Abstract: A shift in caries prevalence from occlusal surfaces to approximal surfaces has been demonstrated by epidemiological studies. Two recent meta-analyses evaluated the performance of visual examination and radiography for carious lesion detection, and reported low sensitivity but high specificity for early approximal caries detection. This suggests that the conventional methods have a higher risk of failing to detect approximal lesions. Consequently, in caries susceptible populations, there is a risk of progression of non-cavitated lesions to irreversible tooth destruction before the lesions are detected. This paper aims to review the performance of unconventional and novel methods for approximal caries detection. In vitro and in vivo studies identified through a MEDLINE search using keywords such as caries detection, approximal caries detection, light fluorescence and dental caries, and transillumination and dental caries were reviewed. The unconventional methods known to be used for approximal caries detection and included in this review are: cone beam computed tomography, fiber-optic trans-illumination, digital imaging fiber optic trans-illumination, near-infrared digital imaging transillumination, optical coherence tomography, laser fluorescence, ultrasound, and LED reflection and refraction.

Keywords: approximal caries detection; cone beam computed tomography; transillumination; laser fluorescence; optical coherence tomography; frequency-domain infrared photothermal radiometry; modulated luminescence.

Introduction

The occlusal, approximal, and smooth surfaces at the gingival margins of teeth are very susceptible to dental caries, which usually develop in areas of stagnation where plaque can accumulate undisturbed (1). Current evidence from epidemiological studies focusing on children, young adults, and adults have shown a shift in caries prevalence from occlusal surfaces at younger ages to approximal surfaces with advancing age (2-7). Unlike the occlusal and free smooth surfaces, the approximal surfaces cannot be visualized directly due to the presence of neighboring teeth. Therefore, clinicians commonly rely on signs of demineralization in bitewing radiographs as an adjunct to visual examination for early detection and monitoring of approximal caries over time.

Meta-analyses (8,9) have demonstrated that visual and radiographic examination for detection of early approximal caries have considerably high specificity (Sp) but low sensitivity (Sn). Dental practitioners traditionally use a combination of the two methods. Several studies reported increased Sn for detection of approximal caries when bitewing radiographs were used in conjunction with visual-tactile examination (10-12). However, approximal
carious lesions were detected much earlier when tooth separation was performed compared to visual-tactile or bitewing radiographic examination without tooth separation (11-13). Unfortunately, tooth separation may not always result in improved accessibility for direct examination of the approximal lesion, and may also create patient discomfort. Moreover, it also requires an additional visit from the patient (11-13). Therefore, tooth separation is not popular as a routine method for approximal caries detection, making an adjunctive method necessary.

This review paper aims to provide an overview of the current methodologies used for the detection of caries on approximal surfaces. However, this paper is not a systematic review of the literature. We performed a MEDLINE search with key words such as caries detection, approximal caries detection, light fluorescence and dental caries, and transillumination and dental caries. We included in vivo and in vitro studies published in English, and clearly reported the Sn and Sp values along with a reference “gold” standard of the tested method.

Cone beam computed tomography (CBCT)

CBCT is a modification of medical computed tomography (medical CT) that uses a cone beam of X-rays instead of the conventional fan beam. It generates three-dimensional (3D) images at lesser radiation doses and lower cost than the conventional medical CT. The subsequent 3D image can be sectioned using imaging software and viewed in frontal, sagittal, and axial planes. CBCT has been used for several dental diagnostic purposes such as dental implant treatment, craniofacial anomalies, endodontics, orthodontics, and periodontics (14-19). Several studies have reported the use of CBCT for enamel and dentin caries detection (20-33). The majority of these studies was in vitro and compared the performance of CBCT to conventional or digital intraoral radiography, histology, or micro computed tomography (micro CT) as the gold standard. They reported that CBCT did not improve the accuracy of caries detection when compared with conventional or digital intraoral radiography (20-22,24,26,34).

Regarding cavitated approximal caries detection, CBCT demonstrated a significantly higher Sn than intraoral conventional and digital radiography in an in vivo study (35) which used direct visual examination of the approximal surface after tooth separation as a reference standard. However, none of the included teeth had metallic restorations; thus, they were less likely to exhibit beam hardening artifact, which has a profound effect on the quality of CBCT images. In addition to beam hardening artifacts, the higher cost and radiation dose of the CBCT compared to intraoral radiography limits its use as a primary radiographic modality for dental caries detection (36).

**Fiber-optic trans-illumination (FOTI) and digital imaging fiber optic transillumination (DIFOTI)**

FOTI is a simple technique that uses a narrow beam white light to transilluminate the tooth. Friedman and Marcus (37) suggested this technique for caries detection. The principle of FOTI is 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 (37).

The Sn of FOTI has been shown to vary between 0.50 and 0.85 (38,39), with higher Sn values for dentin lesions than for enamel lesions (40-42). Peers et al. (43) carried out an in vitro comparison of the performance of radiography and FOTI using histologic examination as the gold standard. They found no significant differences in the Sn values of radiography (0.59) and FOTI (0.67) with regard to approximal caries detection. FOTI is widely accepted by clinicians as a valid method for detection of approximal caries in anterior teeth as well as dentin-involved caries in posterior teeth (44).

DIFOTI is based on the same principle as FOTI, and uses visible light (wavelength range between 450 and 700 nm) to transilluminate the tooth along with a charge coupled device (CCD) camera. DIFOTI can capture real time images from the occlusal or buccal and lingual surfaces.

Schneiderman et al. (45) compared DIFOTI with radiography in an in vitro study, with histologic examination as a gold standard. DIFOTI showed a higher Sn (0.56) and lower Sp (0.76) than radiography, which showed Sn and Sp values of 0.21 and 0.91, respectively. Moreover, another in vivo study showed that DIFOTI exhibited higher Sn than visual examination after cavity preparation (used as a reference standard) for detection of cavitated approximal lesions (46). DIFOTI also exhibited a correlation between the degree of darkened shadow and the lesion depth in occlusal and smooth surface lesions in vivo (Ando M. Performance of digital imaging fiber-optic transillumination (DIFOTI) for detection of non-cavitated primary caries. Preliminary report, Therapeutic Technologies, 2006). Hence, the gray scale value may be used to objectively assess carious lesions.

DIFOTI offers several advantages over bitewing radiography, including elimination of radiation hazard associated with bitewing radiography, images viewed...
in real time, reduced patient discomfort as no intra-oral films or sensors are used, and higher Sn than radiography for early caries detection (43,45,47). However, the disadvantages of DIFOTI are as follows: it has not been proven that DIFOTI can objectively quantify lesion size, depth, volume, and mineral content; DIFOTI cannot differentiate between carious lesions and developmental defects such as fluorosis; it does not determine caries activity; and the higher Sn value might lead to higher false positive values, which might lead to overtreatment.

Near-infrared digital imaging transillumination (NIDIT)

Another detection method that used the same principle of transillumination as FOTI and DIFOTI was introduced in Europe in 2012 (DIAGNOcam, KaVo, Biberach, Germany) and in USA in 2013 (CariVu, DEXIS, LLC, Hatfield, PA, USA) (48). Instead of using visible light, as in DIFOTI, this device uses a near infrared (wave length: -780 nm) light to transilluminate the tooth. The system consists of a CCD sensor to capture the images, connection to a computer, special software, and elastic arms containing a near infrared light source that transmits light through the gingiva, alveolar bone, root of the tooth, and up to the crown. The image displays from the occlusal surface (48).

Staninec et al. (49) carried out an in vivo evaluation of the performance of a prototype device that uses NIR light at a wavelength of 1,310 nm from the buccal, lingual, and occlusal views for detection of approximal caries. Thirty-three lesions were included, based on bitewing and occlusal views for detection of approximal caries. The NIDIT prototype device detected 32 lesions when all views (occlusal, buccal, and lingual) were used to evaluate the approximal sites.

Another in vivo study evaluated the efficacy of visual examination, radiography, laser fluorescence (LF) pen (DIAGN0dent Pen, KaVo; See below “Laser Fluorescence” section) and NIDIT (DIAGNOcam, KaVo) in the detection of dentinal approximal carious lesions. Visual and radiographic examinations after caries excavation was considered as the reference standard. Visual examination performed poorly (Sn value: 0.16) compared to the other methods (Sn value: 0.66 for LF pen, 0.99 for NIDIT when the lesion was extended to the dentin-enamel junction, and 0.96 for radiography) (50). However, there were no studies that evaluated the efficacy of NIDIT imaging for measurement of the true lesion depth, validity, and reliability. Hence, there is a need for validation of NIDIT imaging for the detection of early non-cavitated carious lesions. An in vitro model that simulates the clinical situation by allowing the light to transmit through a certain material thickness as well as through the roots and up to the crown of the tooth should be established (50).

Optical coherence tomography (OCT)

OCT is a novel non-invasive, non-irradiative imaging technique that uses infrared light to produce a real time cross-sectional image of a tissue. It constructs images from the back-scattered light of a transilluminated tissue, based on the differences in the optical absorption and scattering properties of the tissue (51,52). OCT has been used in several clinical applications including dermatology (53,54), gastroenterology (55), ophthalmology (56), and dentistry (57,58). OCT in dentistry can be used for early caries detection (58), tooth crack diagnosis (59), and assessment of marginal integrity of existing restorations (60,61).

Swept-source optical coherence tomography (SS-OCT) is an improved modification of traditional OCT systems. One in vivo study compared the performance of SS-OCT and bitewing radiography for approximal caries detection (58). The reference standard was based on information collected from direct visual examination before caries excavation, visual examination after caries excavation, radiography, and SS-OCT. Of these, SS-OCT demonstrated significantly higher Sn and Sp values than radiography for enamel and outer one-third dentin caries detection (58). However, for deep dentinal caries, SS-OCT produced significantly lower Sn than radiography, while the Sp was the same. This is due to significantly greater SS-OCT beam attenuation and scattering in dentin than in enamel (57). Also, in this study, the pulp chambers did not appear clearly in the OCT images, preventing determination of the lesion depth in relation to the pulp. This is an important clinical shortcoming, especially in case of symptomatic teeth.

Laser fluorescence (LF)

LF caries detection (DIAGN0dent pen, KaVo) is based on the principle that when a red light (wavelength -655 nm) is applied to a tooth, the caries-related changes in the tooth tissues lead to an increase in fluorescence (62). It was suggested that these changes in fluorescence are due to protoporphyrin, a photosensitive pigment present in carious tissues as a result of bacterial metabolic activities (63). Clean and healthy teeth produce little or no fluorescence, while carious teeth produce fluorescence proportional to the degree of caries (62). LF provides values from a point of application that can be used to estimate the depth of the carious lesion. These values range from 0 to 99. For example, scores from 0 to 10...
might be interpreted as healthy, while scores above 30 might indicate a lesion that requires restorative treatment (62,64). A laser fluorescence pen (LF pen) (DIAGNOdent Pen, KaVo) with a smaller tip design was introduced to allow detection of approximal carious lesions. Lussi and Hellwig (65) reported that its performance was similar to the traditional LF on occlusal surfaces. Ribeiro et al. (66) compared the performance of visual examination, bitewing radiography, and LF pen for detection of approximal caries on primary teeth in vivo, and micro CT after tooth exfoliation served as the gold standard (66). Before tooth separation, the LF pen demonstrated higher Sn and lower Sp than visual and bitewing radiographic examinations for detection of enamel caries. For dentinal lesions, the Sn of LF pen was higher than visual examination but lower than bitewing radiography and the Sp was significantly lower than both visual examination and bitewing radiography. Tooth separation significantly improved the Sn and Sp values of visual and LF pen examinations for detection of both enamel and dentinal carious lesions. For enamel caries, visual examination exhibited higher Sn, while LF pen presented significantly higher Sn for dentinal caries detection. After tooth exfoliation, in vitro LF pen examination was performed and improved Sn and Sp for both enamel and dentinal lesions was observed. This could be because the laser light could now directly access the tooth surface (66). A systematic review of LF (67) concluded that it exhibited higher Sn than other traditional diagnostic methods. However, it also has a higher tendency to produce false-positive diagnoses, which suggests that it should be used with caution and not as a primary diagnostic method (67).

**Ultrasound**

The use of diagnostic ultrasound in dentistry was first reported more than 50 years ago (68). Ultrasound uses sound waves with frequencies higher than that which humans can hear (69). This frequency limit is approximately 20 kHz. Ultrasound imaging offers several advantages including simplicity, low-cost, no harmful side effects, and provision of real time images (70). For caries detection, ultrasound is based on the substantial differences in sonic conductivity between sound and demineralized enamel (70). An in vitro study evaluated an ultrasonic caries detection device and radiography for cavitated approximal caries detection, with histology as the gold standard (71). Both the Sn and Sp of the ultrasonic caries detection device were 1.00, while the Sn for radiography was 0.90 and the Sp was 0.92 (71). In vivo, the same ultrasonic device system produced a mean Sn (measured by three examiners) of 0.82 and Sp of 0.75 for cavitated approximal caries detection. In this study, visual examination after cavity preparation was used as the reference standard (72). For radiography, the mean Sn and Sp were 0.49 and 0.90, respectively. The authors suggested that the specificity of the device can be improved by enhancing the ultrasound signal processing algorithm to reduce false positive diagnoses (72). Although, the ultrasonic caries detection device showed promising results, there are no other studies that focus on the efficacy of this system.

**LED fluorescence**

This method detects differences in the reflection and refraction of infrared energy from red light-emitting diode (LED) that is carried by a fiber optic cable to a tooth. The presence of a carious lesion will lead to changes in these properties. Another fiber optic cable serves as a photodetector that transmits the captured light to a microprocessor, which compares the signals to defined parameters (73). A caries detection method based on this principle was introduced as Midwest Caries I.D. (Dentsply, York, PA, USA).

One in vitro study (73) evaluated the performance of LED fluorescence, LF pen, radiography, and visual examination for approximal enamel and dentin caries detection. Visual examination and radiography performed better in terms of Sn and Sp for both enamel and dentin lesions. The authors concluded that LED fluorescence was not adequate for approximal caries detection, perhaps due to loss of signal during signal transduction through the occlusal part of the lesion (73).

**Frequency-domain infrared photothermal radiometry and modulated luminescence (PTR/LUM)**

The Canary System (Quantum Dental Technologies, Toronto, Canada) is based on photothermal radiometry and modulated luminescence technology (PTR/LUM). The manufacturer claims that this system can detect caries from 50 μm to 5 mm depth, including those under sealants and around the margins of restorations; is not affected by stains or calculus; and does not require a dry field.

PTR is based upon the modulated thermal infrared response (black body or Plank radiation) of a medium that results from repeated irradiation of a specimen. Black body radiation is a type of electromagnetic radiation surrounding or within a body in thermodynamic equilibrium with its environment or emitted by a black body when the temperature is uniform and constant. The radiation has a specific constant and intensity dependent
only on the temperature of the body (74-76). A change in the temperature of the sample surface will occur as a result of the conversion of the absorbed radiation energy to thermal energy. The change in the thermal emissions caused by the modulated temperature can be measured using an infrared detector that constitutes the PTR signal (75,76).

LUM is based on the conversion of optical energy to radiation energy. When a molecule absorbs optical energy from a laser source, it results in excitation of its chromophores to a higher energy state, followed by de-excitation to a lower energy state and emission of longer wavelength energy. This emitted longer wavelength can be detected by a photodetector, which constitutes the LUM signal (75,76).

The PTR/LUM caries detection method has demonstrated higher Sn and Sp than visual examination, radiography, and LF for early occlusal caries detection (77). For early approximal caries detection, PTR has shown an increase in the amplitude by more than 300% after 80 h of artificial demineralization. However, LUM was found to have a lower ability than PTR to detect early approximal lesions (77,78). An in vitro study evaluated the performance of PTR/LUM, visual examination, and radiography, with polarized light microscopy as a gold standard for approximal caries detection. The Sn of PTR/LUM was higher than both visual examination and radiography. There was no significant difference in Sp between PTR/LUM and radiography, but the Sp of visual examination was significantly lower (78). The PTR/LUM method is still new and further studies are needed to evaluate its performance.

Approximal caries detection remains a challenging task for clinicians. Here we reviewed several methods that can be used for approximal caries detection. In order for it to be relevant in clinical practice, the alternative method should perform the same or better than conventional examinations, particularly intraoral radiography, in terms of validity and reliability. CBCT demonstrated higher Sn than intraoral radiography for cavitated approximal caries detection. However, it did not improve the accuracy of non-cavitated caries detection. Although FOTI, DIFOTI, and NIDIT demonstrated equivalent or higher Sn than conventional methods, they cannot objectively quantify carious lesions, cannot differentiate between caries and developmental defects, and cannot assess carious lesion activity. SS-OCT demonstrated significantly higher Sn and Sp for enamel and outer one-third dentin caries detection. However, for deep dentinal caries, the Sn was significantly lower. The LF pen presented higher Sn but lower Sp than conventional methods. LED fluorescence has been shown to be unsuitable for approximal caries detection, while NIDIT, ultrasonic, and PTR/LUM exhibited promising results. However, further validation of these methods is required.

Methods presenting higher Sn may increase false positive diagnosis, which may lead to unnecessary overtreatment. Therefore, it is important to note that these alternative methods should not be used alone, but as adjunct methods to support conventional ones.

Conflict of interest
The authors have no conflict of interest to declare.

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