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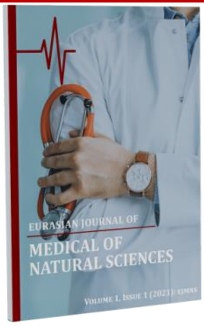

EARLY CARIES DETECTION, DIAGNOSIS, AND MONITORING: PAVING THE WAY FOR PERSONALIZED DENTAL CARE

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ABSTRACT
Dental caries continues to be a major global health concern. The World Health Organization's 2022 reports emphasize that despite significant efforts and scientific progress in caries detection and management, the overall situation has shown only minimal improvement over the past three decades. This persistence may be attributed to outdated concepts, developed nearly a century ago, that still influence modern approaches to caries management. There is an urgent need to rethink professional strategies for preventing and managing caries. Modern dentistry has the potential to greatly benefit from adopting innovative concepts and advanced technologies for caries detection and treatment. Among these, optical-based caries detection methods, which have been established for over a decade, align with contemporary understandings of the disease and adhere to international recommendations emphasizing early detection and minimally invasive management. This narrative review explores the current state of knowledge and recent advances in caries detection, diagnosis, monitoring, and management, while offering insights into future directions for clinical practice and research.

1. Introduction

The 2017 Global Burden of Disease study, published in *The Lancet*, reported that among 328 examined diseases, dental caries in permanent teeth had the highest prevalence and ranked second in incidence. Alarmingly, over one-third of the global population lives with untreated dental caries. For deciduous teeth, untreated caries remains the most prevalent chronic childhood disease, affecting an estimated 514 million children worldwide.

This underscores the need to shift the focus from merely treating the symptoms of dental caries (such as cavities, discoloration, and pain) to preventing the disease and managing its early signs (such as initial lesions and biofilm dysbiosis). Dentistry's early establishment as a surgical discipline in the 20th century led to a primarily operative approach for managing dental caries. Initially, this approach was necessary due to the limited means available at that time to treat extensive caries and related complications. However, with the widespread adoption of oral hygiene practices and fluoridated toothpaste, the presentation of dental caries has changed. Today, clinicians primarily encounter slow-progressing, non-cavitated early lesions. Unfortunately, the current restorative-focused practice does not adequately reflect the growing body of evidence supporting the effectiveness of early prevention and non-invasive management strategies.

A key issue is that operative intervention remains the dominant strategy taught in dental schools and practiced by most dentists. Historically, dental caries was viewed as an irreversible process that required mechanical removal of the affected tissue, as advocated by G.V. Black's "extension for prevention" concept. However, in 1935, the discovery of enamel "white spots," initially believed to be photographic artifacts, laid the groundwork for understanding early enamel lesions. Subsequent research in the 1940s and 1950s expanded this understanding, and by the 1970s, dental caries was recognized as a multifactorial infectious disease associated with bacterial biofilm on the tooth surface. This evolving knowledge highlighted that demineralization is a reversible sign of active disease, a concept that became widely accepted by the late 1980s.

Fejerskov et al. defined dental caries as "the results (the signs and symptoms) of a localized chemical dissolution of the tooth surface caused by metabolic events taking place in the biofilm (dental plaque) covering the affected area." More recently, the World Health Organization (WHO) classified dental caries as a "plaque (biofilm)-mediated, non-communicable disease (NCD), with a complex network of biological, genetic, behavioral, socioeconomic, and lifestyle-related risk factors, similar to other NCDs such as obesity and diabetes." This classification highlights the fact that no single risk factor—whether bacterial load, sugar intake, or salivary flow—can independently predict or manage the occurrence of dental caries.

Over the past few decades, novel approaches to managing dental caries have emerged in response to this evolving understanding of the disease. These approaches have sparked ongoing debates and discussions about optimizing caries prevention and treatment. A key concept in modern caries management acknowledges caries as a non-communicable disease closely linked to individual behaviors and lifestyle factors.

Traditional preventive measures, such as improving oral hygiene, using fluoridated toothpaste, applying topical fluoride, and modifying the diet in individuals showing early signs of caries, have often been labeled as "prevention." However, this term may be misleading, as these interventions do not entirely prevent caries but rather slow down or delay the progression of non-cavitated lesions into cavitated ones. Unfortunately, the term "prevention" is often contrasted with "treatment," where the latter is understood as operative interventions such as drilling and restoration. Many patients, dentists, and policymakers tend to favor operative treatments as the primary means of managing caries, without considering that once a tooth is restored, it enters a "restorative cycle," which increases the likelihood of tooth loss over time.

The conventional operative approach has set the expectation that achieving a fully restored dentition with no visible signs of caries is the gold standard. This perspective has made it difficult to accept that not all lesions are active or pose a risk to the patient's health.

Recognizing that arrested lesions can be viewed as "scars" has the potential to transform the way clinicians approach caries management and conduct clinical examinations.

Today, it is evident that dental professionals must adopt new concepts and leverage available technologies to improve caries detection, assessment, and management. This review aims to explore the latest evidence surrounding contemporary concepts in caries management, with a particular focus on modern optical-based technologies such as near-infrared transillumination and laser fluorescence imaging. These technologies, when combined with non-invasive and minimally invasive treatments like sealing and infiltrating early lesions, align with modern caries management principles and international guidelines.

The review presents a comprehensive approach to caries management that integrates current evidence on caries detection, activity assessment, and patient risk evaluation. Ultimately, it encourages readers to reflect on the existing landscape and emphasizes the need for future research to support personalized dental care. To develop this review, relevant studies published in the past decade were retrieved from electronic databases, including PubMed, Scopus, and Science Direct.

2.Caries Terminology, Severity, and Activity Assessment

A clear understanding and consistent use of dental caries terminology is essential for effective teaching, communication, and research. Various classification systems exist, most of which are based on the lesion's location, depth, and clinical characteristics. More recent therapeutic classifications of primary caries emphasize that the primary focus should be on determining lesion activity and assessing enamel surface integrity.

During clinical examination, when formulating a care plan for the patient, this assessment should be conducted at multiple levels: the patient level, the oral cavity level, the tooth level, and the lesion surface level.

2.1. Caries Lesion Severity Assessment

Assessing the severity of caries lesions helps categorize the progression of mineral loss, ranging from minor enamel changes to advanced stages involving dentin and, eventually, the dental pulp. Various classification methods can be used for this evaluation. Clinically, lesions may be categorized into non-cavitated, micro-cavitated, and cavitated stages. Similarly, clinical and radiographic staging classifies lesions as initial, moderate, or extensive. Additionally, lesion progression may be assessed from non-cavitated lesions to pulpal sepsis.

2.1.1. Non-Cavitated Lesions

Non-cavitated lesions, also known as pre-cavitated, incipient, or early lesions, are commonly referred to as "white spot" lesions due to their characteristic white appearance. This discoloration results from changes in the mineral content and porosity of the enamel surface. In some cases, the demineralization may even extend to the dentin and trigger a response long before the formation of an actual cavity.

It is crucial to avoid using a sharp probe during clinical examinations, as applying excessive pressure can irreversibly damage the demineralized enamel surface and convert a reversible lesion into a cavitated one. A dull-ended probe with gentle pressure is recommended for examining these lesions.

Non-cavitated lesions can either be active or arrested, and their management depends on determining the lesion's activity. The clinician's judgment, based on the lesion's clinical characteristics and an overall assessment of the patient's oral health status, is essential for distinguishing between the two.

- Active Non-Cavitated Lesions: These lesions can often be managed through remineralization using fluoride and calcium-based products.
- Arrested Non-Cavitated Lesions: If non-invasive management proves ineffective, sealing or infiltrating the lesion with resin can prevent further demineralization by forming a diffusion barrier that protects against acid exposure.

2.1.2. Cavitated Lesions

As tissue destruction progresses, the enamel's mechanical resistance diminishes, leading to surface breakdown and the formation of micro-cavities. These small, localized surface defects initially affect only the enamel but can extend deeper, eventually exposing dentin and giving rise to what is classified as a "cavitated lesion."

Cavitated lesions that expose dentin are more challenging to clean due to the accumulation of biofilm, which accelerates lesion progression. Such lesions are generally considered irreversible and require restorative intervention, except in certain situations where biofilm control can be effectively maintained, such as in vestibular-accessible lesions.

- **Assessment of Cavitated Lesions:** While cavitated lesions on occlusal and vestibular surfaces can be readily assessed through clinical examination, proximal lesions typically require radiographic evaluation. Although earlier studies suggested that all proximal lesions reaching the inner half of the dentin on bitewing radiographs are cavitated, more recent research indicates that only one in three lesions in the first third of the dentin may be cavitated.

Traditionally, cavitated lesions have been managed by removing the carious tissue and restoring the defect with a filling. However, in certain cases, sealing cavitated lesions can arrest their progression by depriving bacteria of carbohydrates essential for their metabolism. Sealed bacteria become non-cariogenic due to reduced metabolic activity, effectively halting lesion progression.

- **Sealing Moderate Lesions:** Moderate lesions with micro-cavities confined to the enamel may be successfully sealed. However, for cavitated lesions that expose dentin, guidelines recommend complete excavation to ensure the long-term success of the restoration. The periphery of the lesion should consist of hard, clean enamel and dentin, while deeper areas may retain re-mineralizable dentin to facilitate healing and maintain structural integrity.

By adopting a comprehensive approach to lesion assessment and integrating evidence-based methods, clinicians can enhance the effectiveness of caries management and provide optimal care for their patients.

2.2. Caries Lesion Activity Assessment

To establish personalized and minimally invasive oral care, it is essential to categorize caries lesions as either "active" or "arrested" and to continuously monitor their status. Only a few validated systems are available for assessing lesion activity, including the International Caries Detection and Assessment System (ICDAS) and the Nyvad criteria, both of which rely on evaluating the lesion's clinical characteristics.

Caries activity is a reflection of the mineral balance over time, indicating net mineral loss, net mineral gain, or stability. It serves as an indicator of caries initiation or progression, while lesion inactivity suggests that the caries process has stopped or regressed. The primary objective of caries lesion activity assessment is to distinguish between active and inactive lesions, which allows for optimal care planning aimed at halting active lesions. However, even inactive lesions and healthy tooth surfaces require continuous care and routine monitoring to maintain oral health.

2.2.1. Active Lesions

Evaluating lesion activity involves considering multiple factors such as the lesion's color, location, texture, and certain clinical aspects not directly related to the lesion itself.

- **Color and Surface Appearance:** Active pre-cavitated enamel lesions typically present as whitish or yellowish opaque areas with a loss of surface luster. The lack of luster results from mineral dissolution and the resulting porosity in the enamel structure.
- **Surface Texture:** When gently probed with a dull-ended instrument, the surface of an active lesion feels rough and porous, indicating ongoing mineral loss.
- **Plaque Coverage:** Active lesions are often covered by plaque, which contributes to continuous demineralization. Plaque accumulation over these lesions can accelerate the caries process by maintaining an acidic environment that further weakens the enamel and promotes lesion progression.

Identifying and addressing active lesions at an early stage is critical to preventing the transition to cavitated lesions, thereby preserving tooth structure and minimizing the need for invasive treatment.

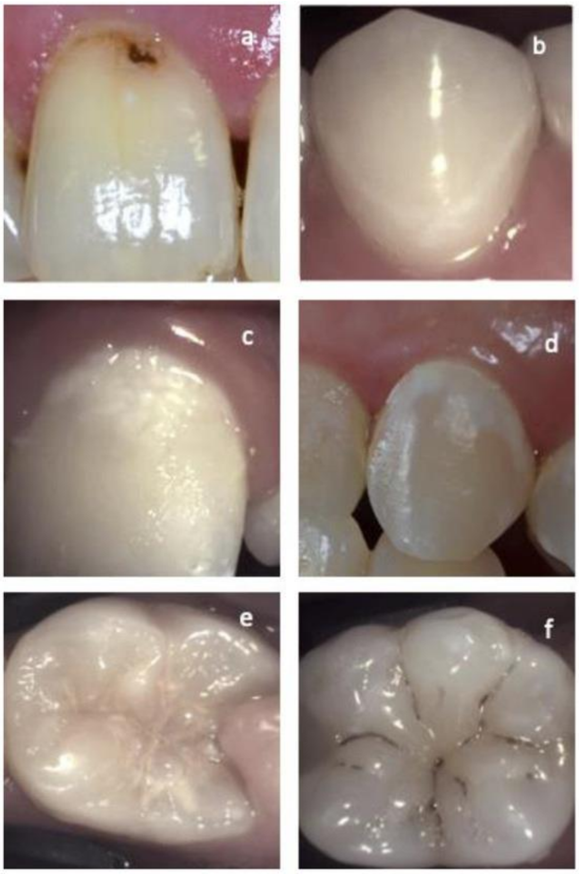

Figure 1. Various examples of active and arrested lesions on vestibular and occlusal surfaces.

(a) An arrested cavitated enamel lesion, characterized by a dark color, absence of plaque on the surface, and a band of healthy enamel near the gingival margin. (b) An arrested non-cavitated enamel lesion on the vestibular surface, identified by a clean, shiny, and smooth surface, with healthy enamel separating the lesion from the gingiva. This contrasts with images (c) and (d), where active non-cavitated lesions are visible.The difference between lesion activity on occlusal surfaces is illustrated in the following images: (e) An active occlusal lesion and (f) an arrested occlusal lesion.

Smooth surface caries lesions are commonly found near the gingival margin (Figure 1d), and similar to proximal lesions, the presence of plaque and bleeding on probing of the adjacent gingival area strongly indicates lesion activity.

Occlusal caries typically present with intact fissure morphology, where the lesion extends along the walls of the fissures (Figure 1e).

The microbiological profile tends to change depending on the activity of the lesion. However, studies have shown that non-cavitated lesions contain very few bacteria, and they do not exhibit the characteristics of an established biofilm.

2.2.2. Arrested Lesions

When an enamel lesion becomes arrested, the surface often appears whitish, brownish, or black (Figure 1a, b, f). Arrested lesions are characterized by a shiny surface that feels hard and smooth when probed gently. In smooth surface lesions, a thin line of healthy enamel separates the lesion from the gingiva. Additionally, the absence of plaque accumulation and lack of adjacent gingival bleeding are strong indicators of lesion inactivity. Arrested cavitated dentin lesions usually appear dark, and the dentin feels shiny and hard upon gentle probing.

It is important to recognize that caries development is a dynamic process. Just as active caries can be arrested, the reverse can also occur. Without proper management, such as maintaining a healthy diet, ensuring good oral hygiene, controlling plaque, and using remineralizing agents, previously arrested lesions may reactivate. In the absence of protective measures, active non-cavitated lesions can progress to cavitated lesions.

3. The Paradigm Shift in the Understanding and Management of Dental Caries

The understanding of dental caries has undergone a significant transformation over the past century. In the early 1900s, caries was perceived and managed as an infectious disease, leading to an aggressive approach aimed at removing all infected tissue—a concept known as “extension for prevention.”

By the 1950s, the relationship between biofilm, sugar, and caries development became better understood. This realization highlighted that bacteria and sugar together are essential for initiating caries, which eventually led to the introduction of preventive measures, including the widespread use of fluoride.

A more in-depth focus on biofilm complexity emerged in the late 1980s, leading to the recognition of dysbiosis as a key factor in caries progression. This marked the transition to understanding dental caries as a non-communicable disease (NCD) linked to various biological, behavioral, and environmental factors. This shift in understanding has been one of the driving forces behind the paradigm shift in cariology research and clinical practice over the past decade.

A notable milestone in this transformation was the introduction of the sealant technique, which creates a barrier between bacteria and the oral environment, revolutionizing the approach to caries management after years of relying on the extension for prevention model.

Recent changes in our understanding of dental caries, combined with declining rates of severe caries and slower lesion progression, have influenced modern approaches to detection and management. The limitations of visual, tactile, and radiographic examinations, coupled with the growing emphasis on minimizing ionizing radiation exposure, have fueled interest in exploring less invasive and more precise management strategies.

To provide more preventive and minimally invasive care, early detection of carious lesions—preferably while they are still confined to the enamel—is essential. Early detection increases the likelihood of successfully managing lesions using non-invasive or micro-invasive techniques. To achieve this goal, alternative caries detection methods with higher sensitivity for identifying and monitoring initial lesions have been actively investigated over the past two decades. Among these, optical-based caries detection methods have gained significant attention for their potential to diagnose early lesions more accurately.

The management of dental caries has also shifted considerably in the past decade. Treatment decisions, which were once based primarily on radiographic lesion depth, are now guided by a more comprehensive understanding of the patient's risk profile, enamel surface integrity, and lesion activity. Modern treatment strategies emphasize these factors, enabling clinicians to tailor preventive and therapeutic interventions more effectively and promoting a more patient-centered and conservative approach to dental care.

4. Initial Caries Detection Methods

As with most diseases, detecting advanced signs of dental caries is easier than identifying the earliest indications. Early detection of enamel lesions is critical for two primary reasons: first, it increases the likelihood of identifying non-cavitated lesions, allowing for more opportunities to apply non-invasive and micro-invasive treatments effectively; and second, it enables the monitoring of lesion progression after implementing these preventive measures. Detecting carious lesions involves identifying signs of dental caries, which can be observed at various stages, such as non-cavitated, micro-cavitated, and cavitated lesions. Through a thorough clinical examination of a dry and clean enamel surface, these lesions can be detected in occlusal fissures, on vestibular surfaces, and even on proximal surfaces.

Complementary detection tools, including radiographic, optical, and electrical methods, can also be employed to enhance caries detection. In vitro methods, such as histology, polarized light microscopy, transmission electron microscopy, scanning electron microscopy (SEM), and confocal laser scanning microscopy (CLSM), provide additional insights. Before the introduction of bitewing X-rays by H.R. Raper in 1925, proximal caries lesions were primarily detected through clinical and tactile examinations, which were effective for identifying cavitated lesions but inadequate for detecting early, non-cavitated lesions. For much of the past century, the standard approach to caries detection and treatment planning in dental practice relied on a combination of visual, tactile, and radiographic examinations.

Identifying enamel cavitation is crucial for managing and monitoring caries progression. While occlusal lesions can be relatively easy to identify, detecting cavitated lesions on proximal surfaces is more challenging. Clinical examinations alone have been shown to detect only 12–50% of cavitated proximal lesions, underscoring the need for improved methods. The use of sharp dental probes during clinical examinations has been criticized for over a decade due to their potential to cause irreversible damage to demineralized enamel, potentially transforming reversible lesions into cavitated ones. Despite these concerns, many general dentists continue to use sharp probes for tactile assessments. The use of a ball-ended explorer has been recommended as a safer and more effective alternative. While sharp probes may provide a better distinction between rough and smooth surfaces, ball-ended probes reduce the risk of damaging enamel due to their rounded tips.

Visual examinations aimed at detecting non-cavitated lesions have shown highly variable results, with sensitivity ranging from 0.20 to 0.96 and specificity between 0.50 and 1.00, highlighting inconsistencies in diagnostic accuracy among clinicians. Due to the difficulty in detecting early proximal lesions through clinical examination alone, reliance on radiographic techniques, particularly bitewing radiographs, has become common. However, radiographs exhibit low sensitivity (0.14–0.38) and high specificity (0.59–0.90) for detecting dentin caries lesions, making them inadequate for detecting early enamel lesions.

Studies suggest that 30–40% of enamel must demineralize before a lesion becomes visible on a radiograph, with some indicating that as much as 40–60% of decalcification is required for a lesion to be detectable. Moreover, bitewing radiographs cannot determine the status of enamel surface integrity (whether cavitated or not) or assess the lesion's activity. In recent decades, improvements in dental hygiene and regular patient follow-ups have led to significant global changes in caries prevalence, resulting in the emergence of "hidden caries," where lesions develop in occlusal and proximal surfaces that are not easily detected by traditional methods. These changes have increased the need for better tools to detect and manage caries at an earlier stage.

A recent systematic review and meta-analysis evaluating the accuracy of bitewing radiography for caries detection confirmed its effectiveness in identifying cavitated proximal lesions and its suitability for detecting dentin caries lesions. However, it also highlighted the need for more advanced techniques to accurately detect early enamel caries. While visual inspection and intraoral radiographs remain essential tools for detecting dentin caries, they exhibit suboptimal sensitivity for identifying early lesions, emphasizing the need for more sensitive and reliable detection methods.

4.1. Light-Based Caries Detection and Monitoring Methods

Several non-invasive techniques have been developed for the early detection of caries, primarily leveraging the mineral and optical properties of enamel to distinguish between healthy and demineralized enamel. These methods employ various wavelengths and technologies, including laser fluorescence devices, electrical caries monitoring, photo-thermal radiometry, fiber-optic transillumination, and near-infrared transillumination and reflectance.

4.1.1. The Use of Fluorescence in Caries Detection and Monitoring

Fluorescence is one of the key mechanisms through which materials emit light when suitably activated. In dentistry, light-induced fluorescence utilizes the natural fluorescence of teeth to differentiate between carious and healthy dental tissues. Numerous imaging techniques for caries detection rely on the fluorescence response of organic components within teeth, with devices categorized into red, blue, and green light-based systems. The color of emitted fluorescence always differs from the excitation light due to variations in energy, wavelength, and photon energy. As a result, violet or blue excitation light produces emissions in green, orange, or red wavelengths, while visible red excitation results in emissions within the near-infrared spectrum. This phenomenon is referred to as the Stokes shift.

Red fluorescence is used in devices like DIAGNOdent and DIAGNOdent Pen (KaVo, Biberach, Germany), which utilize a small laser with an excitation wavelength above 655 nm. The device's tip emits the excitation light and collects the resulting fluorescence, displaying results on a continuous scale ranging from 1 to 99. These devices operate on the principle that carious tissue emits more fluorescence than healthy tissue due to the presence of bacterial by-products, such as porphyrins.

Green fluorescence is utilized in devices that employ quantitative light-induced fluorescence (QLF). QLF leverages the fluorescence properties at the green-yellow end of the spectrum (around 370 nm), capturing the emitted fluorescence or refracted light to measure tooth fluorescence. This method provides a quantitative assessment of fluorescence loss, often represented as a numerical value (ΔF), which correlates with lesion depth.

Blue fluorescence devices function within the blue/violet spectrum (400 nm to 450 nm) and produce red luminescence in regions associated with bacterial activity, often linked to dental caries. In contrast, healthy areas of the tooth continue to fluoresce green. Various software-based devices in this category provide imaging of luminescence regions, including DIAGNOcam Vision Full HD (KaVo, Germany), VistaProof (Durr Dental), and SoproLife (ACTEON, France). While some devices use software to generate a numeric score from 0 to 5, many rely on the operator's interpretation of the imaging results, classifying lesions from sound to visible dentin caries.

This technology has demonstrated an estimated sensitivity of 0.70 (with a 95% confidence interval of 0.64 to 0.75) at a fixed median specificity of 0.78 and an intraclass correlation coefficient (ICC) of 0.96. Moreover, intra- and inter-examiner agreements have been reported at 0.93 and 0.92, respectively, highlighting the potential of this technology to minimize diagnostic discrepancies that frequently arise when evaluating non-cavitated early caries lesions using only visual and radiographic methods.

Violet light at a wavelength of 405 nm generates strong signals from numerous bacterial species involved in the caries process. Secondary colonizers of carious lesions, such as Lactobacilli, emit more visible red fluorescence than mutans streptococci. Additionally, Actinomyces odontolyticus exhibits robust porphyrin fluorescence. Protoporphyrin IX, a derivative of hemoglobin and a component of the heme biosynthetic pathway, is involved in this process. Since porphyrin derivatives are absent in healthy tooth structures, they serve as reliable markers for bacteria associated with dental caries. Fluorescence in these fluorophores is most pronounced in the visible violet-blue range (390–420 nm), with peak excitation occurring around 405 nm.

Red light emissions under violet light excitation are particularly effective in detecting key cariogenic bacteria. However, it is important to consider that the fluorescence characteristics of specific bacterial species can vary depending on environmental factors, such as the availability of nutrients, including blood and associated metalloporphyrins. This understanding has led to the preference for 405 nm violet light-emitting diodes (LEDs) as the illumination source of choice, which have been integrated into various complementary devices for caries detection. These devices include intraoral cameras, pen-shaped illuminators, microscopes, and dental high-speed handpieces, aiding in caries detection during both routine clinical examinations and the excavation of carious lesions.

These tools provide information about lesion size, fluorescence loss, bacterial activity (as indicated by red fluorescence), and staining intensity. They can also detect and assess mature deposits of dental plaque biofilm older than 24 hours, which exhibit high levels of porphyrins and produce strong red fluorescence when excited by violet light. Consequently, fluorescence-based methods not only assist in caries detection but also provide a reliable means for evaluating and monitoring lesion activity, as demonstrated in multiple studies.

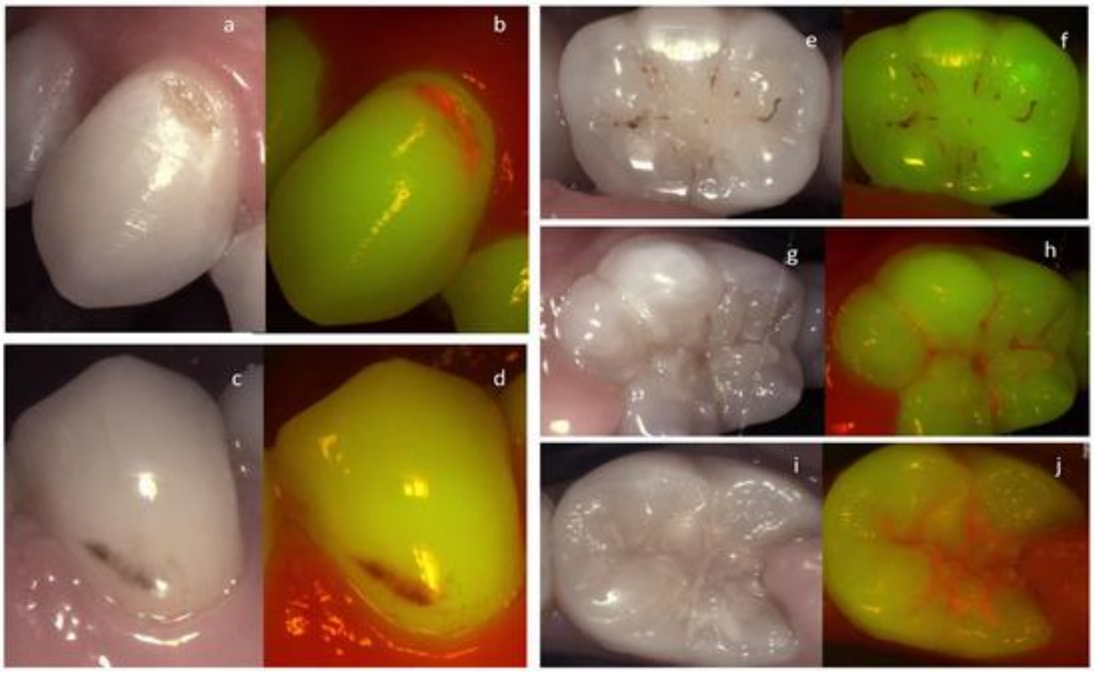

Figure 2. An active cavitated vestibular lesion on the upper canine (a, b) is easily identifiable in the fluorescence image due to the presence of bright red fluorescence. In contrast, the lesion on the lower premolar (c, d) is considered arrested based on clinical assessment using the Nyvad criteria. The absence of red fluorescence, the presence of a brown area indicating fluorescence loss, and surface staining further confirm this in the fluorescence image. A similar pattern is observed in the images of the molars on the right, where the arrested occlusal lesion (e, f) shows characteristics distinct from the active occlusal lesions (g–j).

The visual representation of plaque fluorescence in documented images can significantly enhance patient management and serve as a valuable tool for motivating patients. These images are easier for patients to comprehend, enabling better engagement during discussions about the importance of biofilm management. However, despite its advantages, light-induced fluorescence for caries detection has certain limitations when used solely for this purpose. Carious lesions can sometimes be misidentified due to the presence of contaminants such as blood, calculus, or plaque, which may cause false positive readings and potentially lead to overtreatment, particularly in the hands of inexperienced practitioners.

4.1.2. The Use of Near-Infrared Transillumination in Caries Detection and Monitoring

Transillumination is one of the oldest alternative methods for caries detection after radiographs. This technique relies on the optical properties of enamel, which change even with slight modifications in enamel porosity, resulting in increased light scattering when it passes through demineralized enamel. During light scattering, the direction of photons changes without losing energy, deviating from their original path as they interact with obstacles within the tissue, such as areas of enamel demineralization. Since scattering is highly sensitive to wavelength, shorter wavelengths scatter more than longer ones, which limits the effectiveness of caries detection methods that rely on wavelengths in the visible spectrum (400–700 nm).

Fiber optic transillumination (FOTI) was introduced in the early 1970s to detect proximal caries. It proved to be sensitive to early changes in enamel structure and was described as a useful adjunct to radiography and clinical examination. However, diagnosing caries using FOTI by the naked eye is prone to considerable inter- and intra-examiner variability. This limitation led to the development of digital fiber optic transillumination imaging (DIFOTI**)** in the 1990s, which enabled the capturing of images and improved lesion monitoring over time. DIFOTI was validated through multiple in vitro and in vivo studies and demonstrated higher sensitivity for detecting early enamel lesions and monitoring their progression compared to other detection methods. Although the technique was extensively studied and compared with radiography and tactile clinical evaluation, findings on its effectiveness yielded mixed results.

The development of near-infrared transillumination (NIRT) for caries detection began around 1995. This method employs near-infrared wavelengths, which interact with dental tissues to allow visual differentiation between healthy and demineralized tissue. Fried et al. demonstrated that dental enamel becomes highly transparent when illuminated with NIR light, while dentin scatters both visible and NIR light. Consequently, this technique is particularly suitable for examining carious lesions in enamel but is less effective for detecting lesions in dentin. Imaging with NIR light at 1310 nm has shown considerable potential for detecting early demineralization, outperforming dental X-rays in certain applications. Although this method was initially used to detect proximal caries, it has since been shown to effectively identify occlusal caries and cracks as well. Several studies have confirmed that NIR transillumination has higher sensitivity than bitewing radiographs for detecting both proximal and occlusal caries and can also be used for lesion monitoring.

Over the past decade, NIRT imaging has been further investigated for various applications, including detecting primary and secondary caries on occlusal and proximal surfaces, monitoring early caries progression, guiding caries removal, and detecting caries under sealants. Compared to bitewing radiographs, the occlusal viewing angle of NIRT images

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makes it easier to pinpoint the exact position of proximal decay in the bucco-oral dimension, allowing for more precise access to the lesion and minimizing unnecessary removal of healthy tissue.

In 2012, the DIAGNOcam device (KaVo, Biberach, Germany), which utilizes 780 nm near-infrared transillumination technology, was introduced. This was followed by the 2021 release of an updated version, DIAGNOcam Vision Full HD, which combined near-infrared transillumination with clinical imaging and fluorescence. This integration of three imaging modalities provides a significant advantage to clinicians by offering comprehensive information from multiple perspectives, enhancing diagnostic accuracy and facilitating the development of an appropriate management plan. Additionally, 3D oral scanners have recently integrated these technologies, further expanding the scope of caries detection.

During transillumination, the camera is equipped with two flexible silicon extensions that illuminate the tooth from both the vestibular and oral sides. Near-infrared (NIR) light passes through periodontal and dental tissues, with an infrared-sensitive camera capturing images from the occlusal surface. The 780 nm wavelength used in NIRT falls within the **optical window** of tissues, ensuring superior light transmission through tissues, allowing deeper penetration, and producing higher-quality images compared to visible light.

Recent studies and reviews on near-infrared transillumination technology suggest that it has the potential to become a valuable alternative to bitewing radiography for early proximal caries detection, particularly for monitoring enamel lesions during recall visits. One notable advantage is that NIRT does not involve ionizing radiation, meaning it can be used more frequently without concerns about radiation exposure. Supporting this concept, a study demonstrated that NIRT imaging provided diagnostic outcomes comparable to those obtained with bitewing radiographs. Lesions detected using NIRT showed strong correlations with both X-ray images and clinical assessments, with agreement rates of 97% between NIRT and X-rays and 96% between NIRT and clinical evaluations.

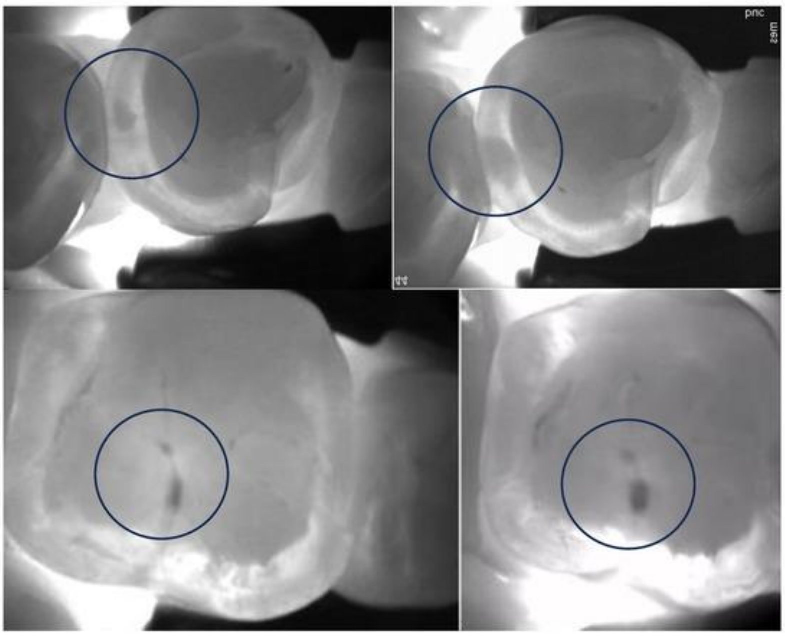

Figure 3. The progression of occlusal (top images) and proximal (bottom images) lesions, highlighted within the circles, is evident and confirmed after approximately two years of monitoring.

A recent clinical study demonstrated that NIRT devices outperform bitewing (BW) radiographs in detecting early proximal enamel lesions. Moreover, when NIRT was used to assess proximal caries at two-year intervals, the reproducibility of caries detection was shown to be excellent compared to BWs taken from the same patients. NIRT identified a significantly higher number of enamel caries lesions than radiographs, detecting approximately four times as many lesions that had progressed to the enamel–dentin junction compared to BW radiography. Similar findings have been reported in recent studies, reinforcing the high reliability of NIRT and its strong correlation with clinical and radiographic examinations in identifying dentin caries lesions.

5. A Proposal of a Workflow Integrating Near-Infrared Transillumination and Fluorescence into the Caries Management System

Dentists today have more treatment options and scientific evidence at their disposal than ever before. The field is increasingly embracing minimally invasive, evidence-based, and personalized approaches that prioritize the promotion and maintenance of oral health. Taking into account the various aspects discussed previously, it is clear that the tools and knowledge required for the comprehensive management of early carious lesions are already available. However, to date, there is no established management system in the literature that fully integrates near-infrared transillumination (NIRT) and fluorescence into the caries management workflow and decision-making process. Incorporating these technologies has the potential to detect subclinical lesions that are not visible during routine clinical examinations, provide valuable insight into lesion activity, enhance the effectiveness of existing management strategies, and help identify high-risk patients before symptoms become clinically or radiographically apparent.

Based on the available evidence and clinical experience gained over the past decade, this paper proposes a structured approach for managing occlusal caries that combines simplified ICDAS-based clinical scoring, NIRT image interpretation, lesion activity assessment using both clinical criteria and fluorescence signal, and caries risk evaluation tools such as Cariogram or CAMBRA. This strategy enables clinicians to create individualized care plans by selecting appropriate elements from noninvasive, micro-invasive, or restorative treatment options, while also supporting structured follow-ups and active monitoring of lesion progression or arrest.

The scoring methods included in this proposal are adapted from previously published models for clinical, NIRT, and fluorescence assessment, with modifications aimed at optimizing the workflow. Scoring should be performed under proper lighting and magnification, and patients should ideally brush their teeth beforehand. Lesions are classified as early (ICDAS codes 1 and 2, affecting enamel), moderate (ICDAS codes 3 and 4, representing micro-cavitated enamel or non-cavitated dentin lesions), or advanced/extensive (ICDAS codes 5 and 6, with visible dentin and more significant cavitations). Radiographically, early and moderate lesions

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typically do not appear on bitewing images or are limited to the outer third of the dentin, while advanced lesions often extend into the deeper layers.

A common point of uncertainty for many practitioners is whether professional cleaning should occur before or after the examination. Accurate scoring requires clean and dry tooth surfaces, but the presence of plaque or calcified deposits can obscure lesions and reduce the reliability of clinical assessments. On the other hand, cleaning before the exam eliminates plaque entirely, preventing evaluation of lesion activity based on plaque presence and hindering the assessment of the patient's oral hygiene capabilities.

An alternative is to have the patient brush prior to the examination. This approach allows the clinician to evaluate the patient's plaque removal ability, while any remaining plaque can be selectively removed by the practitioner during the exam.

Fluorescence and NIRT imaging can complement the clinical examination by confirming visual findings or revealing lesions not detectable through visual inspection alone. This additional information is especially useful when managing early and moderate lesions, enhancing diagnostic confidence and enabling earlier, more targeted interventions.

Near-Infrared Transillumination Scoring

Early demineralization can be clearly observed on NIRT images (Figure 6). Very early, subclinical enamel lesions appear as thin dark lines tracing the path of the occlusal fissures. As the lesions progress toward the enamel–dentin junction, these lines become darker and wider. In moderate lesions, a broader shadow beneath the enamel suggests dentin involvement. These cases may present with enamel cavitation, aligning with an ICDAS score of 3, or may lack visible cavitation, corresponding to an ICDAS score of 4.

Figure 6. Near-Infrared Transillumination Scoring. Occlusal lesion progression on NIR images is visualized by the presence of dark lines within the fissures in early-stage lesions. As the lesion advances, these lines widen, indicating moderate involvement extending into the outer third of the dentin. In severe cases with dentin cavitation, however, the full extent of the lesion within the dentin cannot be accurately assessed using this method.

The contrast of lesions in transillumination increases as the lesion depth progresses, with severe lesions exhibiting significantly higher contrast compared to shallower ones. However, a limitation of the near-infrared transillumination (NIRT) method is its inability to provide precise information about lesion depth once it reaches the dentin. In such cases, bitewing X-rays may be warranted to assess lesion depth and facilitate ongoing monitoring.

At the early stages of lesion development, NIRT scoring may occasionally lead to over-detection. Lesions corresponding to scores 1 and 2 on NIRT images may be clinically classified as ICDAS codes 0, 1, or 2. While these early lesions may not require immediate invasive treatment, their presence should alert the clinician that the surface is at increased risk. The primary therapeutic objective at this stage is to enhance preventive and prophylactic measures to arrest lesion progression. Longitudinal monitoring allows for continued assessment of lesion activity, and if the lesion progresses to score 3 despite non-invasive management, a micro-invasive approach may be considered.

5.3. Fluorescence Image Scoring

The use of ICDAS and Nyvad criteria is highly effective for detecting and assessing the activity of early occlusal lesions. However, for accurate results, the surface must be thoroughly cleaned and dried for 5 seconds—an essential step that is often overlooked, particularly in population-level caries screenings. Combining visual examination with fluorescence imaging can improve the detection and monitoring of early lesions. However, it is important to note that fluorescence images should not be used for caries detection without first cleaning the surface, as the presence of plaque or surface discoloration may lead to false-positive results.

That said, if the presence of cariogenic plaque (indicated by a red fluorescence signal) on the occlusal surface is interpreted as a sign of lesion activity, as described by Nyvad, this method can greatly enhance lesion activity assessment and monitoring. The scoring system described below (Figure 7) evaluates lesion activity at each stage to guide the preventive care plan. Moderate lesions, which are often a mixture of active and arrested lesions, are generally considered active. The management of these lesions is primarily determined by the patient's individual risk profile.

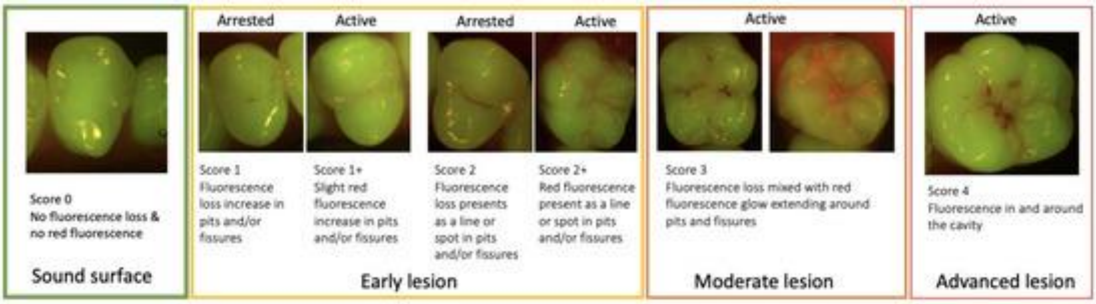

Figure 7. Fluorescence image scoring.

Conclusions

The incorporation of advanced technologies, including near-infrared transillumination (NIRT), fluorescence-based imaging, and other innovative modalities, offers significant potential to enhance patient-centered oral healthcare. A growing body of scientific evidence supports the approach of managing caries as a disease through the application of evidence-based principles and personalized treatment strategies. It is essential for practitioners worldwide to integrate this knowledge into their daily clinical practice to ensure improved patient outcomes.

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