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Near-IR Multi-modal Imaging of Natural Occlusal Lesions

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Abstract

Reflectance and transillumination imaging show demineralization with high contrast in the near-IR. The objective of this study is to use lesion size and contrast acquired in reflectance and transillumination near-infrared imaging modes to estimate the severity of natural occlusal caries lesions. Previous studies have shown that near-infrared (NIR) light can be used to effectively image artificial carious lesions. However, its efficacy on natural lesions requires further exploration. Fifty extracted teeth with varying amounts of occlusal decay were examined using a NIR imaging system operating at 1310-nm. Image analysis software was used to calculate contrast values between sound and carious tooth structure. After imaging, teeth were histologically sampled at 1-mm intervals in order to determine lesion depth. Lesion contrast in transillumination mode significantly increased with lesion depth ($p < 0.001$), while lesion contrast in reflectance mode did not increase. The lesion area demonstrated a significant increase with lesion severity in both imaging modes. These results suggest that lesion contrast and area can be used to estimate lesion severity in NIR images.

Keywords

Near-IR imaging; occlusal surfaces; dental caries; transillumination; reflectance imaging

1. INTRODUCTION

Optical transillumination was used extensively before the discovery of x-rays for detection of dental caries. 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 interproximal lesions¹⁻⁶. During fiber optic transillumination (FOTI) a carious lesion appears dark upon transillumination because of decreased transmission due to increased scattering and absorption by the lesion. A digital fiber optic transillumination system, called DiFoti, that utilizes visible light for the detection of caries lesions, has been recently developed by Electro-optics Sciences, Irvington, NY⁷. 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 interproximal caries lesions⁸⁻¹². However, since this system operates in the visible range the light cannot penetrate very far through enamel and the results are mixed.

Near-IR light can penetrate much further through tooth enamel due to the markedly longer mean free path of the photons, i.e., enamel is virtually transparent in the near-IR with optical attenuation 1-2 orders of magnitude less than in the visible range^{13,14}. Transillumination imaging at longer wavelengths in the near-IR has been investigated in the region accessible to conventional silicon based CCD cameras, namely 830-nm^{15,16} and at 1310-1550 nm¹⁷ where maximal transmission occurs. Near-IR images were acquired of simulated and natural caries lesions on extracted human teeth. Two setups were employed in these near-IR studies one optimized for imaging interproximal lesions through transillumination of teeth¹⁶ and another system that enabled the acquisition of fairly uniform high contrast images of occlusal lesions¹⁷. Various light sources were investigated for NIR imaging including Fabry-Perot NIR diode lasers, tungsten-halogen lamps and broadband superluminescent diodes (SLD). The SLDs provided a high intensity uniform illumination source from an optical fiber and the high bandwidth avoided the production of laser speckle for better images. 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 order of magnitude upon demineralization due to the formation of pores—on a similar size scale to the wavelength of the light—that act as Mie scatterers¹⁸. Transmission measurements through demineralized tissue sections at 1310-nm show that demineralized enamel attenuates the laser beam by a factor of 20-50 times greater than sound enamel^{19,20}.

Early enamel white spot lesions can be discriminated from sound enamel by visual observation or by visible-light diffuse reflectance imaging^{21,22}. The visibility of scattering structures on highly reflective surfaces such as teeth can be enhanced by use of crossed polarizers to remove the glare from the surface due to the strong specular reflection from the enamel surface^{23,24}. The contrast between sound and demineralized enamel can be further enhanced by depolarization of the scattered light in the area of demineralized enamel^{25,26}. The contrast between sound and demineralized enamel is greatest in the near-IR due to the minimal scattering of sound enamel and this can be exploited for reflectance imaging of early demineralization¹⁸. Wu et al.²⁷ reported the first high contrast polarized reflectance images of early demineralization on buccal and occlusal tooth surfaces measured at $\lambda=1310$ -nm and found that the contrast was significantly higher at 1310-nm than in the visible range.

Two distinct advantages were noted in our previous NIR imaging studies over visible light methods. In NIR images of the occlusal surfaces, stains were often not visible since the organic molecules responsible for pigmentation absorb poorly in the near-IR¹⁷ making it easier to identify areas of demineralization. Mild developmental defects²⁸ and shallow demineralization²⁷ appeared differently from deeper more severe demineralization due to caries suggesting that we may be able to gauge the severity of lesions by analyzing both NIR reflective images and NIR transillumination images of these surfaces. The purpose of this work is to test the hypothesis that NIR reflectance and transmission (multimode) images can be used to estimate the severity of natural caries lesions on the occlusal surfaces.

2. MATERIALS AND METHODS

Near-IR Imaging

Fifty extracted teeth were collected in the bay area with CHR approval and sterilized by gamma irradiation. We rejected 15 samples due to the presence of proximal lesions and a lack of any discernable lesion. Radiographs and visible light images were acquired of each tooth. The occlusal surface of each tooth was examined using multiple NIR imaging modes. Both NIR reflectance and transmission images were taken using the configurations shown in Fig. 1. Multiple transillumination images were taken after rotation of each tooth in 30° rotating intervals in order to view the tooth from all aspects. Reflectance images were acquired in only one orientation. A single-mode fiber-pigtail coupled to a 1310-nm superluminescent diode (SLD) with an output power of 15-mW and bandwidth of 35-nm (Model SLED1300D20A by Optospeed, Zurich, Switzerland) was used to illuminate the tooth. For the transillumination measurements the output from the optical fiber was collimated by a 20-mm NIR fiber-collimator (μLS Micro Laser Systems, Garden Grove, CA) and focused by a 150-mm focal length cylindrical lens at a position just above the cementum-enamel junction of each tooth. For reflectance measurements crossed polarizers were used to remove the specular reflection from the tooth surface (glare).

Images were captured using an InGaAs focal plane array (FPA), SU320-KTSX (Goodrich, Princeton, NJ), in conjunction with an Infinimite™ video lens (Infinity, Boulder, CO).

For transillumination images the intensity in the lesion area is lower than the surrounding sound enamel while for reflectance images the contrast is reversed with higher intensity in the lesion area. In transillumination, a sheet of light aimed at the CEJ moves coronally through the tooth and finally reaches the camera. Since lesions cause an increased scattering of light before it reaches the camera, lesions appear darker than sound enamel. In reflectance, light is directed towards the occlusal surface from the vicinity of the camera. The increased scattering caused by carious tissue is reflected back towards the camera and, therefore, appears lighter than sound enamel.

Intensity values for the near-infrared images were captured using Igor image analysis software. Regions of interest were drawn according to the outline of the lesion. A single evaluator was used for the evaluation of all samples. Contrast was calculated according to the following equations for reflectance and transmission:

$$C_R = (I_L - I_S) / I_L \quad \text{and} \quad C_T = (I_S - I_L) / I_S$$

where C_R is the contrast in reflectance, C_T is the contrast in transmission, I_L is the intensity in the lesion area, and I_S is the intensity in the sound area.

We call the ratio of contrast in transmission divided by the contrast in reflection as the multimode contrast ratio (C_R):

$$C_R = C_T / C_R$$

Multiple lesions were analyzed from samples affected by more than one lesion.

Histology

After imaging, teeth were mounted on orthodontic resin blocks to act as placeholders for histological sectioning. Sections were cut at 1-mm intervals using a linear precision saw, the IsoMet 5000 (Buehler, Lake Buff, IL). Lesions were then classified according to the lesion depth as follows: (E) enamel only, (D1) penetration to the dentinal-enamel junction (DEJ) but less than half way to the pulp chamber, and (D2), more than half way through the dentin into the inner dentin adjacent to the pulp chamber.

3. RESULTS

Figure 2 shows a comparison between the two NIR imaging modes, visible light reflectance and an x-ray. It is difficult to ascertain the severity of the lesion in the reflected light image (visible) due to the heavy staining. The lesion does not appear in the x-ray. The NIR-transillumination shows the lesion in the fissure area with high contrast. The mean contrast values are shown for reflection and transillumination in Figure 3. The lesion contrast in the NIR reflectance images did not increase significantly with lesion severity score (depth) ($p>0.05$) as anticipated.

The lesion contrast in transillumination increased with lesion depth. The contrast of the severe D2 lesions were significantly higher than the shallower lesions ($p<0.01$). The mean contrast of the dentinal lesions (D1) was higher than for the lesions confined to enamel (E) however they did not break statistically ($p>0.05$).

The ratio of contrast in transillumination over reflection was also calculated to determine if this value provided greater separation between the lesions. However, this parameter did provide a significant improvement over transillumination contrast alone. There was still a significant difference between the deep dentinal lesions and the shallower lesions ($p<0.01$) but not between enamel and shallow dentinal lesions ($p>0.05$) as can be seen in Fig. 4.

The area of the lesion in both the reflectance and transillumination NIR images was also measured and the lesion area increased with increasing lesion severity as can be seen in Fig. 5. In reflectance all three groups broke statistically. In transillumination, the area measurements of enamel lesions could be differentiated from those of dentinal lesions ($p<0.01$). The lesion contrast ratios and areas are tabulated in Table I for comparison.

4. DISCUSSION

This initial pilot study indicates that the NIR lesion area and contrast can potentially be used as an indicator of lesion severity of natural occlusal caries lesions. Each imaging mode has its own unique advantages that support combined multimodal implementation to facilitate a more robust caries diagnosis. In particular, transillumination demonstrates higher contrast with increasing lesion depth, while reflection images are a good means of surveying shallow demineralization and lesion size as an indicator of depth. Polarized reflectance

measurements also provide improved contrast over visible light images²⁷ and can potentially be used to better detect shallow demineralization in high risk areas.

Ideally we would like to be able to estimate from the NIR image whether or not the lesion has penetrated into the dentin or is only confined to the enamel. Although there was a concomitant increase in lesion area and contrast with increasing lesion severity, the enamel only lesions did not break statistically with the outer dentin lesions in this study. However, the results of this approach are encouraging and we plan to repeat the study in the near future with an improved NIR imaging system with higher resolution and a larger array and different illumination imaging configurations. In the area measurements there was better discrimination of lesion severity particularly for reflection measurements.

As with most diagnostic methods, time and experience are required to calibrate the evaluator in the interpretation of near-infrared images. In the transillumination arrangement employed in this study, light strikes one side of the tooth, resulting in variations of appearance depending on the relative orientation of the lesion and source. For example, regions of interest for sound tissue should be chosen such that it is in the same horizontal plane as the lesion. Failure to do so results in skewed intensity values due to the varying amount of tooth structure through which NIR light must travel. Similarly, contrast values are dependent on the distance of the area of interest to the light source. When the lesion is closer to the light source, lesions appear particularly high in contrast due to light reflecting directly towards the camera off the proximal surface of the tooth; lesions further from the source are barely visible due to the high level of scattering that has occurred before reaching the lesion. Hence, efforts should be made to use images in which the lesion is in approximately the middle 1/3 of the tooth when drawing regions of interest. Furthermore, the image contrast is sensitive to the topography of the tooth. Sound and demineralized tooth structure should ideally be sampled from a single triangular ridge or tooth plane. Care should thus be taken in drawing areas of interest when analyzing in transillumination mode.

Images acquired in reflection are not dependent on the relative positioning of the lesion and source. However, the tooth topography also provides challenges in reflection as well. Cavitation is a particular challenge since the cavitated area can serve as a light trap causing cavitated lesion areas to appear dark.

Lastly, there lies an inherent difficulty in identifying sound areas of tooth structure. The occlusal surface constantly undergoes demineralization and remineralization resulting in some degree of demineralized surfaces in most if not all samples. Since NIR images detect demineralized tissue, large areas of the occlusal surface may appear generally demineralized. This is particularly evident in reflection images since this mode manifests shallow occlusal demineralization with higher contrast than transillumination. Moreover, for reasons mentioned above regarding similar illumination of lesions and sound tissue, it is preferred to take sound areas of interest that are in close proximity to the lesion. Often times this is not possible due to a lack of sound area or unclear demarcation of the lesion outline.

This preliminary analysis of NIR multimodal imaging on natural occlusal lesions shows that this technique has the potential to evaluate lesion severity based on image contrast and

lesion area. This finding, in conjunction with previous studies showing NIR discrimination of caries, staining and fluorosis, makes this technique an extremely useful tool for the assessment of occlusal caries. Ultimately a study with multiple evaluators and increased sample size is the next step in determining technique efficacy.

5. ACKNOWLEDGEMENTS

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Fig. 1.

(top) Orientation of light source and detector for NIR-reflectance and (bottom) NIR-transillumination through the occlusal surface.

Fig. 2.

(A) Visible-light reflectance image, (B) radiograph, (C) NIR-transillumination image, and (D) NIR-Reflectance image for one of the teeth.

Fig. 3.

The mean $\pm$ s.d. contrast values for NIR-transillumination (top) and NIR-reflectance(bottom).

Fig. 4.
The mean $\pm$ s.d. multimode contrast ratios for (C_T/C_R).

Fig. 5.
The mean $\pm$ s.d. lesion area for NIR-transillumination (top) and NIR-reflectance (bottom).

Table I

Table of values for mean contrast ratio and lesion area (transmission).

Depth Category	N	(C_T/C_R)Mean Contrast Ratio (s.d)	Mean # Pixels in Lesion Area (s.d.)	Statistical Grouping*
E	19	0.75 (0.29)	213 (225)	D1
D1	16	1.14 (0.32)	294 (208)	E
D2	12	1.98 (1.11)	908 (931)	

* groups are statistically similar $p > 0.05$.