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Attempting near-infrared transillumination imaging with simple instrumentation for studying dental lesions

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Abstract:

During the past decades, near-infrared (NIR) methods have been applied to many aspects of life, particularly in dentistry. X-ray methods involve reliable techniques that dentists use to evaluate tooth structure lesions. However, X-ray methods still have some limitations, such as affecting patient health and dentists. In addition, early demineralised enamel is barely detected by X-ray methods. Many studies have demonstrated the usefulness of NIR light for observing tooth structure due to the differences of the optical properties between sound and demineralised tooth tissues under NIR wavelengths. Early demineralisation located under the enamel layer can be observed by NIR imaging (780-1,300 nm). The areas suspected to be demineralised enamel are distinct from the stain and pigmentation because stain and pigmentation do not appear in NIR images. The demineralised areas are substantially darker than the surrounding sound tissues under NIR light. In this study, two optical systems with transillumination and scattering techniques using NIR light (940 nm) were built for capturing occlusal and approximal images of teeth. The systems fulfill some requirements, such as simple setup, safety, and affordable price for the purpose of the replacement of imported equipment.

Keywords: **approximal lesion, demineralisation, near-infrared, occlusal, teeth.**

Classification number: **2.3**

Introduction

Dental lesions are one of the most common diseases, affecting people of all ages across the world, and particularly children. Diagnoses of damaged structures of teeth in general and early dental present challenges for dentistry. Some available diagnostic methods for dental lesions include X-rays, clinical visual inspection, caries indicator dyes, fluorescent methods, electrical conductance measurements (ECM), etc.

The visual method is the most popular diagnostic method in dentistry because it can detect most occlusal lesions, cavitated enamel, and dentine lesions with high specificity. However, with low sensitivity, this method has trouble detecting early enamel lesions and proximal and hidden caries [1, 2].

In addition to the visual method, X-rays are commonly used as a diagnostic tool in dentistry. When X-rays pass through the oral cavity, much of the X-rays are absorbed by hard tissues such as teeth and bones [3]. The absorbed X-rays will pass through the film or a digital sensor, creating a radiographic image of the tooth. This method makes it possible to observe the structure of hard tissue and surrounding soft tissues that cannot be observed by clinical examination methods, such as proximal tooth surfaces or hidden caries. However, this method also produces many adverse effects, particularly for children and pregnant women, through the use of ionising radiation.

Today, in dentistry, near-infrared technology has been studied for decades and is being applied to the detection of early damages without use of ionising radiation [3, 4]. The NIR method yields tooth structure images detected by NIR camera. The images created are based on the optical properties of the tooth due to the transmission, absorption, and scattering of dental tissues in NIR wavelength. Because the absorption coefficients are exceptionally small in visible

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and NIR light, while scattering is strong in visible light and weak in NIR, enamel is translucent in the near infrared light. For dentin, the absorption coefficient depends upon the wavelength in the visible region with a value of $\mu_a \sim 4$ cm^{-1}, while the scattering is strong throughout the visible and NIR regions. Therefore, NIR light is the optimum wavelength for imaging dental lesions, particularly dentin caries [5].

The damaged tooth structure is mostly demineralised enamel, in which mineral density is reduced. As a result, demineralisation creates gaps in enamel and dentin tissues. Near-infrared light is scattered at the wall of these gaps and substantially attenuated by the absorption with the elongated pathlength due to multiple scattering [6]. For demineralisation, the scattering coefficient of demineralised enamel increases by one to two orders of magnitude at a wavelength of 1,300 nm [7]. According to the difference in optical properties between sound and demineralised enamel, their contrast in NIR images is rather pronounced. Notably, X-rays do not distinguish between sound enamel and demineralised enamel [4, 6].

NIR technology has been investigated for several decades around the world, and some NIR dental diagnostic devices have been commercialised. This study has aimed to build simple optical systems with reasonable prices. Many researchers have indicated that a wavelength of 1,300 nm is more effective than 940 nm due to the higher contrast of images at 1,300 nm, but performance is challenging because of the limited equipment (LED and camera). Therefore, the system used a 940-nm wavelength of which the extinction is lower than 40 cm^{-1} in enamel, and absorption of water is negligible [4]. 940-nm LED and NIR cameras are available at an affordable cost. This study has designed the transillumination and scattering NIR optical systems to record the approximal and occlusal images of teeth.

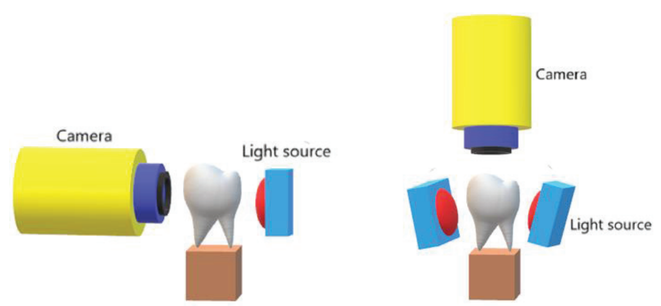
Materials and methods

The transillumination system illustrated in Fig. 1A consists of a light source, a tooth sample, and an NIR camera. An approximal image of tooth was observed clearly by this system. The transillumination method suits thin teeth such as incisors and canines. Samples were illuminated in visible light and 940-nm wavelengths and operated with an LED. An oral camera was used for capturing images. The camera was connected to a computer with a USB cable 2.0. The LED intensity and source-to-sample distance (about 1-1.5 cm) were adjusted for each sample to control image quality. Tooth samples were placed on a 360^0-rotating table to capture all sides of samples (Fig. 2A).

The optical scattering system is illustrated schematically in Figs. 1B and 2B. It consists of two 940-nm LEDs, a specimen, and an NIR camera. This system used two symmetrical light sources on two opposite sides of the sample. The scattering system was used to observe the occlusal surface. This method is an effective means of observing molar teeth because of their thickness. The camera was placed above the tooth and perpendicularly to the light path. The quality of the tooth structure image depends upon the position of the camera, the light sources, and tooth. The distance between the sample and the camera is about 1 to 1.5 cm, and the light sources were located below the gum line of the teeth. The power of the light sources is an important factor as well. If LED power is overly high, the recorded images will be overwhelmed by light, and no details of teeth can be seen. For this system, the power of each LED was 1.5 W.

Technical specifications of 940-nm LED: consumption power 1.5/3 W, input voltage 2.0 to 2.4 V, forward current 0.3-0.6 A, lumen efficiency 100 lm/W, and emitting angle 140^0.

Technical specifications of camera: sensor type CMOS, spectral range 350-1,000 nm, resolution 2Mpx, image rate 15 fps, focal length 1 to 2 cm, input voltage 5 V, temperature range $10-75^0$C, and outer dimensions of 17 cm (height) 2 cm (width) 1 cm (depth). With the purpose of designing a dental diagnostic device in the future, the size and the focal length of the selected camera are suitable for intraoral *in vivo* examination.



(A) (B)

Fig. 1. Schematic diagram of transillumination (A) and scattering systems (B).

(A) (B)

Fig. 2. Appearance of transillumination (A) and scattering systems (B).

Results and discussion

White-spot lesions

There are many causes of forming white spot lesions which are often overlooked in clinical observation, such as demineralisation, fluorosis, enamel hypoplasia, etc. Although X-rays are the gold standard in dentistry, but it is unable to detect white spot lesions at early stages [8]. Substantial research has demonstrated that the observation of early tooth lesions is more effective by NIR imaging. Under NIR light, many lesions appear with high contrast because the scattering coefficient of damaged tissue is lower than that of healthy enamel [5]. This is the sign of demineralisation appearing at the first stage of the progression of tooth lesion.

Figure 3 depicts a tooth sample with white-spot lesions. Under visible light (Fig. 3A), at the center of the chewing surface, relative to more translucent, healthy enamel, an opaque white area appeared. According to the doctor's conclusions based on clinical observations and X-ray (Fig. 3C), this sample has positive status. However, on the NIR image (Fig. 3B), the contrast of circled area is higher than the surrounding healthy enamel, which has demonstrated that the origin of this lesion is not fluorosis because fluorinated enamel is white in both NIR and visible images [4]. This is one of the advantages of the NIR method, which is useful to observe disease progression and improve diagnostic accuracy.

The similar results of white spot lesions are depicted in samples 2 and 3 (Figs. 4, 5).

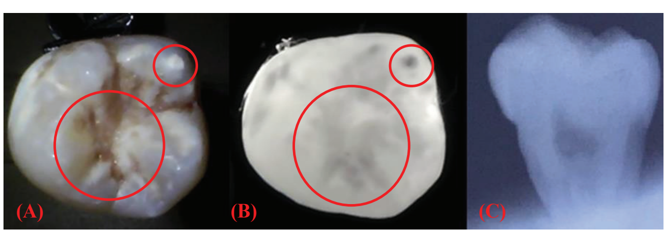


Fig. 3. Sample 1 under visible light (A), NIR light (B), and X-rays (C).

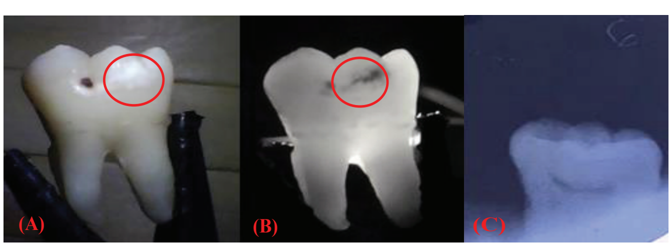


Fig. 4. Sample 2 under visible light (A), NIR light (B), and X-rays (C).

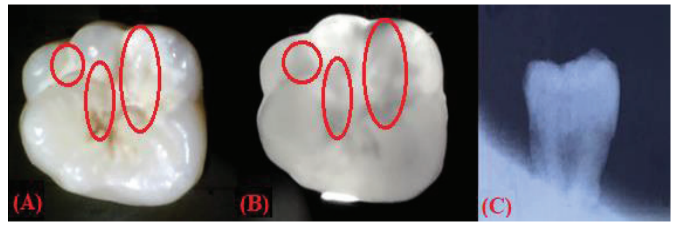


Fig. 5. Sample 3 under visible light (A), NIR light (B), and X-rays (C).

Occlusal lesions

Occlusal lesion is a type of injury that can easily be observed by infrared light scattering. It is formed by food debris inserted between occlusal pits and confused with dental plaque or fluorosis or enamel hypoplasia. In the NIR image, occlusal lesion is not mistaken for plaque or stains on the tooth.

Figure 6 demonstrates a tooth sample having a large area of demineralisation on the occlusal surface. However, this lesion is not clear on the X-ray film (Fig. 6C), but in the NIR image (Fig. 6B). The NIR image displays a high-contrast area, substantially darker than the surrounding area. For this sample, demineralisation occurred in a large area so that a deep hole was formed. Substantial research has indicated that the broken crystal structure of demineralised tissue can cause unkeeping of water in tissue and precipitates the creation of gaps in the enamel. In this area, the light is attenuated more by the absorption with the elongated pathlength due to multiple scattering [9, 10]. Therefore, the demineralised tissue is darker than surrounding healthy tissue under NIR light.

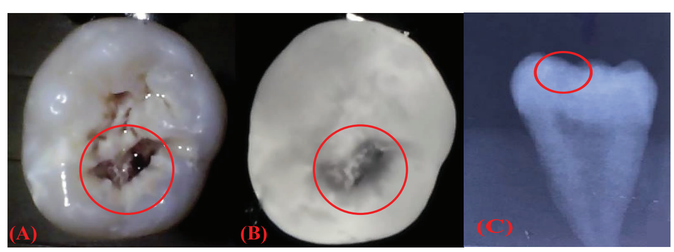


Fig. 6. Sample 4 under visible light (A), NIR light (B), and X-ray (C).

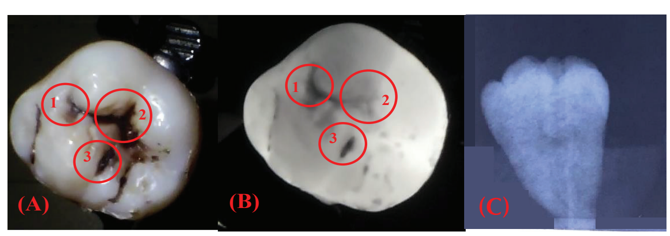


Fig. 7. Sample 5 under visible light (A), NIR light (B), and X-ray (C).

Figure 7 illustrates a sample with the appearance of an early cariuos lesion. Under visible light (Fig. 7A, circled area 2) on the occlusal surface, a large area regarded as a lesion appeared in the occlusal grooves. However, in the NIR image (Fig. 7B), this area does not exhibit a more severe lesion relative to other regions (circled area 1 and 3) because the concentrated dental plaque in the occlusal surface is easily confused with lesions under visible light. The disappearance of these plaques under infrared light demonstrates the effectiveness of the NIR method for the diagnosis of dental lesions. In addition, in the NIR image, the circled region 1 appears with a higher contrast than the surrounding enamel; however, it is regarded as a minor injury under visible light. The circled area 3 appears clearly under both visible and infrared light. In X-ray films (Fig. 7C), there is no recognition of the existence of these lesions.

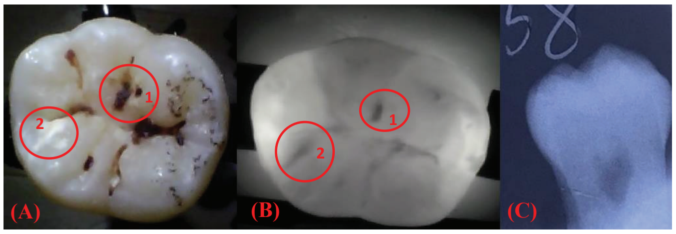


Fig. 8. Sample 6 under visible light (A), NIR light (B), and X-ray (C).

For teeth with many signs of injury on the occlusal surface, as illustrated in Fig. 8, the NIR method has exhibited high efficiency in determining the exact position of lesion. Under visible light (Fig. 8A), the brown regions are suspected of the demineralisation, which cannot be observed in the X-ray image (Fig. 8C). However, some brown stains, such as area 1, were apparent under NIR illumination. In addition, another region of injury (circled area number 2) could be observed clearly in the infrared image, while in visible light, it is difficult to be distinguished because of the similar color relative to healthy enamel.

Recurrent caries under fillings

Fillings are frequently used in the treatment of cavities at the stages of enamel or dentin decay. After fillings, the lesions can be relapsed, and they are referred to as 'recurrent caries under fillings'. The proportion of secondary caries is exceptionally high after filling in permanent teeth or primary teeth. Secondary caries primarily occur because of the formation of micro cracks after filling. When the micro crack width exceeds 50 micron, saliva enters the micro cracks between the filling and the tooth tissue. The cariogenic bacteria in the saliva grow when the environment of micro cracks is appropriate, thereby producing secondary caries [11].

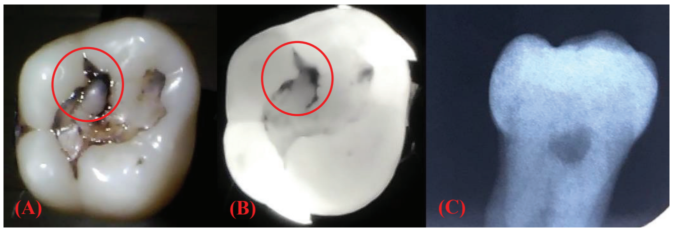


Fig. 9. Sample 7 under visible light (A), NIR light (B), and X-ray (C).

Figure 9 depicts a tooth sample with a filling on the occlusal surface. Under visible light (Fig. 9A, circled area), there were some dark areas around the filling, which rendered it difficult to distinguish between plaque and demineralisation, while the X-ray image (Fig. 9C) did not provide any information of the suspected lesion under filling because of the limitation of X-ray in scanning the occlusal surface. Because plaques do not absorb NIR light and disappear completely in NIR images [5], the darker area in Fig. 9B demonstrated the clear appearance of demineralised lesion.

Tooth discolorisation and plaque

Figure 10 illustrates a discolored sample with a cavity on the enamel surface and calculus. Under visible light, it is easy to recognise that the color of tooth changed to black. Fig. 10B displays a NIR image captured by the transmission method, in which calculus and discolored areas appeared as black. However, as mentioned above, infrared light cannot be absorbed by plaque and discolored area; therefore, they are not apparent in the NIR image. This means that in this sample, the demineralisation occurred under the calculus and discolored area. Notably, even the X-ray films (Fig. 10C) allow the definition of the presence of caries without the detection of early damages. This property of the tooth and NIR light interaction can be applied to distinguish demineralisation from discoloration and calculus.

The same results were recorded with other samples (Figs. 11, 12).

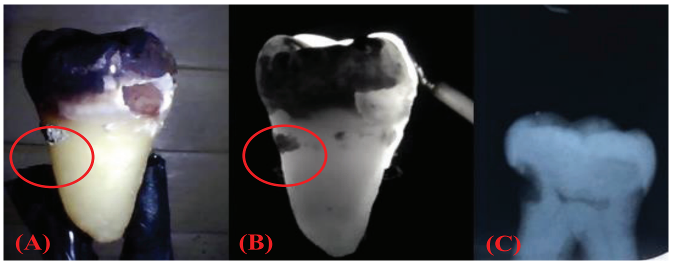


Fig. 10. Sample 8 under visible light (A), NIR light (B), and X-rays (C).

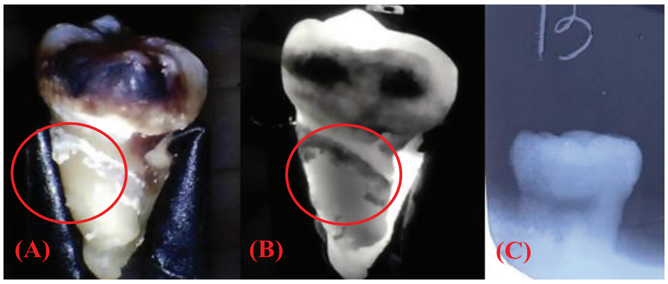


Fig. 11. Sample 9 under visible light (A), NIR light (B), and X-rays (C).

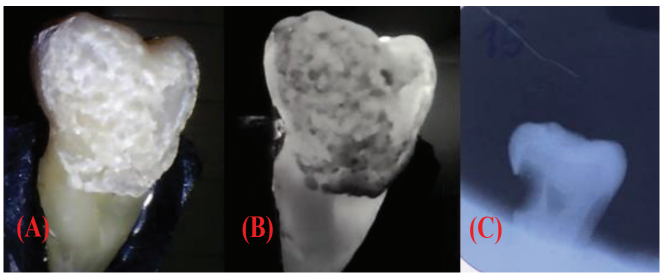


Fig. 12. Sample 10 under visible light (A), NIR light (B), and X-rays (C).

Conclusions

With the purpose of studying, designing, and manufacturing a dental diagnostic device with advantages such as simple setup, safety, and affordable price, in this study, two optical systems with transillumination and scattering techniques using 940 nm LED were designed and built. These systems were used to observe the approximal and occlusal of teeth, and they were able to discriminate between the demineralised and discolored teeth. The result indicates the possibility of applying the NIR technique in the development of a specificity and sensitivity dental screening tool without the use of ionising radiation. This method can support clinicians in detecting the early dental lesions. In the future, the hardware of the optical systems requires further improvement, and a photo processing software will be developed to increase the image quality.

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The authors declare that there is no conflict of interest regarding the publication of this article.

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