Emerging technologies for diagnosis of dental caries: The road so far

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It is now universally recognized that the development of new technologies for early detection and quantitative monitoring of dental decay at an early stage of formation could provide health and economic benefits ranging from timely preventive interventions to reduction in the time required for clinical trials of anticaries agents. The use of technologies as adjunct to clinical visual examination for caries diagnosis will facilitate preventive care in dentistry to lower treatment cost as well as reduce the cost and time for testing potential anticaries agents. This article describes the various technologies available to aid the dental practitioners in detecting dental caries at the earliest stage of its formation, assessing the activities of the detected carious lesion, and quantitatively or qualitatively monitoring of the lesion over time. The need and the importance of these technologies were also discussed. The data discussed are primarily based on published scientific studies and reviews from case reports, clinical trials, and *in vitro* and *in vivo* studies. References have been traced manually by MEDLINE® or through manufacturer's websites. While some of the devices are fully developed and commercially available, others are still under development. The devices vary in their modes of action as well as their capability as caries diagnostic aids. It is clear that the differences in caries presentations and behavior in different anatomical sites make it unlikely that any one diagnostic modality will have adequate sensitivity and specificity of detection of carious lesions for all sites; a combination of diagnostic tools will help us diagnose lesions earlier and detect failing restorations sooner, all to avoid more costly, destructive dental procedures and truly take dentistry into the preventive rather than the reactive mode. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3116632]

I. INTRODUCTION

Why new technologies for early detection of dental caries? The need for the identification and clinical staging of the presence, activity, and severity of dental caries is of paramount importance in the deployment of treatment strategies that employ increasingly important nonsurgical modalities such as fluorides, antimicrobials, sealants, and no treatment.[1] The remineralization observed in clinically arrested lesions and the conversion of clinically active to inactive lesions support the nonrestorative management of carious lesions. Therefore, sensitive diagnostic techniques are needed to provide acceptable compromises between sensitivity and specificity for a wide range of applications for individual patient care as well as for research purposes. A variety of innovative technologies have been developed and introduced in the last few years to aid clinicians not only in early caries detection but to make a firm diagnosis and treat cases conservatively. Furthermore, the differences in caries presentations and behavior in different anatomical sites make it unlikely that any one diagnostic modality will have adequate sensitivity and specificity of detection for all sites.[2] Hence, it is now universally recognized that the development of new technologies for the detection and quantification of dental caries at an early stage of its formation could provide health and economic benefits ranging from timely preventive interventions to reduction in the time required for clinical trials of anticaries agents.[1]

The extensive availability of fluoride in communal water supplies, fluoride-containing oral hygiene products, as well as increased public awareness of oral hygiene and more positive attitudes have changed the behavior of dental decay. The development and progression of dental decay from early tooth demineralization to frank cavity is now very slow, giving the dentist the opportunity of capturing the caries lesion at its early stage of formation. At this stage the lesion can be reversed by personal dietary and preventive actions and by professional application of chemotherapeutic agents such as fluoride varnish before it reaches the advanced stages requiring costly and agonizing dental fillings. This ultimately will result to a long term health and economic benefit,[3] as demonstrated by cost-estimation modeling of preventive interventions, which predicts cost savings of $66–73 per tooth surface prevented from needing repair among young Medicaid-enrolled children[4] and a savings of 7.3% from regular screening and early intervention.[5]

At the clinical dental practice level, caries diagnosis also has a significant impact since it rules treatment decisions. The diagnosis of early caries lesions has been considered the cornerstone of cost-effective health care delivery and quality of dental care.[6] The ability to accurately detect the developing lesions at a very early stage in a dental practice and to quantify the size of the lesions will provide the practitioner with an effective means of determining caries status and of monitoring the effectiveness of professional treatments for reversing and controlling the caries process.[1] Both at the pa-

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tient level and the community level, early detection measures can have a positive impact by ensuring that preventive treatment is delivered to those who need it. Thus continued research to develop accurate methods for the early detection of dental caries has a remarkable potential for enhancing dental health and merits priority consideration.

Furthermore, the development of novel technologies for the early detection of dental caries may be expected to have a major impact upon clinical dental research. Stookey *et al.*[1] indicated that at the present time conventional procedures to conduct controlled clinical investigations of caries-preventive measures require the use of a large number of subjects (due to the variability in caries formation between children, the inability to include a negative control treatment regimen for ethical reasons, and the subjectivity of the conventional caries detection methods) with a test period of 3 yr (to permit the development of frank lesions detectable with current accepted methods). These requirements necessarily demand an appreciable cost ($\$3-5\times10^6$) as well as a time period of at least 4 yr, allowing for the time to recruit the subjects, complete all examinations, and perform the statistical analyses. The identification of methodologies capable of accurately detecting and quantifying the size of early lesions may be expected to permit the use of lesser numbers of subjects and shorter time periods to assess the impact of treatment measures than is possible with present-day methods, and thereby to support the clinical evaluation and development of novel methods that are even more effective for the prevention and control of dental caries.

The above discussions indicate that there would be an enormous benefit for clinical practice and clinical research if lesions could be detected at an early stage. However, existing diagnostic modalities (visual and radiographic examinations) appear to have satisfactory sensitivity and specificity in diagnosing substantial, cavitated dental caries which cannot be controlled by chemical therapeutic treatments. The importance of radiographs to diagnose initial carious lesions in approximal surfaces is well established.[7] However, radiographic evaluation of occlusal surfaces has been found of minimal diagnostic value for detecting enamel caries and superficial dentin caries[8,9] because of the large amounts of surrounding sound enamel. On the other hand, radiographs have been shown to underestimate the size of the lesion considerably.[10] Digitally enhanced radiography was developed to improve the use of radiograph for diagnosis of early caries. Using computer technology to enhance images from a video camera or from a digital x-ray sensor has been proven to be an objective and reproducible methodology.[11,12] A further use of radiographs is to monitor lesion progression; however, the main disadvantage is the high false-positive rates when used for occlusal caries detection[13] in addition to the unavoidable hazards of ionizing radiation. Specifically, these two modalities (visual and radiograph) do not appear to have sufficient sensitivity or specificity to efficaciously diagnose noncavitated caries, root caries, or secondary caries. Besides, they have two basic problems: (a) they are based on subjective criteria such as color, hardness, and resistance to remove the explorer, and therefore inadequate at times of decreasing caries prevalence when lesions develop at slower rates and cavitations occur much later;[6] (b) they do not consider the dynamic nature of the caries process. It is now known that the development of dental caries is a dynamic process involving a continuum that progresses from sound enamel to subclinical demineralization, early clinical (noncavitated), and frank (cavitated) caries. The subclinical stage can only be detected with the aid of an advanced technology while early clinical caries can be detected easier and faster with the aid of the advanced technologies than visual clinical examination. The preclinical and early clinical are the stages of caries development that can be reversed by chemotherapeutic agents. The first move toward increasing the sensitivity of visual caries detection was made by the evolution of magnifying devices such as head-worn prism loupe. This has been shown to improve the sensitivity by 50%,[14,15] and therefore can be used to increase accuracy of caries diagnosis but cannot detect the subclinical stage of caries formation. Furthermore, the dynamic nature of caries is such that the caries process may be active, inactive (arrested), or reversed at any stage of development with a change in the biochemistry of the oral environmental such as change in oral hygiene and/or diet of the patient or application of a chemotherapeutic agent. This changing activity of the caries lesion necessitates that caries lesions need to be monitored over time especially with application of a chemotherapeutic agent. This has led to a further advancement in technological development toward the evolution of new technologies that can detect as well as monitor the overall activity of the caries lesion by quantification of the changes in mineral content of the lesion over time. In view of the above considerations, over the past decade there has been an interest in developing new technologies to aid the dentist in detecting various stage caries formation and quantitatively assessing the activity state of noncavitated carious lesions. The following methods have been developed and are still undergoing modifications in response to information from practitioners.

A. New technologies for clinical diagnosis of early dental caries

A variety of innovative technologies have been developed and introduced in the last few years to aid clinicians not only in early caries detection but make a firm diagnosis and to treat cases conservatively. These technologies use the alteration in fluorescence, reflectance, electrical conductance or impedance, and ultrasound transmittal properties of enamel with demineralization to monitor changes in caries lesion over time. Going down the memory lane from the earliest to the latest, some of these technologies are as follows.

1. Fiber-optic transillumination

Fiber-optic transillumination (FOTI) as a caries detection technique is based on the fact that carious enamel has a lower index of light transmission than sound enamel.[16] The light is absorbed more when the demineralization process disrupts the crystalline structure of enamel and dentin. In essence this gives that area a more darkened appearance. This method of caries detection uses a light source, prefer-

ably bright, to illuminate the tooth. Caries or demineralized areas in dentin or enamel show up as darkened areas with this technique. This effect can be achieved with a fiber optic illuminator, which is readily available at the handpiece coupler of the dental operatory and has been used for detection of approximal and occlusal caries. Posterior approximal caries can be diagnosed with the light probe positioned on the gingivae below the cervical margin of the tooth, whereby the light passes through the tooth structures and approximal decay produces a dark shadow on the occlusal surface. Although this device has the advantage that the examination is done with an operating light source already available in general practice, it is only useful for approximal and occlusal lesions; its sensitivity and specificity are not sufficient for detection of very early caries. Besides, it is not quantitative and therefore not useful as a caries monitor over time. However, studies on the diagnostic efficacy of this device present conflicting results. One study[17] compared FOTI with radiographic examinations for occlusal caries and concluded that radiographic examinations were a better diagnostic tool than FOTI. A contrary result was found in a study conducted in 1992.[18] According to another study conducted in 1992,[19] transillumination exhibited a low sensitivity to caries detection but showed a high positive predictive value. Ismail,[20] in his review of the diagnosis of precavitated lesions using different diagnostic methods, found the use of explorer to be the least effective method for the detection of carious lesions. FOTI exhibited a better sensitivity than clinical inspection in detecting precavitated lesions that had a shadow or opacity underneath the marginal ridge. Another study[21] also reviewed the diagnosis of caries on proximal surfaces and found that FOTI was superior to visual inspection and radiography. However in a previous review[22] radiography was superior to FOTI. A conclusion can be obtained from some of the previous studies that FOTI is a cost efficient noninvasive adjunct to a clinical examination in the detection of posterior dental caries.[23]

2. Digital imaging fiber-optic transillumination

This is a digitized and computed version of the FOTI. While FOTI was designed for detection of approximal and occlusal caries, digital imaging fiber-optic transillumination (DIFOTI) is used for detection of both incipient and frank caries in all tooth surfaces.[24–29] DIFOTI can also be used to detect fractures, cracks, and secondary caries around restorations. DIFOTI uses white light to transilluminate each tooth and to instantly create high-resolution digital images of the tooth. It is based on the principle that carious tooth tissue scatters and absorbs more light than surrounding healthy tissue.[27] Decay near the imaged surface appears as a darker area against the more translucent brighter background of surrounding healthy anatomy. A single fiber-optics illuminator in the mouthpiece delivers light to one of the tooth's surfaces. As this light travels through layers of enamel and dentin, it scatters in all directions toward the nonilluminated surface (usually the opposite surface). The light is then directed through the mouthpiece to a miniature electronic charge coupled device (CCD) camera in the handpiece.[28] The camera digitally images the light emerging from either the smooth surface opposite the illuminated surface or the occlusal surface. These images are displayed on a computer monitor in real time and stored on the hard drive for easy retrieval for comparative review of images over time.[28] Image acquisition is controlled with software and a foot pedal. Images of the teeth can be viewed by both the clinician and patient, and therefore can be used for patient education and motivation. It is important to note that DIFOTI images the light emerging from surface closest to the CCD camera. It does not image the tooth material between the light source and the CCD camera, and therefore cannot indicate the depth of lesion penetration.[29] Schneiderman *et al.*[28] demonstrated a method of using DIFOTI to quantitatively monitor lesion progression and reported a successful result. Inherent with the high sensitivity of the device,[27,28] dark areas in DIFOTI images may sometimes be due to stains or calculi on tooth surface; therefore it is suggested that prophylaxis should be carried out prior to the use of the device in order to increase the specificity.[16]

3. Quantitative light-induced fluorescence

This is a prominent diagnostic system in dentistry. The quantitative light-induced fluorescence (QLF) technology was introduced in 1995[30] and was quickly used to monitor caries lesions over time.[31,32] Since then several studies have demonstrated the ability of the QLF™ system to detect and monitor caries in real time, both in children and adults.[33–35] QLF uses the natural fluorescence of the teeth, which is determined by the light absorption and scattering properties of the teeth, to discriminate between caries and surrounding sound enamel. The autofluorescence of tooth tissue decreases with demineralization and QLF measures the percentage fluorescence change in demineralized enamel with respect to surrounding sound enamel and relates it to the amount of mineral lost during demineralization. Caries lesions appear dark when viewed with QLF, and this is based on the principle that a demineralized tissue limits the penetration of light due to excessive scattering of photons entering the lesion with consequent limitation to the chance of a photon being absorbed and fluorescence remitted. Furthermore, excessive scattering in carious tissue prevents the light entering the tissue from reaching the DEJ and dentin where the chance of absorption by a fluorophore for fluorescence remittance is a magnitude higher. Light entering the sound enamel is scattered about a factor of 10 less than in carious enamel, so photons travel further in sound enamel and may reach dentin and along their path may be absorbed by a fluorophore leading to excitation of fluorescent photons. Hence, a caries lesion is observed as a dark spot surrounded by highly luminescent sound enamel. The QLF system comprised of a special intraoral camera device connected to a computer fitted with a frame grabber (Comet, Matrox, Electronic Systems, Ltd., Quebec, Canada) and to which the QLF software (QLF version 2.0.0.37, Inspektor Research Systems BV, Amsterdam, The Netherlands) was installed. To visualize and capture the tooth surface image, white light from a special arc lamp (Philips bv, Eindhoven, The Netherlands) based on xenon technology is filtered through a blue-transmitting bandpass filter (Philips bv, Eindhoven, The Netherlands)

with peak intensity of $\lambda = 370$ nm and bandwidth of 80 nm to provide illumination of the tooth surface with a blue-violet light with an intensity of 13 mW/cm^2. A dental mirror provided uniform illumination of the tooth surface, and with the aid of a color CCD sensor (Sony LS-1P, Tokyo, Japan), which had a yellow-transmitting ($\lambda \geq 520$ nm) filter (Philips bv, Eindhoven, The Netherlands) positioned in front of it (to filter out all reflected and back-scattered light), the fluorescent image of the tooth surface is recorded and digitized by the frame grabber to be available for quantitative analysis using the QLF software.[36] Once the fluorescent image of the tooth is captured and recorded by the PC, analysis of the lesion can be initiated by a user-defined patch with borders placed on sound enamel surrounding the lesion. The sound fluorescence radiance values inside the patch are reconstructed through two-dimensional linear interpolation of sound enamel values on the patch borders.[37] The decrease in fluorescence was determined by calculating the percentage of difference between the actual and the reconstructed fluorescence surface. Any area with a drop in fluorescence radiance of more than 5% is considered to be a lesion.[38] The QLF software automatically gives the value for the percentage of fluorescence radiance loss ΔQ (percent) and simultaneously data storage.[37,38] Several advantages in the practicality of use and accuracy in quantifying demineralization have been reported. It uses ordinary white light sources, which are an advantage over ionizing radiation of x ray. The main advantages of QLF are the following: (1) the increased contrast between carious and sound enamel makes earlier and faster for detection of lesions possible and (2) the examination presents no danger to patient or operator, since the excitation light is white light and of relatively low intensity. This method has been used to monitor demineralization *in vitro*,[34,35,39,40] to assess incipient lesion remineralization *in situ*,[41] to assess demineralization *in vivo*,[41–46] and to quantitatively monitor tooth whitening.[47,48] Several studies used QLF in orthodontic patients for longitudinal studies of white spot lesions around brackets.[31,49,50] A multicenter study[51] used QLF to monitor caries development in 127 children aged 9–12 yr for 12 months and reported sensitivity of 77% and specificity of 71% for detection of occlusal lesions and sensitivity and specificity of 79% and 75%, respectively, for detection of smooth surface lesions. Visual clinical examination in this study scored sensitivity of 38% and specificity of 79% for occlusal surface lesions. Many other applications have been reported for early diagnosis and quantification of mineral loss using the QLF method such as detection of recurrent caries around restorations, detection of occlusal caries, and in fluoride studies.[45,52–56] The QLF technique has been validated against the TMR technique, the *in vitro* gold standard, in both permanent and deciduous teeth[44,57] showing excellent correlations. When compared to DIAGNOdent, QLF was found to have a better correlation with changes in mineral content on smooth surface caries.[58,59] Moreover, the repeatability and reproducibility of QLF have been tested *in vivo*[59] with the results showing intraclass correlation coefficients (r) of 0.93–0.99 and the interexaminer reliabilities between 0.95 and 0.99. Although high sensitivity was reported,[33] this system has a low specificity in that it cannot distinguish between caries, stains on tooth surface, and white spot due to developmental anomalies such as fluorosis. Recent development in QLF incorporates a red fluorescence detector; excitation of red extrinsic fluorophores from bacterial metabolites (porphyrins) by blue light causes plaque/calculus/bacterially infected caries lesions to appear red on a bright green background,[60] enabling the use of QLF to quantify and monitor plaque.

4. DIAGNOdent laser system

This is a laser fluorescence system that detects changes in the tooth structure due to demineralization. These structural changes cause an increase in the fluorescence at specific excitation wavelengths. The intensity of the fluorescence depends upon the wavelength of the light as well as the structure and condition of hard dentinal tissues. DIAGNOdent with a laser diode that generates a pulsed 655 nm laser beam via a central fiber is transported to the tip of the device and into the tooth. When the incident light interacts with tooth substance, it stimulates fluorescent (or luminescent) light at longer (Stokes shifted) wavelengths. The intensity of fluorescence is a function of the degree of demineralization or bacterial concentration in the probed region. In fact, the full fluorescence mechanism(s) of the DIAGNOdent is still only partly understood. There are two theories regarding its mode of action. The first theory is that when the red incident light meets a change in tooth tissue (porosity due to demineralization), it stimulates fluorescent light of a different wavelength. This generated fluorescent light travels through additional light fibers that are concentrically arranged around the central fiber (a filter eliminates ambient light) into a microprocessor, which analyses and translates the signal into an acoustic signal and a digital display of numerical figures which shows both a real-time and a maximum value, ranging from 0–99.9, which can be used in the diagnostic protocol. The second theory is that DIAGNOdent responds to the fluorescence emitted from the metabolites of cariogenic bacteria, i.e., it is measuring the level of cariogenic bacterial activity in terms of metabolites. The DIAGNOdent operates on the premise that a high level bacteria reading indicates a probability of having a decalcified enamel structure. Hence, one weakness of this technology is that all bacteria, not only caries-related bacteria, produce fluorescence. A lot of organic and nonorganic materials such as stains, plaque and calculus, some prophy paste, food, and even the tooth itself can cause fluorescence. In any case, one of the advantages of the system is that the quantitative nature of its readings gives a basic guideline as to when to intervene. Decay in a patient can be followed longitudinally to monitor the extent of the decay at every recall. It was concluded in an *in vitro* study[61] that this laser device had a higher diagnostic validity than the electrical caries monitor (ECM) and may be a valuable tool in the longitudinal monitoring of caries and in assessing the outcome of preventive interventions. However, it is pertinent to mention that other studies have shown and it has been acknowledged by the developers of DIAGNOdent that factors such as the presence of bacterial plaque, dental prophylactic pastes, fissure sealants, and composite resin materials give false positive readings with this instrument.[10,22,23]

5. Electrical caries monitor

This technology is based on the electrical conductivity differences between sound and carious dental tissues. ECM is based on the principle that electrical conductivity is a function of porosity. Enamel demineralization results to increased porosity of the enamel tissue and saliva fills the pores and forms conductive pathways for electrical transmission. Since saliva is a better electrical conductor than enamel tissue, the conductivity increases with demineralization. On this basis, ECM measures the electrical resistance of a site on the tooth during controlled drying. By drying the tooth surface, the resistance is determined by the tooth structure, avoiding electrical conductance by surface liquid (saliva). High measurements indicate well-mineralized tissue while low values indicate demineralized tissue. The electrical conductivity of a tooth changes with demineralization even when the surface remains macroscopically intact. Example of this device is the lode electronic caries monitor. Conductivity is measured from the probe tip in the fissure through the dental pulp to a handheld earth lead with the patient forming part of the circuit. A major advantage of the ECM is to present objective readings, which have the potential for monitoring lesion progression, arrest, or remineralization. The sensitivity and the specificity of this machine have been reported to be very high, 0.75 and 0.77, respectively, when used to detect occlusal caries *in vivo* and *ex vivo*,[19,62–66] indicating that it is a valid indicator for detecting the presence or absence of lesion porosity. A strong relationship between both lesion depth and mineral content in enamel has been shown with ECM readings.[67] The only drawback is the fact that it is time consuming to use in a routine full-mouth examination.

6. Midwest Caries I.D.

The Midwest Caries I.D. detects differences of optical behavior inside the tooth related to change in the tooth structure and it is therefore not sensitive to bacterial content. The Midwest Caries I.D. uses infrared and red light emitting diodes (LEDs) and a fiber optic to distribute light to the observed area present at the probe tip. A second fiber optic collects light from the observed area to a photodetector that measures returned collected light. This photodetector then transmits the signal to a microprocessor that compares signal levels with defined parameters. When the result is positive, the processor deactivates the third green LED and pulses at a higher intensity than the red LED. When the detection is negative (i.e., healthy tooth area), the green LED is dominant resulting in a green illumination when healthy structure is detected and red illumination when caries are detected. A buzzer also beeps with different frequencies to indicate the intensity of demineralization detected. The Midwest Caries I.D. can be used for approximal caries detection during the examination by slightly angling and moving the probe along the marginal ridge just over the vulnerable approximal area. This approach seems much more convenient than the DIAGNOdent® approach since it enables minimal dilution of the light signal from all surrounding structures (which is the case for transillumination) by sending and capturing the light signal in a direct line toward the vulnerable regions inside the enamel.[68] One of the few studies evaluating this device reported the sensitivity and specificity to be higher than that of DIAGNOdent.[68] Interproximal detection using the Midwest Caries I.D. and x rays as a gold standard showed a sensitivity of 80% and specificity of 98%.[69] However, this device can give false positive signals in cases of teeth with growth malformations in the enamel or the dentin, teeth with thick, dark stains, hypermineralization, hypocalcification, dental fluorosis, and atypically shaped teeth due to alteration in the translucency of enamel caused by these conditions.[68] Light penetration is limited into the enamel and up to 3 mm in approximal area. Midwest Caries I.D. cannot be used on composites or amalgams but can be used to check the marginal ridges of occlusal amalgams. If the probe is tipped at too much of an angle when checking for approximal caries, total surface light reflection can occur giving a false positive. Opaque artifacts (plaque, calculus, and organic plug) can cause false positives.[68]

7. Polarization-sensitive optical coherence tomography

While all the above technologies use only the alteration of fluorescence, reflectance, electrical conductance, or impedance properties of enamel with demineralization to monitor changes in caries lesion over time, optical coherence tomography (OCT) can additionally produce an image of tissue microstructure of the caries lesion to show the changes within, and therefore can be compared both qualitatively and quantitatively with histological methods such as microcomputed tomography and transverse microradiography, the current gold standard for measuring demineralization.[70–73] OCT technology is an imaging modality that provides a tool for noninvasive evaluation of tissue microstructure by providing high spatial resolution ($\sim 10-20$ μm) and real-time, two-dimensional depth visualization.[74] The principle of OCT is similar to B-mode ultrasound imaging, except that OCT uses near infrared (NIR) light instead of sound. First demonstrated in 1991,[75] OCT creates a two-dimensional map of the tissue microstructure by illuminating the tissue with low-power NIR light, collecting the backscattered light, and analyzing the intensity.[74] OCT is based on confocal microscopy and low coherence interferometry. Based on the principle that the highest quality image information is contained in the portion of the detected light that is relatively unscattered and therefore travels the most direct path through the tissue, OCT uses low coherence interferometry to selectively remove the component of backscattered signal that has been multiply scattered, resulting in very high resolution images. Although the first application of low coherence interferometry in the biomedical optics field was for the measurement of the eye,[76] since then OCT has been used to provide images of tooth structures.[77–81] Following the modification of the system to produce polarization-sensitive OCT (PS-OCT), the application of OCT in dentistry has widened covering *in vitro* images of dental caries.[82] However, most reports refer to longitudinal OCT imaging only. Recently Amaechi and co-workers[70–73,83–88] used a combination of *en face* PS-OCT technology with confocal microscopy developed initially for

retina imaging[89,90] to further the application of the OCT into dental tissue imaging. This combined system can operate in different regimes to deliver A scans, B scans (longitudinal images), and C scans (*en face* or transverse images). The confocal image, which can be displayed sideways, along with the *en face* OCT image at each depth, was useful in identifying the caries lesion and aligning the tooth. This was especially useful for the *in vivo* application of the system. Using this system, they demonstrated the ability of OCT to quantitatively and qualitatively detect and monitor incipient enamel[70,72,73,83–86] and root caries[71] as early as 24 h in its development. OCT was able to discriminate between sound and demineralized (carious) tooth tissue by the differences in reflectivity. Other studies examined the influence on OCT imaging of factors such as lesion staining, ambient lighting, and the presence of saliva or bacterial plaque, which have been identified to adversely affect other technologies, especially those based on tooth tissue fluorescence, and reported that these factors do not influence OCT imaging and measurements.[87] The use of A scan from OCT imaging to produce quantitative data relating to the degree of change in reflectivity, and hence the degree of change in mineral level, of the tooth tissue following development of caries was also demonstrated in one study.[83]

8. CarieScan

This device is based on the proven technology of alternating current impedance spectroscopy and involves the passing of an insensitive level of electrical current through the tooth to identify the presence and location of the decay. The frequency domain is based on a sinusoidal signal applied to a sample at known amplitude and frequency. The response waveform is then measured and the impedance calculated by a transfer function relationship of the applied voltage perturbation and acquired response current. It is the first dental diagnostic tool to use ac impedance spectroscopy to quantify dental caries early enough to enhance preventative treatment. According to the originators,[91] the CarieScan is not affected by optical factors such as staining or discoloration of the tooth; it provides a qualitative value based on the disease state rather than the optical properties of the tooth. The device is indicated for the detection, diagnosis, and monitoring of primary coronal dental caries (occlusal and accessible smooth surfaces), which are not clearly visible to the human eye. It cannot be used to assess secondary caries, the integrity of a restoration, dental root caries, and the depth of an excavation within a cavity preparation. This device uses disposable tufted sensors for single use and a test sensor (nondisposable), which is used to test the device and confirm if the system is operating correctly. For assessment of caries, while tufted sensor brush contacts the tooth surface being examined, a soft tissue contact, which is a disposable metal clip that is placed over the lip in the corner of the patient's mouth, connects to the CarieScan via a soft tissue cable to complete the circuit. During measurement, a green color display indicates sound tooth tissue, while a red color indicates deep caries requiring operative, and a yellow color associated with a range of numerical figures from 1 to 99 depicts varying severity caries, which require only preventive care. Accompanying the CarieScan is the CarieScan-Plus, which is a wirelessly linked control system designed to be used as a patient management system, allowing data to be automatically captured, filed, and recalled electronically on a by-tooth, by-surface, by-date basis for dental health monitoring. This enhances communication with the patient as an aid to preventive motivation and caries control. A systematic review[92] comparing CarieScan with clinical visual examination, bitewing radiograph, and DIAGNOdent reported CarieScan to have a superior sensitivity and specificity (both 92.5%) over other methods.

9. Frequency-domain infrared photothermal radiometry and modulated luminescence

Although still under development, the most recent technology in the field of caries diagnosis is the combined frequency-domain laser-induced infrared photothermal radiometry and modulated luminescence (PTR/LUM). Some of the inherent advantages of the adaptation of PTR to dental diagnosis in conjunction with LUM emission as the dual-probe technique have been reported in recent literature.[93–97] The PTR technique is based on the modulated thermal infrared (blackbody or Planck radiation) response of a medium, resulting from optical radiation absorption from a low-intensity laser beam (~mW) and optical-to-thermal energy conversion followed by modulated temperature rise ("thermal waves") usually less than 1 °C in magnitude. The generated signals from PTR/LUM instrument carry subsurface information in the form of a spatially damped temperature depth integral. Thus, PTR has depth-profilometric ability: it can penetrate and yield information about an opaque or highly scattering medium well beyond the range of optical imaging. The laser-intensity modulation-frequency dependence of the penetration depth of thermal waves makes it possible to perform depth profiling of materials.[98] In PTR applications to dental hard tissue, optical and thermophysical material properties and depth information are obtained in two distinct superposed modes: conductively, from near-surface distances (~5–500 μm) controlled by the thermal diffusivity of enamel and the modulation frequency of the laser beam intensity, and radiatively, through midinfrared blackbody emissions from considerably deeper regions commensurate with the optical extinction (penetration) depth of the diffusely scattered laser optical field, a diffuse photon-density wave (several millimeters).[96,99] Owing to its depth-integral nature, the PTR signal consists of both surface and subsurface responses of dental tissue and as such it is expected that it can distinguish between caries, stains on tooth surface, and developmental white spots, unlike the fluorescence device such as QLF.[95,96] The radiative mode operates through emission of midinfrared blackbody photons that undergo much reduced scattering than the NIR source photons due to their much longer wavelength. These IR photons exit the dental tissue through spectral windows of relative transparency in enamel.[100] Fluorescence techniques monitor radiative emission variations between optically excited healthy and carious dental fluorophores and have been the mechanism behind the commercially available DIAGNOdent instrument.[101–103] A reader may at first take PTR/LUM to be

a point signal collection procedure and may thus be subject to the same limitation as DIAGNOdent. The most fundamental difference lies in the fact that PTR/LUM is a depth-profilometric technique, whereas DIAGNOdent and all other photonics-based technologies to date are not. PTR/LUM is sensitive to changes in both optical and thermal properties of the sample with zero PTR signal baseline unless there is optical absorption on the surface or in the bulk of the solid, whereas the DIAGNOdent only senses differences in optical properties through dc fluorescence changes and in the presence of a significant signal baseline even under conditions of healthy enamel. These differences render the combination of PTR and LUM techniques to have the highest signal dynamic range in detecting very early demineralization and thus predictably yield the best diagnostic results in caries diagnosis.[95,96] The introduction of modulated (dynamic) fluorescence ("luminescence") at the University of Toronto[93,99] revealed the existence of two relaxation lifetimes originating in the hydroxyapatite composition of dental enamel. Variations in LUM emission fluxes and lifetimes between healthy and carious enamel were shown to have a limited depth-profilometric character.[95,96] A combination of PTR and LUM has been developed into an analytical caries diagnostic tool of combined specificity and selectivity, substantially better than the DIAGNOdent, radiographic, and visual methodologies.[95,96] The combined technique and instruments PTR and LUM outputs four signal channels simultaneously: amplitudes and phases of photothermal and luminescence waves generated in response to harmonic laser source excitation. A study[95] that compared the caries diagnostic ability of PTR/LUM, DIAGNOdent, visual inspection, and radiographs with histological technique as the gold standard showed that the combined PTR/LUM method is superior to all other tested methodologies with sensitivity of 81%/79% and specificity of 87%/72% for caries level of enamel and dentin, respectively. Combining PTR and LUM showed a superior sensitivity and specificity over either PTR or LUM alone. In a second study,[97] the authors used a 670 nm, 450 mW laser at 30 Hz to examine approximal caries and demonstrated PTR to have the potential to be a reliable noninvasive tool for the detection of early approximal demineralized lesions, which cannot be detected by conventional bitewing radiography.

10. Cone beam computed tomography

The application of cone beam computed tomography (CBCT) in dental caries diagnosis has not been widely studied. The first and only study[104] that compared caries diagnosis ability of two CBCT systems, NewTom 3G (Quantitative Radiology) and 3DX Accuitomo, and two intraoral modalities, Digora-fmx (Soredex) and film (Kodak Insight), with histological technique serving as the validation standard concluded that the NewTom 3G CBCT had a lower diagnostic accuracy for detection of caries lesions than intraoral modalities and the 3DX Accuitomo CBCT. The Accuitomo CBCT had a higher sensitivity than the intraoral systems for detection of lesions in dentin, but the overall true score was not higher.[104] The investigation to apply in caries diagnosis stems from its numerous advantages when compared to all current forms of x-ray imaging. CBCT utilizes the least amount of radiation to obtain a diagnostic image while remaining cost effective for patients.[105] By comparison, the NewTom® 3G generates an average CBCT study using 12.0 μSv. This radiation dose is similar to a quarter panoramic image or five dental x rays using high-speed film.[105] Because less radiation means less exposure time, the complete cycle to make one slice by the NewTom® 3G takes 36 s, while the actual exposure time to the patient is 5.6 s.[105] By comparison, a panoramic image requires 20–100 μSv. CBCT scanners are more accurate than dental periapical films or panoramic x rays. While there is clearly less radiation used to generate a panoramic image, the amount of information it renders is less accurate and not as useful when compared to the three-dimensional images of a CBCT scan.[106]

II. CONCLUSION

It is clear from the above discussion that the differences in caries presentations and behavior in different anatomical sites make it unlikely that any one diagnostic modality will have adequate sensitivity and specificity of detection of carious lesions for all sites; a combination of diagnostic tools will help us diagnose lesions earlier and detect failing restorations sooner, all to avoid more costly, destructive dental procedures and truly take dentistry into the preventive rather than the reactive mode.

[1]G. K. Stookey, R. L. Isaacs, A. G. Ferreira Zandona, M. Ando, C. Gonzalez, M. S. Mau, S. A. Kelly, and M. Analoui, Proc. SPIE **3593**, 154 (1999).
[2]J. Bader, D. Shugars, and A. Bonito, *et al.*, J. Dent. Educ. **65**, 1162 (2002).
[3]M. Savage, Pediatr. Res. **114**, 418 (2004).
[4]F. J. Ramos-Gomez and D. S. Shepard, J. Calif. Dent. Assoc. **27**, 539 (1999).
[5]A. I. Zavras, B. L. Edelstein, and A. Vamvakidis, J. Public Health Dent. **60**, 182 (2000).
[6]E. H. Verdonschot, B. Angmar-Mansson, J. J. ten Bosch, C. H. Deery, M. C. Huysmans, N. B. Pitts, and E. Waller, Caries Res. **33**, 32 (1999).
[7]E. A. Kidd and N. B. Pitts, Br. Dent. J. **169**, 195 (1990).
[8]C. McKnight-Hanes, D. R. Myers, J. C. Dushku, W. O. Thompson, and L. C. Durham, Pediatr. Dent. **12**, 212 (1990).
[9]C. M. Flaitz, M. J. Hicks, and L. M. Silverston, Caries Res. **27**, 65 (1993).
[10]J. P. van Amerongen, C. Penning, E. A. Kidd, and J. M. ten Cate, Caries Res. **26**, 89 (1992).
[11]N. B. Pitts and C. E. Renson, J. Dent. Res. **64**, 1221 (1985).
[12]N. B. Pitts, Br. Dent. J. **162**, 378 (1987).
[13]D. N. Ricketts, E. A. Kidd, B. G. Smith, and R. F. Wilson, J. Oral Rehabil. **22**, 15 (1995).
[14]A. H. Forgie, C. M. Pine, and N. B. Pitts, Quintessence Int. **33**, 13 (2002).
[15]R. Haak, M. J. Wicht, M. Hellmich, A. Gossmann, and M. J. Noack, Caries Res. **36**, 249 (2002).
[16]E. Lynch and L. Abu-Naba'a, Dental Products News Journal, November 21, 2005.
[17]S. L. Creanor, J. I. Russell, D. M. Strang, and C. K.Burchell, Br. Dent. J. **169**, 126 (1990).
[18]A. Wenzel, E. H. Verdonschot, G. J. Truin, and K. G. Konig, J. Dent. Res. **71**, 1934 (1992).
[19]E. H. Verdonschot, E. M. Bronkhorst, R. C. Burgersdijk, K. G. Konig, M. J. Schaeken, and G. J. Truin, Caries Res. **26**, 59 (1992).
[20]A. I. Ismail, Community Dent. Oral Epidemiol. **25**, 13 (1997).
[21]H. M. van Rijkom and E. H. Verdonschot, Caries Res. **29**, 364 (1995).
[22]E. H. Verdonschot, E. M. Bronkhorst, and A. Wenzel, Community Dent. Oral Epidemiol. **19**, 329 (1991).
[23]C. M. Pine and J. J. ten Bosch, Caries Res. **30**, 381 (1996).
[24]J. Yang and V. Dutra, Dent. Clin. North Am. **49**, 739 (2005).
[25]A. T. Stodt, Schweiz Monatsschr Zahnmed **114**, 882 (2004).

[26]D. A. Young, Gen. Dent. **50**, 320 (2002).
[27]S. Keem and M. Elbaum, IEEE Trans. Med. Imaging **16**, 653 (1997).
[28]A. Schneiderman, M. Elbaum, T. Shultz, S. Keem, M. Greenebaum, and J. Driller, Caries Res. **31**, 103 (1997).
[29]D. A. Young and J. D. Featherstone, J. Am. Dent. Assoc. **136**, 1682 (2005).
[30]E. de Josselin de Jong, Caries Res. **29**, 2 (1995).
[31]S. Al-Khateeb and C. M. Forsberg, Am. J. Orthod. Dentofacial Orthop. **113**, 595 (1998).
[32]A. G. Ferreira Zandoná, R. L. Isaacs, M. H. van der Veen, and G. K. Stookey, in *Early Detection of Dental Caries II: Proceedings of the 4th Annual Indiana Conference*, Indianapolis, IN, USA, edited by G. K. Stookey (Indiana University, Bloomington, 2000), pp. 219–230.
[33]B. T. Amaechi and S. M. Higham, J. Biomed. Opt. **7**, 7 (2002).
[34]B. T. Amaechi and S. M. Higham, Proc. SPIE **4432**, 110 (2001).
[35]B. T. Amaechi and S. M. Higham, Caries Res. **35**, 269 (2001).
[36]Technical Manual for Quantitative Light-induced Fluorescence, Version 2000, Inspektor Research Systems BV, Amsterdam, The Netherlands.
[37]M. H. van der Veen and E. de Josselin de Jong, Caries Res. **33**, 318 (1999).
[38]E. de Josselin de Jong, Caries Res. **29**, 2 (1995).
[39]U. Hafström-Björkman, F. Sundström, E. de Joselin de Jong, A. Oliveby, and B. Angmar-Månsson, Caries Res. **26**, 241 (1992).
[40]M. Ando, A. F. Hall, G. J. Eckert, B. R. Schemehorn, M. Analoui, and G. K. Stookey, Caries Res. **31**, 125 (1997).
[41]S. Al-Khateeb, A. Oliveby, E. de Josselin de Jong, and B. Angmar-Månsson, Caries Res. **31**, 132 (1997).
[42]B. Angmar-Mansson and J. J. ten Bosch, Dentomaxillofac Radiol. **30**, 298 (2001).
[43]S. Al-Khateeb, C. M. Forsberg, E. de Josselin de jong, and B. Angmar-Mansson, Am. J. Orthod. Dentofacial Orthop. **113**, 595 (1998).
[44]M. Ando, M. H. van der Veen, B. R. Schemehorn, and G. K. Stookey, Caries Res. **35**, 464 (2001).
[45]S. Tranaeus, S. Al-Khateeb S. Bjorkman, S. Twetmen, and B. Angmar-Mansson, Eur. J. Oral Sci. **109**, 71 (2001).
[46]R. O. Rocha, T. M. Ardenghi, L. B. Oliveira, C. R. M. D. Rodrigues, and A. L. Ciamponi, Caries Res. **37**, 437 (2003).
[47]B. T. Amaechi and S. M. Higham, J. Clin. Dent. **13**, 100 (2002).
[48]B. T. Amaechi and S. M. Higham, Proc. SPIE **4249**, 157 (2001).
[49]P. E. Benson, N. Pender, and S. M. Higham, Eur. J. Orthod. **25**, 149 (2003).
[50]P. E. Benson, N. Pender, and S. M. Higham, Eur. J. Orthod. **25**, 159 (2003).
[51]J. M. ten Cate, M. D. Lagerweij, J. S. Wefel, B. Angmar-Mansson, A. F. Hall, A. G. Ferreira-Zandona *et al.*, in *Early Detection of Dental Caries II: Proceedings of the 4th Annual Indiana Conference*, Indianapolis, IN, USA, edited by G. K. Stookey (Indiana University, Bloomington, 2000), pp. 231–259.
[52]M. H. van der Veen and E. de Josselin de Jong, Monogr. Oral Sci. **17**, 144 (2000).
[53]D. J. White, R. V. Faller, and W. D. Bowman, J. Dent. Res. **71**, 929 (1992).
[54]L. E. Tam and D. McComb, J. Can. Dent. Assoc. **67**, 459 (2001).
[55]C. O. Hazelrigg, J. A. Dean, and M. Fontana, Pediatr. Dent. **25**, 119 (2003).
[56]I. A. Pretty, G. S. Ingram, E. A. Agalamanyi, W. M. Edgar, and S. M. Higham, J. Oral Rehabil. **30**, 1151 (2003).
[57]G. N. Komarov, B. T. Amaechi, and S. M. Higham, Caries Res. **37**, 313 (2003).
[58]X. Q. Shi, S. Tranaeus, and B. Angmar-Månsson, Caries Res. **35**, 21 (2001).
[59]S. Tranaeus, X. Q. Shi, L. E. Lindgren, K. Trollsås, and B. Angmar-Månsson, Caries Res. **36**, 3 (2002).
[60]M. H. van der Veen, R. Z. Thomas, M. D. Lagerweij, J. L. Ruben, and M. C. D. N. J. M. Huysmans, Caries Res. , **36** 315 (2002).
[61]A. Lussi, S. Imwinkelried, N. Pitts, C. Longbottom, and E. Reich, Caries Res. **33**, 261 (1999).
[62]D. N. Ricketts, E. A. Kidd, P. J. Liepins, and R. F. Wilson, Caries Res. **30**, 148 (1996).
[63]W. P. Rock and E. A. Kidd, Br. Dent. J. **164**, 243 (1988).
[64]P. F. Ashley, A. S. Blinkhorn, and R. M. Davies, J. Dent. **26**, 83 (1998).
[65]Y. L. Fennis-Ie, E. H. Verdonschot, and M. A. van't Hof, J. Dent. **26**, 403 (1998).
[66]P. F. Ashley, A. S. Blinkhorn, and R. M. Davies, J. Dent. **26**, 83 (1998).
[67]D. N. Ricketts, E. A. Kidd, P. J. Liepins, and R. F. Wilson, Caries Res. **30**, 148 (1996).
[68]H. Ciaburro, D.M.D. and Krause & Al, Occlusal caries detection in posterior teeth: An *in vivo* comparison of D-Carie and DIAGNOdent, sponsored study by NEKS Technologies, Inc.
[69]F. Martel, D.M.D., Interproximal caries detection: An *in vivo* comparison of D-Carie with x rays, sponsored study by NEKS Technologies, Inc.
[70]B. T. Amaechi and A. Podoleanu, J. Biomed. Opt. **8**, 642 (2003).
[71]B. T. Amaechi and A. Podoleanu, Oral Health Prev. Dent. **2**(4), 377 (2004).
[72]B. T. Amaechi and A. Podoleanu, Laser Phys. **13**, 703 (2003).
[73]B. T. Amaechi, A. G. Podoleanu, G. Komarov, S. M. Higham, and D. A. Jackson, Proc. SPIE **4610**, 100(2002).
[74]*Handbook of Optical Coherence Tomography*, edited by B. E. Bouma and G. J. Tearney (Marcel Dekker, New York, 2002).
[75]D. Huang and E. A. Swanson, Science **254**, 1178 (1991).
[76]A. F. Fercher and E. Roth, Proc. SPIE **658**, 48 (1986).
[77]F. I. Feldchtein, G. V. Gelikonov, V. M. Gelikonov, R. R. Iksanov, R. V. Kuranov, A. M. Sergeev, N. D. Gladkova, M. N. Ourutina, J. A. Warren, Jr., and D. H. Reitze, Opt. Express **3**, 239 (1998).
[78]A. Baumgartner, S. Dichtl, C. K. Hitzenberger, H. Sattmann, B. Robl, A. Moritz, A. F. Fercher, and W. Sperr, Caries Res. **34**, 59 (2000).
[79]A. Baumgartner, C. K. Hitzenberger, S. Dichtl, H. Sattmann, A. Moritz, W. Sperr, and A. F. Fercher, Proc. SPIE **3248**, 130 (1998).
[80]B. W. Colston, Jr., U. S. Sathyam, L. B. DaSilva, M. J. Everett, P. Stroeve, and L. L. Otis, Opt. Express **3**, 230 (1998).
[81]W. Colston, Jr., M. J. Everett, L. B. DaSilva, L. L. Otis, P. Stroeve, and H. Nathel, Appl. Opt. **37**, 3582 (1998).
[82]D. Fried, J. Xie, S. Shafi, J. D. Featherstone, T. M. Breunig, and C. Le, J. Biomed. Opt. **7**, 618 (2002).
[83]B. T. Amaechi, S. M. Higham, and A. Podoleanu, J. Oral Rehabil. **28**, 1092 (2001).
[84]B. T. Amaechi, A. G. Podoleanu, G. Komarov, S. M. Higham, and D. A. Jackson, in *Computer Methods in Biomechanics and Biomedical Engineering – 4*, edited by J. Middleton, N. G. Shrive, and M. L. Jones (University of Wales Press, Cardiff, 2002), Chap. 3.20.
[85]B. T. Amaechi, A. G. Podoleanu, C. Mujat, A. Dogariu, S. M. Higham, and D. A. Jackson, Proc. SPIE **4619**, 253 (2002).
[86]B. T. Amaechi, A. G. Podoleanu, J. A. Rogers, S. M. Higham, S. Dunne, and D. A. Jackson, Proc. SPIE **4619**, 180 (2002).
[87]B. T. Amaechi, A. G. Podoleanu, S. M. Higham, and D. A. Jackson, Proc. SPIE **4610**, 196 (2002).
[88]A. Gh. Podoleanu, R. B. Rosen, J. A. Rogers, G. M. Dobre, R. G. Cucu, D. A. Jackson, S. Dunne, and B. T. Amaechi, Proc. SPIE **5068**, 248 (2003).
[89]A. Gh. Podoleanu and D. A. Jackson, Appl. Opt. **38**, 2116 (1999).
[90]A. Gh. Podoleanu, J. A. Rogers, D. A. Jackson, and S. Dunne, Opt. Express **7**, 292 (2000).
[91]http://www.idmos.com/.
[92]J. D. Bader, D. A. Shugars, and A. J. Bonito, J. Dent. Educ. **65**, 960 (2001).
[93]L. Nicolaides, A. Mandelis, and S. H. Abrams, J. Biomed. Opt. **5**, 31 (2000).
[94]A. Mandelis, Proc. SPIE **4710**, 373 (2002).
[95]R. J. Jeon, C. Han, A. Mandelis, V. Sanchez, and S. H. Abrams, Caries Res. **38**, 497 (2004).
[96]R. J. Jeon, A. Mandelis, V. Sanchez, and S. H. Abrams, J. Biomed. Opt. **9**, 804 (2004).
[97]R. J. Jeon, A. Matvienko, A. Mandelis, S. H. Abrams, B. T. Amaechi, and G. Kulkarni, J. Biomed. Opt. **12**, 034028 (2007).
[98]M. Munidasa and A. Mandelis, in *Photothermal and Photoacoustic Science and Technology*, Photothermal Imaging and Microscopy Vol. I, edited by A. Mandelis (Society for Optical Engineering (SPIE), Bellingham, USA, 1992), pp. 300–358.
[99]L. Nicolaides, C. Feng, A. Mandelis, and S. H. Abrams, Appl. Opt. **41**, 768 (2002).
[100]M. J. Zuerlin, D. Fried, J. D. B. Featherstone, and W. Seka, IEEE J. Sel. Top. Quantum Electron. **5**, 1083 (1999).
[101]R. Hibst and K. Konig, U.S. Patent No. 5,306,144 (1994).

[102] R. Hibst and R. Paulus, Caries Res. **33**, 295 (1999).
[103] R. Hibst, R. Gall, and M. Klafke, U.S. Patent No. 6,024,562 (2000).
[104] F. Haiter-Neto, A. Wenzel, and E. Gotfredsen, Dentomaxillofac Radiol. **37**, 18 (2008).
[105] A. A. Winter, A. S. Pollack, H. H. Frommer, and L. Koenig, N. Y. State Dent. J. **71**, 28 (2005).
[106] M. Sonick, J. Abrahams, and R. Faiella, Int. J. Oral Maxillofac Implants **9**, 455 (1994).