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Diagnostic tools for early caries detection

Andréa Ferreira Zandoná, DDS, MSD, PhD; Domenick T. Zero, DDS, MS

Although there has been a significant decrease in caries prevalence in children from most developed countries, caries remains one of the most prevalent diseases, with 91 percent of adults experiencing caries in their lifetimes.¹ The widespread use and availability of fluoride has changed the behavior of carious lesions dramatically.^{2,3} The resulting slower progression of carious lesions has afforded the dental profession the opportunity to diagnosis and manage caries at an early stage, and this has led to renewed interest by researchers, clinicians and manufacturers of diagnostic tools in caries. However, this opportunity is not without its challenges from both a diagnostic and a treatment planning perspective.

The management of dental caries demands detection of carious lesions at an early stage.⁴ Since previous caries experience is the best predictor for future caries, the development of technology to detect and quantify early carious lesions and to assess carious lesion status directly (active versus inactive) may prove to be the best way to identify patients who require intensive preventive intervention.⁵ Most studies do not report the presence of non-cavitated lesions, though they have been shown to have predictive value.^{6,7}

Several new detection methods have been developed recently, and a

ABSTRACT



Background. Management of dental caries demands early detection of carious lesions. This article provides an overview of the state-of-the-art methodologies for the detection and assessment of early carious lesions.

Types of Studies Reviewed. The authors reviewed MEDLINE for available literature on new caries detection methodology and tools, using terms such as “early caries detection,” “fluorescence” and “transillumination.” Their review was not a systematic review of the literature. They included in their review in vitro, in situ, in vivo and clinical studies, as well as position papers, editorials and consensus conferences statements published in English.

Results. Each early caries detection tool has advantages and disadvantages; some perform better on certain surfaces than others. Therefore, their performance threshold and the operator’s influence on performance must be considered. Not all methods accurately detect early lesions, and false positives and false negatives may occur. Detecting early lesions in combination with assessing activity status is essential for establishing the prognosis and threshold required for preventive intervention. Clinically useful tools to help make such decisions are under development.

Clinical Implications. Early caries detection methods should be an adjunct to clinical decision making, supporting preventive treatment planning in conjunction with caries risk assessment but not justifying premature restorative intervention.

Key Words. Caries; enamel, evidence-based dentistry; fluorescence; preventive dentistry; radiograph.

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few have been introduced to clinical practice. Dentists, however, seem to be slow in adopting these new caries detection and treatment modalities.⁸ The objective of this article is to provide an overview of the state-of-the-art methodologies for detection of carious lesions and their uses in the early diagnosis of dental caries. We reviewed MEDLINE for available literature on new caries detection methodology and tools, using terms such as “early caries detection,” “fluorescence” and “transillumination”; our review, however, was not a systematic review of the literature. We included in our study *in vitro*, *in situ*, *in vivo* and clinical studies, as well as position papers, editorials and consensus conferences statements published in English.

EARLY DETECTION OF DENTAL CARIES

The ideal caries detection method should capture the whole continuum of the caries process, from the earliest stages through the cavitation stage. It should be accurate, precise, easy to apply and useful for all surfaces of teeth, as well as for caries adjacent to restorations.⁹ Assessment of lesion activity also is of importance.¹⁰

Traditionally, we have relied mostly on visual examination, with or without tactile sensation, aided by radiography for caries detection. Typically, to evaluate the caries status of a patient, we make a dichotomous decision (absence or presence) based on subjective signals such as color, translucency and hardness using relatively crude instruments such as explorers and radiographs. Often, the end result is low sensitivity and high specificity, meaning a large number of lesions may be missed. It is well-recognized that dental caries is a dynamic disease process, in which early lesions undergo many demineralization and remineralization cycles before being expressed clinically. Generally, only cavitated lesions are recorded; however, there is a consensus among researchers that the understanding of the caries process has progressed far beyond the point of restricting the evidence for dental caries at the cavitation level involving enamel or both enamel and dentin.¹¹ In the research arena, recording lesions only at the cavitation level is no longer acceptable, as determined at the 2004 International Consensus Workshop on Caries Clinical Trials in Loch Lomond, Scotland.¹¹

Several criteria have been proposed to reduce subjectivity, increase sensitivity and monitor lesions at an early stage (precavitation) and eval-

uate activity.^{12,13} The most recent development, the International Caries Detection and Assessment System (ICDAS),^{11,14} is meant to be a unifying set of predominantly visual criteria that can be used to describe the characteristics of clean, dry teeth at both the enamel and dentinal caries level and to assess caries activity (Figure 1). These criteria are being used in several clinical research studies. Preliminary data from ongoing studies and recently completed studies indicate that ICDAS is repeatable¹⁵ and has good sensitivity and specificity when compared with polarized light microscopy.¹⁴

Use of an explorer to detect caries has been studied extensively. There is a consensus that using an explorer to forcefully probe suspected carious pits and fissures does not add to diagnostic yield and may be damaging.¹⁶⁻²⁰ More appropriate strategies involve using explorers to remove plaque and lightly assess surface hardness.²¹

There also has been an effort to identify more technologically advanced measures to detect incipient dental caries. These technologies include quantitative laser or light fluorescence (QLF), electrical conductance measurements (ECM), infrared (IR) laser fluorescence, direct digital radiography and Digital Imaging Fiber-Optic Trans-Illumination (DIFOTI) (Electro-Optical Sciences, Irvington, N.Y.).²²⁻²⁴ All of these methods are available to dental practitioners. The research and evidence supporting the use of these methods are at different stages of development. It appears that methods based on optical properties (fluorescence and transillumination) have the most potential.²⁵

Fluorescence can be used for caries detection because of the difference in fluorescence observed between sound and demineralized enamel,²⁶ which is greater when the enamel is illuminated by light in the blue-green range (488 nanometers).²⁷⁻²⁹ Two methods based on the fluorescence of the organic components of teeth have been developed for use in caries detection and are available commercially; they are QLF (QLF-clin, Inspektor Research Systems BV, Amsterdam, Netherlands), which uses an arc lamp with a 290- to 450-nm wavelength, and DIAGNOdent (KaVo Dental, Lake Zurich, Ill.), which uses IR light and has a 655-nm wavelength. Another approach that has been investigated but has not yet been developed commercially involves a fluorescence spectrophotometer, which uses several wavelengths.³⁰

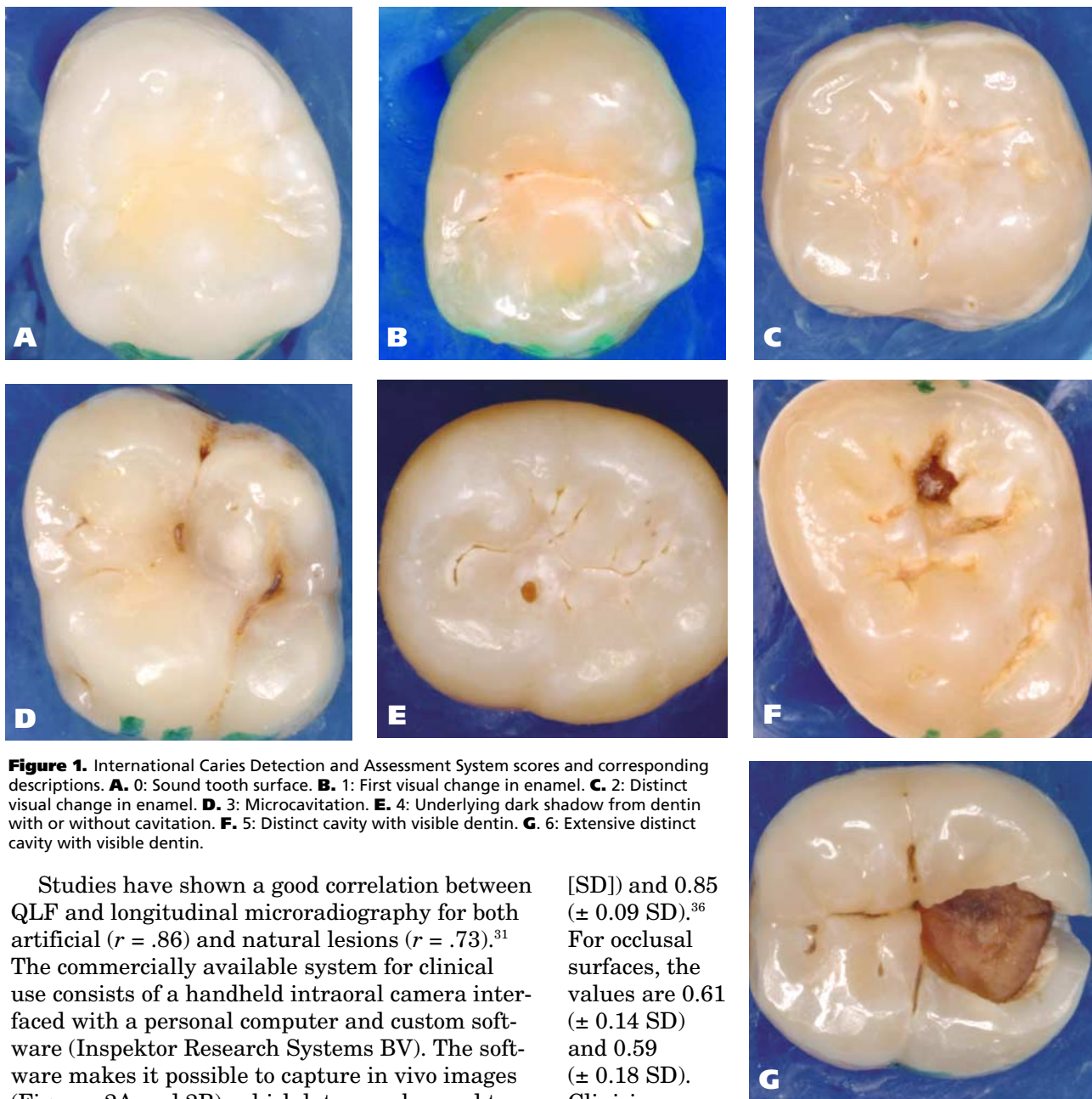


Figure 1. International Caries Detection and Assessment System scores and corresponding descriptions. **A.** 0: Sound tooth surface. **B.** 1: First visual change in enamel. **C.** 2: Distinct visual change in enamel. **D.** 3: Microcavitation. **E.** 4: Underlying dark shadow from dentin with or without cavitation. **F.** 5: Distinct cavity with visible dentin. **G.** 6: Extensive distinct cavity with visible dentin.

Studies have shown a good correlation between QLF and longitudinal microradiography for both artificial ($r = .86$) and natural lesions ($r = .73$).³¹ The commercially available system for clinical use consists of a handheld intraoral camera interfaced with a personal computer and custom software (Inspektor Research Systems BV). The software makes it possible to capture in vivo images (Figures 2A and 2B), which later can be used to quantify the lesion size, depth and volume from the image of the tooth. The parameters produced by the software are lesion area (in square millimeters), lesion depth (percentage of fluorescence loss) and lesion volume (the product of lesion area in mm^2 and the lesion depth in percentage of fluorescence loss).³²

Several in vitro studies have shown a good correlation between percentage of fluorescence loss and depth, demineralization time or both.³³⁻³⁷ For smooth surfaces, the mean sensitivity and specificity of QLF is $0.76 (\pm 0.02$ standard deviation

[SD]) and $0.85 (\pm 0.09$ SD).³⁶ For occlusal surfaces, the values are $0.61 (\pm 0.14$ SD) and $0.59 (\pm 0.18$ SD).

Clinicians can obtain more useful information by calculating the positive predictive value (PPV), which indicates the probability that a patient has a carious lesion when the test method gives a positive result, and the negative predictive value (NPV), which is the probability that the patient is caries-free when the test method gives a negative result. Pretty and colleagues³⁶ summarized the PPV and NPV for QLF both in a high-risk population and a low-risk population. In a high-risk population, the PPV would vary between 0.90 and 0.98 depending on the surface and type of lesion (primary, sec-

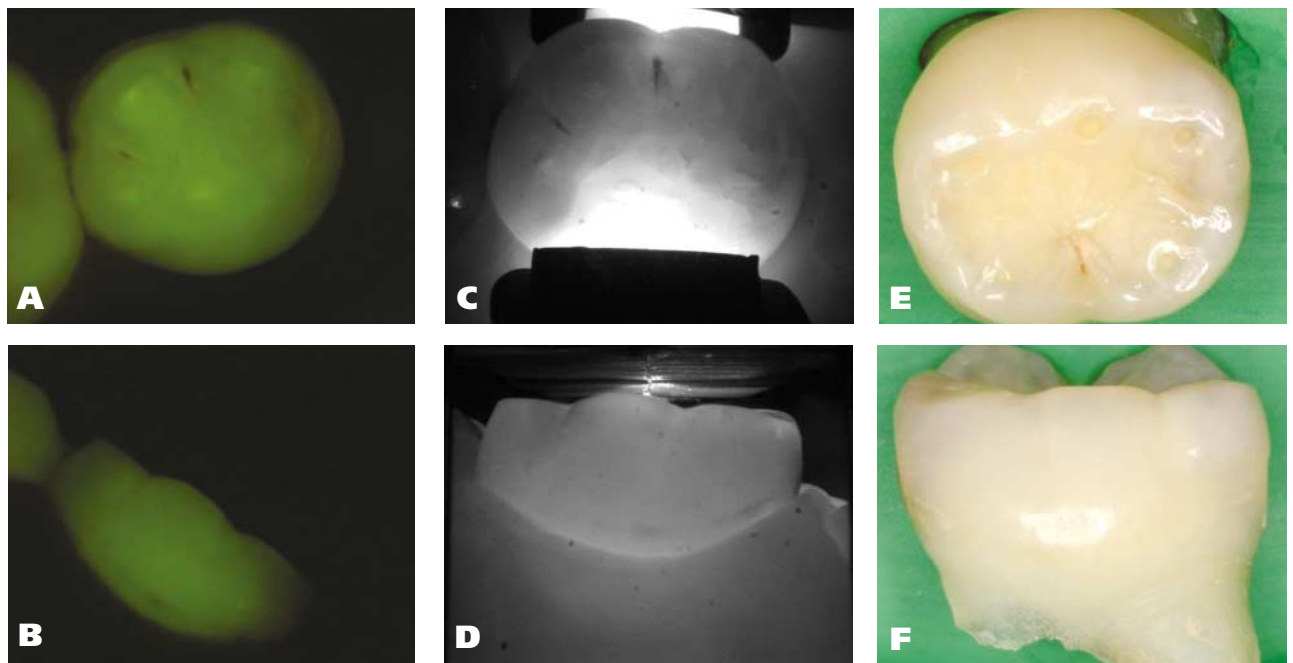


Figure 2. Examples of lesions on occlusal (A) and buccal (B) surfaces imaged with quantitative laser or light fluorescence, examples of lesions on occlusal (C) and buccal (D) surfaces imaged with digital imaging fiber-optic transillumination, and examples of lesions on occlusal (E) and buccal (F) surfaces imaged with corresponding white light after the tooth was exfoliated. Figures 2C and 2D were provided by Dr. Masatochi Ando.

ondary or around orthodontics brackets), and NPV would vary between 0.35 (occlusal surfaces) and 0.70 (secondary lesions). In a low-risk population, the values are inverted; PPV would vary between 0.20 (occlusal surfaces) and 0.65 (around orthodontic brackets), and NPV would vary between 0.95 (occlusal) and 0.98 (secondary or around orthodontic brackets). Therefore, if QLF is used in a high-risk population, a positive result would indicate that the clinician could be more than 90 percent certain that the tooth was carious. A negative result would indicate that the certainty was less and was more dependent on the surface type; that is, greater certainty (70 percent) of a caries-free surface if the surface investigated was around a restoration than if it was on an occlusal surface (35 percent). Several studies have demonstrated that the system can be used reliably by different examiners.³⁸⁻⁴¹ Concerns about the system relate to the confounding effects that stains, plaque, and fluorosis or other enamel opacities such as hypomineralization can have on lesion depth.^{42,43}

Using a different wavelength and light source, Hibst and Paulus⁴⁴ developed a system (DIAGNOdent) using IR light to detect caries based on the difference in fluorescence between sound and demineralized enamel. In vitro studies

have shown that the system has higher sensitivity and specificity than ECM for smooth surfaces⁴⁵ and occlusal surfaces⁴⁶ with high interexaminer agreement.⁴⁵⁻⁴⁷ An in vivo study showed that the system can be an adjunct to a visual examination for the detection of early enamel lesions on smooth surfaces,⁴⁷ another found the system to have low detection ability for early lesions.¹⁴ The system may overscore lesions compared with a visual examination, which may be caused by a disturbance in tooth mineralization (not due to caries, but to developmental hypomineralized regions) and can be a disadvantage.⁴⁸ Some areas such as the central and distal fossae seem to have higher initial readings,⁴⁹ and in older patients the diagnostic performance might decrease.⁵⁰ Although further research is needed to explain these findings, it is likely that the higher readings reflect different maturation levels and presence of stains. During clinical use as with other caries detection methods, the tooth surfaces must be plaque-free for accurate measurement. Also, the device must be calibrated frequently for longitudinal comparisons,⁵¹ the surfaces must be plaque-free, and the probe must be rotated in all directions to obtain the highest reading.⁴⁸

Recent developments with this technique have led to the introduction of a hand-held laser caries

detection aid (DIAGNOdent pen, KaVo, Biberach, Germany).⁵² This device is similar to DIAGNOdent in that it emits red light with a wavelength of 655 nm and has a filter blocking light below a wavelength of 665 nm to eliminate reflected and ambient light, but it uses a probe with a tip that is designed specifically to fit the interproximal space between posterior teeth. The probe tip is a wedge-shaped, solid, single sapphire fiber with a prismatic shape. To help the operator place the probe on approximal surfaces on the buccal and lingual sides of anterior and posterior teeth, the tip can be rotated around its long axis. When the hand-held laser caries detection aid was tested *in vitro* on occlusal surfaces, sensitivity values for lesions in outer enamel, inner enamel and dentin ranged between 0.78 and 0.96, and specificity values ranged from 0.69 to 0.89; there was no difference between the tip of the new device and the tip of the old device.⁵³ For detection of approximal lesions, specificity values for white spots through lesions involving dentin ranged from 0.81 to 0.93, sensitivity values ranged from 0.84 to 0.92, with no difference between the two tips.⁵² When they compared the hand-held laser caries detection aid with bitewing radiographs, the likelihood ratios were higher for the hand-held laser caries detection aid on enamel lesions (13.3 versus 1.7) and similar for dentinal lesions (4.8 versus 5.3). Likelihood ratios describe the relationship between true positives and false positives; therefore, an enamel lesion detected by the hand-held laser caries detection aid is more likely to be present. Lussi and colleagues⁵² concluded that the new laser fluorescence system might be a useful additional tool in detecting approximal caries and, because of its good reproducibility ($\kappa > 0.74$), it could be used to monitor caries regression or progression on approximal surfaces. The hand-held laser caries detection aid recently has been made available commercially.

Fiber-optic transillumination (FOTI) allows for the detection of a carious lesion because of the changes in the scattering and absorption of light photons resulting from a local decrease of transillumination owing to the characteristics of the carious lesion. When it is used for the detection of

interproximal caries, a high-intensity light is placed on the buccal surface, and the interproximal surface is observed by transillumination through the occlusal surface.⁵⁴ Enamel lesions appear as gray shadows, and dentinal lesions appear as orange-brown or bluish shadows.⁵⁵ Most studies of FOTI have shown good sensitivity (89 percent for dentinal lesions)⁵⁶ and specificity values for detection of interproximal lesions in dentin when compared with bitewing radiographs.⁵⁷ Both the 2001 National Institutes of Health (NIH) Consensus Development Conference on Diagnosis and Management of Dental Caries Throughout Life in Bethesda, Md.,⁵⁸ and the 2004 International Consensus Workshop on Caries Clinical Trials in Loch Lomond, Scotland,¹¹ concluded that there is an adequate body of evidence supporting the use of FOTI for detection of interproximal lesions.

Studies have investigated the use of FOTI on occlusal surfaces.^{55,59,60} In an *in vitro* study, FOTI performed as well as visual examination, had higher specificity both for enamel lesions (96 percent sensitivity and 74 percent specificity) and dentinal lesions (89 percent sensitivity and 92 percent specificity) and had a better correlation with histology.⁵⁵ No clinical studies to date have reported occlusal caries with FOTI.

DIFOTI is a more recent development combining FOTI with a charge-coupled device digital intraoral camera.²⁴ One *in vitro* study indicated that the method has higher sensitivity than does a radiographic examination for detecting lesions on interproximal, occlusal and smooth surfaces.²⁴ With this system, the images are captured and displayed on a computer screen (Figures 2C and 2D), which can be compared with the clinical presentation (Figure 2E and 2F); however, as with FOTI, the detection is based on a subjective interpretation of the appearance of the lesion. There have been no published clinical studies supporting this approach, even though the method is available commercially.

ECM is another method that has been proposed as a caries detection method. The concept was mentioned by Magitot⁶¹ in 1878. Sound surfaces have little or no conductivity and demineralized surfaces have measurable conductivity that

No single caries detection method can be used on all surfaces under all circumstances. Therefore, clinicians must decide which tooth surfaces will benefit from the use of an additional detection method.

increases according to the demineralization level.⁶² Two devices have been developed for clinical use limited to occlusal surfaces⁶³ that measure electrical conductance by placing the tip of the instrument on the fissure or groove and the connector on a high-conductivity area such as the skin. A review article by Huysmans⁶⁴ concluded that there is variation among the results from using this method, but usually sensitivity is heightened compared with a visual examination and specificity is lower. Clinically, this would mean that a false positive reading is given for 23 to 29 percent of sound teeth, increasing the risk of patients' experiencing inappropriate restorative intervention.⁶⁵ Several factors can influence the ECM readings, such as dehydration state,⁶⁶ tooth maturation stage⁶⁷ and the presence of stains.⁶⁸

The NIH consensus conference concluded that "the current diagnostic practices are inadequate to achieve the next level of caries management in which non-cavitated lesions are identified early so that they can be managed by non-surgical methods."⁵⁸ Therefore, one must evaluate the findings from early caries detection methods carefully before making clinical diagnostic decisions solely on the basis of the values provided. As we described earlier, there are differences in performance based on surface type for each of the caries detection methods; thus, their performance threshold also must be considered. Not all methods can detect early lesions accurately, and false positive and false negative results may occur. There also is a strong operator influence on the performance of the methods, with different operators obtaining different results.

No single caries detection method can be used on all surfaces under all circumstances. Therefore, clinicians must decide which tooth surfaces will benefit from the use of an additional detection method. If the goal is to have a method to follow interproximal lesions without increasing radiation exposure, FOTI and DIFOTI seem to work adequately. If the goal is to follow occlusal surfaces, a threshold must be identified, depending on whether the objective is to monitor early lesions or to identify lesions that should be restored. QLF is better suited to monitor early lesions and DIAGNOdent works better on more advanced lesions. However, independent of the

method chosen, clinicians must be properly trained to minimize the possibility of false positives or false negatives, which can lead to overtreatment or undertreatment, respectively.

At the current state of development, early caries detection tools such as QLF, ECM, DIAGNOdent, DIFOTI or FOTI should be used as an adjunct to clinical decision making and serve primarily as a support tool for making preventive treatment plan decisions in conjunction with caries risk assessment. It is important that all these tools be used as diagnostic adjuncts to aid in early caries detection and not as a justification for premature restorative intervention.

ASSESSING THE ACTIVITY STATUS OF EARLY LESIONS

While detecting noncavitated carious lesions is important, it represents only part of the diagnostic process necessary to properly assess the patient's caries status. The current understanding of the dynamic nature of the caries process, in which lesion progression can be arrested at any stage of the process, supports the importance of clinically assessing caries activity.¹⁰

The diagnosis process should include assessing if early lesions are active (progressing), arrested or regressing. Diagnosing caries activity permits dentists to make informed decisions regarding the use of sealants and topical fluoride varnish treatment on a tooth surface-specific basis. Evidence of clinically evident active disease is a strong indicator that caries is occurring elsewhere in the mouth at a subclinical level. Thus, the early diagnosis of dental caries disease activity also can increase the reliability of caries risk assessment so that appropriate whole-mouth preventive intervention can be initiated.

A brief review of the physical chemistry of the caries process can be helpful in understanding what happens clinically. Acids produced by the plaque biofilm must diffuse inward and reaction products (calcium and phosphate) must diffuse outward through the enamel surface layer for the caries process to progress. The first visual clinical presentation of dental caries, which often is referred to as a "white-spot" lesion, actually is a relatively late stage of the caries process. The increase in porosity below the enamel surface

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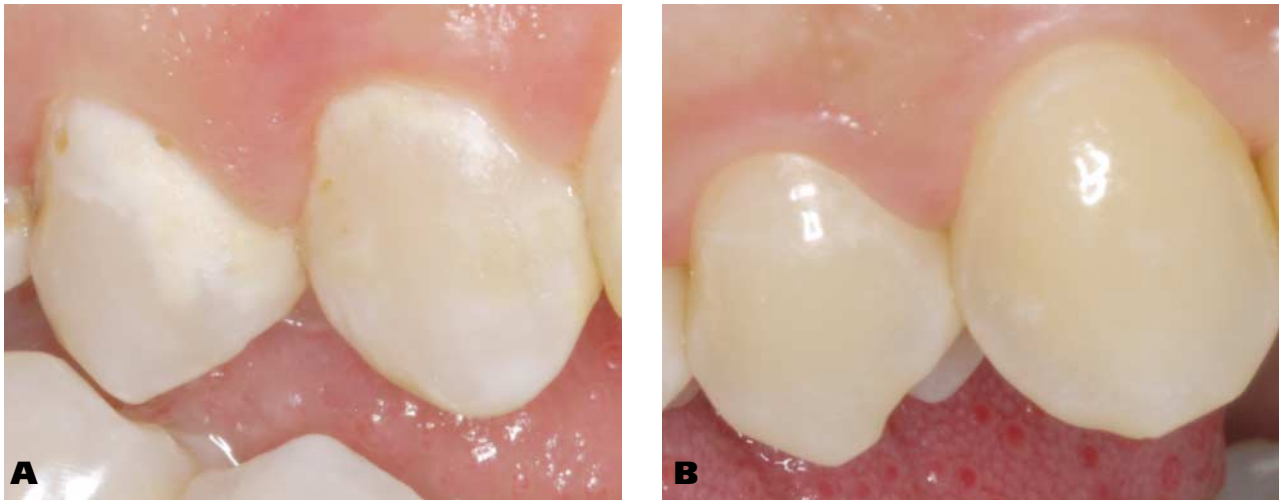


Figure 3. A. An active white-spot lesion on the buccal surface of teeth nos. 5 and 6. The surface can be described as dull, rough and chalky white in a plaque stagnation area with adjacent mild gingivitis. B. A distinct case with an arrested white-spot lesion on the buccal surface of teeth nos. 5 and 6. The surface can be described as shiny, smooth, translucent and having healthy adjacent gingiva.

results in the scattering of light and loss of enamel translucency and thus the white appearance. Therefore, the porosity of the enamel surface will determine if a lesion is actively progressing or has been arrested. Available preventive strategies are successful at preventing lesion progression by directly or indirectly affecting the porosity of the tooth surface; sealants block the diffusion of acids through the enamel surface, fluoride helps maintain the integrity of the enamel surface through its protective and remineralizing effects, and plaque removal and diet modification reduce or eliminate the caries challenge to the enamel surface by permitting saliva to stabilize and repair the surface. In addition, the plaque can serve as a mineral-rich reservoir that is immediately available during an acid challenge to stabilize and repair the enamel surface.

Active lesions have a dull chalky appearance on the surface, owing to light scattering (Figure 3A). Other factors such as lesion location also can help determine activity. Active lesions are likely to be in plaque stagnation areas and close to the gingival margin, while arrested lesions will tend to be in areas that are not plaque stagnation areas (such as in an interproximal surface in which a tooth is no longer present) and further from the gingival margin (indicating that the lesion may have occurred during eruption). Clinically, arrested lesions tend to have smooth surfaces that reflect light, giving a shiny appearance, which also may accumulate pigmentation (Figure 3B). Arrested lesions will tend to have

hard, intact surfaces, while active lesions will have a softer chalky surface due to increased porosity, which can be determined by gently dragging an explorer across the tooth surface.

In many cases, white spots are lesions that have self-arrested as part of the natural history of the disease or have arrested owing to a change in the local environment. These lesions can be considered scars from disease activity occurring years or even decades earlier. Arrested lesions are more resistant to subsequent cariogenic challenges than sound enamel and, thus, should not receive restorative treatment unless the patient has esthetic concerns.⁶⁹ An active lesion may become visibly shinier (reflect more light) owing to the repair of the surface layer after preventive treatment (application of fluoride and improved tooth brushing); however, depending on the depth of the white-spot lesion, it may be impossible to completely eliminate the optical changes in the body of white-spot lesions. Once the porous surface layer of an early lesion is remineralized, the deeper body of the lesions is effectively cut off from salivary minerals (calcium and phosphate) and fluoride.

With the ubiquitous use of fluoride, it is likely that many incipient lesions are arrested before they ever become clinically detectable or require clinical intervention. Backer Dirks⁷⁰ established that white spots do not necessarily progress to a frank cavitation, and they may take on the appearance of sound enamel over time. Enamel demineralization is a daily occurrence that does not necessarily lead to dental caries. Therefore,

the loss of tooth mineral should not be considered to be a disease process. However, demineralization that results in net loss of tooth structure can be considered to be a disease process, which may or may not require intervention. If the rate of demineralization does not exceed a threshold level, the process may be self-limiting, as long as the enamel surface layer remains macroscopically intact. The challenge is to detect lesion activity at a threshold that leads to appropriate early intervention but not to overtreatment (that is, restoration). Although white spots formed on buccal smooth surfaces have been the most extensively studied, pit and fissure caries and root caries also pass through an incipient stage with subsurface demineralization that can be characterized based on lesion activity.

The assessment of the caries activity status of early lesions is as challenging as it is important. The challenge for clinicians is that careful visual and tactile inspection is required to assess lesion activity. Clinical diagnosis criteria have been developed^{12,13} and validated in a high prevalence caries population⁷¹ to assess lesion activity. Caries activity criteria are being evaluated as part of ICDAS. The criteria are based on the physical properties of surface reflection and texture of early lesions, with chalky rough surfaces being active, and smooth, shiny surfaces being inactive. The color of the lesion also can be used to make the distinction between arrested and active lesions, with arrested lesions having an internal brown pigmentation and surface stain and active lesions retaining their white appearance.

A recent study⁷² pointed out the difficulty in trying to differentiate active lesions from inactive lesions in one appointment without specific training or calibration. Given the highly site-specific nature of caries, it is possible to have areas that are arrested and active on the same tooth surface. There also is the possibility of lesions being in a transitional stage, either going from active to inactive or from inactive to active. When there is uncertainty about the diagnosis, the clinician has the option to defer giving a definitive diagnosis until the next recall visit.

The future holds promise for the development of clinically useful tools to help dentists make decisions about the activity status of carious lesions. Available technology, such as

DIAGNOdent and ECM, may be useful only for monitoring changes in lesion activity over time. QLF has the potential for detecting the caries activity of lesions by measuring the pattern of fluorescence radiance change during dehydration.^{73,74} The development of user-friendly technology to help dentists make real-time assessments of the activity status of early lesions should be given the highest research priority.

CONCLUSIONS

Scientific evidence that the early stages of caries can be arrested and possibly reversed if the caries challenge is modified or removed (reduced cariogenic diet, improved oral hygiene) or if the protective factors are increased (fluoride in various delivery modalities, increased salivary flow for those with decreased salivary flow), provides strong support for taking a more conservative approach to the management of noncavitated dental caries. A challenging problem facing dentists' every day is determining whether preventive intervention or a combination of preventive and restorative intervention is required based on the severity and activity status of noncavitated carious lesions. A clinically useful tool to detect and assess early caries should not lead to the overdiagnosis of caries and possible overtreatment but help clinicians detect caries at a threshold that requires preventive intervention.

We have reviewed several new approaches that may help clinicians with this diagnostic process. Each of these caries detection tools has certain advantages and disadvantages. As with other methods, early detection should not be an excuse for early restorative intervention.⁶⁵ However, the key question as to whether they improve patients' dental health outcomes has yet to be answered. ■

The challenge is to detect lesion activity at a threshold that leads to appropriate early intervention but not to overtreatment.

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