Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2018 ; 10473: . doi:10.1117/12.2296030.

SWIR reflectance imaging of demineralization on the occlusal surfaces of teeth beyond 1700 nm

Chung Ng, Jacob C. Simon, Daniel Fried, and Cynthia L. Darling

University of California, San Francisco, San Francisco, CA 94143-0758

Abstract

Most new lesions are found in the pits and fissures of the occlusal surface. Radiographs have extremely low sensitivity for early occlusal decay and by the time the lesion is severe enough on a radiograph it typically has penetrated well into the dentin and surgical intervention is required. The occlusal surfaces are heavily stained and visual and tactile methods for their detection also have poor sensitivity and specificity. Previous studies at wavelengths beyond 1300-nm have demonstrated that stains are not visible and demineralization on the occlusal surfaces can be viewed without interference from stains. New extended range InGaAs near-IR cameras allow access to wavelengths beyond 1700-nm. The objective of this study was to determine how the contrast of occlusal lesions varies with wavelength from the visible to 2350-nm. The lesion contrast was measured in 55 extracted teeth with suspected occlusal lesions using reflectance measurements from 400–2350-nm using Si and InGaAs imaging arrays. The highest lesion contrast in reflectance was measured at wavelengths greater than 1700-nm. Stains interfered significantly at wavelengths shorter than 1150-nm. This study indicates that the optimum wavelengths for reflectance imaging decay in the occlusal surfaces are greater than 1700-nm.

Keywords

NIR imaging; SWIR imaging; occlusal lesions; dental; reflectance imaging

1. INTRODUCTION

Studies indicate that light scattering in dental enamel decreases with increasing wavelength and increased water absorption decreases the backscattered light (reflectance) from sound tooth structure [1, 4, 5]. SWIR imaging allows greater diagnostic capabilities than the current standard of bitewing radiographs for both interproximal and occlusal carious lesions [6–12, 13]. Therefore, higher contrast between sound and demineralized enamel is expected at longer SWIR wavelengths beyond 1700-nm and preliminary reflectance measurements support this hypothesis. Hyperspectral measurements by Zakian et al. [14] showed the tooth continuing to get darker and darker with increasing wavelength. The magnitude of absorption by water at 1940-nm (120 cm^{-1}) is 4 times higher than at 1450-nm (29 cm^{-1}) [2], see Fig. 1. Higher contrast translates to higher diagnostic performance and earlier detection of demineralization. The spectral response of InGaAs can be extended well beyond 1700-nm to reach the strong water absorption band at 1940-nm by removing the underlying InP substrate on which the InGaAs is deposited. In this study, an extended range InGaAs camera sensitive from 1000–2350-nm was used. Previous studies demonstrated that SWIR

reflectance measurements at wavelengths coincident with higher water absorption yield higher contrast than other existing methods including QLF [15]. Even though light scattering in enamel is at a minimum in the SWIR, light scattering in sound dentin is high. At wavelengths highly absorbed by water, i.e., 1450 and 1940-nm, deeply penetrating light is absorbed by the water in the surrounding/underlying sound enamel and dentin, thus increasing lesion contrast. The scattering coefficient of enamel is 20 to 30 times higher in the visible versus the SWIR at 1300 nm [1, 3]. SWIR imaging allows greater diagnostic capabilities than the current standard of bitewing radiographs for both interproximal and occlusal carious lesions [6–12, 13]. The principal reason there has been limited success for caries-detection schemes such as fiber optic transillumination [16–21] and the optical caries monitor [22], along with fluorescence based methods is that stains interfere to produce false positives and prevent accurate measurement of lesion severity [23–36]. Both *in vitro* and *in vivo* studies show that stains completely mask demineralization in the pits and fissures [37]. The highly conjugated molecules such as melanin, porphyrins produced by bacteria and those found in food dyes accumulate in dental plaque. They are responsible for the pigmentation in the visible range and do not absorb light beyond 1200-nm [38, 39].

The 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 measurements at SWIR wavelengths and determine if higher lesion contrast is attainable at wavelengths greater than 1700-nm.

2. MATERIALS AND METHODS

2.1 Sample preparation

Fifty-five teeth with suspected caries lesions on the occlusal surfaces were collected (CHR approved) and sterilized with gamma radiation. Teeth were mounted in black orthodontic acrylic blocks. Samples were stored in a moist environment of 0.1% thymol to maintain tissue hydration and prevent bacterial growth [15].

2.2 Reflectance Measurements

The setup of Fig. 2 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 imager. Crossed polarizers were used to remove specular reflection (glare) that interferes with measurements of the lesion contrast.

A DMK-3002-IR near-IR sensitive CCD camera (Imaging Source, Charlotte, NC) equipped with a Infinity Infinimite lens was used to acquire visible and 850-nm images. A 150-W fiber-optic illuminator FOI-1 (E Licht Company, Denver, CO) coupled to an adjustable aperture was used as a light source and a 850-nm filter with a 70-nm bandwidth was used for the 850-nm images.

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) was used to acquire images from 1000–2200-nm. A stabilized Tungsten IR light source,

Model SLS202, from Thorlabs (Newton, NJ) with a peak output at 1500-nm and collimating optics. Several bandpass [BPwavelength(bandwidth)] and longpass [LPwavelength] filters were used to select wavelength intervals in the NIR and SWIR including: BP850(90), BP1150(78), BP1300(90), BP1460(85), BP1675(90) and LP1695.

All image analysis was carried out using the Igor pro software from Wavemetrics (Lake Oswego, OR) image analysis package. A square area of 500 pixels was taken around the area of most severe staining and demineralization (I_L) and an equivalent area of sound enamel (I_S). The following formula was used to calculate the reflectance contrast $(I_L - I_S)/I_L$ which varies from 0 to 1 for positive contrast, where 1 is the maximum achievable contrast and 0 is no contrast. At shorter wavelengths the high absorption by stains masks the demineralization and the contrast becomes negative and in this case the contrast is no longer bound between 0 and 1 and can be lower than -1. 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 Prism statistical software from GraphPad (San Diego, CA).

2.3 Quantitative Light Fluorescence

Quantitative light fluorescence (QLF) images using a USB microscope with 5 blue illumination blue light emitting diodes and a 510-nm longpass filter, Model AM4115TW-GFBW from BigC (Torrance, CA). The same demineralization (I_L) and sound enamel (I_S) areas measured for the 55 samples in Sec. 2.2 was measured with QLF. However, QLF utilizes fluorescence loss so the intensity of sound enamel is higher than stained and demineralized enamel and the following formula for contrast was used $(I_S - I_L)/I_S$ which the contrast varies from 0 to 1 for positive contrast. A paired t-test (two-tailed) was used to compare the contrast between the contrast measured with the QLF and the highest contrast measured with NIR/SWIR reflectance.

2.4 Histology & Polarized Light Microscopy (PLM)

After all diagnostic images were captured, samples were serially sectioned into ~200- μ m thick mesio-distal slices using a linear precision saw, Isomet 5000 (Buehler, Lake Buff, IL). Thin sections were subjected to histological examination by polarized light microscopy and transverse microradiography.

Polarized light microscopy (PLM) was used for histological examination using a Meiji Techno RZT microscope (Saitama, Japan) with an integrated digital camera, Canon EOS Digital Rebel XT (Tokyo, Japan). Sample sections 200- μ m thick were imbedded in deionized water and examined in the bright field mode with crossed polarizers and a red I plate with 550-nm retardation.

3. RESULTS

Examples of reflectance images taken from one of the samples with both light stain and occlusal demineralization is shown in Fig. 3. The visible light image in Fig. 3A shows white areas in the grooves indicative of demineralization and some darker discolored areas in the

grooves due to stains. The QLF image in Fig. 3B shows dark areas that correspond to both areas of demineralization and absorption by stains.

NIR & SWIR reflectance images are shown in the next three images of Fig. 3 and areas of demineralization are whiter than the surrounding sound enamel. The contrast between the sound and demineralized areas progressively increases from 850 to 1695-nm while the reflectivity from sound tooth structure decreases. The highest contrast between sound and demineralized tooth structure is beyond 1695-nm (1695–2350-nm).

The tooth was sectioned at the position of the two thin lines shown in Fig. 3A and a polarized light micrograph (PLM) is shown in Fig. 3F. Extensive demineralization in the occlusal groove penetrating to the dentin is clearly visible confirming that demineralization is indeed present.

A second tooth with extensive staining is shown in Fig. 4. In Fig. 4A the tooth looks somewhat similar to the tooth in Fig. 3 with some moderate staining however definitive whiter areas of demineralization are not visible. The most severe decay appears to occur in the fissure at the position of the two thin lines in Fig. 4A which is much darker than the surrounding stain. The QLF image shows several areas of fluorescence loss indicative of decay and the marked area of the fissure appears with high contrast. The NIR reflectance image at 850-nm, Fig. 4C, shows no white areas of demineralization however there are a few dark areas in the fissures particularly in the marked area. The SWIR reflectance image at 1300-nm, Fig. 4D, shows only very minor white areas in a few of the fissures, however there is nothing visible in the marked fissure area. Beyond 1695-nm, Fig. 4E, the same areas of demineralization that are visible at 1300-nm are also visible with higher contrast but there is no demineralization in the marked fissure area. Note that some of the white spots around the outside of the tooth in Fig. 4E are due to specular reflection and not demineralization. High extinction ratio polarizers operating at wavelengths beyond 1700-nm have only become recently available and we did not have them for this study. Specular reflection changes with a slight tilt of the tooth while the reflectivity of demineralization remains stable. The tooth was sectioned at the position of the two thin lines (marks) and the PLM micrograph shows that there is stain in the center of the fissure however, the fissure walls are completely intact and there is no demineralization present. In fact, it is remarkable that it was possible to cut a thin section only 200- μ m thick of the tooth without loss of the mass of organic matter (stain) in the fissure. The mean lesion contrast was highest for 1695–2200-nm where it was 0.68 ± 0.21 .

4. DISCUSSION

The lesion contrast measurements indicate that the lesion contrast continues to increase beyond 1700-nm (1695–2220-nm) where there is decreasing light scattering in the sound enamel and there is increasing light absorption by water (Fig. 1). Current NIR imaging devices on the market for caries detection operate at 780 and 850-nm where these studies show that there is significant interference from stains. In addition, the contrast between sound and demineralized tooth structure is markedly higher at longer SWIR wavelengths than it is at 850-nm. The primary disadvantage of operating at longer SWIR wavelengths is

that silicon based imaging technologies are only efficient at wavelengths less than 1000-nm. Alternative imaging technologies such as InGaAs and Ge-enhanced SI are still expensive. Less expensive scanned SWIR LED and diode light sources and Galvanometer or MEMS based scanning systems are also feasible (see paper 10473-7 in this symposium). The limited use of these more novel semiconductors technologies is a major reason for the high cost and as use is expanded prices are expected to decrease. The cost has decreased significantly in the past ten years as the performance has increased. Using the newly available extended range InGaAs imaging array sensitive beyond 1700-nm, we have demonstrated that even higher lesion contrast is attainable at longer SWIR wavelengths. Wavelengths at longer wavelengths beyond 1700-nm may also be advantageous for assessing lesion activity by looking at the lesion contrast during drying since the longer wavelengths are more sensitive to changes in water. Therefore, the wavelengths beyond 1700-nm where light scattering is low and water absorption is high are best for SWIR reflectance measurements.

Acknowledgments

This work was supported NIH/NIDCR Grant R01-DE014698.

References

1. Fried D, Featherstone JDB, Glana RE, Seka W. The nature of light scattering in dental enamel and dentin at visible and near-IR wavelengths. *Appl Optics*. 34(7):1278–1285.1995;
2. Hale GM, Querry MR. Optical constants of water in the 200-nm to 200- μ m wavelength region. *Appl Optics*. 12:555–563.1973;
3. Jones RS, Fried D. Attenuation of 1310-nm and 1550-nm Laser Light through Sound Dental Enamel. *Lasers in Dentistry VIII. Proc SPIE*. 4610:187–190.2002;
4. Chung S, Fried D, Staninec M, Darling CL. Near infrared imaging of teeth at wavelengths between 1200 and 1600 nm. *Lasers in Dentistry XVII. Proc SPIE*. 7884 X:1–6.2011;
5. Simon JC, Chan KH, Darling CL, Fried D. Multispectral near-IR reflectance imaging of simulated early occlusal lesions: variation of lesion contrast with lesion depth and severity. *Lasers Surg Med*. 46(3):203–15.2014; [PubMed: 24375543]
6. Lee C, Darling CL, Fried D. In vitro near-infrared imaging of occlusal dental caries using a germanium enhanced CMOS camera. *Lasers in Dentistry XVI*. 7549 K:1–7.2010;
7. Buhler C, Ngaothepitak P, Fried D. Imaging of occlusal dental caries (decay) with near-IR light at 1310-nm. *Optics Express*. 13(2):573–82.2005; [PubMed: 19488387]
8. Fried D, Featherstone JDB, Darling CL, Jones RS, Ngaothepitak P, Buehler CM. Early Caries Imaging and Monitoring with Near-IR Light. *Dental Clinics of North America - Incipient and Hidden Caries*. 49(4):771–794.2005;
9. Hirasuna K, Fried D, Darling CL. Near-IR imaging of developmental defects in dental enamel. *J Biomed Opt*. 13(4):044011.2008; [PubMed: 19021339]
10. Lee D, Fried D, Darling C. Near-IR multi-modal imaging of natural occlusal lesions. *Lasers in Dentistry XV. SPIE*. 7162 X:1–7.2009;
11. Staninec M, Lee C, Darling CL, Fried D. In vivo near-IR imaging of approximal dental decay at 1,310 nm. *Lasers Surg Med*. 42(4):292–8.2010; [PubMed: 20432277]
12. Jones G, Jones RS, Fried D. Transillumination of interproximal caries lesions with 830-nm light. *Lasers in Dentistry X. SPIE*. 5313:17–22.2004;
13. Jones RS, Huynh GD, Jones GC, Fried D. Near-IR Transillumination at 1310-nm for the Imaging of Early Dental Caries. *Optics Express*. 11(18):2259–2265.2003; [PubMed: 19466117]
14. Zakian C, Pretty I, Ellwood R. Near-infrared hyperspectral imaging of teeth for dental caries detection. *J Biomed Opt*. 14(6):064047.2009; [PubMed: 20059285]

15. Fried WA, Darling CL, Chan K, Fried D. High Contrast Reflectance Imaging of Simulated Lesions on Tooth Occlusal Surfaces at Near-IR Wavelengths. *Lasers Surg Med.* 45(8):533–541.2013; [PubMed: 23857066]
16. Barenie J, Leske G, Ripa LW. The use of fiber optic transillumination for the detection of proximal caries. *Oral Surg.* 36:891–897.1973; [PubMed: 4524840]
17. Pine, CM. Early Detection of dental caries. Indiana University; 1996. Fiber-Optic Transillumination (FOTI) in Caries Diagnosis; 51–66.
18. Holt RD, Azevedo MR. Fiber Optic transillumination and radiographs in diagnosis of approximal caries in primary teeth. *Community Dent Health.* 6:239–247.1989; [PubMed: 2679987]
19. Mitropoulis CM. The use of fiber optic transillumination in the diagnosis of posterior approximal caries in clinical trials. *Caries Res.* 19:379–384.1985; [PubMed: 3861261]
20. Hintze H, Wenzel A, Danielsen B, Nyvad B. Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces. *Caries Res.* 32(3):204–9.1998; [PubMed: 9577986]
21. Schneiderman A, Elbaum M, Schultz T, Keem S, Greenebaum M, Driller J. Assessment of Dental caries with Digital Imaging Fiber-Optic Transillumination (DIFOTI):In vitro Study. *Caries Res.* 31:103–110.1997; [PubMed: 9118181]
22. ten Bosch JJ, van der Mei HC, Borsboom PCF. Optical monitor of in vitro caries. *Caries Res.* 18:540–547.1984; [PubMed: 6593126]
23. Benson PE, Pender N, Higham SM. Quantifying enamel demineralization from teeth with orthodontic brackets--a comparison of two methods. Part 2: validity. *Eur J Orthod.* 25(2):159–65.2003; [PubMed: 12737214]
24. de Josselin de Jong, E; Hall, AF; van der Linden, AHIM. QLF:A Monte Carlo simulation model; Proceedings of the 1st Annual Indiana Conference, Early Detection of Dental Caries I; 1996. 91–104. Vol.
25. Stookey GK. Quantitative light fluorescence: a technology for early monitoring of the caries process. *Dent Clin North Am.* 49(4):753–70.2005; [PubMed: 16150315]
26. Tranaeus S, Al-Khateeb S, Bjorkman S, Twetman S, Angmar-Mansson B. Application of quantitative light-induced fluorescence to monitor incipient lesions in caries-active children. A comparative study of remineralisation by fluoride varnish and professional cleaning. *Eur J Oral Sci.* 109(2):71–5.2001; [PubMed: 11347658]
27. Tranaeus S, Shi XQ, Lindgren LE, Trollsas K, Angmar-Mansson B. In vivo repeatability and reproducibility of the quantitative light-induced fluorescence method. *Caries Res.* 36(1):3–9.2002; [PubMed: 11961323]
28. Alfano RR, Lam W, Zarrabi HJ, Alfano MA, Cordero J, Tata DB. Human teeth with and without caries studied by laser scattering, fluorescence and absorption spectroscopy. *IEEE J Quant Electr.* 20:1512–1515.1984;
29. Angmar-Mansson, BA, Al-Khateeb, S, Tranaeus, S. Early Detection of dental caries. Indiana University; 1996. Intraoral use of quantitative light-induced fluorescence detection method; 39–50. Vol.
30. Lussi A, Hibst R, Paulus R. DIAGNOdent: an optical method for caries detection. *J Dent Res.* 83(Spec No C):C80–3.2004; [PubMed: 15286128]
31. Lussi A, Imwinkelreid S, Pitts NB, Longbottom C, Reich E. Performance and Reproducibility of a Laser Fluorescence System for Detection of Occlusal Caries in vitro. *Caries Res.* 33:261–266.1999; [PubMed: 10343088]
32. Shi XQ, Tranaeus S, Angmar-Mansson B. Comparison of QLF and DIAGNOdent for quantification of smooth surface caries. *Caries Res.* 35(1):21–6.2001; [PubMed: 11125192]
33. Stookey GK. Optical methods--quantitative light fluorescence. *J Dent Res.* 83(Spec No C):C84–8.2004; [PubMed: 15286129]
34. ten Bosch, JJ. Early detection of Dental caries II. Indiana University; 1999. Summary of Research of Quantitative Light Fluorescence; 4261–278. Vol.
35. Shi XQ, Welander U, Angmar-Mansson B. Occlusal caries detection with Kavo DIAGNOdent and Radiography:An in vitro comparison. *Caries Res.* 34:151–158.2000; [PubMed: 10773633]

36. Ferreira Zandona AG, Analoui M, Beiswanger BB, Isaacs RL, Kafrawy AH, Eckert GJ, Stookey GK. An in vitro comparison between laser fluorescence and visual examination for detection of demineralization in occlusal pits and fissures. *Caries Res.* 32(3):210–8.1998; [PubMed: 9577987]
37. Chung S, Fried D, Staninec M, Darling CL. Multispectral near-IR reflectance and transillumination imaging of teeth. *Biomed Opt Express.* 2(10):2804–2814.2011; [PubMed: 22025986]
38. Kleter GA. Discoloration of dental carious lesions (a review). *Arch Oral Bio.* 43:629–632.1998; [PubMed: 9758045]
39. Sarna T, Sealy RC. Photoinduced oxygen consumption in melanin systems. Action spectra and quantum yields for eumelanin and synthetic melanin. *Photochem Photobiol.* 39:69–74.1984; [PubMed: 6422483]

Fig. 1.

The attenuation coefficient for dental enamel (red) and the absorption coefficient of water (black) in the visible to IR [1–3]. NIR range is 700–1000 nm (blue) and SWIR range is 1000–2500 nm (gray).

Fig 2.
Imaging configuration for cross-polarized reflectance with (A) tooth, (B) light source and (C) imaging cameras.

Fig 3.

Images of a tooth with demineralization. (A) visible, (B) QLF, reflectance at (C) 850, (D) 1300 and (E) 1695–2350-nm. A PLM image cut at the position of the two thin blue lines in (A) is shown in (F) with obvious decay present penetrating to dentin.

Fig 4. Images of another tooth without demineralization. (A) visible, (B) QLF, reflectance at (C) 850, (D) 1300 and (E) 1695–2350-nm. A PLM image cut at the position of the two thin blue lines in (A) is shown in (F). Only stain is visible suspended in the occlusal pit.