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High-Contrast Reflectance Imaging of Composite Restorations Color-Matched to Tooth Structure at 1000–2300-nm

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Abstract

A major advantage of composite restoration materials is that they can be color matched to the tooth. However, this presents a challenge when composites fail and they need to be replaced. Dentists typically spend more time repairing and replacing composites than placing new restorations. We have shown in previous studies that high-contrast images of composite can be acquired in occlusal transmission mode at near-IR wavelengths coincident with higher water absorption. The purpose of this study was to determine if similar high-contrast images can be acquired in reflectance mode at longer wavelengths where water absorption is even higher. Extracted human teeth with existing composite restoration (n=14) were imaged at wavelengths from 900–2300 using an extended range InGaAs camera. Our results indicate that NIR wavelengths longer than 1400-nm coincident with higher water absorption yield the highest contrast between dental composites and tooth structure in reflectance.

Keywords

Near-IR reflectance imaging; dental enamel; dentin; composite restoration

1. INTRODUCTION

Dentists spend more time replacing existing restorations that fail due to microleakage and secondary decay than they do on placing new restorations. Composite restorations are often color matched to the tooth structure, which makes it difficult to differentiate between them. This poses a challenge when those composites have to be removed. We have developed various approaches to facilitate their selective removal. One approach is to employ selective laser removal methods with or without spectral feedback [1–5]. Another potential approach is to image the teeth at other wavelengths where the composite is more visible and we have shown in previous studies that high-contrast images of composite can be acquired with the occlusal transmission mode at near-IR wavelengths coincident with higher water absorption [6–8]. In addition, being able to discriminate between sound enamel, demineralized enamel and composites will allow better detection of secondary caries lesions[9]. Therefore there is a need for new imaging tools that are capable of monitoring decay around existing restorations. Light scattering in sound dental enamel decreases markedly in the near-infrared (NIR) region and studies have shown that enamel has the highest transparency near 1310-nm[10]. At this wavelength, enamel is virtually transparent in the NIR, the attenuation coefficient is only 2 to 3 cm⁻¹, which is a factor of 20 to 30 times lower than in the visible region[11]. Even though the light scattering for sound enamel is at a minimum in the NIR,

the light scattering coefficient of enamel increases by 2–3 orders of magnitudes upon demineralization due to the formation of pores on a similar size scale to the wavelength of the light that act as Mie scatterers [12]. In addition to the high transparency of enamel in the NIR, there are other important advantages for imaging dental caries. In NIR images of occlusal surfaces, stains are not visible since the organic molecules responsible for pigmentation absorb poorly in the NIR making it easier to identify areas of demineralization [13, 14]. Several *in vivo* and *in vitro* NIR imaging studies have demonstrated that NIR imaging at wavelengths greater than 1300-nm are well suited for caries screening and have the potential for greater diagnostic performance than radiographs. [15–20]. Dental composites also have unique spectral signatures in the NIR due to combination absorption bands that can be used for differentiation from tooth structure and other types of composites. Dental resins have absorption bands in the NIR that arise from overtones and combinations of the fundamental mid-IR vibrational bands due to C-H, N-H, and O-H groups in both the resin and water with the most prominent bands located at 1171, 1400, 1440, 1620, and 1700-nm [21–23]. Since dental composites contain less water than dental hard tissues and the absorption and scattering properties vary in the NIR, we suspected that the contrast would be greater at longer wavelengths. At longer wavelengths, water absorption increases significantly and reduces the penetration of the NIR light [24]. Reflectance measurements can also be highly effective at NIR wavelengths and we have demonstrated that they can be used to acquire high contrast images of dental decay [6, 15, 25–27].

In summary, the objective of this study was to investigate the contrast at multiple NIR wavelengths 1500, 1675, 1695, 1718, and 2000-nm between the sound enamel and the composite restoration area on the occlusal surfaces of molars and premolars. In addition, we investigated the contrast at wavelengths beyond 1700-nm where water absorption is even higher using an extended range InGaAs camera.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Extracted molars and premolars that contained composite were collected (CHR approved) from oral surgeons in the San Francisco area (n=14) and sterilized with gamma radiation. Criteria for selection included size and visibility of composite, and amount of decay near the composite. Samples then had their roots removed and were mounted individually on Delrin blocks. All samples were then stored in a moist environment of 0.1% thymol to maintain tissue hydration and prevent bacterial growth.

2.2 NIR Reflectance Images

The setup for NIR reflectance imaging is shown in Fig. 1. A Sensors Unlimited (Princeton, NJ) Model GA1280J (1280 × 1024) InGaAs camera sensitive from 900–1700-nm with a Goodrich SWIR optimized f=50-mm lens (f/1.4) and a Xenics (Leuven, Belgium) Model Xeva-2.35–320 sensitive from 900–2350-nm (320×240 pixel) extended range InGaAs camera with a Navitar SWIR optimized f=35-mm lens (f/1.4) were used. A stabilized Tungsten IR light source, Model SLS202, from Thorlabs (Newton, NJ) with a peak output at

1500-nm and collimating optics and a 150-W fiber-optic illuminator Model FOI-1 from the E Licht Company (Denver, CO) were used as the illumination sources. Crossed NIR polarizers were used along with various long-pass LP (wavelength (bandwidth)) and band-pass BP (wavelength) filters (Fig. 2) from Spectrogon (Parsippany, NJ) BP1675(90); Omega Optical H1718 (Custom Filter); Edmund Scientific, (Barrington, NJ) LP1650; Thorlabs BP2000(500) and LP1500. Visible reflectance images were acquired using a Dinolite Edge Model AM4815ZTL extended depth of field microscope with crossed polarizers from Dunwell Tech. (Torrance, CA).

2.3 Image Analysis

Two points from a line profile across the composite and sound tooth surface were selected from the NIR images on the occlusal surfaces from each region on each tooth. The composite region of the tooth typically had higher intensities, therefore the image contrast was calculated using the equation $(I_C - I_S)/I_C$; where I_S was the intensity of the sound enamel point of interest, and I_C was the intensity of the composite point of interest. The image contrast varies from 0 to 1 with 1 being very high contrast and 0 having no contrast. The contrast was calculated for each wavelength with the points of interest being the same for each wavelength on each individual sample. All image analysis was carried out using Igor pro software (Wavemetrics, Inc., Lake Oswego, OR). A one-way analysis of variance (ANOVA) followed by the Tukey–Kramer post hoc multiple comparison test was used to compare groups for each wavelength employing Prism software (GraphPad, San Diego, CA).

3. RESULTS AND DISCUSSION

Figure 3 shows occlusal reflectance images for two teeth taken at five different wavelengths along with the visible reflectance images. The composite is visible with markedly higher contrast in the NIR compared to the visible. This is likely due to the reduced water content of the composite versus the peripheral enamel and dentin. The first tooth in Fig. 3 also contains a small lesion in the central fissure and this lesion shows up with extremely high contrast. Visible images taken using the Dinolite are also shown in Fig 3. Even after the teeth are air dried, it is hard to identify the composite restorations shown by the yellow arrows. In the NIR reflectance images, the composite restoration appears lighter than the surrounding sound enamel. There was insufficient light throughput for the bandpass filters centered at 1675-nm and 1718-nm and the aperture in front of the InGaAs camera had to be opened fairly wide reducing contrast and blurring the images. Therefore, we did not include these images in the final analysis and Fig. 4.

The mean contrast between tooth structure and composite through reflection for each wavelength range is shown in Fig. 4. The contrast is much larger at the higher NIR wavelengths, while unfiltered standard InGaAs (900–1700) and the visible have a much lower contrast. There is no statistical difference in the contrast between the remaining wavelengths shown in the graph, although the mean contrast with the long-pass 1500-nm filter using the standard InGaAs camera is lower than for the 1500, 1695, and 2000-nm filters on the extended InGaAs camera.

The higher contrast of the NIR wavelengths compared to the visible is likely due to differences in water absorption between composite and tooth structure. Higher absorption by water occurs near 1900-nm and we anticipated higher contrast beyond 1700-nm.

This study clearly demonstrates that NIR reflectance has considerable potential for the imaging of composite restorations. The NIR wavelengths coincident with higher water absorption yielded significantly higher contrast than other methods. The contrast was higher at further wavelengths beyond 1700-nm but the difference was not statistically significant. The high contrast between sound enamel and composites suggests that NIR imaging may be advantageous for screening for secondary caries. In addition to the high contrast in this study, another potential advantage NIR imaging has over visible imaging methods and fluorescence-based methods is the lack of interference from stains and discoloration, since stains are not visible in the NIR. In addition, NIR reflectance is easier to employ clinically than NIR transillumination.

Acknowledgments

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Fig. 1. NIR reflectance setup consisting of a (A) broadband NIR lightsource (B) filter holder, (C) InGaAs camera and (D) tooth holder.

Fig. 2.
Approximation of the wavelength ranges of each filter. Intensity not to scale.

Fig. 3.

Images of two teeth with composites at the positions of the yellow arrows. Occlusal reflectance images are shown for the 1500-nm, 1675-nm, 1695-nm, 1718-nm, and 2000-nm filters with the extended range InGaAs camera (900–2350-nm) as well as for visible light.

Contrast Comparison Between Different Wavelengths

Fig. 4.

Mean contrast values between the sound enamel and composite restoration area for (n=14) teeth at multiple wavelengths. Bars with same color represent statistically similar groups ($P>0.05$). * Standard InGaAs camera (900–1700-nm)