IEEE Journal of Translational Engineering in Health and Medicine

Received 27 January 2017; revised 23 March 2017; accepted 4 April 2017.
Date of publication 19 April 2017; date of current version 1 May 2017.

Digital Object Identifier 10.1109/JTEHM.2017.2695194

Near-Infrared Imaging for Detecting Caries and Structural Deformities in Teeth

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This work was supported by the Department of Media Arts and Sciences of the Massachusetts Institute of Technology.

ABSTRACT 2-D radiographs, while commonly used for evaluating sub-surface hard structures of teeth, have low sensitivity for early caries lesions, particularly those on tooth occlusal surfaces. Radiographs are also frequently refused by patients over safety concerns. Translucency of teeth in the near-infrared (NIR) range offers a non-ionizing and safe approach to detect dental caries. We report the construction of an NIR (850 nm) LED imaging system, comprised of an NIR source and an intraoral camera for rapid dental evaluations. The NIR system was used to image teeth of ten consenting human subjects and successfully detected secondary, amalgam–occluded and early caries lesions without supplementary image processing. The camera-wand system was also capable of revealing demineralized areas, deep and superficial cracks, and other clinical features of teeth usually visualized by X-rays. The NIR system's clinical utility, simplistic design, low cost, and user friendliness make it an effective dental caries screening technology in conjunction or in place of radiographs.

INDEX TERMS Demineralization, dental caries, near-infrared imaging, transillumination.

I. INTRODUCTION

Dental caries, more commonly known as cavities or tooth decay, is one of the most prevalent clinical conditions in the world. The World Health Organization estimates that 60-90% of school children and nearly 100% of adults have or have had caries [1], with indications that global incidence rates are increasing [2]. Tooth decay is the predominant chronic health condition amongst persons aged 6-19 [3]. While it is assumed that industrialized nations have better oral hygiene due to implementation of public health measures (e.g. water fluoridation) and improved living conditions [4], some developed nations have caries incidence rates greater than those of resource-limited settings [5]. Tooth decay occurs when oral bacteria metabolize sugars and starches found in food and produce acids that erode the enamel of the tooth [6]. Caries are strongly correlated with the presence of dental plaque which is produced by the same antagonizing bacteria [7], [8]. With time, the enamel layer is compromised and the acids attack the inner dentin and eventually the soft pulp [9], causing pain, sensitivity, stains, and halitosis. Tooth decay can also contribute to infection and inflammation of the surrounding gingiva.

Dentists treat caries by manually removing the compromised tooth material and filling the remaining void. To help locate and determine the depth of the decay, dental professionals commonly rely on radiographs in conjunction with white light visual examination. The most popular radiographic views are bitewing, periapical, and occlusal views. Because traditional radiographs capture a two-dimensional projection of all superimposed material between the film and source, there is attenuation of finer detail. The orientation and severity of the feature directly affects its radiographic visibility; as such, some incipient caries, early demineralization, and cracks will not appear on the X-rays. Caries adjacent to and within direct line-of-sight of opaque amalgam fillings, such as instances of secondary caries, may also not be visible. Furthermore, modern radiographs generate concern among patients who seek to reduce their exposure to ionizing radiation. It is not uncommon for patients to refuse radiographs despite the wishes of dental professionals. Dentists who lack radiographs of a patient are denied valuable diagnostic information.

The scattering properties of enamel and dentin in the NIR range were first characterized by Fried et al. in 1995 [10].

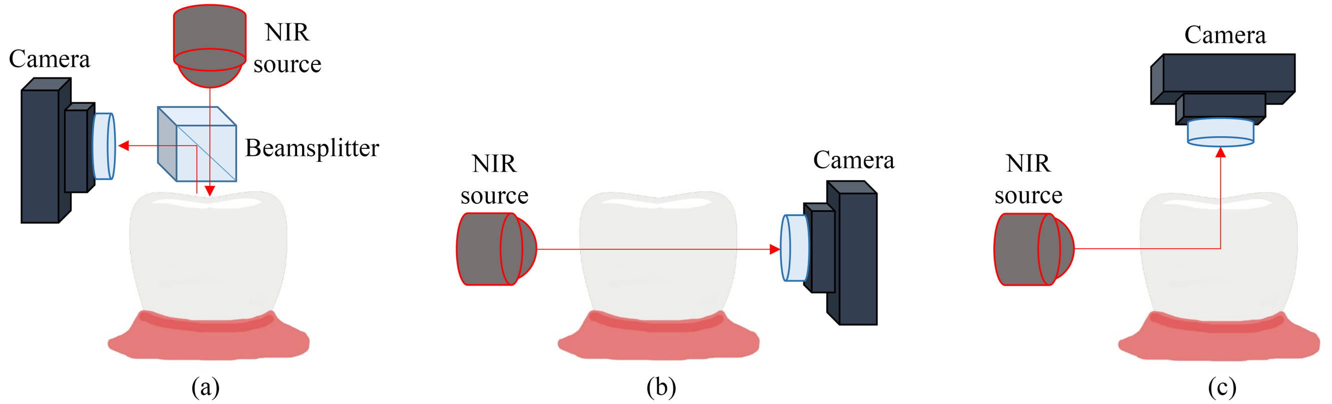

FIGURE 1. **Common NIR imaging modes. (a) Reflectance imaging has light directed at the tooth, with reflected rays collected by a camera positioned in a desired orientation; a beamsplitter is commonly employed to redirect the illuminated surface for imaging. (b) Transillumination imaging focuses on capturing the source light after it has transited the tooth. Emitters of low coherence, such as SLDs and LEDs, are usually placed adjacent to the tooth to maximize the input of light; lasers can be placed further away. Transillumination most commonly has the tooth positioned between the source and camera, although this orientation is not mandatory. If the camera is angled to view the occlusal surface and is orthogonal to light source, the tooth is undergoing occlusal transillumination imaging (c).**

Depending on the wavelength, most NIR light can be transmitted across healthy enamel with marginal scattering; 1310 nm light represents an optimal imaging wavelength as it strikes a balance between enamel and water attenuation [11], [12]. However, dental caries and demineralization scatter transiting NIR light and appear as dark areas [13]. The depth of caries and other features can be further interrogated when comparing the dark and translucent areas at different viewing angles, illumination modes, and NIR wavelengths [14]–[19]; Fig. 1 illustrates common viewing and illumination methods for NIR dental imaging. Cracks in the tooth are easily visualized in the NIR range as well [20]. Stains, which absorb light and hamper assessment of the underlying material, do not manifest at NIR wavelengths of 1200 nm and greater [21]. At 1310 nm, mild fluorosis and other shallow defects may be discernable depending on their severity, geometry, and method of imaging [22]; Hirasuna et al. suggest multimodal NIR imaging as a potential means for differentiating between mild fluorosis and deeper caries. Taken altogether, NIR dental imaging has produced condition-dependent applications that challenge or exceed two-dimensional radiographs without the use of ionizing radiation, and work has been done to compare the diagnostic capabilities of both technologies [15], [19], [23].

While much of the research into NIR dental imaging occurs around 1310 nm, neighboring NIR wavelengths have also demonstrated potential application depending on the illumination mode and target feature, and it is not uncommon for researchers to image the tooth across the NIR range and into the short-wavelength infrared range [14], [17], [24]. As current CCD and CMOS technologies have sensitivities that extend into the NIR range [25], [26], some NIR imaging is realizable with many commercial cameras. InGaAs infrared cameras, as used in some of the previously cited work, are capable of capturing in the NIR and short-wavelength range, typically operating on wavelengths of 0.9-1.7 μm [27]; the spectral range can be further extended to 2.5 μm with enhanced cooling. However, InGaAs cameras are comparatively more expensive that CCD and CMOS cameras, pose numerous challenges for use in vivo, and typically have restricted access. While not as spectrally powerful as an InGaAs camera, and despite the increased scattering properties of enamel below 1300 nm [28], CCD and CMOS technologies remain viable options for NIR dental imaging closer to the visible spectrum [28]–[30].

A small selection of market devices utilizing NIR light are available for purchase, such as the DEXIS CariVu^{TM} (DEXIS, LLC, Hatfield, PA) and Dürr Dental's VistaCam iX (Dürr Dental, Bietigheim-Bissingen, Germany). The DEXIS CariVu uses a CCD sensor and NIR light maximized at 788 nm for fixed-angle occlusal surface transillumination imaging. The DEXIS CariVu has two light sources that enter the buccal and lingual side of a target tooth for transillumination, and its camera is oriented directly towards the occlusal surface. The VistaCam iX by Dürr Dental is a software-assisted handpiece incorporating a variety of illumination modes, including a "Proxi" interchangeable head that emits 850 nm light for caries detection via reflectance imaging. When the Proxi head is attached to the VistaCam iX handpiece, two NIR emitters are positioned on either side of a CMOS sensor.

Despite the range of technology available to the clinician, challenges in detecting secondary and intraproximal caries in both NIR imaging and two-dimensional radiographs persist. Furthermore, there have been no studies which utilize a CCD or CMOS sensor in non-occlusal imaging schemes. To test the capability of an NIR intraoral imager in both reflectance and transillumination modes, as well as make the device angle independent for flexibility in imaging occluded clinical features, we decoupled the camera sensor and illumination source into two separate wands. The user then has improved control for manipulating the frame and angle of capture, the amount of illumination, and the manner in which the tooth is illuminated. A study population of 10 individuals was recruited to test the NIR system on a variety of teeth, ranging from healthy, restored, and those under suspicion of requiring excavation. Our results show that the NIR system was capable of detecting clinical conditions usually imaged via X-rays as well as new dental lesions currently lacking diagnostic imaging.

II. METHODS AND PROCEDURES

A. DEVICE CONSTRUCTION

Our NIR system was composed primarily of two intraoral wands. The first wand contained a USB CMOS camera board with its infrared filter removed, inserted into a custom 3D-printed wand housing. Reduction of the housing profile was critical for granting the camera access to as much of the mouth as possible. An 850 nm LED was embedded into a second wand, to be used as the source illumination. Wands were sealed with a hard epoxy resin. During operation, the NIR system was connected to a computer and a generic webcam application launched; live video feed was displayed onscreen. While using the NIR system, the dental professional held a wand in each hand, allowing for positional flexibility of the camera, as well as the proximity of the illumination source to the tooth.

B. CLINICAL RESEARCH

The Massachusetts Institute of Technology's Institutional Review Board, the Committee on the Use of Humans as Experimental Subjects reviewed and approved the clinical protocol (1603518840). Subjects aged 18-70 were invited at Hampden Dental Care in Lakewood, Colorado to participate in the study via a phone call or email one week prior to visiting the clinic site for routine dental prophylaxes. During the actual visit, subjects were explained the details of the study and provided the opportunity to ask questions, refuse participation, or provide written consent. After written consent was obtained, overhead lights were turned off while a dentist imaged sites of interest with both the NIR system and a white light intraoral camera. The NIR system was used to capture approximal and occlusal views in both reflectance and transillumination modes. A DEXIS CariVu was employed for occlusal imaging. The CariVu was selected as a reference dental imaging technology as it was the most easily obtainable and widely used NIR market device in North America. Periapical/bitewing radiographs from a Kodak RVG 6100 Digital Radiography System (Carestream Dental, Atlanta, GA) were recovered from patient histories and used for X-ray comparison.

III. RESULTS

10 individuals with a variety of fillings, caries, and other dental conditions were imaged. Fig. 2a shows a white light image of tooth 9 from a 56-year-old female. Features became more readily visible under NIR transillumination (Fig. 2b); two restorative fillings on either proximal surface (Fig. 2b, blue outlines) appear smooth and homogenous in texture in comparison to the genuine tooth material. Reduced translucency located throughout the tooth is indicative of areas of demineralization. The large demarcated patch of demineralization (Fig. 2b, yellow outline) was dental attrition compounded from the patient's overbite; repeated impact from the incisal edge of the matching lower tooth eroded the protective enamel. Numerous vertical craze lines are easily visible and appear to be miniscule sites of demineralization; it is probable that their location renders them easily cleaned during brushing, mitigating progression of caries. A horizontal fracture along the center of the tooth spans the distance between the two restorations (Fig. 2b, cyan outline). Caries appear as regions darker and more clearly defined than demineralization; the secondary caries (Fig. 2b, red outline) have manifested along leaking fillings. Features are harder to discern in the radiograph (Fig. 2d); for instance, the horizontal fracture detectable in Fig. 2b, but not in Fig. 2d.

Fig. 3 compares images of a tooth with an amalgam filling extending over the occlusal surface, captured by multiple image systems. The amalgam appears opaque in both the CariVu image (Fig. 3a) and the radiograph (Fig. 3c), largely preventing assessment of the tooth material obscured by the filling. However, using the NIR system to scan along the margin of the filling revealed a hidden secondary caries that was not readily apparent in the white light (Fig. 3b), CariVu or radiograph (Fig. 3d, blue outline) images. The dentist confirmed the presence of the secondary caries under the amalgam post-extraction. Evaluating the integrity of a filling is crucial for determining when it warrants replacement [31], so any method that can bypass optically-opaque features and resolve secondary caries is of interest.

The images captured by the NIR system revealed clinical conditions, including caries, demineralization, fractures, cracks, and craze lines. Analogous among radiographs was a comparative loss of fidelity in all features. The detail afforded by NIR images offers the possibility of preemptive assessment of conditions prior to their visibility on a radiograph, such as incipient caries. Differentiation of deeper caries from surface artifacts such as stains was bypassed via altering the camera view and illumination, which could be observed in real-time; however, the most extreme surface anomalies within any subject were marginal, and further testing would be required to see how capable the NIR system would be at circumventing more extensive surface features. Nonetheless, the importance of positional flexibility is demonstrated. The NIR system can be deployed as quickly as any conventional intraoral camera and without requiring the patient to leave the examination chair. The dentist could then promptly reconfirm caries geography and depth prior to irreversible excavation.

As the NIR system and the CariVu could only image approximately one tooth at a time, radiographs remained a faster method for surveying multiple teeth at once. The surface of the tooth opposite the camera, as well as larger teeth, were more difficult to image with the NIR system. Radiographs could also provide information deeper into the

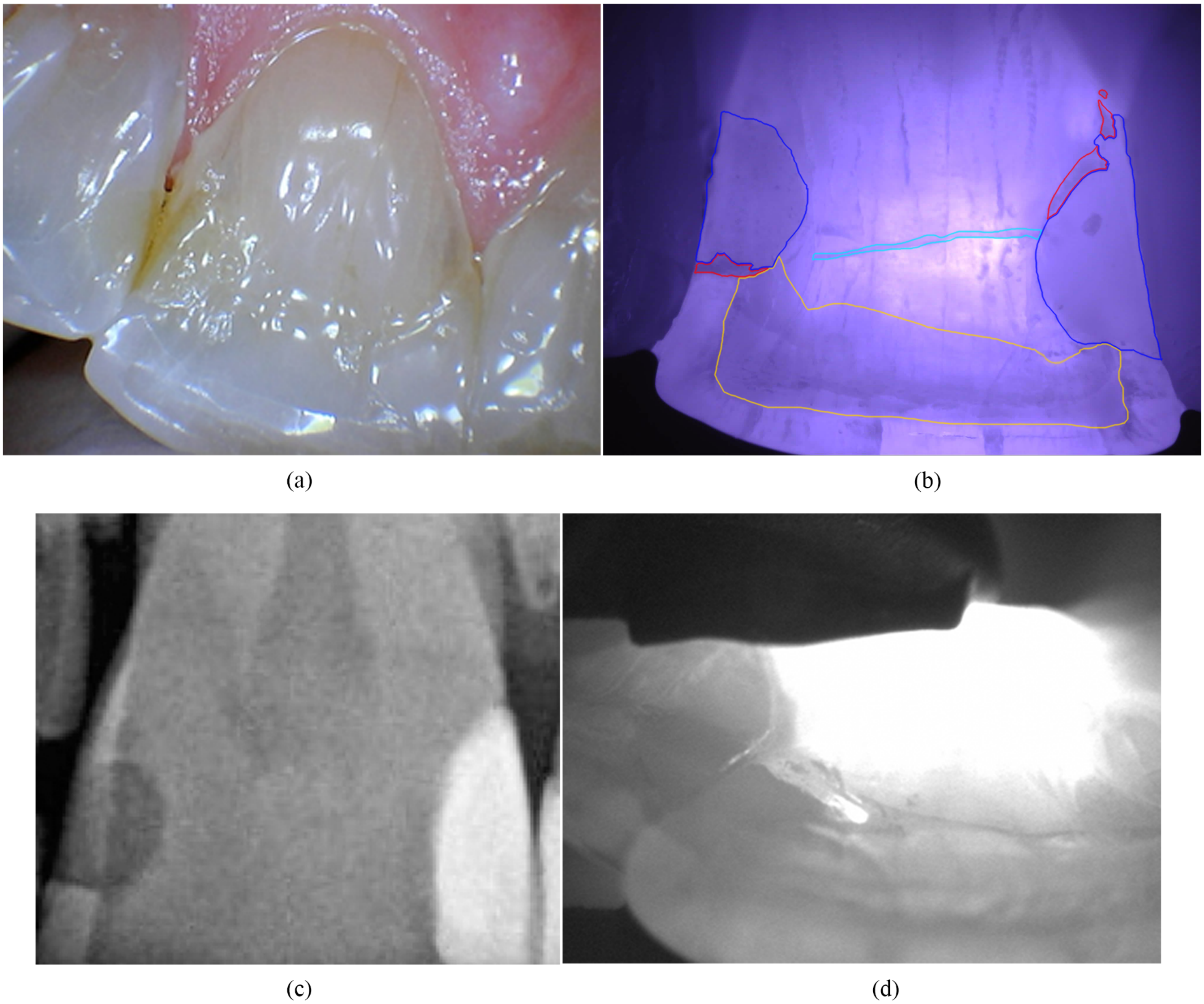

FIGURE 2. **Archetypical examples of dental features in various NIR modes. Images are of tooth 9 in a 56-year-old female; views in (a)-(c) are taken from the lingual side with the distal direction leftwards. (a) White light image. (b) The NIR system's transillumination image exhibits areas of reduced luminescence indicative of demineralization or caries. Caries are darker and more pronounced than demineralization. Select areas of interest are highlighted; two proximal restorations (blue) displaying leakage and secondary caries (red). A large area of demineralization (yellow) denotes a region where the incisal edge of tooth 24 on the mandible has caused enamel attrition. A large horizontal fracture (cyan) runs between the two restorations. (c) Periapical radiograph section with both proximal restorations visible and darkening from corresponding secondary caries. (d) In the DEXIS CariVu occlusal view, teeth lacking a larger occlusal surface, such as this incisor, are more difficult to image.**

tooth volume, on the root, and on the surrounding bone. However, the use of non-ionizing radiation was a major incentive for the patients to be imaged with either the CariVu or the NIR system. Despite this, the fixed angle of the CariVu presented unique shortcomings primarily due to its fixed plane of imaging. Other reasons that inhibited satisfactory imaging with the CariVu included tooth geometry, the CariVu head not properly fitting a certain tooth, and the size and/or location of the target caries. Some of these factors contributed to the imaging difficulties present in the tooth featured in Fig. 2d. The fixed angle also prevented examination under the filling in Fig. 3a. Since the illumination and camera are separate wand entities in the NIR system, a view or set of views could be established to overcome tooth geometry limitations. On the other hand, a single-point light source did not transilluminate the tooth as uniformly as the CariVu during occlusal imaging. Table 1 lists comparisons between NIR technologies.

The single-point wand configuration was selected after preclinical prototypes of various fixed-angle geometries were used to probe extracted teeth. LEDs of varying wavelength from the 780-1550 nm range were also tested on extracted teeth. Preliminary findings suggested that LEDs of 850 nm wavelength worked best with our selected CMOS camera board for lesion contrast. Images acquired unfavorable amounts of noise at illuminations above 950 nm. Further

TABLE 1. NIR Dental Imaging System Comparison.

Capability	2D radiographic	DEXIS CariVu	NIR system
Multiple view angles	Yes – requires new X-ray administration for each view	No (occlusal view only)	Yes
Incipient carious lesions	Limited (due to sensitivity)	Limited (due to view)	Yes
Fine feature visualization (early conditions, cracks, craze lines)	No	Limited (due to view)	Yes
Capable of bypassing opaque amalgam	Limited (due to amalgam orientation and view)	Limited (due to view)	Yes
Avoids ionizing radiation	No	Yes	Yes

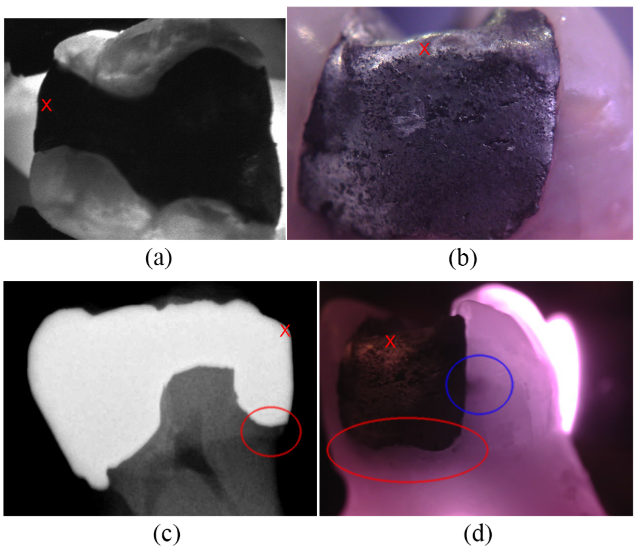

FIGURE 3. Multiple images of an amalgam filling under different imaging modes. The presence of the metal amalgam inhibits assessment. The red "X" denotes the same amalgam edge in all images. (a) The DEXIS CariVu's occlusal imaging shows some demineralization. (b) White light examination reveals no immediate problems. (c) Amalgam appears opaque in the two-dimensional radiograph and blocks evaluation of superimposed tooth material. Secondary caries has started in the lower amalgam margin, as circled in red. (d) Scanning of the amalgam margin with the NIR system shows secondary caries along the bottom of the amalgam circled in red, as seen in the radiograph in (c). Midway down the side of the filling, circled in blue, was another secondary caries spot undetected by the other imaging methods. No indication of this caries is present in the white light image in (b). (a) was taken *in vivo*, and (b)-(d) were taken after extraction.

testing revealed that a bandpass filter in front of the camera aperture was not necessary if the room was sufficiently dark; thus, room lights were turned off during data collection, and an optical filter omitted from the camera probe to further minimize profiling.

At the 850 nm wavelength, transillumination imaging was far more diagnostically functional than reflectance imaging. Attempts at using the NIR system for pure reflectance imaging did not take advantage of the tooth material's optical channeling. Consequently, reflectance imaging light did not penetrate deep into the tooth to reveal subsurface conditions. While it is possible that LED intensity could have been increased or exchanged for a laser source, the LED transillumination proved to be much more practical. The intensity output of the selected LEDs was more than enough to optically saturate the tooth during transillumination. Furthermore, laser excitation harbors increased safety concerns in living patients; even invisible, the amplified light from a coherent NIR source can permanently damage the eye. The inability to see the beam also adds to the danger of accidental exposure.

The cost to build the NIR system was modest (less than $100) and mostly attributed to the USB webcam, which was approximately $80; the emitter itself was a few dollars. Previous work from our group has constructed similarly-themed solutions for retinas [32], ear [33], and skin imaging [34]. With the advent of rapid prototyping and computer vision algorithms, construction and use of cost-effective oral imaging technologies will exponentially change access to oral healthcare globally.

IV. CONCLUSION

In a study of 10 subjects with varying dental conditions, we test a custom NIR system capable of illuminating at 850 nm and imaging with a standard CMOS USB camera. The decentralization of camera sensor and illumination source into multiple wands was essential for navigating the non-uniform topology of the mouth, and is highly recommended as a NIR dental imaging configuration. The NIR system was capable of displaying subsurface caries, including those around fillings, demineralization, fractures, and cracks, all without the use of ionizing radiation. The superb detail of the images, primarily in comparison to conventional radiographs, potentially grants the clinician greater diagnostic power. Furthermore, the inexpensive cost of the components required to produce such high quality images adds a new dimension that is in contrast to conventional imaging approaches.

ACKNOWLEDGMENT

Authors thank Mrinal Mohit of the MIT Media Lab and the staff of Hampden Dental Care.

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