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REVIEW

A comparison of near-infrared imaging with other diagnostic tools for dental caries

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ABSTRACT

Dental caries is one of the most common diseases in the world, and global incidence rates are increasing. The early detection of dental lesions enables a conservative approach to be employed and represents a priority in modern dentistry. Recent studies have suggested that conventional diagnostic methods, such as visual tactile inspection and X-ray examination, exhibit low sensitivity and are not very effective in early diagnoses. Consequently, late detection of decay is associated with an increased loss of tooth structure. New diagnostic systems based on optical properties have been developed to facilitate early detection. Several studies have evaluated the performance of near-infrared imaging (NIRI) as an early diagnostic tool. NIRI using light ranging from 700 to 1700 nm has demonstrated better optical properties compared to conventional optical systems using light in the visible spectra. NIRI enables deeper penetration of the light in the tooth tissue, weak scattering with lower background noise and strong photon absorption with detailed images. Several *in-vivo* studies have demonstrated that NIRI technology has the potential to improve performance compared with current diagnostic methods. NIRI exhibits increased sensitivity compared to radiographs and is more suitable to identify approximal enamel lesions. This paper aimed to review these recent advances and their potential applications in daily clinical practice.

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Untreated dental caries is the most common health condition in the world and global incidence rates are increasing.[1] Tooth decay is the predominant chronic disease among persons aged 6-19 years. In recent decades, improved dental hygiene and the widespread use of fluoride have led to important changes in caries features with the identification of more concealed lesions and “hidden” caries, prompting the need for earlier detection.[2]

The power of diagnostic tests is typically considered in terms of sensibility and specificity. Test sensitivity is the ability of the test to identify the disease, whereas test specificity is the ability to identify patients without the disease.

Traditionally, teeth are examined by means of clinical evaluation supported by radiograph examination. With the aid of a probe and a dental mirror, the visual tactile method is the first step in detecting the presence or absence of caries lesion.

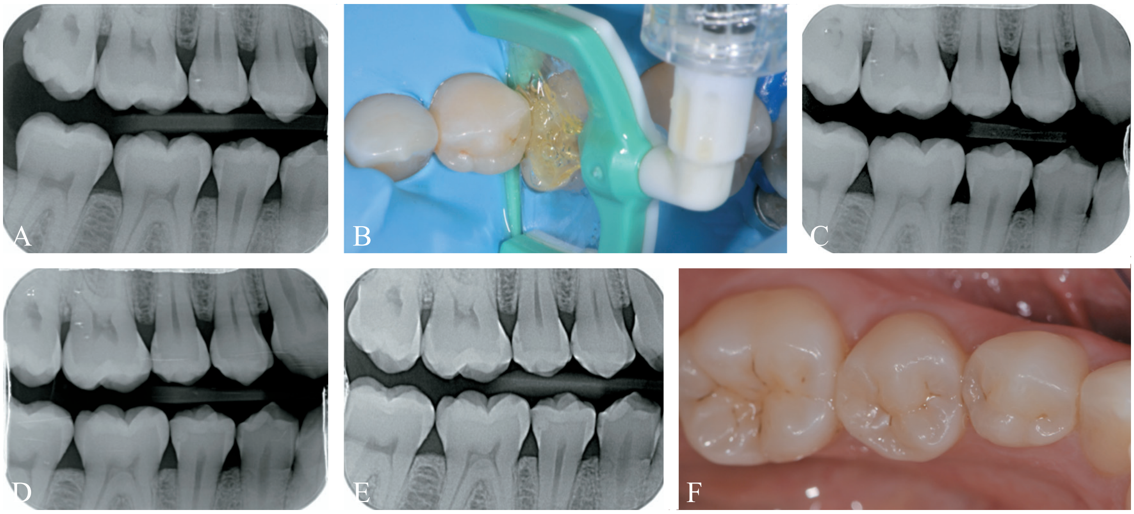

Figure 1.—A) Pre-operative bite-wing radiograph showing initial interproximal carious lesions distally to teeth 34 and 35; B) tooth 34 was treated with a minimally invasive resin infiltration technique; C) postoperative radiograph showing the direct restoration on tooth 35 and the appearance of the lesion after infiltration with an unfilled radiotrasparent resin. D) 1-year; and E) 2-years; F) control radiographs showing the arrest of the lesion on tooth 34 and the 2-years clinical image.

However, this method exhibits minimal sensitivity, especially for early lesions of the proximal tooth surface that are difficult to inspect visually, and it might cause irreversible tooth damage.[3] To help locate and evaluate lesion depth, intraoral radiography is the most common adjunct diagnostic method. The main disadvantages of bidimensional X-ray include patient exposure to radiation and the underestimation of the size and actual depth of the lesion. Specifically, 30-40% of the enamel has to be demineralized before the lesion is viewable by X-ray examination.[4] In fact, intraoral periapical and bitewings images are 2D images of 3D structures. Thus, the exclusive use of conventional diagnostic methods is associated with a high risk to miss lesion detection. In addition, if caries lesions are detected early, noninvasive treatment can be implemented (Figure 1). The main criterion for making operative decisions is lesion progression into the dentin. One of the most used classifications of caries proposed by Anusavice and Benn is based on lesion depth: E1 is a lesion that extends to the outer half of enamel, E2 is a lesion that extends to the inner half of enamel, D1 is a lesion that extends to the outer third of dentin, D2 is a lesion that extends to the middle third of dentin and D3 is a lesion that extends to the inner third of dentin.[5, 6]

Several methods based on optical principles, such as fiber-optic transillumination (FOTI), digital imaging fiber-optic transillumination (DIFOTI) and near-infrared imaging (NIRI), have been developed with the purpose of detecting the initial enamel changes in caries.[7] Caries disease causes increased porosity that induces a modification in the optical properties of the affected dental tissue.[8]

NIRI is an evolution of the DIFOTI method that uses visible light (400-700 nm) and subsequently resulted in the development of the FOTI method. FOTI, which uses wavelengths in the visible range, is based on the principle that transillumination of areas with disrupted enamel crystals in demineralized tooth tissues results in dark shadows due to changes in the light scattering and absorption of light photons.[9] DIFOTI is based on the same optical principle as FOTI. DIFOTI uses visible light (450-700 nm) to transilluminate the tooth along with a charge-coupled device (CCD) camera, and it can capture real-time images from the occlusal or buccal and lingual surfaces. DIFOTI offers several advantages over bitewing radiography, especially with regard to elimination of exposure to ionizing radiations associated with bitewing radiography, real-time images, reduced patient discomfort as no intraoral films or sensors are used and increased sensitivity compared with radiography for early caries detection.[10] However, DIFOTI has the limit of background noise of dental hard tissue produced by light scattering. Zijpand and Bosch demonstrated light scattering is high in the visible range.[11] Therefore, as a result of strong light scattering, wavelengths in the visible range are inefficient in imaging through greater than 1 mm or 2 mm of tooth structures.[12]

This paper aimed to review recent advances of NIRI and their potential application in daily clinical practice and compare it with other diagnostic tools.

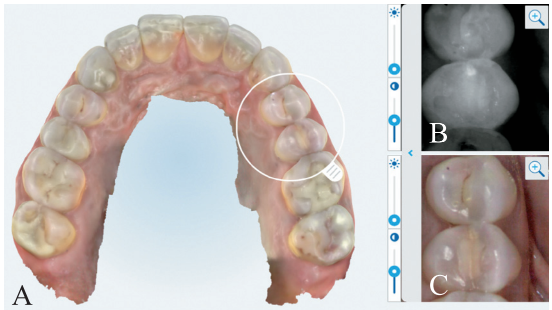

Figure 2.—A) Scan of an upper arch using an intra-oral scanner with NIRI function; B) showing a brighter area mesially to the left second premolar that clearly indicates the presence of an interproximal carious lesion. C) The color image of the same area in B obtained by the same scan.

Optical properties of dental hard tissue in the visible and near-infrared light

Basic knowledge of optical and physic properties of NIR light propagating through sound and carious dental hard tissues is essential for the development of optical diagnostic systems because they are based on changes in the optical properties of demineralized tissues.[12] Optical diagnostic systems are based on observations of the interaction between light and hard tissues of the tooth and observations of energy in the form of a wave in the electromagnetic spectrum emitted from the tooth.[13] Through the illumination and the capture of images of the tooth structures penetrated by nonionizing light ranging from 700 to 1700 nm, NIRI has the potential for improved performance compared with current methods used to detect caries.[14] Physical principles underlying optical caries detection are scattering and absorption. Dental hard-tissue optics is complex given the inhomogeneous and anisotropic nature of these biological components.[15] Anisotropic scattering distributions depend on tissue orientation relative to the irradiating light source in addition to the polarization of the incident light.[11, 16]

Scattering

Scattering is the process in which the direction of a photon is deviated without loss of energy. The interaction with particles or objects in the medium through which the light passes forces the incident light to change its path. Scattering is highly conditioned by the wavelength of the electromagnetic spectra. Shorter wavelengths scatter much more than longer wavelengths; therefore, scattering is a limit of wavelengths in the visible range (400 to 700 nm).[13] Enamel lesions appear whiter than the surrounding healthy tissue as an effect of the increased scattering of light within the lesion.[17] Technologies measuring lesion severity are based on variation in scattering between sound and carious enamel. The progressive dissolution of the mineral crystals during the decay process produces micropores that likely are scattering centers and strongly scatter light. At 1310 nm, the scattering coefficient is increased more than two orders of magnitude in demineralized tissue and is highly forward directed.[18] The predominant cause of scattering is dentinal tubules.[19] The scattering properties of enamel and dentin in the NIR range were first outlined by Fried *et al.* in 1995.[20] NIR light penetrates more transparent enamel and is strongly scattered by lesions in enamel and dentin (Figure 2). The use of longer wavelengths, such as wavelengths in the NIR spectra (780 to 1550 nm), the results in improved optical properties with a deeper penetration of the light in the tissue and a weak scattering. Enamel is highly transparent in the NIR range.[12, 15, 20-22] Therefore, this region of the electromagnetic spectrum is advantageous to the development of new optical diagnostic tools based on transillumination.

Absorption

Absorption is the process in which incident photons are stopped by an object, and the wave energy is absorbed by the object's molecules. For example, water is a strong absorber of infrared light. The energy lost is mainly converted into heat or into another wave at a longer wavelength and less energy through the process of fluorescence. Fluorescence is the result of the interaction of the light illuminating the object and the molecules in this object. The molecules absorb the energy with subsequent electronic transition to the next electronic state, where the electrons remain for a short period of time. From here, the electrons may fall back to the ground state and release the gained energy in the form of fluorescence light of a longer wavelength and color related to the energy given off; thus, fluorescent light can be emitted.[8]

The desirable optical tissue properties for using NIRI technology are weak scattering and strong absorption.[20]

Hydration of the tooth

The state of hydration of the tooth influences lesion contrast.[23, 24] According to the absorption coefficient of water, the NIR wave region can be divided into two categories: minimal water absorption (from 800 to 1350 nm) and greater water absorption (at 1460 nm and wavelengths longer than 1500 nm).

Chung *et al.*[23] performed two studies to determine which NIR wavelengths provide the highest contrast of demineralization of caries lesions. Increasing water absorption appeared to decrease the contrast for transillumination of proximal surfaces. They found that transillumination at 1300 nm provided the highest contrast for interproximal lesions. In contrast, for imaging occlusal lesions, the contrast was improved using a 1400-nm longpass filter compared with both the 1300-nm bandpass and 1300-nm longpass filters. The mechanisms of increased contrast were not understood; however, one possible explanation could be a marked decrease in the scattering of dentin.[23] Water absorption is high between 1400 and 1500 nm and decreases over 1500 nm. Loss of mobile water that is concentrated at the prism boundaries markedly reduced the transparency of the enamel at all NIR wavelengths in occlusal transillumination. Mobile water leaves pores that act as scattering sites. Furthermore, wavelengths with increased water absorption are also likely more powerful for transillumination around composite restorations that have lower water content.[23]

In an *in-vitro* study, Lee *et al*. investigated whether a correlation between the rate of water loss and the degree of demineralization existed and whether that rate could be measured by NIR imaging. Changes in the rate of water loss can be related to changes in lesion structure because the enamel is composed of 96% hydroxyapatite and up to 3% water by weight. Demineralized enamel loses its mineral content, and the pores are occupied by mobile water. However, in remineralized lesions, the highly mineralized surface layer decreases permeability, inhibiting free diffusion of water from the lesion body to the other surface. This study demonstrated that NIR imaging was suitable for the detection of remineralization in simulated caries lesions, and NIR wavelengths longer than 1400 nm are well suited for the assessment of remineralization.[24]

Influence of stains and pigmentation on lesion contrast

In the visible wavelengths, it is not easy to diagnose decays because tooth staining in the pits and fissures can confound diagnosis by masking demineralization. In NIR images, stains are not visible, and demineralized areas are more opaque than the sound enamel.[21] The organic molecules responsible for pigmentation absorb poorly in the NIR, making it easier to identify areas of demineralization and improving specificity with diagnostic tools employing NIR light. Therefore, contrary to visible wavelengths, in the NIR range, stains can be easily differentiated from demineralization.[25] Almaz *et al*. and Ng *et al*. performed a study that suggested that stains interfere significantly with the lesion contrast at wavelengths shorter than 1150 nm; in wavelengths ranging from 1200-1600 nm, imaging is not significantly influenced by the presence of stain in the pits and fissures.[26, 27]

NIRI of fluorosis

In recent years, the increasing use of fluoride has led to a reduction of the prevalence of caries and to a growing prevalence of fluorosis. Fluorosis is the hypomineralization of enamel and is characterized by greater surface and subsurface porosity of enamel.[28] According to Hirasuna *et al*., NIR methods can potentially evaluate the severity and extent of enamel defects since the increased surface porosity of developmental defects causes increased light scattering and increased attenuation in the NIR light. Developmental defects appear differently in NIR images compared with caries lesions due to the location and milder severity of demineralization of developmental defects.[29]

Correlation between lesion severity and NIRI contrast

Hirasuna *et al*. suggested that it is possible to estimate the severity of lesions by analyzing imaging in NIR wavelengths.[29]

When the lesion extends into the dentin, the amount of water increases. The effect is augmented light scattering due to the porous structure of the lesion; these physical effects can be used as a system to estimate the extension of tooth decay. NIRI diagnostic tools can potentially improve and simplify the decision-making process and treatment planning, reducing unnecessary invasive procedures.[30]

Lee *et al*. performed a study to determine whether the lesion contrast acquired in NIRI modes can be used to estimate the severity of occlusal caries lesions. The authors found a correlation between lesion contrast and lesion depth. For example, lesion contrast of D2 lesions is significantly increased compared with D1 lesions.[31] Hence, increasing lesion contrast in NIR images corresponds with increasing lesion depth and severity.[32-34]

NIRI of composite restorations

The dissimilar contrast between sound enamel and composites suggests that NIRI may be used to rapidly screen secondary caries.[35] The reduced water content of the composite *versus* the peripheral sound enamel and dentin allows the composite to be visible with significantly higher contrast at 1460 and 1550 nm. Indeed, the contrast between sound enamel and composite materials increased with wavelength; the contrast is higher at 1550 nm compared with 1460 nm.[36]

Comparing the NIR light transillumination and the radiographic evaluation of proximal carious lesions adjacent to composite restorations, NIRI exhibits sensitivity close to that of radiographic examination and increased specificity. Its overall accuracy is similar to radiographic examination and greater than visual-tactile method accuracy.[37]

In-vivo studies

Some *in-vivo* studies have been conducted in recent years to compare NIRI with other diagnostic tools for diagnosis of occlusal and interproximal dental decays, as listed in Supplementary Digital Material 1: Supplementary Table I.

The *in-vivo* and *in-vitro* comparison of visual inspection, laser fluorescence (DIAGNOdent pen) and the NIR transillumination technique (DIAGNOcam) in detection of occlusal non-cavitated lesions has revealed NIRI to be the most effective method for the diagnosis of occlusal caries without cavitation and the most closely correlated to histological results compared with visual inspection and laser fluorescence.[38]

On interproximal surfaces, NIR light exhibits significantly increased sensitivity compared with radiographic examination, whereas radiographic

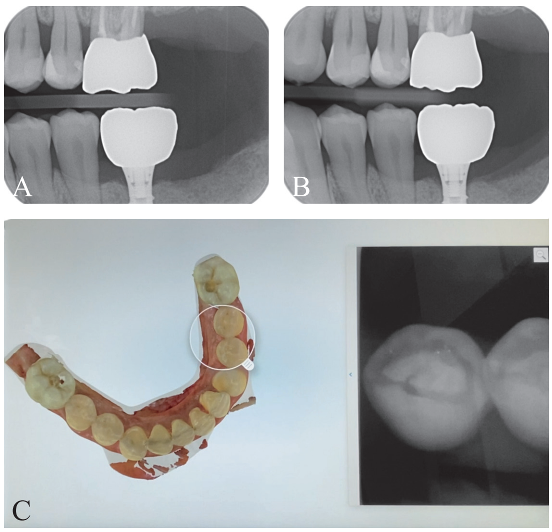

Figure 3.—A) Pre-operative bite-wing radiograph in which no carious lesions could be detected. B) 1-year control radiograph after resin infiltration treatment to arrest caries showing no progression of the lesion. C) NIRI image of the lower teeth of the radiograph obtained from a scan using an intra-oral scanner with the NIRI function, showing an initial enamel carious lesion on the mesial surface of the left second lower premolar that could not be detected radiographically.

examination exhibits increased specificity. The higher sensitivity of NIR light renders it a more accurate method as an aid to conventional tools without the hazards of ionizing radiation, especially for early decay that is not visible in radiographic examination (Figure 3).[39]

In detection of approximal dentinal caries, NIRI exhibited sensitivity similar to that of radiographic examination but increased correlation with the gold standard (opening of the approximal surface using a diamond-bar).[40] Simon *et al*. demonstrated that NIRI is significantly more sensitive than digital radiographic examination for the detection of lesions on both occlusal and proximal surfaces but with lower specificity.[35]

Several studies have stressed the different diagnostic power for dentin and enamel lesions. A similar agreement between NIRI and bitewings has been reported for dentin lesion, whereas transillumination was more suitable than bitewings to identify approximal lesions in enamel.[41, 42] An *in-vivo* study performed by Russotto *et al*. revealed that radiographic examination is better than near infrared transillumination (NIRT) in terms of sensitivity for interproximal caries, and NIRT is significantly better than radiographic examination in terms of specificity. However, NIRT exhibited sensitivity similar to radiographic examination when only enamel caries were evaluated, and the method likely reduces false positive diagnoses of enamel carious lesions registered using radiographic examination.[43]

Other studies have found no differences between NIRI and other diagnostic systems in detection of interproximal dental caries, but NIRI demonstrated the advantage of not requiring ionizing radiation.[44, 45]

A study by Błażejewska *et al*. comparing NIRI (DIAGNOcam™, KaVo Dental GmbH; Biberach an der Riß, Germany) and bitewing radiovisiography revealed better sensitivity and specificity for the radiovisiography but without statistically significant differences. However, NIR light can motivate the patient's interest in oral health and

TABLE I.—*Summary of* in-vitro *studies comparing different diagnostic methods.*

Author	Reference	Sample size	Diagnostic methods compared	Sensitivity/ Specificity	Outcomes	Validation criteria	Wavelenght
Marinova-Takorova *et al*.[49]	J of IMAB 2014	60 teeth	Near-IR imaging, laser fluorescence, visual-tactile method, dye staining method and radiographic examination	/	Near-IR imaging was the diagnostic system better correlated with the visual-tactile method	/	780 nm
Litzenburger *et al*.[50]	Dentomaxillofac Radiol 2018	100 pairs of images	Near-IR imaging and bitewing radiography	/	Near-IR imaging was more reliable than bitewing radiography	Reference diagnosis of two experienced dentists	/
Elhennawy *et al*.[37]	J Dent 2018	200 teeth	Near-IR imaging, visual-tactile method and radiographic evaluation	0.63/0.95 for any lesions, 0.69/0.94 for cavitated lesions	Near-IR seemed useful for detecting approximal caries lesions adjacent to restorations	Transverse microradiography and visual assessment	780 nm
Maia *et al*.[51]	Dentomaxillofacial Radiol 2011	14 teeth	Near-IR imaging and bitewing radiographs	0.88/0.72	Near-IR imaging showed reliability and better diagnostic power than radiographs for enamel caries	Stereomicroscope images	1.28 µm

can be used in cases with precautions for radiological examination.[46]

The NIR system has also the potential to identify fractures and cracks without the use of ionizing radiation, and the excellent detail of images compared with conventional radiographs potentially provide increased diagnostic power.[47] NIR transillumination at 1300 nm has the potential to detect cracks and fractures due to the high transparency of enamel. The interference of cracks and fractures with light propagation aids in crack identification and in gauging of their depth and severity.[48]

In-vitro studies

In-vitro studies comparing the effectiveness of NIRI, laser fluorescence, visual-tactile method, dye staining method and radiographic examination have demonstrated that NIRI exhibits the highest diagnostic power (Table I).[37, 49-51]

For occlusal dental caries, the dye staining method has been the least sensitive method, followed by the radiographic examination. The results obtained by NIRI and laser fluorescence have been similar, but NIRI has been better correlated with the visual-tactile method.[49] NIRT has been significantly more reliable than bitewing radiography likely because interproximal enamel decays exhibit unambiguous characteristics in NIR images.[50] NIRI demonstrated better sensitivity and specificity compared to radiographs of interproximal surfaces.[51, 52] In contrast, in a study by Elhennawy *et al*., NIRI exhibited sensitivity similar to that of radiographic examination and increased specificity in detecting proximal carious lesions adjacent to composite restorations. Its overall accuracy is similar to radiographic examination and increased compared with visual-tactile method accuracy.[37]

Limitations of the study

In-vitro studies have also demonstrated some limits of NIRI technology. The lesion extent is determined with difficulty when assessing lesions adjacent to restorations, especially those that extend into dentin. Thus, the method is limited in assessing the proximity of lesions to the pulp[52] and is not able to gauge the pulp outline.[45]

Conclusions

Research on optical diagnostic systems has advanced rapidly over the past several years. Early diagnosis is essential for a conservative therapeutic approach, which is a priority in modern dentistry. Dental radiography presents some limits, such as exposure to radiation and inability to diagnose of dental decay early. NIRI has no side effects, does not require any ionizing radiation and demonstrates an estimated increased sensitivity. Furthermore, NIRI could be used in everyday clinical practice to monitor early enamel decay, allowing noninvasive therapy.

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