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Authors
Almaz, Elias C
Simon, Jacob C
Fried, Daniel
et al.

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Influence of stains on lesion contrast in the pits and fissures of tooth occlusal surfaces from 800–1600-nm

Elias C. Almaz, **Jacob C. Simon**, **Daniel Fried**, and **Cynthia L. Darling**•
University of California, San Francisco, San Francisco, CA 94143-0758

Abstract

For over one hundred years, x-rays have served as a cornerstone of dentistry. Dental radiographic imaging technologies have constantly improved, however, detecting occlusal lesions remains as one of the greatest challenges due to the low sensitivity of radiographs and the overlap of enamel. Once detected, occlusal lesions have penetrated far into the dentin, necessitating invasive restorative treatment. The adoption of near-infrared (NIR) systems in dentistry introduces the potential for early detection of occlusal lesions. Commercially available NIR systems for intra-oral applications currently operate near 800-nm; however, extrinsic stains may interfere with the detection of demineralization of the underlying enamel surface. Higher wavelengths such as 1300-nm render stains nearly transparent and enhances the contrast of sound enamel to demineralized enamel. This novel finding promotes minimally invasive dentistry and allows oral health professionals the ability to detect, image, track, and monitor early lesions without repeated exposure to ionizing radiation nor invasive treatment.

Keywords

dental; near-infrared; imaging; occlusal lesions; stains; transillumination; reflectance

1. INTRODUCTION

The scattering coefficient of enamel is 20 to 30 times higher in the visible versus the NIR at 1300 nm [1, 2]. Furthermore, the process of enamel demineralization modifies the tissue's optical properties resulting in increased light scattering by 1–2 orders of magnitude [3]. Due to the magnitude of this change, high contrast between sound and demineralized enamel can be imaged using NIR sensitive detectors. Occlusal and interproximal decay can be detected via transillumination or reflectance. NIR imaging allows greater diagnostic capabilities than the current standard of bitewing radiographs for both interproximal and occlusal carious lesions [4–10, 11].

The potential for minimally invasive clinical treatment of early carious lesions is limited due to the low resolution of radiographs and overlap of enamel on radiographic film [12]. Oral examinations can also misdiagnose a lesion due to the high reflectively of enamel, thus concealing shallow or superficial lesions. Furthermore, visual and radiographic diagnosis

•cynthia.darling@ucsf.edu.

have poor diagnostic performance for occlusal lesions [13, 14]. The ability to detect and monitor early lesions without exposure to ionizing radiation facilitates minimally invasive dentistry by providing a means to diagnose, treat, and arrest/reverse early demineralization. Additionally, NIR technologies can reliably track carious lesion severity allowing the monitoring of the effectiveness of topical fluoride treatment.

Optical transillumination was used extensively before the discovery of x-rays for the detection of carious lesions. Over the past two decades there has been continued interest in this method, especially with the availability of high intensity fiber optic based illumination systems for the detection of approximal lesions [15–20]. Carious lesions appear dark upon transillumination because of decreased transmission due to increased scattering and absorption by the lesion. Several studies have been carried out using visible light transillumination either as an adjunct to bitewing radiography or as a competing method for the detection of approximal caries lesions [21–23, 24]. However, light scattering prevents imaging through the entire tooth at visible wavelengths [1, 2]. More recently, a NIR system has been introduced that uses occlusal transillumination with 780-nm light [25, 26]. We previously investigated using transillumination imaging at 830-nm which has the advantage of utilizing a low-cost silicon CCD sensor optimized for the NIR. The 830-nm system was capable of higher performance than visible systems, but the contrast was significantly lower then that attainable at 1310-nm and simulated lesions could not be imaged through the full enamel thickness [10].

Tooth staining can confound diagnosis by masking demineralization. Previous studies indicate that stains are transparent in the NIR beyond 1300-nm because the organic molecules (chromophores) responsible for pigmentation at visible wavelengths do not absorb light at 1300-nm [5, 27]. Therefore stains can be easily differentiated from actual demineralization in the NIR range, which is not possible at visible wavelengths. A recent study by Chung et al. [28] indicated that absorption due to stains contributed more to the lesion contrast than increased scattering due to demineralization at visible wavelengths [29]. Since it is impractical to remove stains from the deep grooves and fissures on tooth occlusal surfaces, lack of interference from stains at near-IR wavelengths is a significant advantage.

However, the influence of stains at NIR wavelengths has not been quantified. This purpose of this study is to determine the influence of tooth staining found in the pits and fissures of occlusal tooth surfaces on the image contrast of reflectance and transillumination measurements at wavelengths from 800–1600-nm.

2. MATERIALS AND METHODS

2.1 Sample preparation

Twenty-five human teeth with stain on the occlusal surfaces were collected (CHR approved) and sterilized with gamma radiation. Teeth were mounted in black orthodontic acrylic blocks and stored in a moist environment of 0.1% thymol to maintain tissue hydration and prevent bacterial growth.

2.2 NIR transillumination

A NoblePeak Vision Triwave Imager, Model EC701 (Wakefield, MA) was used that employs a Germanium enhanced complementary metal oxide semiconductor (CMOS) focal plane array sensitive in the visible and NIR from 400 to 1600-nm with an array of 640×480 pixels and a 10-µm pixel pitch. An Infinimite™ video lens (Infinity, Boulder, CO) was attached to the Triwave imager. Light from a 150-W fiber-optic illuminator, Model FOI-1, E Licht Company (Denver, CO) coupled to an adjustable aperture and several band-pass (BP) and long-pass (LP) filters were used to provide different spectral distributions of NIR light. Long-pass filters at 1100 and 1500-nm (FEL LP series from Thorlabs (Newton, NJ) and band-pass filters with 40–90-nm bandwidth centered at 830, 1150, 1300 and 1350-nm were used for NIR light. Two imaging configurations were used as shown in Fig. 1. Images of natural teeth with stains on the occlusal surfaces were acquired using the TRANS setup (left) shown in Fig. 1. [9–11] Selected NIR wavelengths were delivered by a low profile fiber optic with dual line lights, Model P39–987 (Edmund Scientific, Barrington, NJ) with each light line directed at the cementoenamel junction beneath the crown on the buccal and lingual sides of each tooth. The fiberoptic line lights were set at a downward angle of ~20° and directed just above the dentin-enamel junction (DEJ). The angle and position were extremely important. If the light is directed too high on the tooth or at an upward angle the light does not enter the dentin of the crown and the contrast of the lesion is greatly reduced.

2.3 Near-IR cross-polarized reflectance

The REF setup [27, 28, 30–33] (right) of Fig. 1 was used for reflectance measurements of natural stained occlusal teeth. Light from the fiber-optic was expanded and collimated and directed towards the tooth at a 30°-degree angle and the reflected NIR light transmitted from the tooth was captured by the Triwave imager. Crossed polarizers were used to remove specular reflection (glare) that interferes with measurements of the lesion contrast.

2.4 Image Analysis and Statistics

All image analysis was carried out using Igor pro software, Wavemetrics (Lake Oswego, OR) image analysis package. A hand drawn region of interest (ROI) was extracted from the most severely stained area of each tooth before and after stain removal with a Varios 350 Lux from NSK (Kanuma, Japan) ultra-sonic scaler. The lateral surface of the scaling tip was adapted to the tooth and applied in brief strokes at sites with extrinsic staining. The same location was used for each filtered image and the image contrast was calculated using the mean pixel intensity of the sound enamel (I_S) outside the ROI area and the mean intensity of the stain or stain/lesion (I_L) inside the ROI. The transillumination contrast formula used was $(I_S-I_L)/I_S$ and the reflectance contrast formula used was $(I_L-I_S)/I_L$ because the lesions appear in opposite contrast measurements. The contrast ratios are normalized from 0 to 1 where 1 represents the maximum contrast value and zero the minimum across the ROI. A repeated measures one-way analysis of variance (ANOVA) followed by the Tukey-Kramer post-hoc multiple comparison test was used to compare the contrast measurements between groups using the statistical software Prism from GraphPad (San Diego, CA).

3. RESULTS AND DISCUSSION

Figure 2 shows a series of multispectral NIR transillumination images of a stained tooth occlusal surface before and after the stain was removed with an ultra-sonic scaler. Bandpass filters centered at 830, 1150, 1300 and 1380-nm were used to segregate the NIR region for each corresponding image. Looking down the 'before' column, it is evident that as the imaging wavelength increases, the absorption from stain diminishes and disappears. Comparing the before and after images captured at the same wavelengths, it is clear that stain removal from the tooth has the most profound effect around 830-nm. Figure 3 is a graph depicting the mean contrast ratio (±SD) measured for all samples versus wavelength before and after stain removal. The stain on the occlusal surface interferes the greatest at 830-nm, and the magnitude of the change falls off significantly when the imaging wavelength is increased to at least 1100-nm. There was a significant difference ($P<0.05$) in the change in lesion contrast before and after stain removal using BP830, LP1100 and BP1150 filters. At 1300-nm the change in lesion contrast is no longer significant and therefore the influence of stain is no longer affecting the diagnostic image.

Figure 4 shows a series of multispectral NIR cross polarized reflectance images of the same sample depicted in Fig. 2 before and after stain removal. Bandpass filters centered at 830, 1150, 1300 and 1380-nm and a longpass 1500-nm filter were used to segregate the NIR region for each corresponding image. The relationship between the appearance of tooth stain and the imaging wavelength is similar to that observed in transillumination. Comparing the before 830-nm and 1500-nm reflectance image demonstrates clearly how the short wavelength absorption of stain masks the bright indications of early demineralization evident in the 1500-nm image. The graph in Fig. 5 shows the contrast ratios measured from the cross polarized reflectance images for all samples versus wavelength before and after stain removal. There was a significant difference in contrast before and after stain removal for BP830 and LP1500 for NIR reflectance imaging (Fig. 5). The contrast measured at 830-nm is negative both before and after stain removal, instead of positive which is expected for demineralization which increases scattering and the reflectivity, indicating that the contrast is dominated by absorption by the stain. At 1500-nm, the contrast is positive before and after stain removal due to demineralization. Even though the change in lesion contrast was significant at 1500-nm, it is not likely that this effect is due to the influence of the stain because the removal of stain should increase the signal from the lesion in reflectance not decrease it. This suggests that some of the lesion imaged at 1500-nm was removed from the tooth surface during the stain removal process. In summary, this study suggests that stains on teeth interfere significantly with the lesion contrast at wavelengths shorter than 1150-nm and imaging wavelengths ranging from 1200–1600-nm are not significantly influenced by the presence of stain in the pits and fissures found on occlusal surfaces. Therefore, NIR imaging performed above 1200 nm can detect early demineralization below stained surfaces.

Acknowledgments

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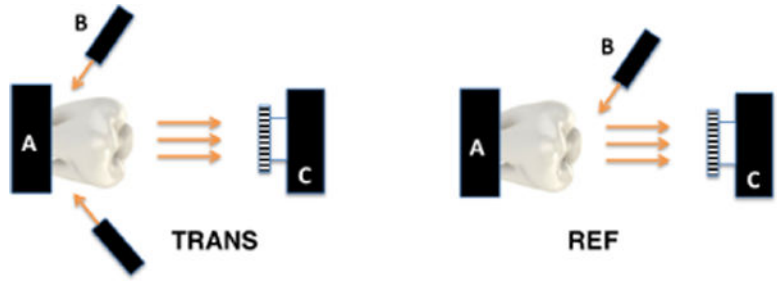

Fig 1.

Imaging configurations for NIR occlusal transillumination and cross-polarized NIR reflectance with (A) tooth, (B) light source, and (C) Imaging camera.

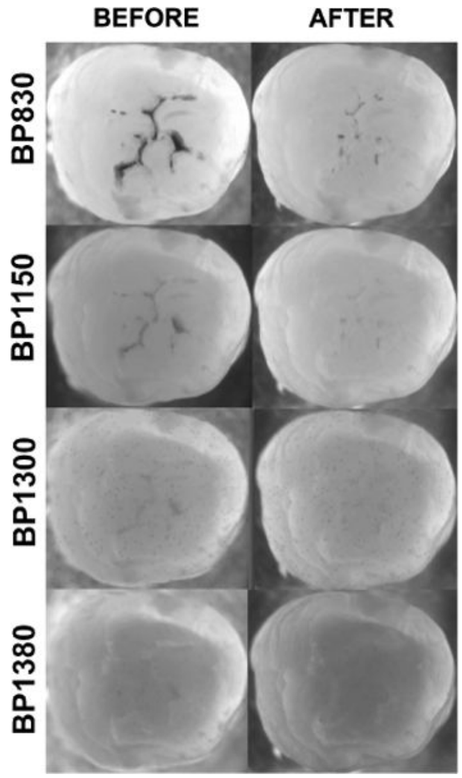

Fig 2.
NIR transillumination images before and after stain removal at BP830, BP1150, BP1300 and BP1380-nm.

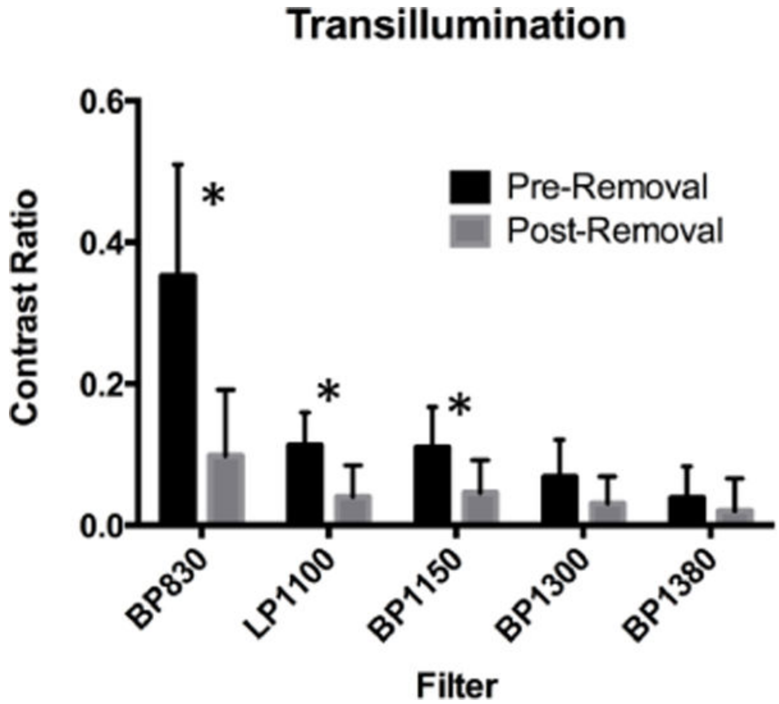

Fig 3.

NIR transillumination imaging of stain covered lesions. There was a significant difference (P<0.05) in contrast at BP830, LP1100 and BP1150 before and after stain removal.

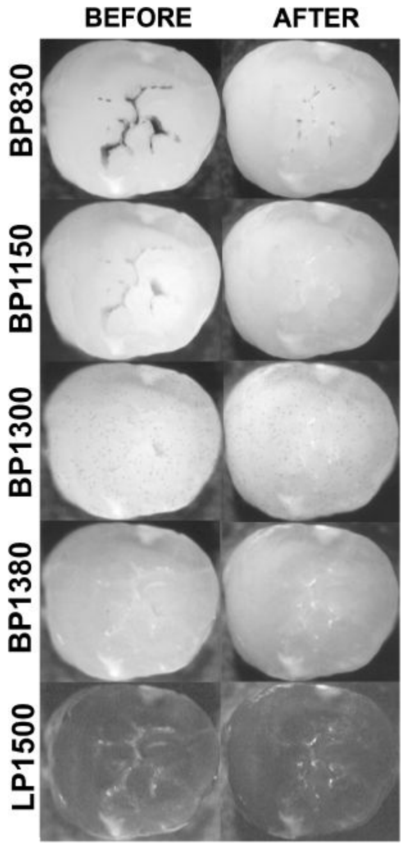

Fig 4.

NIR reflectance images before and after stain removal at BP830, BP1150, BP1300, BP1380. and LP1500.

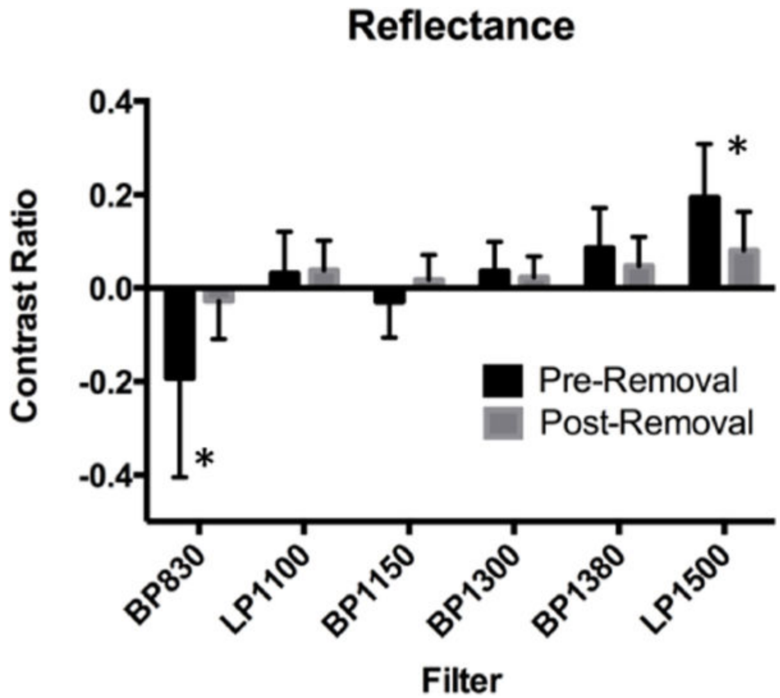

Fig 5.

NIR reflectance imaging of stain covered lesions. There was a significant difference in contrast before and after stain removal at BP830 and LP1500 (P<0.05).