A REVIEW OF EMERGING TECHNOLOGIES FOR DETECTON AND DIAGNOSIS OF DENTAL CARIES

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ABSTRACT

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Objectives: to address emerging technologies presently available to aid in the detection and diagnosis of dental caries and to compare their efficacy and accuracy to visual, tactile, and radiographic examination. **Methods**: The technologies reviewed include fiber-optic transillumination (FOTI), digital imaging fiber-optic transillumination (DIFOTI), near-infrared light transillumination (NILT), quantitative light-induced fluorescence (QLF), laser fluorescence, light emitting diode (LED), alternating current impedance spectroscopy, frequency-domain infrared photo-thermal radiometry and modulated luminescence (PTR/LUM), and cone beam computed tomography (CBCT). References were manually searched using PubMed, Google Scholar, and manufacturer's websites. **Results:** The devices vary greatly in their modes of action as well as their sensitivities and specificities compared to visual and radiographic examination for caries detection. There is also variability among the devices in their capacity to quantitatively measure caries progression and limitations of some devices to measure only specific areas of the teeth. Overall, many of these devices when combined with visual examination can detect caries at the earliest stage allowing the option for preventive care rather than restorative treatment. **Conclusions:** No single device or method alone is sufficient to adequately diagnose carious lesions in all sites. A combination of diagnostic methods and devices greatly increases the ability to detect caries in its earliest stage.

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LIST OF ABBREVIATIONS

1. ICDAS — International Caries Detection and Assessment System
2. FOTI — Fiber-Optic Transillumination
3. DIFOTI — Digital Imaging Fiber-Optic Transillumination
4. NILT — Near-Infrared Light Transillumination
5. QLF — Quantitative Light Induced Fluorescence
6. LED — Light Emitting Diode
7. PTR/LUM — Photothermal Radiometry and Luminescence
8. CBCT — Cone Beam Computed Tomography

CHAPTER I: INTRODUCTION

Definition of dental caries

Dental caries has been described extensively throughout the scientific literature. Robertson (1835) was one of the first to mention caries as a destructive process caused by acid (Black, 1914). Published work by Dr. Magitot of Paris in 1878 clearly demonstrated that caries of the teeth was purely the result of a chemical substance produced in the mouth (Black, 1914). Miles and Underwood of London in 1881 had shown that dentin tubules in caries contained microorganisms. Further study of these microorganisms led to a better understanding of their ability to ferment certain carbohydrates and produce lactic acid, which in time causes the calcium salts in tooth tissue to dissolve (Black, 1914). To date, one of the most straightforward definitions of dental caries, also referred to as tooth decay, is a localized breakdown of dental hard tissues as a result of acid by-products produced from the metabolism of fermentable carbohydrates by bacteria in the plaque biofilm (Selwitz et al, 2007). The disease state of dental caries is a progression or continuum of disease states with increasing severity ranging from sub-clinical, sub-surface changes at a molecular level to deeper lesions involving the dentin that can either have an intact surface or apparent cavitation (Featherstone, 2004).

According to Featherstone (2008), it has long been known that dental decay occurs from bacteria in plaque fermenting foods, producing acid byproducts which dissolve minerals in teeth. He further asserts that this process has been better defined more recently in terms of microbiology, saliva content, tooth mineral composition and ultrastructure, diffusion processes, kinetics of demineralization, the process of remineralization, and factors that contribute to potential reversal of caries.

The bacteria essential to the disease process are identified as being cariogenic and fall into two major groups: mutans streptococci and lactobacilli species, which are contained in dental plaque, can metabolize fermentable carbohydrates and produce organic acid. These bacteria have an aciduric physiology allowing them to thrive with frequent exposure of plaque to low pH, while acid-sensitive species are inhibited (Marsh, 1994). Lactic, acetic, formic, and propionic acids are among those produced by these bacteria which have all been shown to readily dissolve the mineral component of enamel and dentin (Featherstone and Rodgers, 1981). As these acids originate on the surface of the tooth, they quickly diffuse in all directions through the enamel and dentin pores into underlying tissues while dissolving soluble minerals. Given enough time, which may be months to years, the result of this process is cavitation, the end point of the dental caries disease process (Featherstone, 1983).

Prevalence and impact of dental caries

Dental caries persists as one of the most prevalent chronic diseases worldwide. Over one third of the entire global population is affected with untreated caries in permanent teeth (Marcenes, et al, 2013). Bernabé and Sheiham in 2014 conducted a study examining age, period, and cohort trends of caries in permanent teeth in four developed countries. Looking at data from England and Wales, United States, Japan, and Sweden, they demonstrated that caries rates in children have dramatically declined over the past 30 years, however caries levels have been shown to increase into adolescence and furthermore into adulthood. A pattern of large increases in caries with age yet only a relatively small decline over time and generations was observed.

In response to the need to facilitate epidemiologic research of dental caries in young children, the term early childhood caries was proposed by the Centers for Disease Control and Prevention in 1994 to describe the progressive pattern of dental caries in preschool aged children (Kaste and Gift, 1995). While this term is widely used, there is great variability and inconsistency across studies in terms of diagnostic criteria and case definitions used to identify dental caries, thus limiting the ability to fully understand the epidemiology of dental caries in preschool children (Dye, et al, 2015). Nonetheless, the epidemic of early childhood caries has far reaching consequences which include affecting children's development, behavior, and performance. There are also morbidity and mortality considerations associated with dental caries and dental intervention to consider. Furthermore, early childhood caries has a significant impact on the economic burden placed on families, communities, and the health care system (Casamassimo et al, 2009).

While children are unquestionably affected, it has also been shown that there has been a global increase in dental caries in adult populations as well. This increase in dental caries has been deemed a serious dental public health crisis and calls for a focused effort combating the disease (Bagramian et al, 2009).

The diagnostic process

Early detection of caries is essential in present-day caries management. Diagnostic protocols should be developed to avoid the need for invasive restorative treatment through early intervention (Chu et al, 2013). There currently exists a multitude of different diagnostic tools to help detect dental caries, such as visual and tactile inspection, and radiographic examination. For any test to be scientifically acceptable, it must be validated against the true diagnosis or the "gold standard". Three requirements must be met by any reliable gold standard. It should be established by a method that is precise and reproducible, it should reflect the pathoanatomical appearance of the disease, and it should be established independently of the diagnostic method being evaluated (Wulff, 1981). It is possible to apply these three requirements to a valid gold standard for caries diagnosis. Caries can be accurately assessed from histologically prepared ground sections of teeth viewed using stereomicroscopy. This method has been shown to be highly accurate and reproducible (Hintze et al, 1995). Microscopy on ground sections of teeth should therefore be considered to be the gold standard in evaluating the accuracy of any test or study evaluating the diagnosis of dental caries (Wenzel and Hintze, 1999).

When evaluating diagnostic tests for dental caries, it is important to consider the sensitivity and specificity of the test as well as the predictive values. Sensitivity is defined as the proportion of true positives that are correctly identified by the test while specificity is defined as the proportion of true negatives that are correctly identified by the test. Positive predictive value is the proportion of subjects with positive test results who are correctly diagnosed, and negative predictive value is the proportion of subjects with negative test results who are correctly diagnosed (Altman and Bland, 1994a; 1994b). In terms of caries detection and diagnosis, tests with high sensitivity will correctly identify caries when present. Likewise tests with high specificity will correctly identify the absence of caries.

CHAPTER II: CONVENTIONAL METHODS OF CARIES DIAGNOSIS

Tactile and Visual

The diagnosis of dental caries has long been primarily a visual process based on clinical inspection. Further tactile information can be obtained with the use of a dental explorer, or probe. Together these rely on dentist's subjective interpretation of visual cues (Bader et al, 2001). Visual-tactile inspection limits the examiner to assess only those surfaces of teeth that are clinically accessible (Ritter et al, 2013). It has been shown that there is a lack of consistency in the performance of visual and tactile inspections in detecting carious lesions with contradictory results reported. These inconsistencies arise from a wide variety of criteria used for visual inspection as well as varying conditions under which the examinations are conducted (Ismail, 2004).

In order to overcome these limitations, a move was prompted to develop validated caries detection systems. One such system is the International Caries Detection and Assessment System (ICDAS) which employs a visual scoring system for caries detection (Ismail et al, 2007). With the utilization of these detailed and validated methods for visual caries inspection, this method has been shown in recent studies to have good accuracy in the detection of carious lesions with a trend for higher specificity than sensitivity (Gimenez et al, 2015). With regard to existing methods of caries detection and assessment, An International Consensus Workshop on Caries Clinical Trials concluded that visual inspection is the standard of caries diagnosis with an emphasis on further exploration of additional supplemental methods of caries lesion assessment (Pitts and Stamm, 2004).

Radiographic (conventional and digital)

While visual examination demonstrates a high specificity for detecting caries on visible surfaces of teeth, the detection of proximal carious lesions has been shown to be only around 0.30 meaning that about 70% of cavitated caries lesions would be undetected (Peers et al, 1993). Radiographic caries detection used alone or in conjunction with clinical assessment is the most widely used diagnostic tool used by dentists besides visual-tactile screening (Rindal et al, 2010). Adding bitewing radiography as an adjunct to visual examination generally allows for a more sensitive detection of proximal and occlusal caries lesions, provides a better estimation of lesion depth than visual inspection alone, and allows for observing lesion progress over time (Wenzel, 2004). Meta-analysis study has shown that radiographic caries detection is best suited for detecting proximal lesions that are cavitated and lesions extending into dentin, whereas it is less sensitive but highly specific for detection of initial caries lesions (Schwendicke et al, 2015).

CHAPTER III: EMERGING TECHNOLOGIES FOR DETECTION OF EARLY CARIES LESIONS

There are several new technologies that have been developed in the recent years giving rise to numerous innovative devices enabling early detection of caries. These devices are made to facilitate the clinician in making a firm diagnosis and allow for early and conservative treatment. The technologies utilized in these devices include fluorescence, reflectance, and electrical conductance or impedance which can measure demineralization of enamel and allow monitoring of lesion changes over time.

Fiber-optic transillumination (FOTI)

Caries detection by means of fiber-optic transillumination (FOTI) utilizes a high-intensity light source that can be used anywhere in the oral cavity with ease and flexibility. It works on the principle that carious tooth structure has a different index of light transmission compared to sound tooth structure. Since demineralized areas of enamel and dentin exhibit a lower index of light transmission, those areas will appear as a darkened shadow that follows the spread of decay. For proximal caries detection on posterior teeth, the light probe is placed apically past the cervical margin along the gingiva. Light is transmitted through the tooth structures and decay can be seen from the occlusal aspect as a shadow. This shadow in most cases shows an accurate representation of the extent of the undermined carious tooth structure. Additionally, the light source can be positioned at different angles to the tooth allowing a three-dimensional view of caries penetration (Friedman and Marcus, 1970). To visualize caries in both maxillary and mandibular anterior teeth, the probe is placed on the labio-cervical region of the tooth and examined from the lingual surface with a mirror. Recent developments to FOTI involve a thin, flexible fiber-optic tip that can fit into the gingival embrasure below the proximal contact under the marginal ridge. This 0.75 mm diameter tip shows caries with increased delineation over conventional fiber-optic tips (Strassler and Pitel, 2014).

Research on the effectiveness of FOTI as a diagnostic aid has shown conflicting results. A study in 2000 concluded that the diagnostic performance of fiber-optic transillumination is inferior to bitewing radiography (Vaarkamp et al, 2000). For small occlusal caries, FOTI was shown to have a high positive predictive value but low sensitivity, though results were as good as or better than radiography (Verdonschot et al 1992). Another study in 1992 showed FOTI to give significantly better results over visual and radiographic approximal caries detection for both shallow and deep lesions (Wenzel et al, 1992). Yet another study showed that while FOTI by itself detected the least number of carious lesions compared to visual and radiographic examination, some lesions were detected exclusively by just one or two of those methods. Therefore when FOTI was combined with visual examination, there was an additional diagnostic yield of 50% in relation to visual examination only. Based on this and previous studies it can be concluded that FOTI in combination with visual and radiographic examination can help improve the detection of carious lesions (Mailhe et al, 2009).

Digital imaging fiber-optic transillumination (DIFOTI)

Digital imaging fiber-optic transillumination (DIFOTI) was developed to overcome a noted intra- and interobserver variation of FTOI diagnosis by eye. With DIFOTI the images are instantaneously captured and recorded by a CCD imaging camera. The acquired images are digitally processed and able to be viewed on a monitor for the detection of lesions (Schneiderman et al, 1997). It was thought that DIFOTI might be able to improve early detection of carious surfaces. One in vitro study in 2005 demonstrated the ability of DIFOTI to detect lesions with a high degree of sensitivity during early stages of demineralization, however it was not able to measure the depth of the lesion compared to histologic analysis and surface cavitation whereas radiographic film could measure the depth of the lesion (Young and Featherstone, 2005). A later in situ study in 2008 was able to show DIFOTI correlated significantly with the clinical depth of caries, but to a lesser extent than digital and D-speed radiographs. Furthermore, the correlation was better for smaller lesions (Bin-Shuwaish et al, 2008). A more recent 2012 in vitro study further validated the diagnostic accuracy and efficacy of DIFOTI showing it to be superior to radiography for early or small lesions and comparable for larger lesions that extend into dentin (Ástvaldsdóttir et al, 2012).

Near-infrared light transillumination (NILT)

Expanding on the developments in FOTI and DIFOTI which use visible light, a new technology has emerged that uses near-infrared light (NIR) for transillumination of the tooth. The DIAGNOcam (KaVo, Biberach, Germany), introduced in 2012, is a camera system that employs a NIR light source. The light is transmitted through the gingiva, alveolar bone, and root, then up through the crown. Presence of a carious lesion will scatter and reduce the transmitted light. A charged-coupled device sensor captures the clinical data and displays an image of the tooth viewed from its occlusal surface (Söchtig et al, 2014).

Wavelengths of light in the NIR range (700 to 1500 nm), are much longer than in the range of visible light. The longer wavelengths of light exhibit less scatter and can penetrate objects more deeply (Fried et al, 1995). It has been demonstrated that transillumination of teeth in the NIR range causes enamel to appear transparent. This allows for the ability to illuminate from the buccal surface of the tooth and simultaneous visualization of both occlusal and proximal caries lesions (Fried et al 2010). Furthermore since ionizing radiation is not employed, there are no restrictions on image acquisition making this method ideal for monitoring lesion changes over time. Images can also be acquired from different angles to better aid in diagnosis (Staninec et al, 2010).

Quantitative light-induced fluorescence (QLF)

Quantitative light-induced fluorescence (QLF) was first introduced in 1995. This new technology was developed based on the optical phenomena of fluorescence and allowed a quantitative measurement to be calculated in the difference in fluorescence radiance between carious and sound tooth structure (de Josselin de Jong et al, 1995). QLF relies on the natural fluorescence of teeth which decreased with demineralization. Carious lesions will appear dark when viewed with QLF based on the principle that demineralized tissue limits the penetration of light due to excess scattering of photons (Amaechi, 2009). Lesions with a depth of 500 micrometers on smooth and occlusal surfaces can be readily detected using QLF (Karlsson and Tranæus 2008). Significant potential for this technology has been demonstrated in terms of its sensitivity, repeatability, and reproducibility of detecting early caries, as well as longitudinal monitoring lesion progression or regression (Stookey, 2004).

An upgraded version of the device called quantitative light-induced fluorescence-digital Biluminator™ (QLF-D), with a modified filter set, has been shown to be highly effective and comparable to traditional methods in the detection of proximal caries with relatively high sensitivity and specificity at both enamel and dentin caries (Ko et al, 2015). In addition to quantitatively detecting mineral loss, the QLF-D system is able to detect red fluorescence associated with the biofilm. The increase in fluorescence is directly associated with the degree of biofilm maturation and cariogenicity. Therefore QLF-D can also be used to quantitatively monitor the degree of maturation of dental biofilms in real time. The implications of this in clinical practice could allow for determining individual caries risk status and developing appropriate preventive measures (Kim et al 2014).

Laser fluorescence

The DIAGNOdent, introduced by KaVo (Biberach, Germany) in 1998, utilizes laser fluorescence for the detection of caries. The device incorporates a Diode laser which emits a beam at 655 nanometers. This wavelength when irradiated on tooth surface is absorbed by bacterial metabolites and emits a red fluorescence. The degree of fluorescence reflected is quantified as a number between 0 and 99 on the screen of the device with greater numbers indicating greater area of decay (Nokhabatolfoghahaie et al, 2013).

There is a direct correlation between the depth of the carious lesion and the reading given by DIAGNOdent. The value will increase gradually while the lesion is confined to enamel with a dramatic increase once it has penetrated into beyond the dentinoenamel junction. Furthermore, DIAGNOdent was shown to have a high intra-examiner reproducibility which suggests that it can be a suitable method for longitudinal monitoring of carious lesions. Along the same line, it can be helpful in monitoring the outcome of preventive interventions (Bamzahim et al, 2002).

Throughout the literature, there is a wide variability on the reported sensitivity and specificity of the DIAGNOdent with regard to detecting dentinal caries (Bader et al, 2001). Clinically it has been shown that DIAGNOdent has a higher sensitivity and lower specificity at the dentin threshold when compared to radiographic examination and visual inspection. This has led to a recommendation that DIAGNOdent be used only as an adjunct diagnostic tool due to yielding more false positive results than visual and radiographic methods (Matos et al, 2011).

Light emitting diode (LED)

Midwest Caries I.D. (DENTSPLY Professional, York, PA) is a hand held device that utilizes the technology of light emitting diode (LED) reflectance and refraction. It has been shown to be effective in the evaluation of pit and fissure and interproximal caries detection. It works on the principle that healthy tooth structure is usually more translucent than decalcified enamel resulting in a different optical signature between the healthy and demineralized tooth structure. The Midwest Caries I.D. device analyzes the reflectance and refraction of the emitted LED which is converted into an electric signal. A microprocessor contained within the device analyzes the signal using a computer based algorithm that differentiates the presence or absence of changes in optical translucency and opacity. With the presence of caries, the demineralization activates a change in the LED from green to red with a simultaneous audible signal. For interproximal caries detection, the probe must be directed over the marginal ridge area long the long axis of the tooth, and not between the teeth (Strassler and Sensi, 2008).

Midwest Caries I.D. has been shown to have a high level of sensitivity yet a low level of specificity with a high risk for false positive results. In a study comparing Midwest Caries I.D. to the DIAGNOdent pen, the DIAGNOdent was more accurate in determining when teeth were free of occlusal caries than was the Midwest Caries I.D., while the Midwest Caries I.D. revealed the presence of caries more often than the DIAGNOdent did (Aktan et al, 2012). A more recent study reported sensitivity and specificity of the device at 56% and 84 % respectively suggesting that the Midwest Caries I.D. is less than optimal at detecting caries yet is fairly reliable in determining the presence of healthy tooth structure. These results suggest that the Midwest Caries I.D. is only useful as an adjunct and should be coupled with visual, tactile, or radiographic exam (Patel et al, 2014). While the Midwest Caries I.D. has been shown to be useful in detecting the presence of demineralization, one major limitation of the device is that it cannot be used to adequately assess the depth of demineralization (Van Hilsen and Jones, 2013).

Alternating current impedance spectroscopy

The CarieScan PRO is a device that utilizes the technology of alternating current impedance spectroscopy. It relies on the theory that sound dental hard tissue exhibits high electrical resistance or impedance, whereas the more demineralized the tissue, the lower the resistance becomes. The device is intended to detect and monitor primary coronal dental caries at an early enough stage to support preventive treatment. It cannot be used to assess secondary caries or root caries (Amaechi 2009). To date there have been a small number of in vitro and in vivo studies performed on the validity of CarieScan PRO with results showing moderate sensitivity and specificity (Tassery et al, 2013). One study in particular showed that CarieScan PRO did not perform well on primary teeth in comparison to DIAGNOdent pen and ICDAS and validated the manufacturer's claims that the device is unsuitable for use on the primary dentition (Teo et al, 2014).

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

One of the most recent and innovative developments in caries detection is the Canary System. Developed by Quantum Dental Technologies in Toronto, Canada, the Canary System incorporates the combined technologies of photothermal radiometry (PTR) and luminescence (LUM). With this system, pulses of laser light are shone on the tooth where it is converted to heat and light. Where there is a lesion developing, there is a corresponding change in the signal as the heat (PTR) is confined to the area of demineralization and the glow (LUM) decreases. As remineralization occurs, the thermal and luminescence properties will begin to revert back in the direction of healthy tooth structure. The system measures the strength and amplitude, and the time delay or phase of the converted heat and emitted luminescence. An algorithm converts these signals into the Canary Number which can range from 0-100 with under 20 indicating healthy tooth structure. The PTR-LUM technology used in the Canary System has been shown to detect early lesions as small as 50 microns and at a depth up to 5 mm below the tooth surface. It can be used to detect occlusal pit and fissure caries, smooth surface caries, acid erosion lesions, root caries, interproximal carious lesions, and demineralization and remineralization of early carious lesions (Abrams, 2011).

With limited studies conducted to date, the Canary System shows promising potential for use in early caries detection. When compared to conventional methods of visual examination and bitewing radiology for detecting proximal caries, the Canary System had the highest sensitivity, and a specificity that was only slightly lower than bitewings. Overall the Canary System had the highest positive and negative predictive values with histological examination used a reference standard for the presence or absence of carious lesions (Jan et al, 2015). Another study conducted using the Canary System to detect proximal caries on primary molars showed it was well tolerated by the patients and overall had a high sensitivity but low specificity compared to bitewing radiographs. The low specificity was believed to be a result of the Canary System detecting early lesions that don't yet appear on the radiographs (Herzog et al, 2015)

Cone beam computed tomography (CBCT)

With conventional radiography there are inherent limitations largely due to the two dimensional representation of caries which are in reality three dimensional structures. This may lead to a loss of valuable information (Wenzel, 2004). The revolutionary development of cone beam computed tomography (CBCT) and its applications in dentistry allows for true three dimensional high resolution imaging (Kalathingal et al, 2007). The use of CBCT imaging has gained much attention particularly in the applications of dental implant planning and placement, orthodontics, surgery and temporomandibular joint disease. In addition to the aforementioned uses, there has been a modest amount of research focused on the use of CBCT for dental caries diagnosis (Tyndall and Rathore, 2008). A 2011 review showed a tendency of studies to claim the accuracy of CBCT to be higher than conventional methods in detecting occlusal caries and deep dentin caries. However, it pointed out that the evidence was weak at best due to lack of standardization of experimental conditions across the various studies (Park et al, 2011).

One in vitro study of interest demonstrated that enamel demineralization on an approximal surface is not likely to be detected by CBCT examination when there is an amalgam filling in the region of interest. These results stem from the scatter and beam hardening caused by the high-density metallic nature of amalgam. Therefore CBCT should not be used to examine for the presence or absence of caries when amalgam fillings are present in direct contact of the area being evaluated (Kulczyk et al, 1014).

A recent in vivo study assessed and compared the validity of CBCT and bitewing radiography in the ability to differentiate between cavitated carious lesions and non-cavitated demineralization. The accuracy for detecting cavitation with CBCT was high with a significantly higher specificity than bitewing radiography. Specificity was also not compromised meaning that there were no more false positives in intact surfaces being scored with CBCT than with bitewing examination. While it was not suggested that CBCT should be used as a primary means for proximal caries detection, it's validity in detection of surface cavitation is clinically relevant and hence a CBCT examination performed for other reasons should also be assessed for approximal surface cavities in non-restored teeth (Wenzel et al, 2013). A similar result was obtained in a 2014 study that concluded the sensitivity and overall accuracy was significantly higher for CBCT compared to bitewings in detecting proximal cavitated carious lesions, while specificity was not significantly different between the two methods. Given the greater expense and exposure of ionizing radiation, it was not recommended that CBCT is used as a routine primary radiographic examination. However as a pathologic finding that should be treated operatively, a cavitated proximal surface that appears on a CBCT taken for any other application should be included in the report by the oral radiologist or clinician viewing the CBCT (Sansare et al, 2014).

CHAPTER IV: CONCLUSION

Innovative devices designed for dental caries detection have shown a range of accuracy with regard to specificity and sensitivity compared to traditional visual and radiographic examination. No single device or method alone is sufficient to adequately diagnose carious lesions in all sites. A combination of diagnostic methods and devices greatly increases the ability to detect caries in its earliest stage which will allow for a preventive treatment approach rather than more costly and invasive operative interventions.

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