agent and the greater visibility of the subsurface lesion closer to the tooth surface.

One can easily envision how such an optical clearing agent such as VPS can be utilized clinically. After an initial scan of a suspect fissure using OCT those areas can be rescanned after application of a drop of optical clearing agent to enhance the ability to detect the subsurface lesion either by revealing a subsurface reflection that was not visible without enhancement by the agent or by increasing the intensity of a very weak reflection for additional confirmation.

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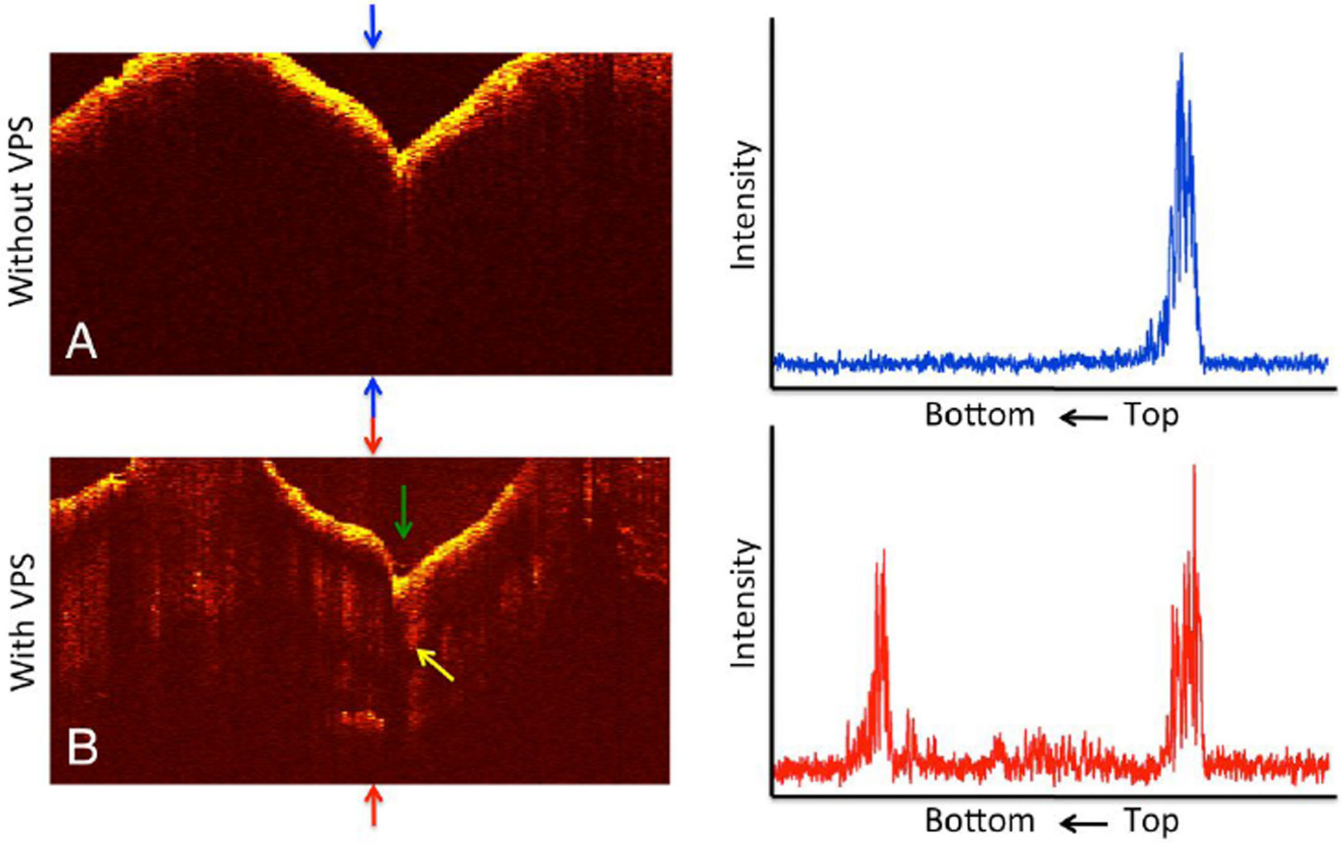

Fig. 1.

(Left) OCT b-scans taken at the same fixed position on a tooth for which the subsurface lesion was not visible before application of VPS acquired without (A) and with (B) VPS. OCT a-scans extracted at the position of the upper and lower red arrows are shown on the right. The green arrow shows the position of the center of the fissure where optical penetration is blocked and the yellow arrow shows the position where deeper enamel demineralization is visible.

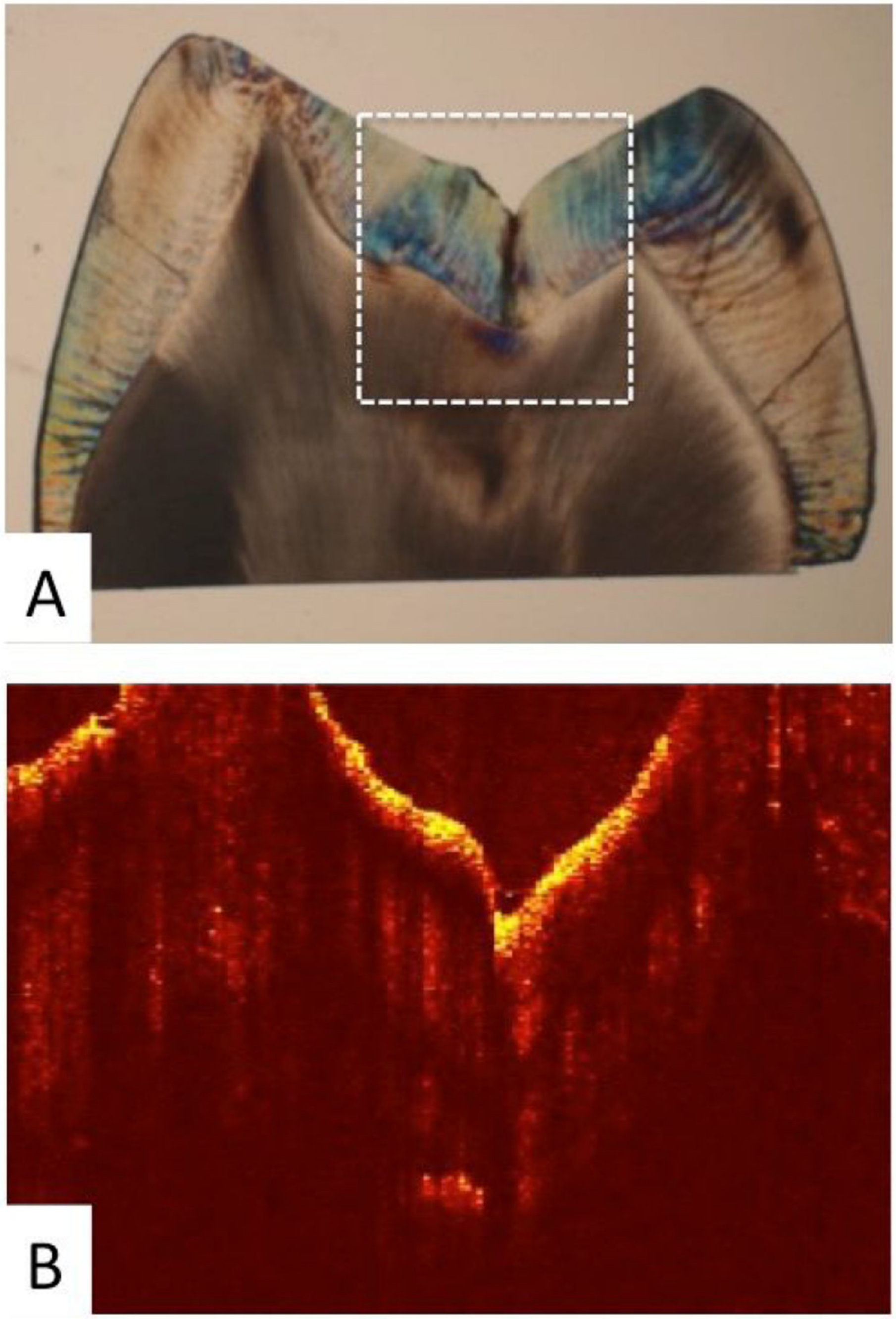

Fig. 2.
Comparison of the OCT scan with applied VPS (B) with a image of the matching histological section (A) confirming lesion position.