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Authors
Simon, Jacob C
Lucas, Seth A
Staninec, Michal
et al.

Publication Date
2014-02-18

DOI
10.1117/12.2045630

Peer reviewed

HHS Public Access
Author manuscript
Proc SPIE Int Soc Opt Eng. Author manuscript; available in PMC 2014 May 07.

Published in final edited form as:
Proc SPIE Int Soc Opt Eng. 2014 February 18; 8929: 89290D–. doi:10.1117/12.2045630.

Transillumination and reflectance probes for *in vivo* near-IR imaging of dental caries

Jacob C. Simon, **Seth A. Lucas**, **Michal Staninec**, **Henry Tom**, **Kenneth H. Chan**, **Cynthia L. Darling**, and **Daniel Fried***
University of California, San Francisco, San Francisco, CA 94143-0758

Abstract

Previous studies have demonstrated the utility of near infrared (NIR) imaging for caries detection employing transillumination and reflectance imaging geometries. Three intra-oral NIR imaging probes were fabricated for the acquisition of *in vivo*, real time videos using a high definition InGaAs SWIR camera and near-IR broadband light sources. Two transillumination probes provide occlusal and interproximal images using 1300-nm light where water absorption is low and enamel manifests the highest transparency. A third reflectance probe utilizes cross polarization and operates at >1500-nm, where water absorption is higher which reduces the reflectivity of sound tissues, significantly increasing lesion contrast. These probes are being used in an ongoing clinical study to assess the diagnostic performance of NIR imaging for the detection of caries lesions in teeth scheduled for extraction for orthodontic reasons.

Keywords

Near-IR imaging; caries detection; transillumination; reflectance; demineralization

1. Introduction

New instrumentation that can replicate and improve upon the diagnostic performance of traditional and digital X-ray technology is needed. The detection of dental decay using non-ionizing, near infrared (NIR) imaging techniques has been well demonstrated by previous *in vitro* and *in vivo* studies reported by our group [1–6].

This article presents the methods and results from an ongoing *in vivo* study in the San Francisco Bay area for the detection of early surface demineralization, occlusal carious lesions and interproximal carious lesions in premolar teeth. Three imaging modalities, namely interproximal transillumination, occlusal transillumination and cross-polarized reflectance are explored for their individual effectiveness in detecting lesions.

Minimal light scattering in sound enamel and varying water absorption along the NIR wave region, make near infrared light more useful than visible light for transillumination and reflectance imaging. Dental hard tissues exhibit high transparency to NIR wavelengths with

*Corresponding author: daniel.fried@ucsf.

optical attenuation coefficients' 1–2 orders of magnitude less compared to visible light [7, 8]. Additionally, the NIR wave region can be purposely segregated into two categories based on the absorption coefficient of water, namely minimal water absorption from 800-nm to 1350-nm, and greater water absorption at 1460-nm and wavelengths longer than 1500-nm.

The transillumination probes designed for this study, interproximal transillumination and occlusal transillumination, use 1300-nm light produced by a broadband super-luminescent diode (SLD) source. Previous studies have shown that 1300-nm light is best for transillumination images due to weak water absorption at that wavelength[9]. The interproximal transillumination probe captures the lingual and facial tooth profiles with the specific intent to detect lesions at the approximal contact. NIR light is directed transversely through the exposed crown and collected 180-degrees from the source (Fig. 1A). Demineralized tissue scatters NIR light and attenuates the amount of light received by the detector. More severe lesions will appear increasingly dark compared to the sound enamel which appears bright.

The occlusal transillumination probe also produces diagnostic images where lesions appear dark relative to bright sound enamel. The occlusal probe introduces diffuse 1300-nm light into the tooth enamel at the gingival margin, from both the lingual and facial sides, via two optical fibers angled apically through the root (Fig. 1B). Light enters the tooth directly or upon reflection from the gingival epithelium, and diffuses throughout the enamel and dentin.

The occlusal probe then captures the light exiting the occlusal surface of the tooth, light that has travelled from the cementoenamel junction plane through the exposed enamel.

The reflectance probes use light coincident with increased water absorption to enhance the contrast of early surface demineralization, specifically in the occlusal pits and fissures. Previous studies have demonstrated that reflectance images of early demineralization appear with the highest contrast when imagined with wavelengths coincident with high water absorption, 1460-nm and >1500-nm [10]. Two reflectance probes were tested in this study (Fig. 1C). An original design was created that used diffuse light from a 1600-nm SLD source, however strong specular reflection from the tooth surface make it difficult to identify areas of demineralization. A second, cross-polarized reflectance probe was designed to eliminate specular reflection utilizing a tungsten-halogen source with a long pass 1500-nm filter. During NIR reflectance, light that is reflected from the enamel surface retains its initial polarization state and is extinguished by cross-polarized filters. In reflectance images the sound enamel is dark and the lesions appear bright, the opposite contrast observed in transillumination.

Imaging dental caries in the NIR has distinct advantages. Stains are invisible in the NIR wave range, since they do not have molecular absorption bands in the NIR. This allows direct assessment of actual demineralization in these difficult to diagnose areas [11]. Developmental defects such as fluorosis or hypomineralized enamel can potentially be differentiated from caries in the NIR because of their differing depth profiles [12]. Mild fluorosis is often shallow in depth and contains a highly mineralized outer layer of transparent enamel [13].

2. Materials and Methods

2.1 Visible Images

Cross-polarization visible reflectance images were acquired for comparison with the cross-polarization NIR images. A Dino-Lite (AnMO Electronics Corp., New Taipei City, Taiwan) AM7013MZT polarizing digital microscope was used to acquire visual images, both wet and dry, of the patients' teeth prior to NIR imaging. The digital microscope captures 5 megapixel (2592×1944) color still images and video. Eight white LED lights contained in the camera illuminate the teeth and the polarizer is adjustable to reduce specular reflection.

2.2 NIR Camera and Optical components

The individual probes are designed to work interchangeably by attaching to a set of universal components connecting the probes to the NIR camera through relay optics. Two iris diaphragms, a 60-nm NIR achromatic doublet AC254-060-C and 150-nm NIR achromatic doublet AC254-150-C (Thor Labs, Newton, New Jersey) lenses project the captured light onto a high sensitivity SWIR (short-wave infrared) InGaAs (indium gallium arsenide) camera, Model GA1280J (Sensors Unlimited, Princeton, NK) with a 1280 × 1024 pixel format and 15-μm pixel pitch. A 360-degree rotation element allows simple flipping of the imaging probe to access the upper and lower teeth. The assembly is physically supported via an aluminum post attached to an elastic band wrapped around the forearm of the clinician. A power supply and output cables attached to the backside of the camera are connected to the data acquisition system through a flexible mesh bundle. Fiber optic cables and waveguides employed for optical delivery are carried in the mesh bundle to the imaging probes.

2.3 NIR Interproximal Transillumination

NIR interproximal transillumination produces diagnostic images similar in appearance to that of conventional bitewing X-rays from both the facial and lingual viewpoints. Figure 3 is a schematic drawing of the imaging probe that couples with the common optical components of the system described in section 2.2. Light centered at 1300-nm is generated using a super-luminescent laser diode (SLD), SLD72 (COVEGA Corporation, Jessup, MD) with 50-nm bandwidth and Newport modular controller model 8008. Fiber optic cables are used to deliver the light into a Teflon diffusing element and labeled B. Light emitted from the diffusing element propagates through the tooth, located between the diffusing element and right-angled mirror (C), and is reflected down the imaging tube through the relay optics and onto the focal plane array of the camera. Each tooth is imaged from the facial side and then the probe is rotated 180-degrees and the tooth is imaged from lingual position.

2.4 NIR Occlusal Transillumination

NIR occlusal transillumination produces diagnostic images unique to NIR imaging systems and capable of detecting occlusal demineralization, occlusal lesions and interproximal lesions [5, 6, 14]. The probe is shown in Fig. 4. Light centered at 1310-nm was provided by a super-luminescent laser diode, COVEGA SLD72, 20-mW, 50-nm bandwidth. Fiber optic cables are used to deliver the light into two diffusing elements made of Teflon (B). The diffusing elements are positioned using the copper tubes (A) and direct the light at the cementoenamel junction (CEJ) and the gingival tissue from both the lingual and facial sides at a shallow angle. The light that enters the tooth diffuses throughout its interior and out the occlusal tooth surface. The right-angled mirror (C) reflects the emitted light down the imaging tube through the relay optics and onto the focal plane array of the camera. The probe is designed to rotate 180-degrees for the imaging of both upper and lower teeth.

2.5 NIR Reflectance and Cross Polarized Reflectance

Initially, a NIR reflectance probe without cross-polarization elements was used to acquire *in vivo* images. For this probe, light centered at 1600-nm was generated using a super-luminescent laser diode with 50-nm bandwidth and Newport modular controller model 8008 and a fiber optic cable was used to deliver NIR light into a Teflon diffusing element. Light passed through the hollow width of the imaging probe and interacted with surface of the tooth where it was reflected or scattered back towards the relay right-angled mirror. Specular reflections from the tooth surfaces make identification of demineralized areas difficult. To overcome this phenomenon, crossed polarizers were used to reduce the amount of reflected light reaching the detector.

A schematic drawing of the reflectance probe with crossed polarizers is shown in Fig. 5. Light from a tungsten-halogen lamp (model HL-2000, Ocean Optics, Dunedin, Florida) equipped with a long pass 1500-nm filter (FEL1500, Thor Labs) was used. The tungsten-halogen source replaced the SLD source used by the previous model in order to reduce speckle noise resulting from coherent interference of the polarized light. Wavelengths longer than 1500-nm were delivered to the probe through a glass fiber optic waveguide (Dolan-Jenner, Boxborough, MA) into the holder labeled A in Fig. 5. The light from the waveguide passes through a polarizing beam splitter model PBS054 (Thor Labs, Newton, NJ) (B) and linearly polarized light is reflected down through the hollow width of the probe and onto the sample surface. The light interacts with the tooth and is reflected or scattered back on to a right-angled mirror (C) and the light is directed down the imaging tube and onto the focal plane array. A second linear polarizer MPIRE-100-C (Thor Labs) oriented perpendicular to the first prevents the specular reflected light from reaching the detector.

2.6 Patient Recruitment, Inclusion Criteria, and Imaging procedures

After obtaining IRB approval, participants were recruited from the patient population of the University of California, San Francisco School of Dentistry, Division of Orthodontics. Subjects with premolars (2–4 teeth) scheduled for extraction were briefed on the parameters of the study by their current doctor, and consent was obtained. The clinician operated the NIR imaging devices in the following order: (1) Conventional photos of the teeth were taken (both wet and air dried). (2) Cross-polarized reflectance imaging for the detection of surface demineralization in the pits and fissures and other external signs of decay. (3) Occlusal transillumination for the detection of interproximal lesions and deeper occlusal lesions. (4) Interproximal transillumination for the detection of interproximal lesions. During reflectance imaging an air spray is employed to dry the tooth surface (increasing lesion contrast) and prevent water/saliva accumulation on the occlusal surface. The air spray is also used to remove air bubbles during transillumination imaging. 8-bit video is simultaneously recorded and saved in real time through the coupled computer system.

3. RESULTS AND DISCUSSION

Figure 6 shows images of a suspected lesion that is visible in all three imaging modalities. Fig. 6A is a facial-interproximal transillumination image of two enamel lesions on adjoining teeth at the contact. The perimeter of the tooth appears bright relative to the darker interior of the tooth corresponding to the enamel and dentin. The lesions can be seen at the adjoining surfaces of the two teeth, the top lesion appears longer and more localized to the surface while the bottom lesion manifests the typical triangular appearance. Figure 6B shows another suspected interproximal lesion (top tooth), imaged from the occlusal surface using the alternative occlusal transillumination modality. The enamel is the bright ring surrounding the darker dentin with the lesions appearing dark in transillumination. From this viewpoint the DEJ is clearly resolved for both teeth which enables a qualitative assessment of lesion depth, in terms of distance from the surface to the DEJ. Figure 6C shows surface demineralization on the occlusal margin of two adjacent teeth imaged with the original reflectance probe. The demineralized tissue appears brighter than the sound tissue. In Fig. 6C the extremely bright reflections are examples of interference from specular reflection mentioned earlier.

Figure 7 contains images of an interproximal lesion imaged in all three NIR modalities. This example illustrates how information regarding the lesion character from the individual probes can be integrated to produce a more comprehensive picture of the lesion’s location. Figure’s 7C and 7B depict a lesion on the lingual side of the distal marginal ridge, with an adjoining amalgam restoration. The reflectance image suggests that the demineralized tissue exists at the occlusal surface while the occlusal transillumination image (7B) reveals the lesion’s depth and position relative to the DEJ. The image in Fig. 7B also shows the lesions lateral width at positions all the way down towards the cervical region of the enamel. Figure 7A shows a lingual-interproximal transillumination image of the suspected lesion and opposing amalgam. The dark region on the left tooth just below the contact is the suspected lesion. It is observed with high contrast relative to the surrounding sound enamel. Figure 7A demonstrates an important factor determining the success of interproximal transillumination images, that is, the height to the gingival tissue and interdental papilla. These tissue are highly scattering, opaque structures in the NIR that block the transversing light employed in the imaging modalities. It has been our experience that younger patients with more healthy gingival prove more difficult to image whereas older patients with greater gingival recession are relatively easier. Figure 7A is an example of a patient with healthy gums and interdental papilla extending up to the contact. Figure 8 presents a case in which the NIR imaging system has indentified suspected secondary caries on the wall of a mesial-occlusal composite resortation. In the lingual-interproximal transillumination image (8A) a composite restoration can be seen illuminated at the proximal contact. Along the facial wall of the composite is a dark area that extends from the composite enamel boundry into the surrounding enamel. At the bottom of the restoration a triangular shaped dark area can be observed deep to the enamel surface of the tooth. The occlusal transillumination image (8B) reveals a similar dark region at the boundary of the composite and the enamel seen on the left side of the image. Figure 8C is included, even though there is no observable demineralizion, to illustrate how this can help locate the lesion boundries. Because the reflectance image 8C is negative, and the lesion is observed in the other below the enamel.

Figure 9 compares the images of the standard reflectance probe and the cross-polarization replacement. Figure 9A was produced by the standard design and exhibits many areas with saturated pixels in areas of high reflectivity. Figure 9B is an example of a cross-polarization image with almost all specular reflections extinguished. Close examination of the occlusal fissures of demineralization in both images, demonstrates the ease in distinguishing demineralization from reflected light in the cross-polarization image compared with the orginal.

In summary, the three probes presentated in this paper are capable of acquiring high quality images of occlusal and interproximal lesions using near-IR light.

Acknowledgments

This project was supported by NIH Grant Number RO1 DE 14698.

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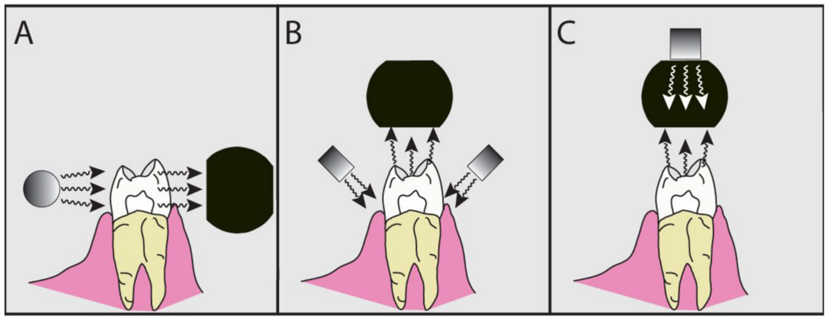

Fig.1.
NIR imaging geometries: (A) interproximal transillumination (B) occlusal transillumination (C) reflectance. Light sources are shown in gray while the detectors are shown in black.

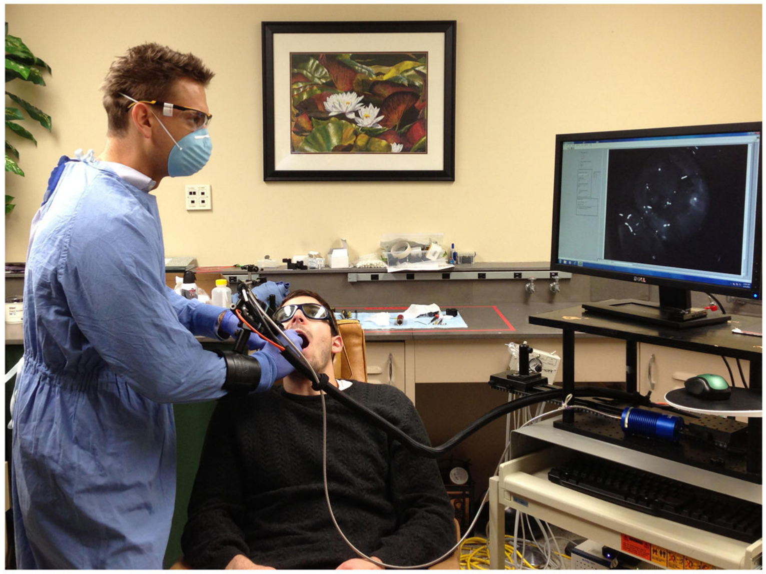

Fig. 2.

NIR imaging system clinical set up. The probe (held in the clinicians right hand) is connected to a real time display through a black wire bundle.

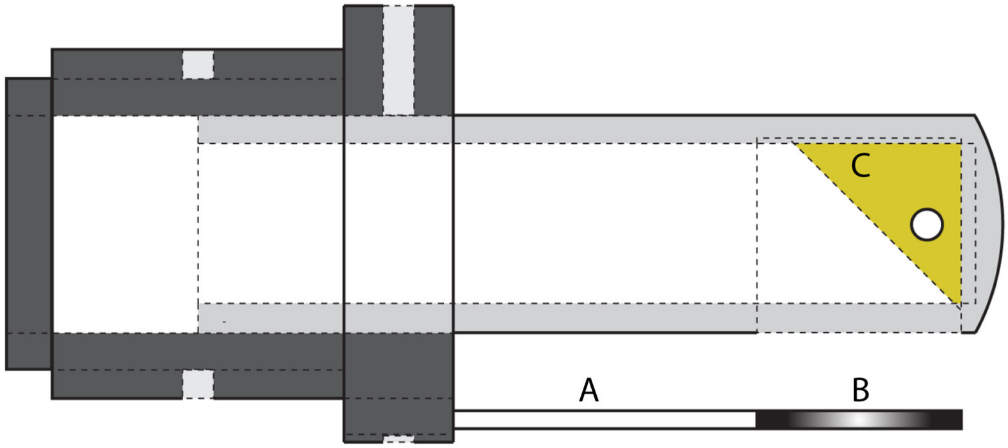

Fig. 3.
Interproximal transillumination probe with (A) Optical fiber guide (clear tubing) (B) Teflon diffuser and (C) right-angle gold plated mirror.

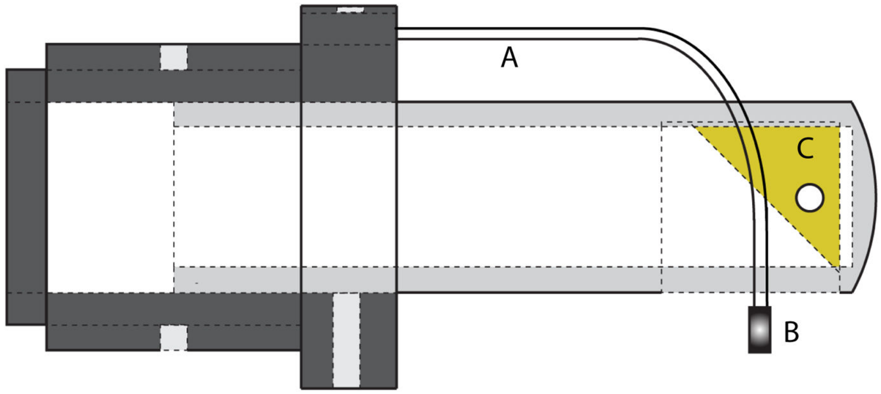

Fig. 4.
Occlusal transillumination probe with (A) optical fiber guide (copper tubing), (B) Teflon diffuser and (C) right-angle gold plated mirror.

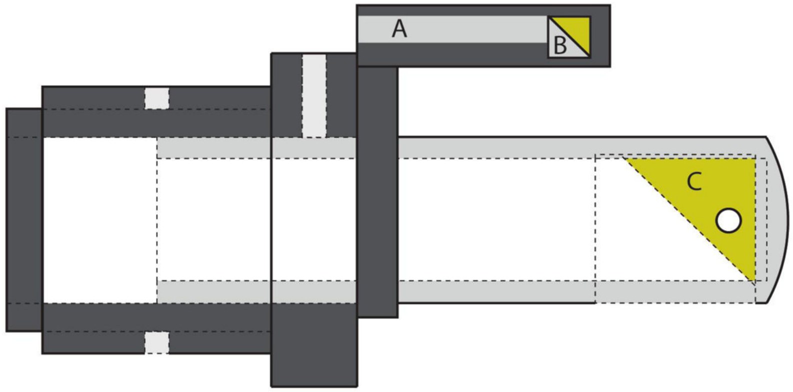

Fig. 5.

Reflectance probe with crossed polarizers (A) fiber optic bundle, (B) polarizing beamsplitter and (C) right-angle gold plated mirror.

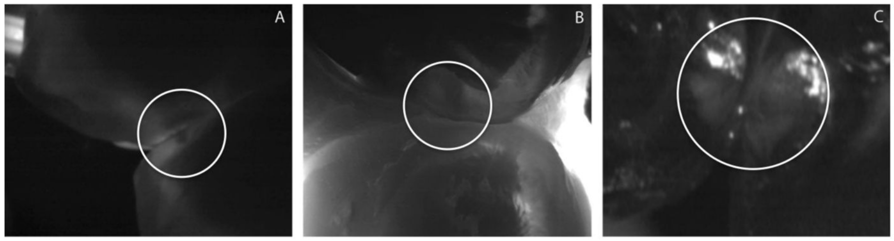

Fig. 6.

Typical lesion appearance for all three modalities (lesion circled). (A) Interproximal transillumination image of adjoining enamel lesions (B) Occlusal transillumination image of approximal lesion (C) Reflectance image of adjoining lesions (Note: different teeth are shown in A–C).

Fig. 7.
Interproximal lesion on a single tooth, imaged in all three NIR modalities (lesion circled). (A) Interproximal transillumination image of (B) Occlusal transillumination and (C) reflectance image.

Fig. 8.
First molar with recurrent caries imaged in all three modalities (lesion circled); (A) interproximal transillumination, (B) occlusal transillumination (C) and reflectance. The lesion can’t be seen in (C) suggesting the lesion is deep below the tooth surface.

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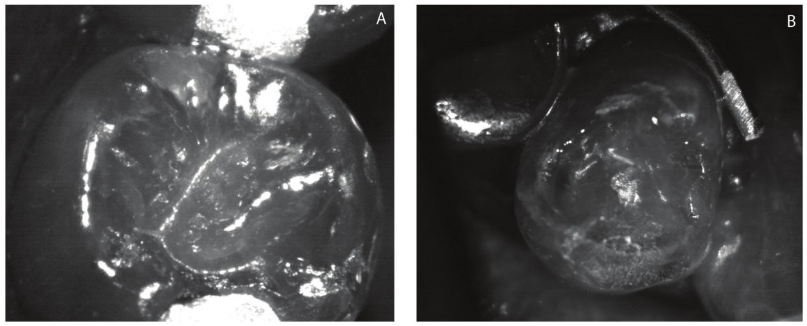

Fig. 9.

(A) Standard reflectance image and (B) cross-polarization reflectance image teeth with occlusal demineralization.