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Multispectral near-IR reflectance and transillumination imaging of teeth

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Abstract: NIR imaging methods do not require ionizing radiation and have great potential for detecting caries lesions (tooth decay) on high-risk proximal and occlusal tooth surfaces and at the earliest stages of development. Previous *in vitro* and *in vivo* studies at 1300-nm demonstrated that high contrast reflectance and transillumination images could be acquired of caries lesions on tooth proximal and occlusal surfaces where most new decay is found. Water absorption varies markedly between 1200 and 1600-nm and the scattering properties of enamel and the underlying dentin have not been characterized in this region. Hyperspectral reflectance studies show lower reflectivity from sound enamel and dentin at NIR wavelengths with higher water absorption. The purpose of this imaging study was to determine which NIR wavelengths between 1200 and 1600-nm provide the highest contrast of demineralization or caries lesions for each of the different modes of NIR imaging, including transillumination of proximal and occlusal surfaces along with cross polarization reflectance measurements. A tungsten halogen lamp with several spectral filters and a Ge-enhanced CMOS focal plane array (FPA) sensitive from 400 to 1600-nm were used to acquire the images of caries lesions on extracted teeth. Artificial interproximal lesions were created on twelve tooth sections of 5 & 6-mm thickness that were used for transillumination imaging. Fifty-four extracted teeth with suspected occlusal lesions were also examined in both occlusal transillumination and reflectance imaging modes. Cavity preparations were also cut into whole teeth and filled with composite and used to compare the contrast between composite and enamel at NIR wavelengths. NIR wavelengths longer than 1400-nm are likely to have better performance for the transillumination of occlusal caries lesions while 1300-nm appears best for the transillumination of proximal surfaces. Loss of mobile water in enamel markedly reduced the transparency of the enamel at all NIR wavelengths. Significantly higher contrast was attained for reflectance measurements at wavelengths that have higher water absorption, namely 1460-nm. Wavelengths with higher water absorption also provided higher contrast of composite restorations.

OCIS codes: (110.0113) Imaging through turbid media; (170.1850) Dentistry

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1. Introduction

Enamel is virtually transparent in the near infrared (NIR) with optical attenuation 1-2 orders of magnitude less than in the visible range [1,2]. Interproximal caries lesions can be imaged by NIR transillumination of the proximal contact points between teeth and by directing NIR light below the crown while imaging the occlusal surface both *in vitro* and *in vivo* [3–5]. The same approach can be used to image occlusal lesions with high contrast [5–10].

Early enamel white spot lesions can be discriminated from sound enamel by visual examination or by visible-light diffuse reflectance imaging [11,12]. The visibility of scattering structures on highly reflective surfaces such as teeth can be enhanced by use of crossed polarizers to remove the glare due to the strong specular reflection from the enamel surface [13,14]. The contrast between sound and demineralized enamel can be further enhanced by depolarization of the scattered light in the area of demineralized enamel [8,15]. The contrast between sound and demineralized enamel is greatest in the NIR due to the minimal scattering of sound enamel and this can be exploited for reflectance imaging of early demineralization [16]. Wu et al. [17] reported the first high contrast NIR reflectance images of early demineralization on buccal and occlusal tooth surfaces. The contrast was significantly higher at 1310-nm than in the visible range and it exceeded the contrast of blue-green or quantitative light fluorescence (QLF) [17]. Zakian et al. [18] carried out NIR reflectance measurements from 1000 to 2500-nm using a hyperspectral imaging system and showed that the reflectance from sound tooth areas decreases at longer wavelengths in the NIR where water absorption is higher.

In addition to the high transparency of enamel in the NIR, there are other important advantages of imaging dental caries in the NIR. 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 [7]. Mild developmental defects [9] and shallow demineralization [17] appear differently from deeper and more severe demineralization due to caries, suggesting that it may be feasible to gauge the severity of lesions by analyzing both NIR reflective images and NIR transillumination images of these surfaces [19]. Therefore, one can hypothesize that lesions which appear with high contrast in reflectance images and don't appear in transillumination images are likely superficial or very shallow [10]. It is likely that optimizing the wavelengths for both imaging modes should improve performance using this approach. Zakian et al. [18] also developed an algorithm combining multiple wavelengths in reflectance to assess lesion severity.

Dental composites contain less water than dental hard tissues and the absorption and scattering properties vary in the NIR. Many composite restorations fail and have to be replaced due to further dental decay around composite restorations. This is called secondary caries. Another objective of this study was to examine composite restorations at multiple wavelengths and imaging modes to determine the best wavelengths for imaging secondary caries in both reflectance and transillumination.

The purpose of this imaging study was to determine which NIR wavelengths between 1200 and 1600-nm provide the highest contrast of demineralization or caries lesions for each of the different modes of NIR imaging including transillumination of proximal and occlusal surfaces along with cross polarization reflectance measurements.

2. Methods

2.1. Sample preparation

Extracted teeth from patients in the San Francisco bay area were collected with approval from the UCSF Committee on Human Research, cleaned, sterilized with gamma radiation, and stored in a 0.1% thymol solution to preserve tissue hydration and prevent bacterial growth. Teeth with apparent occlusal lesions (n = 54) were selected for imaging and mounted in orthodontic resin blocks with the cementoenamel junctions exposed. Radiographs were acquired of each tooth and teeth with radiographically positive lesions were rejected since smaller lesions were more appropriate for this study. In addition, twelve sound human teeth were selected and sections 5-mm and 6-mm thick were cut using a linear precision saw, the IsoMet 2000 (Buehler, Lake Buff, IL). Six sections of each thickness were prepared and subsequently serially polished using 12, 6, 3, 1 and 0.1-µm diamond impregnated disks. A small incision was cut with a small diameter (800-µm) bur into the enamel in the center of each tooth section slightly past the dentin-enamel junction and the hole was filled with hydroxyapatite powder to simulate caries lesions as was done in a similar fashion in prior studies [3,4]. A layer of bonding resin was applied to the outside of the incision to fix the hydroxyapatite in place.

Cavity preparations were cut into three whole teeth and Z250 composite (3M, Minneapolis, MN) was used as a restorative material for multispectral transillumination and reflection measurements to determine the wavelengths that provide the highest contrast between dental composite and enamel.

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2.2. Near infrared (NIR) imaging

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 640x480 pixels and a 10-µm pixel pitch. An Infinimite^{TM} video lens (Infinity, Boulder, CO) was attached to the Triwave imager. Light from a 150-W fiber-optic illuminator 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 and visible light. Visible light was provided using a short pass filter, FSR-KG5 (Newport, Irvine, CA) with a cutoff of 800-nm. Long-pass filters at 1200, 1300, 1400 and 1500-nm (FEL LP series from Thorlabs, Newton, NJ) and band-pass filters with 40-90-nm bandwidth centered at 1300, 1460 and 1550-nm were used for NIR light. The filters were BP1300-90 and BP1460-85 from Spectrogon, Parsippany, NJ and FB1550-40 from Thorlabs. The bandpass filters were chosen near the two extremes of the NIR region between 1200 and 1600-nm; 1300-nm and 1550-nm and the region of peak water absorption 1460-nm. Three imaging configurations were used as shown in Fig. 1. Images of natural lesions on the occlusal surfaces of whole teeth were acquired using the first setup shown in Fig. 1. 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 fiber-optic 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.

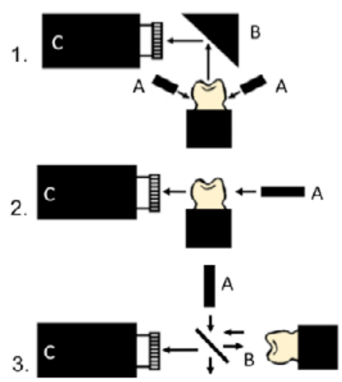

Fig. 1. NIR imaging setups for (1) occlusal transillumination imaging, (2) transillumination of sections with simulated lesions, and (3) occlusal reflectance imaging (A) light, (B) prism or beamsplitter and (C) Ge-CMOS imager.

The second setup shown in Fig. 1 was used for the transillumination of the enamel sections of varying thickness. The output from the fiber-optic was expanded and collimated and a Teflon diffuser was used to homogenize the light incident on the samples.

The third setup of Fig. 1 was used for reflectance measurements of natural occlusal caries lesions. Light from the fiber-optic was expanded and collimated and directed towards the tooth occlusal surface through a broadband beamsplitter (1200-1600-nm) Model BSW12 (Thorlabs, Newton, NJ) and the reflected NIR light from the tooth was transmitted by the beamsplitter to the Triwave imager. Crossed polarizers were used to remove specular reflection (glare) that interferes with measurements of the lesion contrast.

It was necessary to vary the illumination intensity from sample to sample due to the varying transmission of the filters, the spectral responsivity of the imager, and the fact that

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tooth size and shape is highly variable. The gain of the camera was fixed for all the filters with the exception of the BP1550 filter for which the gain was increased by a factor of two. The gain of certain groups of pixels on the Triwave imager varied with wavelength so that either white spots or dark spots were visible when using different filters. These were not dead pixels, they were pixels that manifested a different spectral responsivity. Background images were collected using a white reference target for non-uniformity correction of both the response of the FPA and the uniformity of the light source. This was not possible for the occlusal transillumination measurements and a simple box filter was applied to the image over a range of 5 pixels to remove the small dots from the image. It was easy to avoid questionable pixels for the contrast measurements and they were carried out before filtering.

2.3. Histology and Image analysis

The 54 teeth with occlusal lesions were mounted on orthodontic resin blocks that are used for both imaging and for histological sectioning. After imaging, teeth were cut into serial sections 200-µm thick using a linear precision saw, the IsoMet 5000 (Buehler, Lake Buff, IL). Polarized light microscopy (PLM) was carried out using a Meiji Techno RZT microscope (Saitama, Japan) with an integrated digital camera, Canon EOS Digital Rebel XT (Tokyo, Japan). The sample sections were imbibed in water and examined in the brightfield mode with crossed polarizers and a red I plate with 550-nm retardation. The histological sections were scored according to the maximum penetration of caries in each particular section matching the line-profiles used for the contrast measurements, with E indicating that the lesion was confined to enamel, D1 penetration into the 1st half of dentin and D2 indicates penetration into the 2nd half of the dentin. Histology scores are provided for 52 teeth since we were unable to acquire good sections for two out of the 54 teeth sectioned.

Line profiles 5-pixels wide were taken from what appeared to be the most severe area of the lesion to a sound area in the images using Igor Pro Software (Wavemetrics, Lake Oswego). Line profiles were taken across the lesion and sound areas for the artificial interproximal lesions on the tooth sections using the same approach as shown in refs [3,4]. For the occlusal reflectance and transillumination measurements the line profiles were taken across the most severe fissure area with decay and a sound area as done in refs [6,19]. We avoided teeth with obvious cavitation or with an obvious shadow visible to the naked eye which is indicative of dentinal caries under the sound enamel. Care was taken to sample over dentin for both sound and demineralized areas.

The image contrast was calculated using $(I_L - I_S)/I_L$ for reflectance and $(I_S - I_L)/I_S$ for transillumination where I_S is the mean intensity of the sound enamel, and I_L is the mean intensity of the lesion area. The image contrast varies from 0 to 1 with 1 being very high contrast and 0 being no contrast. Stains can produce negative contrast for reflectance measurements in the visible range.

Repeated measures analysis of variance (ANOVA) followed by the Tukey-Kramer post hoc multiple comparison test was used to compare groups for each type of lesion employing InStat software from GraphPad (San Diego, CA).

3. Results

Multispectral contrast measurements for the 5-mm and 6-mm thick tooth sections are tabulated in Table 1 measured using the various long-pass (LP) and band-pass (BP) filters. The highest contrast was observed for the BP1300 filter. The contrast in the visible (short-pass KG5 glass filter) is not included in Table 1 since it was zero for all the 5-mm and 6-mm samples. Figure 2 shows transillumination images through one of the 5-mm thick sections with an artificial lesion taken at visible wavelengths (KG5 glass filter) and in the NIR with three NIR bandpass filters taken using the setup of Fig. 1(#2). The enamel does not appear to be transparent in the visible, and the lesion cannot be resolved (Fig. 2A).

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Table 1. Mean contrast ± (sd) between the sound and artificial lesion area for the tooth sections of 5-mm and 6-mm thickness (n = 5 each) for fully hydrated, dehydrated, and rehydrated samples[a]

Filters (LP & BP)	Contrast Hydrated	Statistical Group	Contrast Dry	Contrast Rehydrated
5-mm Samples				
a) LP1200	0.45 (0.11)	b,d,e,g	0.033 (0.039)	0.49 (0.096)
b) LP1300	0.47 (0.093)	a, d,e,g	0.042 (0.048)	0.48 (0.083)
c) LP1400	0.37 (0.090)	f	0.032 (0.039)	0.41 (0.11)
d) LP1500	0.46 (0.087)	a,b,e,g	0.064 (0.073)	0.46 (0.076)
e) BP1300	0.48 (0.092)	a,b,d	0.016 (0.039)	0.53 (0.097)
f) BP1460	0.40 (0.092)	c, g	0.045 (0.055)	0.41 (0.10)
g) BP1550	0.42 (0.080)	a,b,d,f	0.069 (0.082)	0.46 (0.082)
6-mm Samples				
a) LP1200	0.45 (0.10)	b,d,e	0.062 (0.085)	0.49 (0.11)
b) LP1300	0.46 (0.078)	a,d,e	0.049 (0.10)	0.48 (0.093)
c) LP1400	0.32 (0.085)	f,g	0.040 (0.074)	0.39 (0.090)
d) LP1500	0.44 (0.079)	a,b,e,f	0.055 (0.12)	0.44 (0.077)
e) BP1300	0.48 (0.085)	a,b,d	0.038 (0.094)	0.52 (0.11)
f) BP1460	0.38 (0.093)	c,d,g	0.044 (0.083)	0.40 (0.079)
g) BP1550	0.35 (0.092)	c,f	0.089 (0.093)	0.43 (0.097)

[a]Repeated measures ANOVA with Tukey-Kramer Post test was used to compare the contrast of the fully hydrated samples. The contrast ratio of the dehydrated over the fully hydrated samples was also calculated. Statistical groups containing the same letter are statistically similar (P>0.05). Statistics are not shown for the dry and rehydrated samples since the statistics for the rehydrated samples were similar to the wet samples and the contrast of the dry samples was too low to be of interest.

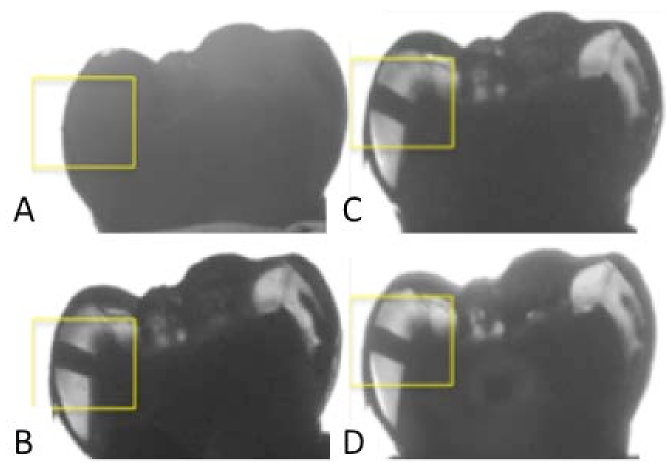

Fig. 2. Transillumination images for a 5-mm thick wet tooth section from Triwave Ge-CMOS imager with (A) KG5 filter 300-800-nm, (B) 1300-nm, (C) 1460-nm, and (D) 1550-nm BP filters. The lesion is in the yellow box.

The state of hydration of the tooth sections profoundly influenced the lesion contrast. The contrast decreased markedly if the samples were left out of water overnight and allowed to dehydrate. This can clearly be seen for a 5-mm thick section in Fig. 3. The lesion contrast appeared to completely recover if the samples were immersed in water overnight and rehydrated. Table 1 also includes the mean contrast values of the dehydrated and rehydrated samples for comparison.

The mean contrast values for the fifty-four occlusal lesions are listed in Table 2 for both reflectance and transillumination measurements. The reflectance measurements for the BP1550 filter are not shown because there was not sufficient intensity for reliable measurements. In the occlusal transmission measurements the highest values for the contrast

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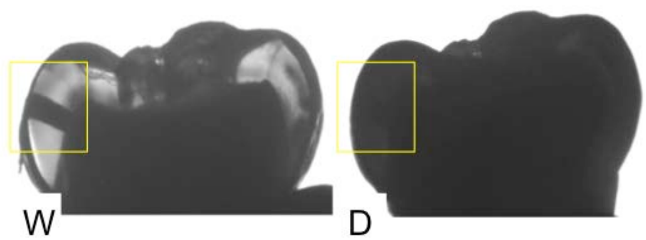

Fig. 3. Transillumination images through a 5-mm thick tooth section with a LP-1300-nm filter (W) wet and (D) dry.

Table 2. Mean contrast ± (sd) of natural occlusal caries lesions on extracted whole teeth measured in reflectance and with transillumination, n = 54[a]

Filters (LP & BP)	Mean contrast (sd)	Statistical group
Reflectance		
a) BP1300	0.16 (0.065)	
b) BP1460	0.33 (0.097)	
c) LP1300	0.21 (0.069)	d
d) LP1400	0.23 (0.087)	c
e) LP1500	0.30 (0.087)	
f) KRS5-(400-800-nm)	–0.093 (0.24)	
Transillumination		
a) BP1300	0.22 (0.079)	d
b) BP1460	0.045 (0.049)	c,f
c) BP1550	0.018 (0.031)	b
d) LP1300	0.213 (0.058)	a
e) LP1400	0.255 (0.099)	
f) LP1500	0.049 (0.057)	b

[a]Repeated measures ANOVA with Tukey-Kramer Post test was used to compare the samples, n = 54. Statistical groups containing the same letter are statistically similar (P>0.05).

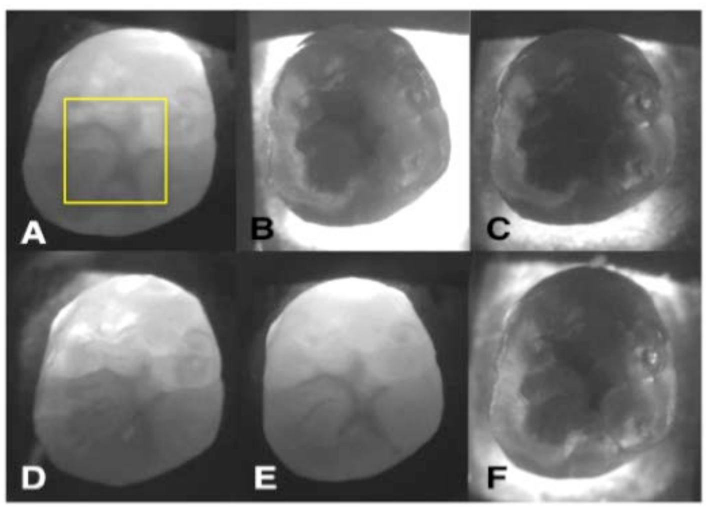

Fig. 4. NIR transillumination images of a tooth with occlusal decay (yellow box) acquired in six wavelength regions generated using (A) 1300, (B) 1460, and (C) 1550 bandpass (BP) filters and (D) 1300, (D) 1400 and (F) 1500 longpass (LP) filters.

was acquired using the LP1400 filter. The contrast values for the other three filters, LP1500 and BP 1460, 1550 were markedly lower. NIR occlusal transillumination images taken using three LP filters at 1300, 1400, and 1500-nm and the three BP filters centered at 1300, 1460 and 1550 are shown in Fig. 4. There are large differences in visibility of the border between

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the enamel and dentin under the sound enamel and the lesion and surrounding sound dentin in these six images. In the three images Figs. 4A, 4D, and 4E taken with the BP1300, LP1300, and LP1400 filters, one cannot resolve the border between enamel and dentin. However, the lesion contrast was highest for these wavelength regions. In the other three images Figs. 4B, 4C, and 4F, taken in wavelength regions with higher water absorption, the enamel and dentin border is visible and the enamel appears more transparent and lighter than the dentin, however, the dentin appears very dark and the lesion contrast is low. The lesion cannot be resolved in the image using BP1550 filter, Fig. 4C and it can barely be seen in the image taken with the BP1460 filter, Fig. 4B. The underlying dentin can clearly be seen in the image taken with the LP1500 filter while allowing the lesion to be seen as well, Fig. 4F.

Reflectance images of a tooth with occlusal decay are shown in Fig. 5 for three filters taken using the setup of Fig. 1(#3). In the visible, (Fig. 5A), the contrast is mostly due to stains localized to the fissures. The area of demineralization should appear whiter in reflectance due to the higher light scattering/reflectivity in the demineralized areas. A much extended area of demineralization is visible at 1300-nm (Fig. 5B) which cannot be seen in the visible (Fig. 5A). The stained areas do not appear to influence the contrast in the NIR. The highest contrast was achieved using the 1460-nm BP filter (Fig. 5C) where the water absorption peaks and the sound enamel appears much darker than in the other wavelength regions. The contrast was also significantly higher at 1460-nm than for 1300-nm and twice the magnitude.

Table 3 lists the mean contrast of the occlusal lesions sorted with respect to the histological score determined after sectioning the teeth and examination of the sections with polarized light microscopy. Statistical comparison using ANOVA indicated that the

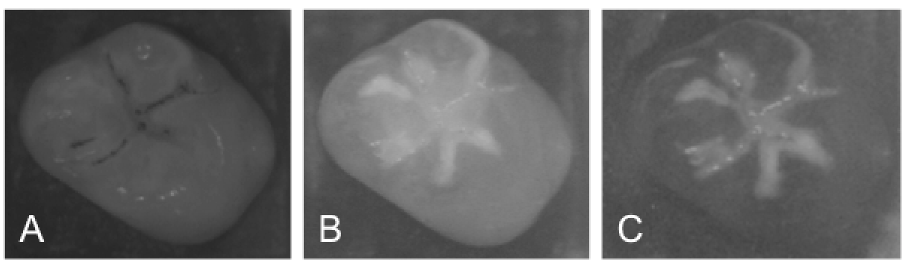

Fig. 5. Reflectance images from Triwave imager with (A) KG5 glass filter 300-800-nm, and (B) 1300-nm and (C) 1460-nm BP filters. Lesion area is best seen in (C) as white areas. The dark areas in (A) are stains.

Table 3. Mean contrast ± (sd) of natural occlusal caries lesions on extracted whole teeth measured in reflectance and with transillumination sorted by histological score, n = 52

Filters (LP & BP)	E (n = 16)	D1 (n = 29)	D2 (n = 7)
Reflectance			
a) BP1300	0.13(0.039)	0.18(0.070)	0.16(0.070)
b) BP1460	0.26(0.104)	0.35(0.085)	0.40(0.080)
c) LP1300	0.17(0.057)	0.22(0.068	0.24(0.062)
d) LP1400	0.20(0.066)	0.26(0.096)	0.21(0.061)
e) LP1500	0.28(0.078)	0.32(0.081)	0.32(0.101)
Transillumination			
a) BP1300	0.17(0.045)	0.24(0.077)	0.25(0.097)
b) BP1460	0.02(0.032)	0.06(0.054)	0.06(0.045)
c) BP1550	0.01(0.027)	0.02(0.029)	0.04(0.046)
d) LP1300	0.19(0.048)	0.22(0.055)	0.25(0.073)
e) LP1400	0.22(0.087)	0.26(0.097)	0.35(0.076)
f) LP1500	0.04(0.042)	0.05(0.061)	0.07(0.075)

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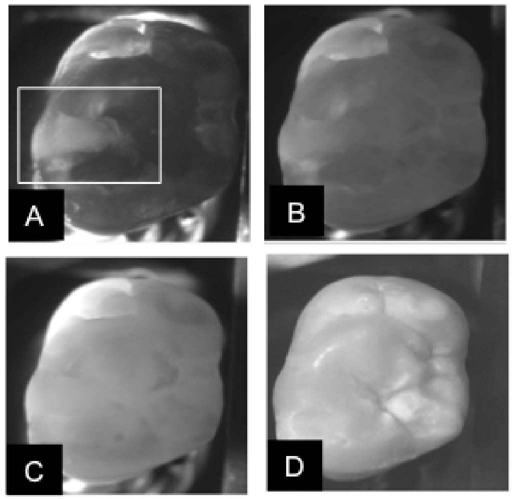

Fig. 6. Images of a tooth with a composite restoration (Z-250, 3M) in the area of the white box. Transillumination images are shown in (A) 1460-nm, (B) 1300-nm, and (C) visible wavelengths while a visible light reflectance image is shown in D.

reflectance measurements using the BP1460 filter showed a significant increase in contrast with lesion severity. The BP1300 and LP1400 filters showed significant increases in lesion contrast with severity for transillumination.

Figure 6 shows NIR and visible light reflectance images of a tooth with a composite restoration. The contrast is quite low between the composite and surrounding tooth structure for both the reflectance and transillumination visible light image. The composite can be seen with higher contrast in the transillumination image taken at 1300-nm, the composite restoration appears lighter. The contrast is much higher at 1460-nm where the composite is much lighter than the surrounding enamel.

4. Discussion

Alternative NIR wavelengths besides 1300-nm are likely to provide higher contrast for certain imaging modes, particularly for imaging lesions in the important occlusal surfaces. Most newly discovered caries lesions are found in the occlusal or biting surfaces of teeth.

For conventional transillumination of lesions on proximal surfaces (lesions at contact points between teeth), 1300-nm provided the highest contrast. This wavelength was used successfully to image interproximal lesions *in vivo* [5]. It appeared that operating at longer wavelengths with higher water absorption decreased the contrast.

The hydration studies involving the transillumination of the tooth sections (Table 1) indicated that loss of mobile water resulted in a significant reduction in sound enamel transparency and loss of lesion contrast. Mobile water is concentrated at the prism boundaries and it is likely that the loss of mobile water leaves pores that act as scattering sites. In a previous study we found that the mean attenuation coefficient of enamel at 1300-nm increased significantly from 2.12 ± 0.82 to 5.08 ± 0.98 with loss of mobile water due to heating [20]. These results indicate that it is extremely important to ensure that teeth are kept well hydrated for NIR imaging studies including optical coherence tomography. Although it appears that drying the teeth greatly reduces the contrast of lesions for transillumination measurements, it has been well established that drying the teeth increases the lesion contrast in reflectance measurements. Lesions are visible with higher contrast if the tooth surface is air-dried and clinicians are taught that if the lesion is only visible when the tooth is dry and it disappears when the tooth is wetted, it is likely to be shallow and superficial. Moreover, the rate of water loss from lesions has also been correlated with lesion activity, arrested lesions are less

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permeable to water due to the highly mineralized outer layer covering the lesion and both thermal imaging [21] and QLF measurements [22] have been used to monitor optical changes associated with water loss. Additional studies are needed to determine if this phenomenon can be similarly exploited at NIR wavelengths.

For the transillumination of occlusal surfaces, which were imaged using the approach in which the NIR light is delivered beneath the crown and the lesions are viewed from the occlusal surfaces (transillumination mode), there was improved contrast for wavelengths longer than 1400-nm (Table 2). The improved performance of wavelengths greater than 1400-nm vs wavelengths greater than 1300-nm or for the 1300-nm region was unexpected and there is not an obvious mechanism for this difference. The occlusal surface topography is complex and the optimal illumination geometry for occlusal lesions has not been established. Light entering the tooth near the gum-line enters the dentin where it is highly scattered and can migrate up through the dentin to the crown providing high contrast or it can migrate around the dentin through the more transparent dentin through internal reflection. Increasing the fraction of light diffusing up through the dentin is likely to produce the highest contrast for occlusal lesions. Differences in the optical properties of both enamel and dentin in the NIR profoundly influence that fraction and the distribution of light exiting the crown. Increased absorption by water is expected to decrease the amount of light diffusing up through the dentin. Water absorption is quite high between 1400 and 1500 nm, and it decreases after 1500 nm. Therefore one would expect similar or improved performance at wavelengths greater than 1500 nm over those beyond 1400 nm. The quantum efficiency of Ge-CMOS drops off rapidly after 1500-nm to less than 20%, therefore the spectral response of the camera may provide an explanation. This warrants further study and we plan to repeat these measurements using an InGaAs imager. Wavelengths where water absorption was high, yielded lower contrast due to the high water content in dentin, as can be seen in Fig. 4. All the underlying dentin including the sound dentin appears very dark due to water absorption so that there is minimal contrast between the occlusal lesions and the surrounding dentin.

The performance of reflectance measurements at wavelengths coincident with high water absorption, i.e., 1460-nm, was significantly higher than at 1300-nm. In a previous study it was shown that the lesion contrast at 1300-nm was higher than that measured using QLF (quantitative light fluorescence) [17]. QLF is considered the most sensitive method for detecting demineralization at the earliest stages and QLF has been investigated extensively for 30 years. Therefore, reflectance measurements at the peak in water absorption near 1440-nm appear very promising for measuring very early demineralization. It is likely that contrast is highest because the higher absorption in dentin reduces backscattered light from the underlying dentin. Hyperspectral reflectance measurements of Zakian [18] show that the dentin gets darker with increasing wavelength even when water absorption is not increasing which suggests that the dentin scattering coefficient may decrease significantly at longer NIR wavelengths.

Studies suggest that the contrast of occlusal lesions in NIR images can be correlated with the lesion severity. Two prior studies showed that the contrast increased significantly with lesion depth in occlusal transillumination measurements at 1300-nm [6,10]. Zakian et al. [18] employed an algorithm to represent the lesion severity employing hyperspectral reflectance values from multiple NIR wavelengths 1090, 1440 and 1610-nm to create a score for caries severity. NIR reflectance measurements carried out on 47 teeth at 1300-nm failed to show a marked increase in contrast with lesion depth in reflectance [10]. It is difficult to use reflectance measurements alone to estimate the depth of caries lesions because the scattering coefficient of dental enamel increases 2-3 orders of magnitude upon demineralization (μ_s = 100-200 cm^{-1}) [16]. Therefore the mean free path of NIR photons in lesions is only 50-µm, and the amount of light reflected from the lesion area should not increase appreciably for lesions that are greater in depth than 500-µm [23], and it should not be feasible to estimate the depth or severity of deeper occlusal lesions from reflectance images alone unless sound enamel is above the lesion. A reflectance only approach may work for imaging lesions in dentin lying beneath sound enamel. Severe lesions under the sound enamel often create a shadow that can be seen even in the visible range. Such lesions should appear with higher contrast at NIR wavelengths due to reduced light scattering in the NIR.

In summary, it appears that NIR wavelengths longer than 1300 nm may enable improved performance for the transillumination of occlusal caries lesions while 1300-nm appears best for the transillumination of proximal surfaces. Markedly higher contrast was attained at wavelengths that have high water absorption, namely 1460-nm, which is consistent with lower reflectivity from sound enamel and dentin [18] and these wavelength regions are likely to be more effective for reflectance imaging. Wavelengths with increased water absorption are also likely to be more effective for imaging around composite restorations due to the lower water content of composite as can be seen in Fig. 6.

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