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Monitoring tooth demineralization using a cross polarization optical coherence tomographic system with an integrated MEMS scanner

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Abstract

New methods are needed for the nondestructive measurement of tooth demineralization and remineralization to monitor the progression of incipient caries lesions (tooth decay) for effective nonsurgical intervention and to evaluate the performance of anti-caries treatments such as chemical treatments or laser irradiation. Studies have shown that optical coherence tomography (OCT) has great potential to fulfill this role since it can be used to measure the depth and severity of early lesions with an axial resolution exceeding 10- μ m, it is easy to apply *in vivo* and it can be used to image the convoluted topography of tooth occlusal surfaces. In this paper we present early results using a new cross-polarization OCT system introduced by Santec. This system utilizes a swept laser source and a MEMS scanner for rapid acquisition of cross polarization images. Preliminary studies show that this system is useful for measurement of the severity of demineralization on tooth surfaces and for showing the spread of occlusal lesions under the dentinal-enamel junction.

Keywords

cross polarization optical coherence tomography; tooth demineralization; dental caries

1. INTRODUCTION

New tools are needed to non-destructively assess carious lesion depth and severity, efficacy of chemical intervention, and testing of anti-caries agents. The National Institute of Dental and Craniofacial research has requested the validation of new technologies for the measurement of tooth surface demineralization or remineralization to serve as a likely surrogate end point in dental clinical trials¹. Several studies have demonstrated that polarization sensitive optical coherence tomography (PS-OCT) can be used to nondestructively measure the severity of subsurface demineralization in enamel and dentin and is therefore well suited for this role²⁻¹⁰. Polarization sensitivity is particularly valuable for imaging caries lesions due to the enhanced contrast of demineralized enamel and dentin caused by depolarization or polarization scrambling from the strong light scattering of the

incident light by the lesion and the confounding influence of the strong surface reflectance of the tooth surface is reduced in the orthogonal polarization. Baumgartner et al.^{11–13} presented the first polarization resolved images of dental caries. PS-OCT images are typically processed in the form of phase and intensity images^{14–15}, such images best show variations in the birefringence of the tissues. Demineralized areas rapidly depolarize or scramble the polarization of incident polarized light and the image in the polarization orthogonal to that of the incident polarization can provide improved contrast of caries lesions. We developed an approach to quantifying the severity of caries lesion by integrating the reflectivity of the orthogonal axis ($\perp$) or cross polarization image³. There are two mechanisms in which intensity can arise in the cross polarization image. The native birefringence of the tooth enamel can rotate the phase angle of the incident light beam between the two orthogonal axes (similar to a wave-plate) as the light propagates through the enamel without changing the degree of polarization. The other mechanism is depolarization or polarization scrambling from scattering in which the degree of polarization is reduced. It is this later mechanism that is exploited to measure the severity of demineralization. Complete depolarization of the incident linearly polarized light leads to equal distribution of the intensity in both orthogonal axes. Demineralization of the enamel due to dental decay causes an increase in the scattering coefficient by a 1–2 orders of magnitude, thus demineralized enamel induces a very large increase in the reflectivity along with depolarization. This in turn causes a large rise in the cross polarization image.

This approach also has the added advantage of reducing the intensity of the strong reflection from the tooth surface that can prevent resolution of the lesion area near the tooth surface, which is important for measurement of the lesion surface zone that can potentially provide information about the lesion activity. A conventional OCT system cannot differentiate the strong reflectance from the tooth surface from increased reflectivity from the lesion itself^{16,17}. Use of cross polarization images facilitates direct integration of the lesion reflectivity to quantify the lesion severity, regardless of the tooth topography and the difficult task of having to deconvolve the strong surface reflection from the lesion surface can be circumvented. Longitudinal studies have demonstrated that PS-OCT can be used for monitoring erosion, demineralization and remineralization^{2–10}. The progression of artificially produced caries lesions in the pit and fissure systems of extracted molars can also be monitored non-destructively and the integrated reflectivity in the cross polarization image correlates well with the growth of the lesion^{4, 18}. Since the most important information about the lesion is near the surface, a cross polarization OCT system is invaluable for imaging dental caries particularly early lesions. Moreover, this approach works well on highly convoluted surfaces. We have also demonstrated that automated algorithms can be applied successfully to calculate the depth of demineralization and the overall or integrated reflectivity from the zone of demineralization¹⁹. This approach has significant advantages because OCT can be used to rapidly acquire 2D and 3D tomographic images of areas of early demineralization on tooth surfaces. In order to rapidly process the images and effectively quantify the lesion severity algorithms are needed to automatically extract lesion depth and severity information.

Most new lesions ~80% are found in the occlusal surfaces and many of these lesions are hidden and difficult to detect. Such lesions are rarely visible on a radiograph until they have

spread extensively through the underlying dentin. Recent studies show that OCT is well suited for detecting lesions that have penetrated through the enamel to the dentin and spread lateral along the DEJ. The situation where carious dentin lies under sound enamel is ideal for OCT imaging and such lesion areas can be detected through the full thickness of enamel. Even though polarization sensitivity may not be required to image deep occlusal lesions, cross polarization images do provide an improvement in contrast and they also help differentiate subsurface artifacts from lesions. We recently acquired a custom designed cross polarization OCT system (CP-OCT) from Santec (Aichi, Japan) that incorporates a scanning hand-piece with micromechanical system (MEMS) mirrors that is capable of acquiring complete 3D scans of tooth surfaces. The system uses a swept laser source operating at 30 kHz with an axial resolution of 11- μ m in air and 7- μ m in enamel. It is capable of acquiring complete tomographic images of a volume of $6 \times 6 \times 7$ mm in less than a second. The imaging system along with close-up images of the scanning hand-piece are shown in Fig. 1. This system can be used *in vivo* and we intend to use it to acquire complete tomographic images of lesions for clinical studies.

In this paper we discuss the performance of this new system for *in vitro* and *in vivo* imaging of early caries lesions and deeply penetrating occlusal lesions.

2. MATERIALS AND METHODS

2.1 Cross Polarization (CP) -OCT System

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 is shown in Fig. 1, the 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 μ m (3 dB). The lateral resolution is 80- μ m ($1/e^2$) with a transverse imaging window of 6 mm $\times$ 6 mm and a measured imaging depth of 7-mm in air. The extinction ratio was measured to be 32 dB.

3. RESULTS AND DISCUSSION

This system is ideally suited for measuring early demineralization on tooth surfaces and we have started a clinical study designed to demonstrate that CP-OCT can be used to measure the development of early white spot lesions on tooth surfaces. Brackets increase plaque retention and we are using OCT to monitor the development of demineralization around the cervical margin of orthodontic brackets for a period of 1-year. The 6×6 mm scanning window is well suited for imaging the area cervical to the bracket, namely between the gums and the bracket. One problem is the risk of scratching the outer window of the scanner on the metallic brackets. We developed a small sterilizable appliance made out of Delrin that fits over the window and prevents the brackets from coming in direct contact with the window of the scanner. Cellophane film is used as an infection control barrier on the handpiece which we found only minimally interferes with the images.

Fig. 2 shows *in vivo* CP-OCT b-scans taken of two teeth with brackets from a test subject. The first image (left) shows the bracket and the area cervical to the bracket. The enamel is sound and the composite adhesive is clearly visible next to the bracket over the sound enamel. The underlying dentin and the dentinal enamel junction (DEJ) is clearly visible. The second image was chosen because there was a developmental defect visible above the bracket and the structure of this defect is clearly visible. It has a distinct zone of hypomineralization which highly scatters in a similar fashion to demineralization (red zone in image). An outer transparent zone covering the lesion is also visible with a higher mineral content (less scattering/reflectivity). Caries lesions that undergo remineralization (arrested lesions) are expected to appear with similar structure in CP-OCT images.

The utility of OCT for assessing the severity of lesions in the occlusal surfaces has been established in *in vitro* and *in vivo* studies^{20, 21}. OCT can be used to show the penetration and spread of occlusal lesions under the enamel. The scan range ~ 7-mm of the Santec CP-OCT is sufficient to reach the DEJ for all areas of the occlusal surface. Fig. 3 shows a tooth with a small area of gross cavitation. The subsurface demineralization along the DEJ and the cavity nicely demonstrate how OCT can be used to both monitor the spread of demineralization under enamel and show the extent of cavitation. The 3D OCT image can be used to extract information about the lateral spread of the lesion. The red areas of Fig. 3B represent the increased subsurface reflectivity of the lesion and replicate the lateral spread beneath the enamel shown as shown in the matching polarized light micrograph taken of a corresponding tooth section.

In summary, the CP-OCT system is well suited for imaging both early demineralization and more severe lesions in the occlusal surfaces. The high-speed MEMS scanner and swept laser and compact handpiece are also practical for acquiring *in vivo* images.

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Fig. 1.
Photographs of the 3D CP-OCT scanner showing the scanning handpiece along with the 6×6 mm scanning window at the end of the scanner.

Fig. 2.

Two in vivo CP-OCT b-scans around orthodontic brackets (left) cervical to bracket showing composite (CP) next to the bracket and the underlying sound enamel(En) and the dentinal enamel junction (DEJ). Another tooth (right) with an area of hypomineralization (HM) on the occlusal side of the bracket which has a distinct transparent outer surface

Fig. 3.

An extracted tooth (A) with a cavitated lesion. The tooth was scanned using the CP-OCT scanner shown in Fig. 1 in the area of the red box and a rendering of the surface topography is shown in (B) from OCT. An extracted CP-OCT b-scan along the dotted line in (A) is shown in (C). Areas of red represent high reflectivity and demineralization which matches the corresponding PLM image of a tooth section cut along the same line in (D).