Published in final edited form as:

Lasers Surg Med. 2010 April ; 42(4): 292–298. doi:10.1002/lsm.20913.

In Vivo Near-IR Imaging of Approximal Dental Decay at 1,310 nm

Michal Staninec, DDS, PhD, Chulsung Lee, Cynthia L. Darling, PhD, and Daniel Fried, PhD*

Department of Preventive and Restorative Dental Sciences, School of Dentistry, University of California, San Francisco, California 94143-0758

Abstract

Objective—The high transparency of dental enamel in the near-IR (NIR) light at 1,310-nm can be exploited for imaging dental caries without the use of ionizing radiation (X-rays). We present the results of the first in vivo imaging study in which NIR images were acquired of approximal contact surfaces.

Methods—NIR imaging hand-pieces 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. The carious lesions were discernible on bitewing radiographs, but were not visible upon clinical examination.

Results—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.

Conclusion—This first in vivo study of imaging at the 1,310-nm wavelength region shows that NIR imaging has great potential as a screening tool for the detection of approximal lesions without the use of ionizing radiation.

Keywords

caries detection; near-IR imaging; inter-proximal caries

INTRODUCTION

In vitro studies have demonstrated the potential of near-IR (NIR) imaging for the detection of dental decay [1,2]. In this article we present the results of the first clinical study employing NIR imaging for the detection of approximal lesions located at the contact surfaces between teeth. Most dental decay is found in either the pits and fissures of the occlusal (biting surfaces) or just below the approximal contact points between teeth, in areas that are difficult to brush and where plaque can accumulate. Previous studies have shown that NIR imaging can be used to detect both types of lesions although this study involved only approximal lesions. Dental enamel manifests high transparency in the NIR; the scattering coefficient of enamel is 20–30 times lower near the telecom wavelengths of 1,310 and 1,550-nm than it is at visible wavelengths [3,4]. This high transparency means that internal structures can be discerned in transillumination and any highly scattering variations in structure will show up as dark areas. Upon demineralization the scattering coefficient increases by 1–2 orders of magnitude at 1,310-nm so that the optimal contrast between sound and demineralized enamel falls at those wavelengths as well [5]. Therefore this

wavelength range is ideally suited for the transillumination of approximal dental carious lesions (dental decay in between teeth). The enamel is so transparent that novel imaging configurations are possible in which the tooth can be imaged from the occlusal surface. Decay in the pits and fissures of the occlusal (biting) surfaces of posterior teeth where most new dental decay occurs can be imaged, and approximal lesions can even be viewed from the occlusal surface [1,2,6].

Optical transillumination was used extensively before the discovery of X-rays for detection of dental carious lesions. 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 approximal lesions [7-12]. 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 FOTI system, called DiFoti, that utilizes visible light for the detection of caries lesions, has been developed over the last 10 years by Electro-optics Sciences (Irvington, NY) [13]. 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 approximal caries lesions [13-18]. However, FOTI and DIFOTI operate in the visible range where light scattering prevents imaging through the entire tooth [3,4].

High contrast NIR images have been acquired of simulated and natural approximal lesions on extracted human teeth [1,2]. Approximal lesions can be viewed using transillumination with the light source and detector placed on opposite sides of the tooth or near-IR light can be delivered near or below the gum-line and both approximal and occlusal lesions can be imaged from directly above the occlusal surface. Imaging at wavelengths that are accessible to conventional silicon based CCD cameras have also been investigated [19]. Imaging systems operating near 830-nm, utilizing a low-cost silicon CCD optimized for the NIR, is capable of higher performance than visible systems, but the contrast is significantly lower than that attainable at 1,310-nm [19], and simulated lesions could not be imaged through the full enamel thickness [19].

There are other important advantages of imaging dental decay in the NIR. Stains are less visible at NIR wavelengths because the chromophores responsible for most stains absorb in the visible range. Therefore stains can be easily differentiated from actual demineralization in the NIR range which is not possible at visible wavelengths. It also appears easier to differentiate between developmental defects such as fluorosis and dental carious lesions in the NIR than in the visible range [20]. Such defects may confound imaging of dental decay at visible wavelengths since the hypomineralized mineral causes increased light scattering similar to that produced by demineralization by caries. Mild fluorosis is shallow in depth with an intact highly mineralized outer layer which can usually be easily differentiated from deeper caries lesions and more severe defects in the NIR images, because deeper lesions appear with increased contrast in the NIR [20,21]. Defects in tooth structure and cracks in enamel are also highly visible at NIR wavelengths.

In addition to the conventional transillumination arrangement in which the NIR light is shined through the tooth contact point and the transmitted light is collected on the other side, images of both occlusal caries lesions and approximal lesions can be acquired by delivering NIR light near the gum-line at the base of the crown and letting the light diffuse up from the root to the occlusal surface and imaging from the top of the tooth [1,2,20,22]. This occlusal view cannot be obtained by direct transillumination as it is not possible to place the light source directly opposite the detector.

Previous NIR imaging studies were conducted ex vivo on extracted teeth and employed imaging setups that are impractical to acquire images in the oral cavity. Therefore it was necessary to develop imaging hand-pieces or probes that could be employed to access all tooth surfaces. Carious lesions are located on either the occlusal (biting) surfaces of teeth or near the approximal contact points between teeth (approximal lesions). In this study only approximal lesions that were of sufficient severity to show up on a bitewing radiograph were investigated and probes were developed to image this decay by transillumination through the tooth (facial–lingual orientation) or by viewing the lesion from the occlusal surface while delivering the light near the gum-line of the tooth. These probes were used to acquire in vivo images of 33 approximal lesions on 18 test subjects.

MATERIALS AND METHODS

NIR Imager and Probes

Two imaging probes were employed to acquire images from either the occlusal surface (top) or the outer facial (buccal or cheek side) or inner lingual (tongue side) of the teeth examined.

Each probe consisted of a 25-mm objective lens, a $\frac{1}{2}$ in. in diameter tube 5 in. long with a relay lens, a mirror and light delivery optics. A high sensitivity InGaAs (indium gallium arsenide) imaging camera, Model SU320KTSX (Sensors Unlimited, Princeton, NJ) was used to collect all the images. For comfort and stability, the video camera/hand-piece assembly was mounted onto the examiner's forearm as shown in Figure 1 and the probes

were held by the $\frac{1}{2}$ in. tube of the probe. Since lesions are detected by differences in optical contrast uniform illumination is critical for NIR imaging. In our previous in vitro studies uniform illumination of the occlusal surface was achieved by use of a cylindrical lens that was employed to deliver the light just above the gingiva (gum-line) [2]. Due to the large size of the cylindrical lens it is not convenient to use a similar setup for in vivo imaging. However, we found that the optical design of Figure 2 is a superior system that can uniformly illuminate the occlusal surface of the tooth as illustrated by the in vitro images of Figure 3. The probe is placed directly over the tooth and optical fibers coupled to Teflon optical diffusers in two arms (A), direct the NIR light to the gingival tissues on the facial and lingual side of the tooth (B) and the mirror (C) directs the light to the camera. The system provides uniform illumination of the crown and the sound enamel is visible as a ring of higher intensity around the central dentin core of the tooth as shown in Figure 3A.

If an approximal lesion is present it appears as a dark area due to the attenuation of the light that is scattered from the underlying lesion. The enamel is illuminated by the scattered light from the inner core of highly scattering dentin and the gingival tissues as the light propagates up from below. Occlusal lesions are also visible as dark areas in the occlusal pits and fissures as we have previously demonstrated and this probe configuration also provides good images of carious lesions in occlusal enamel as shown in Figure 3B. Approximal lesions are visible from below the contact point on adjacent teeth even though the light has to propagate through several mm of enamel.

Our facial–lingual probe is shown in Figure 4. An optical fiber delivers NIR light to a large Teflon diffuser (A) placed on either the facial or lingual side of the tooth to provide uniform illumination of the contact point. The NIR light passes through the tooth (B) and is directed to the imaging camera with a mirror (C) positioned on the opposite side of the tooth. The light source can be rotated for positioning on either the facial or lingual side of the tooth (Fig. 4).

Our facial–lingual probe provides uniform illumination of the contact point between adjoining teeth for optimal lesion contrast and avoids saturation of the imaging camera. In previous in vitro studies we achieved this using crossed polarizers which is more difficult to do clinically [1]. Figure 5 shows visible and NIR images of an extracted tooth with an approximal lesion. The lesion is clearly visible in the NIR with high contrast. Most approximal lesions can be resolved by imaging from the occlusal surface using the probe of Figure 2. Two optical fibers attached to the probe direct NIR light to gingival tissues near the cementum-enamel junction (CEJ) and the transmitted light is collected by a mirror positioned over the occlusal surface. The best viewing direction varies somewhat with lesion location and some lesions were only visible in one particular viewing direction.

Light was provided by one or two 1,310-nm super-luminescent diodes (SLD) from Optospeed (Zurich, Switzerland), two for the occlusal probe and one for the approximal probe with an output power of 15 mW and a 35-nm bandwidth. The power was determined empirically by experimenting with various settings and the bandwidth was chosen because broadband SLDs avoid speckle and the related image degradation that is common with narrow bandwidth light sources.

Patient Recruitment, Inclusion Criteria, and Imaging procedures

Subjects were recruited from the patient population of the University of California at San Francisco School of Dentistry. The examining dentist searched for proximal lesions visible on bitewing or anterior radiographs. When such lesions were located, the patient was offered participation in the study. Informed consent was obtained in accordance with the protocol approved by the Institutional Human Research Committee. Approximal lesions were selected which were visible on bitewing radiographs, but not visible clinically. The lesions ranged from lesions radiographically confined to enamel, to lesions more than halfway through the dentin [23].

The teeth to be examined were gently dried with a stream of air from a dental unit air syringe and video (8-bit) was acquired as the imaging hand-piece was passed over the tooth. Most of the subject teeth were imaged from three directions: occlusal, facial, and lingual. After imaging, the lesion severity was scored by review of the recorded video and the radiographs. The scoring system was as follows: (0) No lesion visible, (1) Lesion less than halfway through enamel, (2) Lesion more than halfway through enamel, but not involving dentin, (3) Lesion involving dentin, but less than halfway to the pulp, (4) Lesion involving dentin, more than halfway to the pulp. Those scores along with the tooth number which represents the position of the tooth in the jaw and the tooth surface (mesial or distal side of tooth) are listed in Table I.

RESULTS

In this study 33 lesions were imaged in 18 test subjects. All the lesions with the exception of one lesion could be seen via NIR imaging. Most of the lesions were small and confined to the enamel and only 10% of the lesions involved dentin (score 3 or 4)—deep enough to require restoration. All of the lesions with the exception of one lesion were classified as Class II, which means they are located between posterior teeth. Class II lesions are much more common and more challenging to image than Class III lesions. Only one lesion was Class III, that is, located between the anterior (front) teeth. Most Class III lesions found in our patient population were not eligible for the study, since we excluded lesions that are visible clinically. These lesions are usually clinically visible because the facial–lingual dimension of anterior teeth is small enough to permit direct visual inspection of approximal surfaces.

Figure 6 shows an image of the only Class III lesion imaged in the study, it is a small lesion located at the contact point of two lower incisors. The facial/lingual probe shown in Figure 4 was used to acquire the images and the probe was moved across three teeth to view two contact points. What is most striking are the high number of large cracks that are clearly visible along with the high transparency of the crowns of the incisor that are thin and mostly enamel. This small lesion appears to involve both opposing teeth and lies just above the interdental papilla. The interdental papilla is soft tissue, part of the gingiva (gums) and it is the triangular-shaped opaque structure that typically appears below the contact point between the teeth. The gingival tissues are highly scattering and are not transparent in the NIR and can potentially interfere with imaging if the papilla covers the point where the teeth make contact.

Figure 7 shows a radiograph of two small approximal lesions located on adjoining teeth across the contact point along with two NIR images taken with the mirror positioned on both the facial and lingual sides of the imaged teeth. The lesions are visible from both views with high contrast. The contrast is much higher for the lesions in the NIR images than for the radiograph. There are also amalgam restorations on the teeth and they are the large highly opaque areas. Typically the best image or highest contrast is from the side closest to the location of the lesion and in some cases the lesions were only visible from either the facial or lingual view. A high gingival margin may also interfere with access by the probe, most likely with the imager on the lingual side of the contact point.

The probe was rotated slightly back and forth over the contact point to produce a stereoscopic perspective in a similar fashion to what was achieved by rotating an extracted tooth during ex vivo video acquisition [1]. This effect is most dramatic for the small amalgam restoration surrounded by the transparent enamel.

Figure 8 shows two lesions imaged from the occlusal surface using the imaging probe of Figure 3 along with the corresponding radiographs. This probe was the easiest to employ in vivo and the probe could be rapidly swept over several teeth to look for lesions. A small approximal lesion viewed from the occlusal surface is shown in Figure 8A,B. The NIR image shows that the lesion is centered right on the contact point. There is a large amalgam restoration in the center of the tooth. A much more severe lesion that penetrates well into the dentin is shown in Figure 8C,D. Even though the dentin is not nearly as transparent as the enamel in the NIR it is still obvious in the NIR images that the lesion has progressed well into the dentin. Even though this lesion is very large in the NIR image and on the bitewing radiograph, it was still not visible by a clinical examination, that is, there was no shadow that is sometimes clinically visible for very large lesions.

Table I contains a list of all of the 33 teeth on 18 test subjects imaged in this study, the teeth imaged involved all tooth types, that is, incisors, canines, and molars on the maxilla and mandible. The severity of the approximal decay was scored by a dentist based for both the NIR images and the radiograph. When diagnosis is made with standard bitewing radiographs, lesions with a score of (4) need to be restored (drilled and filled), lesions with a (3) may need restoration and lesions confined to the enamel (1 and 2) can probably be arrested or remineralized without surgical intervention. Most of the lesions imaged in this study were confined to the enamel (27/33).

Only one lesion (1/33) that was confined to the enamel was not visible in any of the NIR images. All the lesions with the exception of three were visible using the facial/lingual NIR probe (30/33) and all but six were visible using the occlusal probe (27/33). Thus, it appears to be advantageous to use all three views: facial, lingual, and occlusal.

DISCUSSION

This first in vivo study of imaging at the 1,310-nm wavelength region shows that NIR imaging has great potential as a screening tool for the detection of approximal lesions without the use of ionizing radiation. Even though the sensitivity of bitewing radiographs is not very high [24-28], most studies indicate the specificity of bitewing radiographs is above 90%, which makes it a suitable standard for comparison with the first test of this new imaging technology. In a clinical study, it is not possible to extract the teeth and section them to examine with microradiography, which would be the ultimate gold standard for lesion depth. It is important to stress that 97% of the lesions that appeared on bitewing radiographs were seen in the NIR images and that the typical lesions imaged in this study were very small, that is, most were confined to the enamel and only 10% of the lesions were judged large enough to warrant restorations based on bitewing radiographs [23]. There were many areas on the teeth that appeared to be demineralized in the NIR images that did not show up on the bitewing radiographs. This suggests that NIR may be more sensitive than bitewing radiographs for imaging early lesions, however, confirming this clinically is not straightforward since such small lesions do not require restoration and since the teeth are not extracted there is no suitable gold standard for comparison.

At this time it is much too early to base restorative clinical decisions solely on this diagnostic technology. However, it may be possible to follow the progression of demineralization and remineralization, particularly in enamel.

In this study we only looked at approximal lesions and NIR imaging may have even greater potential for imaging occlusal lesions for which bitewing radiographs have very low sensitivity. By the time lesions are visible on a bitewing radiograph they have typically spread to encompass a large area of dentin at which time they require large and deep restorations. A future study is planned to image occlusal lesions. Cracks and damage due to excessive mechanical forces could also be seen on many of the teeth.

Since the NIR does not employ ionizing radiation, there are no restrictions on image acquisition and this method is ideal for monitoring lesions over time and images can be acquired from multiple angles to aid in diagnosis. For example, proximal lesions that are shallow and wrap around the contact point cannot be easily differentiated from deeper lesions that are centered at the contact point on a bitewing radiograph. One advantage of NIR imaging is that a combination of images taken from the occlusal surface and the facial-lingual and lingual-facial aspect can be used to differentiate between these lesion types. A few of the approximal lesions were only visible in the NIR from the occlusal surface using the novel imaging arrangement shown in Figure 2 and they were not visible using either facial-lingual or lingual-facial imaging configurations. This probably occurs due to tooth overlap or the presence of gingival tissue blocking the contact. It is possible that in some clinical situations, particularly in cases with bulky, high gingival tissues, the usefulness of NIR may be limited.

Dentists have based their detection of approximal lesions on bitewing radiographs for more than a century and even though such radiographs may not accurately show the depth and activity of these lesions or show cavitation, the standard of care has evolved based on such images. NIR imaging is a new imaging technology, and it is important to point out that clinicians will also need to develop/evolve methods to effectively interpret the images to assess the depth and severity of the decay and identify potential false positives before this technology can obtain its full potential. One must also be concerned about over detection by a technology that may be more sensitive than existing methods and subsequent abuse and over-treatment. In this study lesions were previously identified with radiographs before

imaging with the NIR, therefore the potential of NIR imaging as a screening tool has not been assessed. The next step is to carry out in vivo studies in which the NIR is used to find lesions and the diagnostic performance can be evaluated, that is, specificity and sensitivity.

Acknowledgments

The authors would also like to acknowledge the contributions of Hobin Kang.

Contract grant sponsor: NIDCR; Contract grant number: R01-DE14698.

REFERENCES

1. Jones RS, Huynh GD, Jones GC, Fried D. Near-IR trans-illumination at 1310-nm for the imaging of early dental caries. *Opt Expr*. 2003; 11(18):2259–2265.
2. Bühler CM, Ngaothepitak P, Fried D. Imaging of occlusal dental caries (decay) with near-IR light at 1310-nm. *Opt Expr*. 2005; 13(2):573–582.
3. Fried D, Featherstone JDB, Glena RE, Seka W. The nature of light scattering in dental enamel and dentin at visible and near-IR wavelengths. *Appl Opt*. 1995; 34(7):1278–1285. [PubMed: 21037659]
4. Jones, RS.; Fried, D. Lasers in dentistry VIII. SPIE; San Jose: 2002. Attenuation of 1310-nm and 1550-nm laser light through sound dental enamel; p. 187-190.
5. Darling CL, Huynh GD, Fried D. Light scattering properties of natural and artificially demineralized dental enamel at 1310-nm. *J Biomed Opt*. 2006; 11(3):034023, 034021–034011.
6. Fried, D.; Featherstone, JDB.; Darling, CL.; Jones, RS.; Ngaothepitak, P.; Buehler, CM. Early caries imaging and monitoring with near-IR light. W. B Saunders Company; Philadelphia: 2005.
7. Barenie J, Leske G, Ripa LW. The use of fiber optic transillumination for the detection of proximal caries. *Oral Surg*. 1973; 36:891–897. [PubMed: 4524840]
8. Pine, CM. Fiber-optic transillumination (FOTI) in caries diagnosis. In: Stookey, GK., editor. *Early Detection of Dental Caries*. Indiana University; Indianapolis: 1996. p. 51-66.
9. Peltola J, Wolf J. Fiber optics transillumination in caries diagnosis. *Proc Finn Dent Soc*. 1981; 77:240–244. [PubMed: 7267640]
10. Holt RD, Azevedo MR. Fiber optic transillumination and radiographs in diagnosis of approximal caries in primary teeth. *Community Dent Health*. 1989; 6:239–247. [PubMed: 2679987]
11. Mitropoulos CM. The use of fiber optic transillumination in the diagnosis of posterior approximal caries in clinical trials. *Caries Res*. 1985; 19:379–384. [PubMed: 3861261]
12. 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*. 1998; 32(3):204–209. [PubMed: 9577986]
13. Schneiderman A, Elbaum M, Schultz T, Keem S, Green-ebaum M, Driller J. Assessment of Dental caries with Digital Imaging Fiber-Optic Transillumination (DIFOTI): In vitro Study. *Caries Res*. 1997; 31:103–110. [PubMed: 9118181]
14. Bin-Shuwaish M, Yaman P, Dennison J, Neiva G. The correlation of DIFOTI to clinical and radiographic images in Class II carious lesions. *J Am Dent Assoc*. 2008; 139(10):1374–1381. [PubMed: 18832273]
15. Young DA, Featherstone JD. Digital imaging fiber-optic trans-illumination, F-speed radiographic film and depth of approximal lesions. *J Am Dent Assoc*. 2005; 136(12):1682–1687. [PubMed: 16383050]
16. Young DA. New caries detection technologies and modern caries management: Merging the strategies. *Gen Dent*. 2002; 50(4):320–331. [PubMed: 12640848]
17. Yang J, Dutra V. Utility of radiology, laser fluorescence, and transillumination. *Dent Clin North Am*. 2005; 49(4):739–752. vi. [PubMed: 16150314]
18. Keem S, Elbaum M. Wavelet representations for monitoring changes in teeth imaged with digital imaging fiber-optic transillumination. *IEEE Trans Med Imaging*. 1997; 16(5):653–663. [PubMed: 9368121]

19. Jones, G.; Jones, RS.; Fried, D. Transillumination of interproximal caries lesions with 830-nm light. In: Rechmann, P.; Fried, D.; Hennig, T., editors. *Lasers in Dentistry X*. SPIE; San Jose: 2004. p. 17-22.
20. Hirasuna K, Fried D, Darling CL. Near-IR imaging of developmental defects in dental enamel. *J Biomed Opt*. 2008; 13(4):044011, 044011–044017. [PubMed: 19021339]
21. Lee, D.; Fried, D.; Darling, C. *Lasers in Dentistry XV*. SPIE; San Jose: 2009. Near-IR multi-modal imaging of natural occlusal lesions; p. X1-X7.
22. Darling C, Fried D. Real-time near-IR imaging of ablation crater formation in dental enamel during laser ablation. *Opt Expr*. 2008; 16(4):2685–2693.
23. Pitts NB, Rimmer PA. An in vivo comparison of radiographic and directly assessed clinical caries status of posterior approximal surfaces in primary and permanent teeth. *Caries Res*. 1992; 26:146–152. [PubMed: 1521308]
24. Peers A, Hill FJ, Mitropoulos CM, Holloway PJ. Validity and reproducibility of clinical examination, fibre-optic trans-illumination, and bite-wing radiology for the diagnosis of small approximal carious lesions. *Caries Res*. 1993; 27:307–311. [PubMed: 8402807]
25. Pine CM, ten Bosch JJ. Dynamics of and diagnostic methods for detecting small carious lesions. *Caries Res*. 1996; 30(6):381–388. [PubMed: 8946093]
26. Purdell-Lewis DJ, Pot T. A comparison of radiographic and fibre-optic diagnoses of approximal caries lesions. *J Dent*. 1974; 2(4):143–148. [PubMed: 4531441]
27. Vaarkamp J, ten Bosch JJ, Verdonchot EH, Bronkhorst EM. The real performance of bitewing radiography and fiber-optic transillumination in approximal caries diagnosis. *J Dent Res*. 2000; 79(10):1747–1751. [PubMed: 11077989]
28. Stephen KW, Russell JI, Creanor SL, Burchell CK. Comparison of fibre optic transillumination with clinical and radiographic caries diagnosis. *Community Dent Oral Epidemiol*. 1987; 15(2):90–94. [PubMed: 3552397]

Fig. 1. System for NIR imaging including InGaAs camera and specialized probes with NIR fiber-optic light delivery and imaging optics. Images are displayed on the monitor and video is stored on a digital video recorder at 8-bit resolution.

Fig. 2.

Probe end for imaging approximal and occlusal lesions from the occlusal surface. Teflon optical diffusers in two arms (A) direct the NIR light to the gingival tissues on the buccal and lingual side of the tooth (B) which diffuses up to the mirror (C) and the camera.

Fig. 3.

In vitro occlusal images taken using the probe shown in Figure 2. Near-IR image of sound tooth, note uniform ring of high intensity around the dentin at the center (**A**) and tooth with occlusal caries lesions, the dark regions (**B**).

Fig. 4.

Probe end for imaging approximal lesions from the facial or lingual contact. Light travels from Teflon diffuser (A) through tooth (B) to mirror/camera (C).

Fig. 5. In vitro approximal lesion imaged from the faciolingual orientation. (**A**) Visible light image of teeth and (**B**) near-IR image with the lesion indicated by the arrow.

Fig. 6.
In vivo image of a class III anterior approximal lesion (**A**) taken from the facial–lingual aspect using the probe of Figure 4, along with the radiograph (**B**).

Fig. 7. Radiograph (**A**) and in vivo NIR images of two small lesions taken from the facial (**B**) and lingual (**C**) views using the probe shown in Figure 4. The boxes demarcate the position of the lesions in each image. The opaque areas represent amalgam restorations.

Fig. 8. Radiographs and in vivo NIR images of two approximal lesions, one small (**A,B**) and another severe (**C,D**) taken from the occlusal surface using the probe shown in Figure 2. The boxes demarcate the position of the lesions in each image.

TABLE I
Lesions Imaged in This Study

Tooth #	X-ray	IR occlusal	IR facial/lingual
3M	2	0	2
3M	2	2	2
4D	2	2	2
12D	4	3	3
18M	2	2	2
19D	2	2	2
19M	2	2	2
20D	2	2	2
21D	4	2	2
29M	2	2	2
29D	1	1	1
21D	2	2	2
9M	2	0	2
13M	3	3	3
29D	2	2	2
30M	2	2	2
30D	3	0	2
31M	2	0	2
19M	2	3	3
20D	2	0	0
20M	2	3	2
12D	2	2	0
13M	2	2	0
4D	3	3	2
5D	2	2	2
29M	2	2	2
29D	2	2	2
30M	1	2	2
18M	3	2	2
19D	2	2	2
19M	1	0	2
20D	2	2	2
4M	2	2	2

Including the tooth #, surface (M) mesial or (D) distal and severity in each imaging modality.

(0) Indicated no lesion was visible, (1) the lesion was visible and confined to the outer half of the enamel, (2) the lesion penetrates into the inner half of enamel, (3) the lesion has reached the dentin, and (4) the lesion has penetrated into the inner half of the dentin.