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Near-infrared imaging of secondary caries lesions around composite restorations at wavelengths from 1300–1700-nm

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ABSTRACT

Background and objectives. Current clinical methods for diagnosing secondary caries are unreliable for identifying the early stages of decay around restorative materials. The objective of this study was to access the integrity of restoration margins in natural teeth using near-infrared (NIR) reflectance and transillumination images at wavelengths between 1300 and 1700-nm and to determine the optimal NIR wavelengths for discriminating composite materials from dental hard tissues.

Materials and methods. Twelve composite margins ($n = 12$) consisting of class I, II and V restorations were chosen from ten extracted teeth. The samples were imaged *in vitro* using NIR transillumination and reflectance, polarization sensitive optical coherence tomography (PS-OCT) and a high-magnification digital microscope. Samples were serially sectioned into 200-μm slices for histological analysis using polarized light microscopy (PLM) and transverse microradiography (TMR). Two independent examiners evaluated the presence of demineralization at the sample margin using visible detection with 10× magnification and NIR images presented digitally. Composite restorations were placed in sixteen sound teeth ($n = 16$) and imaged at multiple NIR wavelengths ranging from $\lambda = 1300$ to 1700-nm using NIR transillumination. The image contrast was calculated between the composite and sound tooth structure.

Results. Intensity changes in NIR images at wavelengths ranging from 1300 to 1700-nm correlate with increased mineral loss measured using TMR. NIR reflectance and transillumination at wavelengths coincident with increased water absorption yielded significantly higher ($P < 0.001$) contrast between sound enamel and adjacent demineralized enamel. In addition, NIR reflectance exhibited significantly higher ($P < 0.01$) contrast between sound enamel and adjacent composite restorations than visible reflectance.

Significance. This study shows that NIR imaging is well suited for the rapid screening of secondary caries lesions.

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1. Introduction

Secondary (recurrent) caries is the major etiologic factor in the failure of dental restorations, and dentists spend more time replacing restorations than placing new ones [1,2]. Conventional clinical methods for evaluating demineralization surrounding restorations rely upon visible inspection for discoloration and gaps/microleakage, and tactile sensation with an explorer or periodontal probe. It is clear from clinical data that neither discoloration nor ditching (for gap distances <500-μm, which are considerable) is a consistent indicator of the integrity of the enamel or dentin, and a considerable number of restorations are unnecessarily replaced using such criteria [2–7]. Inspection via tactile examination also presents the risk of accelerating decay by damaging the protective lesion surface zone. New imaging methods that can discriminate between sound enamel, demineralized enamel and composites with higher diagnostic performance for secondary caries lesions are needed.

To address this need, optical techniques including digital radiographs (X-rays), quantitative laser fluorescence (QLF, collagen fluorescence), and red laser fluorescence (LF, porphyrin fluorescence) have been investigated as alternative, nondestructive approaches for diagnosing recurrent decay, albeit that each modality has significant limitations.

Digital radiographs lack the sensitivity to detect changes present during the early stages of lesion progression. Generating radiographic images requires ionizing X-rays and a direct viewing angle of the interproximal regions to produce a diagnostic image [8]. When imaging restored teeth, amalgam and composite restorations are radiopaque and may mask the presence of caries either partially or completely which contributes to the difficulty of diagnosis, and therefore are poorly suited for detecting secondary caries [9–13].

Quantitative light fluorescence (QLF) uses UV or blue light ranging from 370 to 470-nm in wavelength to excite the proteins in enamel and dentin, and identifies lesions by measuring the loss of fluorescence at wavelengths >500-nm (green light) [14–16]. Measuring lesion severity based on a loss of signal with visible light is problematic due to the high absorption from stain that attenuates light and results in false positives using this method. Secondary caries detection using QLF has been comparable in accuracy to visual diagnosis [13,17,18].

Laser fluorescence (LF) uses ~655-nm light to excite fluorescence of bacteria-produced porphyrins and measures light emission at wavelengths >680-nm (near-infrared) [19,20]. In LF, the presence of a fluorescent signal is used to locate infected areas as a function of bacteria concentration and studies suggest that LF out performs visible and QLF methods for the detection of recurrent decay [13,17,18,21–23]. Unfortunately, LF is prone to false positives due to poor correlation between porphyrin concentration and lesion severity and requires cleaning of tooth surfaces for effective use. Furthermore, the excitation wavelengths used in LF has been shown to cause fluorescence in many dental restorative materials, including some sealants [24,25]. For LF devices such as the DIAGNOdent, this requires the user to continually calibrate the device against a ceramic standard, and against sound enamel for each individual tooth [13].

Near-infrared (NIR) imaging has the potential for improved performance over current methods used to detect recurrent decay by illuminating and capturing images of tooth structures formed by deeply penetrating, non-ionizing light ranging from 700 to 1700-nm in wavelength. Compared to visible light, light scattering in sound enamel at $\lambda = 1300$-nm is ~20×–30× less making sound enamel virtually transparent [26]. When sound enamel becomes demineralized by caries, pores within the lesion grow to a similar size of the wavelength of light and act as Mie scatterers increasing the scattering coefficient 2–3 orders of magnitude [27]. Differences in light scattering between sound and demineralized enamel can be detected by imaging light transmitted through or reflected back from the tooth [28]. Imaging with longer wavelength ($\lambda \geq 1300$ nm) NIR light also avoids the absorption bands of organic molecules responsible for pigmentation allowing direct imaging of decay beneath stained surfaces such as the occlusal grooves [29]. Additionally, composite restorative materials have unique spectral signatures in the NIR resulting from combination absorption bands that can be exploited for differentiating tooth structure and other type of composites. The most prominent dental resin absorption bands lie at 1171, 1400, 1440, 1620 and 1700-nm and result from overtones and combinations of the fundamental mid-IR vibrational bands from C—H, N—H, and O—H groups found in both resin and water [30–32].

Recent studies have investigated the use of polarization sensitive optical coherence tomography (PS-OCT), at ~1300-nm, for the detection of demineralization beneath sealants and composites in addition to primary lesions [33–36]. These studies demonstrated the ability of PS-OCT to produce three-dimensional data sets that accurately indicate demineralized tissue surrounding restorations. Furthermore, PS-OCT can be used to calculate the integrated reflectivity with depth of the tissue, ΔR, a physical quantity that directly correlates with ΔZ, the integrated mineral loss with depth, and the gold standard for lesion severity. Although PS-OCT is a powerful imaging technique, the vast amounts of data produced from each scan and inherent difficulty of presenting and comprehending three-dimensional data sets make it poorly suited as a caries-screening tool. Another challenge is that the scanning area is relatively small compared to the size of the tooth such that you cannot 'see' the entire tooth anatomy, and increasing the scanning area increases the size of the data set and computational burden.

NIR two-dimensional imaging modalities have demonstrated high image contrast for early surface demineralization using NIR reflectance at $\lambda = 1460$-nm and NIR transillumination at $\lambda = 1300$-nm [37–41]. Many composite restorative materials are translucent to NIR light and allow demineralization to be imaged directly through the restorations [42,43]. Additionally, the overall visualization of the restoration boundaries can be enhanced when viewed at different NIR wavelengths [44]. A technique with these abilities should be ideally suited for the detection of recurrent caries in both planes; the surface enamel and the enamel of the cavity wall as defined by Kidd [3]. These caries affected planes are classified as either *outer lesions*, primary lesions that develop from the surface adjacent to the restoration, or *wall lesions*, decay along the enamel of the cavity as a result of microleakage or ditching. With the advantage of real-time video acquisition