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Polarization-sensitive optical coherence tomographic imaging of artificial demineralization on exposed surfaces of tooth roots

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ABSTRACT

Background and objectives. The purpose of this study was to assess the potential of polarization-sensitive optical coherence tomography (PS-OCT) to non-destructively measure the depth and severity of artificial demineralization on exposed root surfaces and measure the degree of inhibition by topical fluoride. Although PS-OCT imaging studies have demonstrated the utility of PS-OCT for imaging carious lesions on enamel and dentin surfaces the influence of the cementum layer that is present on intact root surfaces has not been investigated.

Materials and methods. In this study, extracted human tooth roots were partitioned into three sections with one partition treated with topical fluoride, one partition protected from demineralization with acid resistant varnish, and one partition exposed to a demineralization solution, producing artificial lesions approximately 200-μm deep in root dentin. The lesion depth, remaining cementum thickness and the integrated reflectivity for lesion areas were measured with PS-OCT. These measurements were also compared with more established methods of measuring demineralization, namely transverse microradiography (TMR) and polarized light microscopy (PLM).

Results. PS-OCT was able to measure a significant increase in the reflectivity between lesion areas and sound root surfaces. In contrast to dentin, the cementum layer manifests minimal reflectivity in the PS-OCT images allowing non-destructive measurement of the remaining cementum thickness. The reflectivity of the cementum layer did not increase significantly after substantial demineralization, however it did manifest considerable shrinkage in a fashion similar to dentin and that shrinkage could be measured with OCT.

Significance. This study demonstrates that PS-OCT can be used to measure demineralization non-destructively on root surfaces and assess inhibition of demineralization by anti-caries agents.

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1. Introduction

Root caries is an increasing problem with our aging population [1,2]. It has been well established that root caries can be arrested by fluoride or chemical treatment in a similar fashion to enamel caries [3]. Even though lesions may cover a fairly extensive area on the root surface, they are seldom more than 0.5–1 mm deep [3]. In order to treat such lesions effectively with non-surgical approaches such as fluoride application, it is essential to have non-destructive imaging tools that are capable of assessing the severity of demineralization on root surfaces to determine if the lesion is active and progressing or if it has undergone some remineralization and has been arrested. Current (non-destructive) assessment of lesion activity is based on lesion color and texture that are difficult to quantify [3]. Standard quantitative methods for determining the efficacy of anti-caries agents on root surfaces are destructive and require teeth scheduled for extraction and entail partial destruction of the tooth through sectioning. These methods include microradiography, microhardness and polarized light microscopy (PLM).

Studies have shown that the outer cementum layer is significantly more acid resistant than the underlying dentin [4,5]. Therefore, the cementum layer is an important layer for protection against root surface caries. The loss of the cementum layer cannot easily be determined from microradiographs since cementum has a similar mineral content to dentin. Polarized light microscopy is typically used to measure the thickness of the cementum layer due to differences in birefringence however this also requires thin sectioning and destruction of the tooth.

Optical coherence tomography (OCT) is a high resolution non-destructive optical imaging technique for creating cross-sectional images of internal biological structure [6–8]. OCT is an interferometric technique employing near-IR low-coherence light that is capable of imaging to depths in excess of 1–2 mm in highly scattering tissues such as human dentin and deeper in the more transparent enamel. Several studies have demonstrated the utility of using OCT to image caries lesions and subsurface defects in the tooth. Since it is non-destructive, images of subsurface lesions on intact teeth can be acquired "*in vivo*". In contrast to sound enamel that is highly transparent in the near-IR, sound dentin strongly scatters light in the near-IR and is also highly birefringent which can interfere with polarization resolved imaging [21,22]. Even though the penetration depth is more limited in dentin due to the higher scattering, one can still acquire images of early root caries lesions to depths greater than a mm [17,18]. Demineralized dentin can be discriminated from sound dentin and cementum [16] and root fractures can be imaged from within the root canal [19,20]. In OCT images, the outer cementum can be discriminated from dentin since the cementum manifests a lower reflectivity [16].

There have only been a couple of attempts to quantify the degree of demineralization on dentin and root surfaces. Amaechi et al. [23] measured the % reflectivity loss due to demineralization on root surfaces and showed that this correlated well with mineral loss from microradiography. However, the validity of an approach that relies on the measurement of reflectivity loss is questionable since the reflectivity from the lesion area increases with demineralization for both enamel and dentin producing a overall net increase in reflectivity from the area of the lesion, not a decrease in reflectivity. In a more recent study [24], we demonstrated that polarization-sensitive-OCT (PS-OCT) can be used to measure the depth and severity of artificially produced lesions on dentin surfaces and assess the inhibition of demineralization by topical fluoride. PS-OCT is a form of OCT that is sensitive to changes in the polarization of the reflected light [9]. In PS-OCT, light is typically delivered to the tooth in one polarization and the reflected light from the tooth is measured in both polarization states. PS-OCT has been successfully used to acquire images of both artificial and natural caries lesions, assess their severity in depth, assess the remineralization of such lesions [3] and determine the efficacy of chemical agents in inhibiting demineralization [10]. Polarization-sensitive depth-resolved reflectivity measurements can provide a measure of the severity of natural and artificial caries lesions on smooth surfaces and in the occlusal pits and fissures [11–15]. The high reflectivity at the tooth surface produces a very strong reflection that can interfere with the measurement of early demineralization that is located on that surface. The magnitude of this strong reflection can be reduced using polarized light. Moreover, demineralized areas on the tooth depolarize the incident linearly polarized light and the reflectivity in the orthogonal or perpendicular polarization state to the incident polarization can be directly integrated to provide a measure of the lesion severity [13,16]. We have demonstrated that there was a positive correlation between (ΔR) and (ΔZ) for lesion areas on dentin surfaces [24]. In our approach the reflectivity from each layer of the lesion was measured and those values were subsequently integrated over a specific depth to yield the integrated reflectivity (ΔR) in units of dB μm for direct comparison with the "gold standard", the integrated mineral loss (ΔZ) that is calculated in a similar fashion by integrating the mineral loss over a given depth.

In summary, the principal objective of this study was to demonstrate that PS-OCT can be used to non-destructively measure the thickness of the cementum layer and provide a non-destructive means for quantifying the severity of artificial demineralization on tooth root surfaces and show the inhibition potential of anti-caries agents such as fluoride. The integrated reflectivity in artificial lesion areas on the root surfaces of extracted teeth that were measured with PS-OCT was compared with the well established methods of transverse microradiography (TMR) and polarized light microscopy that require tooth extraction and thin sectioning.

2. Materials and methods

2.1. *Sample preparation*

Teeth extracted from patients in the San Francisco Bay area were collected with CHR approval, cleaned, sterilized with gamma radiation, and stored in a moist environment to preserve tissue hydration with 0.1% thymol added to prevent bacterial growth. The teeth were inspected and the roots of seventeen sound human posterior teeth were cut in half and