Near-Infrared Imaging of Dental Decay at 1310 nm

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J Laser Dent 2010;18(1):8-16

ABSTRACT

In this review paper we present an overview of our research which has shown that dental enamel manifests high transparency in the near-infrared (NIR) and suggests that NIR light at 1310 nm is ideally suited for the imaging of carious lesions on proximal and occlusal tooth surfaces. NIR-sensitive imaging systems with broadband light sources centered at 1310 nm were used to acquire NIR images of lesions in extracted teeth and proximal lesions in vivo. Stains and noncalcified plaque are not visible in the NIR, enabling better discrimination of defects, cracks, and demineralized areas. Carious lesions were visible in the NIR with high contrast and can be viewed from multiple surfaces to aid in diagnosis. These studies indicate that NIR imaging may offer significant advantages over the conventional visual, tactile, and radiographic caries-detection methods.

CARRIES DETECTION AND NEW OPTICAL DIAGNOSTIC TECHNOLOGIES

During the past century, the nature of dental decay or dental caries in the United States has changed markedly due to the introduction of fluoride to drinking water, the use of fluoride dentifrices and rinses, application of topical fluoride in the dental office, and improved dental hygiene. In spite of these advances, dental decay continues to be a leading cause of tooth loss in the United States. The nature of the caries problem has changed dramatically with the majority of newly discovered carious lesions being highly localized to the occlusal pits and fissures of the posterior dentition and the proximal contact sites. These early carious lesions are often obscured or “hidden” in the complex and convoluted topography of the pits and fissures or are concealed by debris that frequently accumulates in those regions of the posterior teeth. Moreover, such lesions are difficult to detect in the early stages of development.

Over the past 30 years there has been an effort to develop optical methods for the detection and imaging of proximal and occlusal dental decay. These methods include fiber-optic transillumination (FOTI), fluorescence-based methods, and optical coherence tomography. There has been renewed interest in optical transillumination, with the availability of high-intensity, fiber-optic-based illumination systems for the detection of proximal lesions. During fiber-optic transillumination, a carious lesion appears dark upon transillumination because of decreased transmission due to increased scattering and absorption of light by the lesion. However, the strong light scattering of sound dental enamel at visible wavelengths, 400-700 nm, inhibits imaging through the entire tooth.

OPTICAL PROPERTIES OF DENTAL ENAMEL AND DENTIN

The near-infrared (NIR) is the region of the electromagnetic spectrum between 0.7 to 2.0 micrometers (µm). NIR light can penetrate much further without scattering through all the tooth enamel, due to the reduced scattering coefficient in normal enamel. Figure 1 graphically depicts that the attenuation coefficient of enamel is markedly less in the wavelength range of 1310 nm (approximately 2-3 cm⁻¹) than at visible red light, at around 600 nm (approximately 50-60 cm⁻¹). The absorption coefficients (µₐ) and scattering coefficients (µₛ) for normal enamel and dentin have been reported between the wavelength range of 200-1550 nm. For enamel, absorption is very weak in the visible range (µₐ < 1 cm⁻¹, λ = 400-700 nm). For dentin in the 400-700 nm wavelength range, the absorption coefficient is essentially wavelength-independent with a value of µₐ ~ 4 cm⁻¹. Scattering in enamel is strong in the visible (µₛ = 60 cm⁻¹ at 632 nm) and decreases ~ λ⁻³ with increasing wavelength to a value of only 2-3 cm⁻¹ at 1310 nm and 1550 nm in the NIR. Therefore, enamel is virtually transparent in the NIR with optical attenuation 1-2 orders of magnitude less than in the visible range.
In contrast, scattering in dentin is strong throughout the visible and near-IR due to forward (Mie) scattering by the dentinal tubules. Longer NIR wavelengths have decreased transmission due to water absorption (see Figure 1). The optimum wavelength region for imaging caries lesions is where scattering is at a minimum in sound enamel. However, the scattering coefficient of enamel should increase markedly with demineralization to provide high contrast of the lesion. Figure 2 shows how the optical attenuation of dental enamel increases at 1310 nm as a function of mineral loss in natural lesions. These transmission measurements through demineralized tissue sections at 1310 nm show that the demineralized tissue attenuates the NIR light by a factor of 20-50 times greater than the sound enamel.

**NIR Imaging Methods**

In our NIR imaging studies, we have employed three different NIR imaging technologies with different spectral responsivities to acquire images of lesions: Indium-Gallium-Arsenide (InGaAs) focal plane arrays (FPAs) that operate from 1000-1600 nm with high sensitivity, a conventional silicon-based charge-coupled device (CCD) camera with the NIR filter removed which is sensitive in the visible range out to 1000 nm, and a new Germanium (Ge)-enhanced complementary metal-oxide-semiconductor (CMOS)-based camera that is sensitive from 500-1600 nm. Various light sources were investigated for NIR imaging including Fabry-Pérot NIR diode lasers, tungsten-halogen lamps, and broadband superluminescent diodes (SLDs). The SLDs provided a high-intensity, uniform illumination source from an optical fiber, and the high bandwidth avoided the production of laser speckle that produces interference patterns because of the light's scattering after striking irregular surfaces. The use of SLDs resulted in the acquisition of better images. Various setups were employed in these studies that were optimized for imaging proximal and occlusal lesions through transillumination of occlusal

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**Figure 1**: Plot of the mean ± standard deviations of the attenuation coefficient for dental enamel (filled circles) and the absorption coefficient of water (open circles) vs. wavelength. (From references #2, 9, 11-12)

**Figure 2**: Optical attenuation (cm⁻¹) at 100 points taken from 10 natural enamel caries lesions (10 points per lesion) produced by 1310-nm laser emission. The solid line represents the best exponential fit, $r^2 = 0.74$ to the attenuation coefficient vs. volume % mineral loss. (From reference #11)
lesions through reflection (Figure 3). These setups employed one or two NIR light sources to provide illumination as uniform as possible and probes were developed for clinical use. The following four imaging devices were used: two high-sensitivity InGaAs FPA s (318 x 252 pixels) (Model SU320KTSX, Sensors Unlimited, Princeton, N.J., and Model Alpha NIR™, Indigo Systems, Goleta, Calif.); a Ge-enhanced CMOS image sensor (Model NP-EC700M-01 evaluation camera, NoblePeak Vision, Wakefield, Mass.); and a near-IR sensitive CCD camera (DMK-3002-IR, Imaging Source, Charlotte, N.C.). NIR light was provided by a \( \lambda = 1310 \text{ nm} \) superluminescent diode with an output power of 15 mW and a 35-nm bandwidth (Model SLED1300D20A, Opto Speed, Zurich, Switzerland) or a tungsten-halogen 150-W fiber-optic illuminator (FOI-1, E. Licht Company, Denver, Colo.) with 90-nm band-pass filters centered at 1310 nm or 830 nm.

**NIR IMAGING OF PROXIMAL LESIONS**

At 1310 nm the dental enamel resembles the appearance of a transparent ice cube. In our early transillumination measurements, we employed cross polarizers to avoid saturation of the InGaAs FPA by the light that did not pass through the tooth. However, in later studies we found that the crossed polarizers were not necessary with more diffuse illumination sources. In our first comprehensive study we used tooth sections of varying thickness with small simulated lesions ~ 1 mm in diameter to determine the image contrast at various wavelengths as a function of enamel thickness. High contrast was measured between simulated and natural caries lesions and sound tissues and we were able to acquire high contrast through the sections of greatest thickness and whole teeth at 1310 nm. Images taken through plano-parallel tooth sections of up to 7-mm thickness show that the simulated lesions can be resolved through the maximum possible thickness of enamel at 1310 nm. The contrast was also measured in the visible region and at 830 nm (Figure 4). The performance at visible wave-
lengths was very poor. The imaging system operating in the NIR around 830 nm, utilizing a silicon CCD optimized for the NIR, was capable of significantly higher performance than the visible system, but it did not provide as high a contrast as that attainable at 1310 nm and could not detect the lesions through the full thickness of the enamel.

Later studies demonstrated that we could see natural caries lesions through whole teeth. Figure 5 shows visible and NIR images of two extracted teeth in contact. One of the teeth has a proximal lesion that is clearly visible in the NIR image. The incremental growth lines are also visible in the higher-resolution 640 x 400 pixel image. We also noticed that if the tooth were rotated back and forth while imaging the interior of the tooth, we acquired a stereoscopic (3-D) view through the transparent enamel. This stereoscopic effect could also be replicated clinically by slightly rotating the probe during imaging.

If the tooth were illuminated with NIR light delivered low on the tooth near the cementoenamel junction (CEJ), proximal lesions could be viewed directly from the occlusal surface. Figure 6 shows in vivo NIR images and a radiograph of a tooth with a small proximal lesion. This is particularly advantageous since multiple views can be acquired of each lesion to aid in diagnosis.

Recently, we completed our first in vivo imaging study. In this study only proximal lesions that were of sufficient severity to show up on an X-ray were investigated. The carious lesions were discernible on bitewing radiographs, but were not visible upon clinical examination.

NIR imaging handpieces were developed and attached to a compact InGaAs focal plane array and subsequently used to acquire in vivo NIR images of 33 caries lesions on 18 test subjects. NIR images were acquired by trans-illumination through the tooth (faciopival orientation) or by viewing the lesion from the occlusal surface while delivering the light near the CEJ of the tooth. NIR images were acquired in vivo from three directions and the majority of lesions examined were too small to require restoration, based on accepted bitewing radiograph criteria. All but one of the 33 lesions examined were successfully imaged from at least one direction. Figure 7 shows in vivo NIR images taken from multiple perspectives, along with a radiograph. Many other lesions were visible in the NIR images that were not visible in radiographs; however, since the teeth were not extracted and such lesions were not restored, there was no histological confirmation of the nature of those lesions.

**NIR IMAGING OF OCCLUSAL LESIONS**

Our first occlusal images were acquired by illuminating the tooth with a “sheet of 1310-nm light” just above the gingiva from one side using a cylindrical lens, and the NIR camera was positioned directly above the occlusal surface as shown in Figure 3 (bottom), so that diffuse light propagates up through the enamel of the crown from the under-
lying dentin. Figure 8 shows a lesion in the pit and fissure area of the tooth. In the NIR in vitro image there is a dark gray/black area at the center of the lesion with very sharp contrast indicative of demineralization near the surface and a larger lighter gray area that is more diffuse in appearance, indicative of deep subsurface decay (Figure 8A). The radiograph of the tooth is shown in Figure 8B. It is difficult to determine from the radiograph whether the tooth contains a lesion because the defect on the X-ray overlaps into the enamel. The histology is shown in Figure 8C and the lesion is present in the enamel as well as into the dentin.

One quickly notices that staining and pigmentation do not interfere in the NIR images and we were easily able to discriminate between stains and plaque and demineralization since the plaque and stains are not visible in the NIR. Dental calculus, accumulated plaque, and organic stains and debris have been found to interfere significantly with visual diagnosis and fluorescence-based caries detection schemes in occlusal surfaces. For example, to use the DIAGNOdent® (KaVo Dental GmbH, Biberach/Riß, Germany), such confounding factors typically have to be removed by prophylaxis (abrasive cleaning) before reliable measurements can be taken. Surface staining at visible wavelengths greatly compounds that problem and it is very difficult to determine whether pits and fissures are simply stained or demineralized. Staining and pigmentation do not interfere with NIR imaging at 1310 nm because the highly conjugated molecules such as melanin and porphyrins produced by bacteria and those found in food dyes that accumulate in dental plaque and stains do not absorb light in the NIR. Calculus or calcified plaque, on the other hand, is mineralized and highly scatters NIR light. Figure 9 contains in vitro images of two teeth; one is highly stained but sound (C), while the other is stained with demineralization (A). In the visible images it is not easy to determine whether there is any decay in the occlusal surfaces of either of these teeth because the pit and fissures are highly stained, obscuring the areas of demineralization. In the NIR images the observer is easily able to determine exactly where the demineralized areas are localized since the stain is not visible and the demineralized areas are more opaque than the sound enamel.

Developmental defects such as fluorosis that appear as white spots on tooth surfaces frequently appear white in NIR transillumination images of the occlusal surface. This reverse in contrast allows discrimination between these developmental defects and deeper areas of demineralization due to caries. In vitro images of a tooth with occlusal lesions that penetrate to the dentinoenamel junction (DEJ) are shown in Figure 10 along with polarized light micrographs (PLMs) of two thin sections cut for histological examination. This tooth is interesting because in addition to the lesions, large areas of the occlusal surface appear with opposite contrast; namely, they appear whiter or with higher intensity than the sound enamel areas. We have observed this phenomenon in previous transillumination images of shallow, artificially demineralized areas in the occlusal surfaces and from shallow developmental defects. The PLMs show a dark...
(brown) band of hypomineralization near the enamel surface (see yellow arrows) with an outer layer of higher mineral content that is transparent, which is typical of mild developmental defects or fluorosis.

**NIR Reflectance Imaging**

Since the light scattering from sound enamel is a minimum which reduces the diffuse reflectance from the sound enamel, NIR reflectance imaging has great potential for imaging early demineralization. In a recent study, we compared the image contrast of four imaging modalities for shallow areas of demineralization on buccal and occlusal tooth surfaces. Lesions were imaged using NIR transillumination, NIR and visible light reflectance, and fluorescence imaging methods. Crossed polarizers were used where appropriate to improve contrast. NIR reflectance imaging had the highest image contrast for both the buccal and occlusal groups and it provided significantly higher contrast than visible light reflectance (P < 0.05). Figure 11 shows in vitro images of the buccal surface of a tooth using the four imaging modalities. Very little reflectance is visible in the NIR reflectance image from the sound enamel areas which results in high contrast between sound and demineralized enamel. Zakian et al. recently reported multispectral reflectance measurements of occlusal caries lesions which confirm that the NIR wavelengths are well-suited for imaging caries lesions and that stains do not interfere at these wavelengths.

**NIR Imaging During Surgical Intervention**

Over the past two years we have presented work showing that NIR imaging can be used to monitor the evolution of ablation craters during laser ablation (drilling) through the transparent enamel. Laser-ablation events can be observed in real time to assess safe laser operating parameters by imaging thermal and stress-induced damage, elaborate the mechanisms involved in ablation such as dehydration, monitor removal of demineralized enamel, and investigate the dynamic changes in the transparency of enamel with water loss. If water cooling is not used, excessive heat accumulation near the laser incisions causes loss of transparency in the enamel at 1310 nm, and dynamic changes in the enamel transparency were directly visible during laser irradiation. Figure 12 shows in vitro images produced during drilling by a rapidly scanned 9300-nm CO₂ laser and by a high-speed handpiece. As expected in this experiment, crack formation can be seen in real time around the periphery of the preparation and thermal damage due to excessive heating causes loss of transparency of the enamel. Therefore, NIR imaging can be used to directly assess the safety of different laser parameters and removal rates and

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**Figure 10:** In vitro images of a tooth sample with both lesions and areas of hypomineralization on the occlusal surface. Visible-light reflectance image (A), NIR transillumination image captured with the Ge-enhanced CMOS camera (B), PLM images (C, D) of the sections cut along the yellow dotted lines in Figure 10A. The yellow arrows in the PLM images indicate the position of hypomineralization.

**Figure 11:** In vitro buccal lesion images are shown for one sample. Visible reflectance with crossed polarizers (A), NIR reflectance with crossed polarizers (B), fluorescence (C), and NIR transillumination with crossed polarizers (D). Note the position of the fiducial marks cut by a CO₂ laser at the midway point of each 2 x 2-mm window. These marks demarcate the position of the line profiles used for calculating the image contrast on each sample. (From reference #20)
make sure sufficient cooling mechanisms are in place. It can also be used to assess the rate of material removal and the uniformity of the crater produced by the laser. Since enamel is highly transparent at 1310 nm, subtle changes in the optical properties of the enamel can be seen such as dehydration. Heating by the laser or an external heat source without a water spray can cause dehydration which increases the opacity of the enamel by 2-3 times. We postulate the filling of the pores left by loss of the water with air results in higher scattering. Figure 13 shows three in vitro images of a tooth section irradiated by a CO₂ laser, also operating at 9300 nm, without water cooling at a low fluence to deliberately overheat the enamel. A large area of the enamel becomes opaque (dark) after laser irradiation. After immersion of water some of the heated areas become transparent again, indicating that the changes are reversible, likely due to the refilling of the pores with water. In some of the areas close to the surface that were heated to the highest temperatures by the laser, the damage is not reversible and cracks are also visible. Nonreversible changes to protein, lipid, and mineral are possible at higher temperatures.

**SUMMARY AND FUTURE WORK**

Initial studies suggest that NIR imaging has considerable potential for the nondestructive imaging of dental caries. Several modes of imaging were investigated using imaging geometries optimized for imaging either proximal or occlusal lesions. Lesions on proximal surfaces were visible with high contrast with transillumination through the facial or lingual tooth surfaces. Moreover, the enamel is so transparent at 1310 nm, that natural proximal lesions can be imaged from the occlusal surfaces. This offers the advantage of being able to illuminate from the buccal (facial) surface of the tooth and image from the occlusal surface (top) with the possibility of simultaneous viewing of both occlusal and proximal caries lesions. The clinician can also acquire multiple images of dental caries by using various orientations of the imaging system and the illumination source to avoid the influence of overlapping teeth, confirm lesion depth, and avoid false positives. Since light scattering provides the high contrast between sound and demineralized enamel, areas that are not as severely demineralized or cavitated are visible with high contrast.

NIR images of occlusal caries demonstrate that NIR imaging can also be used for the detection and imaging of caries lesions in occlusal surfaces where most new decay develops. It is particularly advantageous that pigmentation and staining do not significantly interfere with imaging demineralization in the NIR. This novel and straightforward method exploits the high transparency of dental enamel and the strong scattering and weak absorption of the underlying dentin to deliver a uniform distribution of diffuse NIR light underneath the transparent enamel of the crowns to facilitate high-contrast NIR imaging of the occlusal decay and detect hidden lesions beneath the surface. We have shown that this NIR technology can be used to acquire images of natural occlusal caries lesions, both shallow and deep, that are not detectable by conventional...
means either radiographically or by visual/tactile examination. These studies suggest that NIR imaging has considerable potential as a tool for routine caries screening of the entire dentition. Moreover, this new imaging tool that does not require ionizing radiation may enable the dentist to treat and monitor early dental decay effectively in a nonsurgical manner. The dentist may be able to acquire multiple NIR images of teeth during subsequent visits to determine whether fluoride therapy is effective in arresting the lesion or whether the lesion has expanded, requiring more aggressive intervention. Such an approach is not as practical with radiographic methods due to repeated X-ray exposure. These initial images demonstrate the potential of the NIR for imaging dental decay and for overcoming some of the limitations of conventional methods of caries detection, namely, visual, tactile, and radiographic. Although these preliminary NIR images are very exciting, extensive clinical studies will be needed to assess the diagnostic performance of any devices developed based on NIR technology. The diagnostic performance is likely to be dependent on the training and experience of the operator and there are likely to be false negatives, false positives, and imaging artifacts just like there are for other similar technologies.

**AUTHOR BIOGRAPHIES**

Dr. Daniel Fried is a professor in the Division of Biomaterials and Bioengineering in the Department of Preventive and Restorative Dental Sciences at the University of California, San Francisco School of Dentistry. He received his PhD in Physical Chemistry from Wayne State University in 1992 and his thesis work involved laser ablation and spectroscopy. Dr. Fried has been a researcher in the field of laser dentistry for the past 15 years and his contributions in this field include fundamental measurements of the optical properties of dental hard tissues from the ultraviolet to the infrared, studies of the interaction of carbon dioxide lasers with dental hard tissues for laser ablation of caries and the surface modification of enamel for caries prevention, the use of lasers for the selective removal of caries and composite restorative materials, the assessment of demineralization and remineralization with polarization-sensitive optical coherence tomography, and the development of near-IR imaging for caries detection. In 2009, he received the T. H. Maiman Award from the Academy of Laser Dentistry. He may be contacted by e-mail at daniel.fried@ucsf.edu.

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None of the authors have any commercial disclosures relative to this article. Their work was supported by the NIH Grant 1-R01-14698.

**ACKNOWLEDGEMENTS**

Supported by the NIH/NIDCR Grant 1-R01 DE14698. The authors would also like to thank Robert Jones, Graham Jones, Christopher Bühler, Patarana Ngaetheppitak, Gigi Huyhn, Chulsung Lee, Dennis Hsu, Jen Wu, Ken Fan, Ken Chan, Hobin Kang, Shane Douglas, Dustin Lee, Chulsung Lee, Krista Hirasuna, Kathy Tao, Linn Maung, and John Featherstone.
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