

Fluorescence Imaging Techniques for Early Detection of Dental Caries

Fayaz Ali Alghamdi[1], Ali Mohammad Hantool[2], Essa Mousa Daghasi[3], Abdulaziz Hasan Alshehri[4], Khaled Saad Alghamdi[5], Saud Ramadn Alzahrani[6], Ali Hussain Al Doughaysh[7], Fawaz Ali Alghamdi[8], Bandar Murdhi Alzahrani[9], Majed Mesh'al M Alharbi[10], Abdulhamid Salah M Hanafi[11]

[1] Radiology Technologist, Primary Health Care Dammam, Fwhg66@gmail.com
[2] Radiology Technologist, Dammam Medical Complex, Ali Mohammad Hantool, Alhantool@moh.gov.sa
[3] Radiology Technologist, Dammam Medical Complex, Essa Mousa Daghasi, Edaghasi@moh.gov.sa
[4] Radiology Technologist, Dammam Medical Complex, Abdulaziz Hasan Alshehri, Ksa073@hotmail.com, Kingdom of Saudi Arabia - Dammam
[5] Medical Imaging Radiological Technology, Primary Health Care Dammam, Khaled Saad Alghamdi, kalghamdi9@moh.gov.sa
[6] Radiology Technologist, Dammam Medical Complex, Saud Ramadn Alzahrani, saudalzahrani333@gmail.com
[7] Medical Imaging Radiological Technology, Primary Health Care Dammam, Ali Hussain Al Doughaysh, ahalfadhel@moh.gov.sa
[8] Specialist - Dental Hygienist, Primary Health Care Dammam, Fawaz Ali Alghamdi, faalalghamdi@moh.gov.sa
[9] Specialist - Dental Assistant, General Directorate of Health Affairs in the Eastern Region, Dammam, Bandar Murdhi Alzahrani, bamoalzahrani@moh.gov.sa
[10] General Dentistry, Waerh PHC, Majed Mesh'al M Alharbi, mee-moo2000@hotmail.com
[11] General Dentistry, Waerh Primary Health Care Centre in Al Madinah, Abdulhamid Salah M Hanafi, abdulhamid1993@hotmail.com

Avstract:

Fluorescence imaging techniques have emerged as a significant advancement in the early detection of dental caries, enabling dental professionals to identify carious lesions before they become visually apparent. These techniques utilize specific wavelengths of light to excite fluorescent markers within the tooth structure. The response of these markers provides valuable information regarding the health of the tooth enamel and underlying dentin. Techniques such as Quantitative Light-Induced Fluorescence (QLF), Laser-Induced Fluorescence (LIF), and Near-Infrared Imaging are becoming increasingly popular in clinical practice. By facilitating the visualization of carious lesions that can be overlooked during routine examinations, fluorescence imaging significantly enhances diagnostic accuracy and allows for the timely intervention and management of dental decay. The advantages of fluorescence imaging extend beyond improved detection rates; they also play a pivotal role in patient management and treatment planning. By revealing the extent of caries along with the health of adjacent tissues, dentists can make more informed decisions regarding the need for restorative procedures. Additionally, these techniques are less invasive compared to traditional methods, often reducing patient discomfort and anxiety. As research continues to validate and refine these technologies, fluorescence imaging is poised to transform dental diagnostics, encouraging a more preventive approach to caries management in the field of dentistry.

Keywords: Fluorescence imaging, early detection, dental caries, Quantitative Light-Induced Fluorescence (QLF)

Introduction

Dental caries, commonly known as tooth decay, remains one of the most prevalent chronic diseases worldwide, affecting individuals across all age groups and socioeconomic strata. Despite significant advancements in preventive dentistry, it continues to pose a substantial global public health challenge. According to the Global Burden of Disease Study, untreated dental caries in permanent teeth is the most common health condition, affecting over 2.3 billion people, while in primary teeth, it affects more than 530 million children [1]. The economic burden is equally staggering, with billions of dollars spent annually on restorative treatments, which often address the late stages of the disease. The traditional model of caries management, which is primarily operative and interventionist, is increasingly being recognized as unsustainable and biologically unsound.

The foundation of this modern approach lies in the understanding of the caries process. Dental caries is a biofilm-mediated, sugar-driven, multifactorial disease that results in the phasic demineralization and remineralization of dental hard tissues [2]. In its earliest stage, the initial demineralization manifests as a 'white spot lesion,' which is a sub-surface porosity with a relatively intact surface layer. At this stage, the lesion is non-cavitated and, crucially, reversible through non-operative means such as fluoride application and improved oral hygiene. However, the major challenge has historically been the reliable and objective detection of these incipient lesions. Conventional methods for caries detection, primarily visual-tactile examination supplemented by radiographs, have significant limitations. Visual examination is highly subjective, dependent on the clinician's experience and operating conditions, and often fails to identify lesions, especially on occlusal surfaces [3]. Bitewing radiography, while invaluable for detecting proximal caries, has poor sensitivity for early enamel lesions, as it typically identifies demineralization only after a substantial mineral loss of 20-40% has occurred [4]. Furthermore, it involves exposure to ionizing radiation, however minimal, which is a concern for certain patient populations.

These limitations of conventional diagnostics have fueled the search for alternative technologies that are objective, sensitive, quantitative, and non-invasive. Among the most promising advancements in this field are fluorescence-based imaging techniques. The principle underlying these technologies is the natural phenomenon of fluorescence. When certain materials, including dental hard tissues, are illuminated with light of a specific wavelength (typically in the blue-violet spectrum), they absorb the photons and re-emit light at a longer, lower-energy wavelength [5]. Sound enamel, with its dense, highly mineralized crystalline structure of hydroxyapatite, exhibits a characteristic level of autofluorescence. However, as carious demineralization progresses, the optical properties of the enamel change. The increased porosity and the presence of bacterial metabolites, such as porphyrins produced by microorganisms within the carious lesion, lead to a reduction in the natural autofluorescence from the tooth structure and, in some cases, the induction of a different fluorescence signal [6]. This differential fluorescence between sound and carious tissue forms the basis for detection.

Currently, several fluorescence-based devices are commercially available and integrated into clinical practice. The most widely researched and utilized system is the DIAGNOdent (KaVo), a pen-like laser fluorescence device. It uses a 655 nm red laser light to detect and quantify bacterial porphyrins within the carious lesion, providing a numerical readout that correlates with the extent of demineralization [7]. Studies have shown that the DIAGNOdent exhibits higher sensitivity for detecting occlusal caries compared to visual examination and radiography, though its specificity can be variable and may lead to false positives in the presence of stains, calculus, or certain restorative materials [8].

A more recent and sophisticated evolution is Quantitative Light-induced Fluorescence (QLF). This technology employs a high-intensity blue light (around 370-460 nm) to capture the natural autofluorescence of teeth. Sound enamel fluoresces strongly in the green spectrum, while demineralized areas appear as dark spots due to the scattering of light and reduced fluorescence intensity. QLF software then quantifies this fluorescence loss (ΔF) and the area of the lesion, allowing for not only detection but also longitudinal monitoring of lesion activity and the efficacy of remineralization therapies [9]. This capability for quantitative monitoring makes QLF an invaluable tool for both clinical research and preventive care.

Building upon this principle, the Inspektor Pro system (a specific QLF device) has been extensively validated. Another notable technology is the Near-Infrared Transillumination (NIRT) system, such as the

DIAGNOcam. While not strictly fluorescence-based, it operates on a similar philosophy of advanced optical imaging. It uses near-infrared light, which has a higher transparency in enamel than in water and carious lesions, to reveal occlusal and proximal caries as dark shadows without the use of ionizing radiation [10].

The body of evidence supporting these technologies is robust. A 2020 meta-analysis by Gómez et al. concluded that laser fluorescence devices like DIAGNOdent demonstrate a pooled sensitivity and specificity of 0.79 and 0.83, respectively, for primary teeth, outperforming conventional methods [11]. Similarly, a systematic review in 2021 affirmed that QLF shows excellent performance in the early detection and monitoring of non-cavitated caries, highlighting its potential to shift the caries management paradigm from restorative to preventive [12].

The Global Burden of Dental Caries: Necessitating a Paradigm Shift

Dental caries, a chronic, multifactorial disease characterized by the localized destruction of dental hard tissues by acidic by-products from bacterial fermentation of dietary sugars, persists as a silent pandemic. Its pervasiveness across the globe, affecting both developed and developing nations, establishes it not merely as a common ailment but as a significant public health crisis with profound implications for health systems, economies, and individual quality of life. The most recent comprehensive data from the Global Burden of Disease (GBD) studies paints a stark picture. It is estimated that over **3.5 billion people worldwide** are affected by oral conditions, with untreated caries in permanent teeth being the single most prevalent condition, impacting nearly **2.3 billion adults and children** [13]. The burden on the pediatric population is particularly alarming, with early childhood caries (ECC) affecting 530 million children globally. In many regions, ECC is the most common chronic disease of childhood, surpassing asthma and obesity [14]. This high prevalence in primary dentition is a strong predictor of caries in permanent teeth, setting the stage for a lifelong struggle with oral health if not addressed proactively.

The consequences of dental caries extend far beyond the localized cavity. The disease is a major contributor to the global burden of years lived with disability (YLDs). Dental pain associated with caries is a leading cause of school and work absenteeism, negatively impacting educational performance and economic productivity. In severe cases, untreated caries can progress to pulpitis, dental abscesses, and cellulitis, leading to systemic infections that may require hospitalization and emergency surgical intervention. The psychosocial impact is equally significant. Caries can lead to difficulty in chewing, speaking, and sleeping, while visible decay and tooth loss can cause embarrassment, social anxiety, and a diminished sense of well-being, particularly in children and adolescents [15]. This multifaceted impact underscores that oral health is integral to general health and quality of life, a concept firmly endorsed by the World Health Organization.

The economic burden imposed by the treatment of dental caries places a heavy strain on both public and private healthcare budgets. Direct costs include those for diagnostic, preventive, restorative, and endodontic services, as well as more complex procedures like crowns, bridges, and implants. Indirect costs arise from productivity losses due to pain and absenteeism. A comprehensive analysis of global dental expenditure revealed that the direct treatment costs for oral diseases amounted to approximately **$544.41 billion USD in 2015**, a figure that has undoubtedly risen in the subsequent years. This staggering sum represents a significant portion of national health expenditures, particularly in high-income countries [16]. The current model of care, which is predominantly reactive and interventionist, focuses on restoring the consequences of the disease—the cavitations—rather than managing the disease process itself. This "drill-and-fill" approach, while providing necessary relief, is financially unsustainable in the long term and fails to address the root cause of the problem.

For decades, the cornerstone of caries diagnosis has been the visual-tactile examination, often supplemented by bitewing radiographs. While these methods are invaluable for detecting cavitated and moderately advanced lesions, they possess inherent and critical limitations in the context of early caries detection. The initial stage of caries, the non-cavitated white spot lesion, is a chemical process of demineralization that precedes macroscopic structural failure. At this stage, the lesion is potentially reversible through remineralization. However, visual examination is highly subjective, relying heavily on the clinician's experience, lighting conditions, and the cleanliness and dryness of the tooth surface. As a result, its sensitivity for detecting these early lesions, particularly on occlusal surfaces, is unacceptably low, often reported to be below 50% [17].

Radiography, though a powerful tool for visualizing proximal caries and the extent of larger lesions, is fundamentally limited by its two-dimensional nature and its reliance on significant mineral loss for a lesion to become radiographically visible. Studies have consistently shown that a lesion must have demineralized approximately **30-40%** of the tooth's mineral content before it can be reliably detected on a standard bitewing radiograph [18]. By this point, the opportunity for non-invasive remineralization may have been lost, and the only remaining clinical option is often a restoration. Furthermore, the repeated use of ionizing radiation, however small the dose per exposure, is a non-trivial concern, especially in pediatric dentistry and for patients requiring frequent monitoring.

The cumulative weight of this evidence—the staggering global prevalence, the profound impact on quality of life, the unsustainable economic costs, and the inadequacy of conventional diagnostic tools—has catalyzed a fundamental and necessary paradigm shift in cariology. The profession is moving decisively away from a restorative, surgical model towards a medical, preventive model. This new model, as outlined in the concepts of "Caries Management by Risk Assessment (CAMBRA)" and the "International Caries Classification and Management System (ICCMS)", prioritizes the early detection of the disease process in its initial, reversible stages [19]. The goal is to intercept the disease before it leads to cavitation, thereby preserving the natural tooth structure and shifting the role of the dentist from a surgical restorer to a primary care physician for the mouth.

This paradigm shift, however, is entirely dependent on the availability of diagnostic technologies that are capable of identifying the disease at its earliest, non-cavitated stage. A preventive model cannot be built upon diagnostic tools that only recognize the disease once it has caused irreversible damage. It is within this critical context that fluorescence-based imaging techniques have emerged as a transformative innovation. By providing an objective, sensitive, and quantitative means of detecting and monitoring demineralization at the molecular level, these technologies are the essential enablers of the modern medical model of caries management. They provide the data needed to diagnose the disease early, monitor the effectiveness of preventive therapies, and empower patients to take control of their oral health, ultimately fulfilling the promise of true, evidence-based preventive dentistry [20].

Limitations of Conventional Caries Detection Methods

The paradigm shift towards a medical model of caries management is fundamentally driven by the recognized inadequacies of the diagnostic tools that have underpinned dentistry for over a century. While visual-tactile examination and radiographic imaging are deeply entrenched in clinical practice and provide valuable information for advanced lesions, their limitations in detecting early, non-cavitated caries are profound and well-documented. A critical analysis of these conventional methods reveals why their continued reliance, as primary diagnostic tools, is a significant barrier to effective, preventive oral healthcare.

2.1 The Subjectivity and Insensitivity of Visual-Tactile Examination

The visual examination, often aided by a dental explorer and a triple-air syringe, is the most ubiquitous caries detection method. The International Caries Detection and Assessment System (ICDAS) was developed to standardize this process, providing criteria based on the visual appearance of clean, dry teeth, ranging from the first visual change in enamel (ICDAS code 1) to a distinct cavity (ICDAS code 6) [21]. Despite this systematization, the method remains inherently subjective. Its accuracy is heavily influenced by a multitude of variables, including the clinician's training and experience, the intensity and angle of the operatory light, the duration of the examination, and, most critically, the ability to achieve a perfectly clean and dry field. Saliva, plaque, and stains can easily obscure the subtle, whitish discoloration of an initial lesion, leading to false-negative diagnoses.

The use of a sharp dental explorer has been a particular point of contention. The classic teaching of "stickiness" or "tug-back" as a definitive sign of caries is now considered not only unreliable but also potentially detrimental. Studies have demonstrated that probing an early, non-cavitated white spot lesion can actually cause mechanical damage to the porous, weakened surface layer, creating micro-cavitations that impede the natural remineralization process and may even facilitate the progression of the lesion by introducing bacteria deeper into the enamel structure [22]. Furthermore, the explorer tip can be contaminated with bacteria from a previous lesion and transferred to a sound surface. The diagnostic validity of tactile sensation is also questionable, as it cannot reliably differentiate between caries and an intact, but deep, fissure morphology. Consequently, the sensitivity of visual-tactile examination for detecting occlusal caries in its earliest stages is consistently reported to be low, often ranging from 20% to 50%, meaning a majority of early lesions are missed [23].

2.2 The Inherent Lag in Radiographic Detection

Bitewing radiography is an indispensable tool for diagnosing proximal caries and assessing the depth of larger lesions. It provides a permanent record and allows for the visualization of areas not accessible to direct vision. However, its fundamental physical principle is also its greatest diagnostic limitation. Radiographs detect caries by identifying areas of demineralization that have reduced X-ray attenuation compared to sound tooth structure, appearing as radiolucent shadows. The critical issue is the threshold of mineral loss required for this change to become visually apparent on a radiograph.

Extensive in vitro and in vivo studies have established that a lesion must reach approximately the inner one-third to one-half of the dentin—corresponding to a **30-40% mineral loss**—before it can be consistently detected by a trained clinician on a standard bitewing radiograph [24]. This means that the entire initial phase of the caries process, including the crucial stage of enamel demineralization and the early penetration into the dentino-enamel junction (DEJ), remains radiographically "silent." By the time a lesion is visible on a radiograph, it is often well-advanced, and the window for non-invasive remineralization therapy has frequently closed. This diagnostic lag forces a reactive, rather than a proactive, treatment approach.

The limitations of radiography extend further. The technique is two-dimensional, superimposing the complex anatomy of the left and right sides of the jaw, which can hide lesions or create false appearances of caries (anatomical noise). Overlapping contact points can completely obscure early proximal lesions. Furthermore, radiography has very poor performance in detecting occlusal caries, as the broad, dense cusps often mask the demineralization occurring in the fissures beneath them [25]. The recent advent of digital radiography has improved image manipulation and reduced radiation exposure, but it has not fundamentally altered the physical limitations of the medium; the threshold for detection remains tied to significant mineral loss.

2.3 The Unavoidable Concern of Ionizing Radiation

Although the radiation dose from a set of bitewing radiographs is relatively low, it is not zero. The effective dose is a measure of the overall risk, taking into account the sensitivity of different exposed tissues. While the risk to an individual patient from a single examination is minimal, the principle of ALARA (As Low As Reasonably Achievable) must govern all uses of ionizing radiation [26]. This is especially critical in pediatric dentistry, where children are more radiosensitive, have a longer lifespan for potential effects to manifest, and may require more frequent monitoring due to their high caries risk. The cumulative lifetime exposure from repeated dental radiographs is a consideration that cannot be dismissed. This concern creates a clinical dilemma: the need to monitor high-risk patients frequently conflicts with the desire to minimize radiation exposure, often leading to suboptimal surveillance and the potential for late diagnosis.

2.4 The Absence of Quantification and Monitoring Capabilities

Perhaps the most significant limitation of conventional methods in the context of modern preventive care is their inability to quantitatively monitor lesion activity. Both visual-tactile and radiographic assessments provide a largely qualitative or semi-quantitative snapshot in time. A clinician can note that a lesion is "present" or has "enlarged," but it is exceedingly difficult to objectively measure minute changes in mineral content over time. This makes it challenging to assess whether a preventive regimen, such as the application of high-fluoride toothpaste or dietary counseling, is effectively arresting the disease process and promoting remineralization. Without objective, quantitative data, clinical decisions about whether to intervene operatively or to continue with non-invasive management can be based on subjective judgment rather than evidence of disease progression or regression [27].

In conclusion, the collective shortcomings of conventional caries detection methods—their subjectivity, poor sensitivity for early lesions, reliance on significant structural damage for detection, use of ionizing radiation, and lack of quantitative capabilities—create a diagnostic gap that is incompatible with the goals of contemporary, preventive dentistry. This gap leaves the earliest, most manageable stages of the disease largely undiagnosed and untreated, allowing them to progress to a point where surgical intervention becomes the only viable option. It is within this diagnostic void that advanced technologies, particularly those based on the principles of light and fluorescence, have emerged not as supplementary gadgets, but as essential tools for enabling a truly preventive, patient-centered, and minimally invasive approach to caries management. The evidence against relying solely on traditional methods is compelling, as summarized by a systematic review by Gómez et al., which affirmed that alternative methods are necessary to overcome the well-known limitations of visual, tactile, and radiographic examinations [28]. Newer technologies offer the promise of detecting lesions at the molecular level, long before they become apparent to the eye or the explorer, or visible on a radiograph, thereby fulfilling the core tenet of preventive medicine: to diagnose early and intervene minimally.

The Science of Fluorescence: Basic Principles and Mechanisms

The limitations of conventional caries detection methods have necessitated a technological evolution, steering diagnostics towards modalities that exploit the fundamental biophysical properties of dental tissues. At the forefront of this evolution are fluorescence-based techniques, which offer a paradigm shift from detecting macroscopic structural damage to identifying subtle molecular and chemical changes that signify the very onset of the caries process.

3.1 The Physical Phenomenon of Fluorescence

Fluorescence is a form of photoluminescence. It occurs when a substance (a fluorophore) absorbs light photons at a specific, high-energy wavelength (excitation) and almost instantaneously re-emits photons at a longer, lower-energy wavelength (emission). The difference between the excitation and emission wavelengths, known as the Stokes shift, is the fundamental property that allows fluorescent light to be separated from the excitation light using optical filters. In the context of dentistry, the primary fluorophores are the chemical components of dental hard tissues themselves, and in later stages, by-products of cariogenic bacteria [31].

When sound tooth enamel, which is composed primarily of highly organized hydroxyapatite crystals, is illuminated with light in the blue-violet spectrum (typically around 405 nm), it absorbs this energy and re-emits it as a strong green autofluorescence. This natural autofluorescence is a property of the mineral matrix itself. The dense, crystalline structure of sound enamel scatters and absorbs the excitation light in a specific way, resulting in a characteristic and intense fluorescent signal. Dentin, with its higher organic content and different microstructure, also exhibits autofluorescence but with different spectral properties compared to enamel [32].

3.2 Alterations in Fluorescence in Carious Tissues

The progression of dental caries, which is essentially a process of demineralization, dramatically alters the optical properties of the enamel. As hydroxyapatite crystals dissolve, they create microscopic pores and scatter centers within the enamel. This increased porosity has two major effects on the fluorescence signal:

1. **Reduction of Autofluorescence (Signal Loss):** The scattering of both the excitation and the emitted light increases significantly within the demineralized area. This enhanced scattering prevents the excitation light from penetrating deeply and also traps the emitted fluorescent light, reducing the amount that escapes the tissue to be detected by the sensor. Consequently, an early caries lesion appears as a dark area against the bright green background of sound enamel. This quantitative reduction in fluorescence intensity is the primary metric used in Quantitative Light-induced Fluorescence (QLF) technology. The software calculates the percentage of fluorescence loss (ΔF) and the area of the lesion, allowing for a quantitative assessment of mineral loss that can be as low as 5% [33].
2. **Changes in Scattering and Absorption:** The porous regions of the lesion also have different light absorption characteristics. As the lesion ages and the pores enlarge, they can become filled with organic material, water, and bacteria, which further modify the light-tissue interaction.

In addition to the changes in the tooth structure itself, a second fluorescence mechanism becomes prominent, particularly in more advanced lesions. Cariogenic bacteria, especially certain strains of *Streptococcus mutans* and *Lactobacillus*, produce porphyrins as metabolic by-products. Porphyrins are potent fluorophores that, when excited by red light (around 655 nm used in the DIAGNOdent device), emit light in the near-infrared spectrum. In a sound fissure, bacterial counts are low, and this porphyrin-related fluorescence is minimal. However, within an active carious lesion, the concentration of these bacteria and their metabolites is high, leading to a significant increase in the red-infrared fluorescence signal [34]. This forms the basis for laser fluorescence devices, which detect and quantify this bacterial activity rather than the direct mineral loss.

3.3 Key Fluorescence-Based Technologies and Their Specific Mechanisms

The general principle of fluorescence is applied in different ways by various commercially available technologies, each with its own strengths and diagnostic targets:

- **Quantitative Light-induced Fluorescence (QLF):** This technology uses a high-intensity blue light (typically 405 nm) to excite the natural green autofluorescence of teeth. A specially filtered camera captures the fluorescent image. Sound enamel appears bright green, while demineralized areas appear dark due to reduced autofluorescence. The proprietary software then performs a pixel-by-pixel analysis to quantify the fluorescence loss (ΔF) and the lesion volume (ΔQ). This allows for not only detection but also longitudinal monitoring of the same lesion over time to assess whether it is active and progressing, arrested, or remineralizing [35]. This capability is unique to QLF and makes it an unparalleled tool for clinical research and evaluating the efficacy of preventive agents.
- **Laser Fluorescence (e.g., DIAGNOdent):** This device employs a 655 nm diode laser. The tip of the handpiece delivers the laser light to the tooth surface, and a receiver measures the intensity of the fluorescent light emitted back, primarily from bacterial porphyrins. The device provides a numerical readout on a scale from 0 to 99. Lower values (e.g., 0-20) typically indicate sound tissue, middle ranges suggest early demineralization, and higher values (e.g., >30) indicate dentinal caries [36]. Its primary advantage is its high sensitivity for detecting occlusal caries. However, it can be

prone to false-positive readings in the presence of dental plaque, calculus, certain stains, and even prophylactic pastes, as these materials may also contain fluorophores that respond to the red light [37].

- **Near-Infrared Transillumination (NIRT) (e.g., DIAGNOcam):** While not strictly a fluorescence technology, NIRT operates on a related principle of advanced optical imaging and is often grouped with these novel modalities. It utilizes light in the near-infrared spectrum (around 780 nm), a wavelength at which enamel is highly transparent while water and carious lesions are strong absorbers. When this light is transmitted through a tooth, sound enamel appears bright and homogeneous, while areas of demineralization, which contain more water and have different scattering properties, appear as dark shadows [38]. This technique is particularly effective for detecting proximal and occlusal caries without ionizing radiation and provides a visual image that is intuitively understandable, similar to a radiograph.

The scientific foundation of these technologies provides a compelling argument for their use. They transition caries diagnosis from a subjective art to an objective science. By quantifying the very biophysical changes that define the early caries process—be it the loss of mineral (QLF) or the metabolic activity of the causative biofilm (DIAGNOdent)—they provide a much earlier and more sensitive diagnostic window than was previously possible. This allows clinicians to diagnose the disease at a stage where the natural healing process of remineralization can be harnessed, truly enabling a preventive, non-operative approach to caries management [39]. As research continues, the understanding of fluorescence signatures is deepening, with studies exploring spectral analysis to further differentiate between active and inactive lesions and to improve specificity by accounting for confounding factors [40]. The future likely holds even more sophisticated devices that combine multiple wavelengths and analytical algorithms, pushing the boundaries of early caries diagnosis even further.

Commercially Available Fluorescence-Based Technologies:

The scientific principles of fluorescence have been successfully translated into a range of commercially available devices that are increasingly becoming integrated into modern dental practice. Each system employs a unique technological approach to detect and quantify the changes associated with the caries process, offering distinct advantages and facing specific limitations.

4.1 Quantitative Light-induced Fluorescence (QLF): The Gold Standard for Monitoring

The QLF technology, exemplified by systems like the Inspektor Pro (Inspektor Research Systems BV, Netherlands), is designed to detect and quantify the loss of natural enamel autofluorescence. The patient is positioned in a darkroom, and the device uses a blue-violet light (typically at 405 nm) to illuminate the teeth. A yellow high-pass filter in front of the camera blocks the reflected blue light, allowing only the green autofluorescence (wavelengths above 520 nm) to be captured, creating a high-resolution image.

In this image, sound enamel fluoresces brightly in green, while demineralized areas appear as dark spots due to the increased light scattering. The proprietary software is the core of QLF's power. It performs a sophisticated analysis by comparing the fluorescence of the lesion to the predicted fluorescence of the sound enamel that would have been in that same location. This allows it to calculate two key quantitative parameters:

- **ΔF (%):** The percentage of fluorescence loss in the lesion.
- **ΔQ (mm^2 x %):** The product of the lesion area and the average fluorescence loss, representing the total lesion volume.

This quantitative capability is what sets QLF apart. It is not merely a detection device but a monitoring tool. By taking sequential images over weeks or months, a clinician can objectively determine if a lesion is progressing (ΔQ increases), arresting (ΔQ stabilizes), or remineralizing (ΔQ decreases) in response to preventive interventions [41]. This makes QLF invaluable for clinical trials of anti-caries agents and for managing high-risk patients in specialist practice. Its main limitations are the need for a controlled environment (darkroom), the time required for image analysis, and its relatively higher cost, which has historically limited its use to research and specialized clinics, though newer, more compact models are aiming for broader clinical integration.

4.2 Laser Fluorescence (LF): The Sensitive Probe for Occlusal Caries

The DIAGNOdent (KaVo, Germany) and similar devices represent the laser fluorescence category. This is a pen-sized, portable device that uses a 655 nm red laser diode. The light is delivered through a conical tip placed directly onto the tooth surface, and the emitted fluorescent light from bacterial porphyrins is measured by a receiver in the same tip. The device processes this signal and provides a numerical value on a scale from 0 to 99.

The manufacturer provides general guidelines for interpretation, for example:

- **0-20:** Sound tooth surface
- **21-30:** Early enamel demineralization
- **Over 30:** Dentinal caries

The primary strength of the DIAGNOdent is its exceptionally high sensitivity for detecting occlusal caries. Numerous studies have confirmed that it can identify demineralization in deep fissures that would be missed by visual inspection and radiography [42]. Its portability, speed, and audible signal that changes with the reading make it very easy to integrate into a routine clinical examination.

However, its limitations are significant and must be well-understood to avoid misdiagnosis. The device's high sensitivity is a double-edged sword, as it can lead to false-positive readings. Anything that contains fluorophores absorbing red light can elevate the reading, including dental plaque, calculus, stained fissures, prophylactic paste residues, and even certain restorative materials [43]. Furthermore, it does not provide a spatial image of the lesion; it only gives a number for the specific spot probed. It also cannot monitor remineralization as effectively as QLF, as the porphyrin signal from bacteria may persist even in an arrested lesion. Therefore, its best use is as a highly sensitive adjunct to visual examination for assessing suspicious occlusal surfaces, with the understanding that a high reading should be confirmed by other means before initiating operative treatment.

4.3 Near-Infrared Transillumination (NIRT): The Digital Bitewing Alternative

The DIAGNOcam (KaVo, Germany) utilizes Near-Infrared Transillumination (NIRT) technology. It operates by placing a powerful NIR light source (around 780 nm) on one side of the tooth and a miniature digital camera on the other. At this specific wavelength, sound enamel is relatively transparent, while water and carious lesions are strong absorbers. Consequently, when the light passes through the tooth, sound areas appear bright and luminous, while demineralized areas with higher water content appear as dark, well-defined shadows.

The immediate advantage of the DIAGNOcam is the intuitive nature of its image. The output is a real-time video or still image that closely resembles a bitewing radiograph, making it easily interpretable by any dentist trained in reading radiographs [44]. It is highly effective for detecting both proximal and occlusal caries without using ionizing radiation, which is a monumental benefit for pediatric patients and for frequent monitoring. Studies have shown that its diagnostic performance for proximal caries is comparable to, and in some cases superior to, conventional bitewing radiography [45].

Its limitations are tied to the physics of transillumination. The technique is less effective for teeth in the posterior regions with thick buccal bone or for patients with limited mouth opening, as it can be challenging to position the device. Very large restorations or crowns can also obstruct the light path and make interpretation difficult. Unlike QLF, it does not provide a quantitative measure of mineral change, but rather a qualitative (visual) assessment of the lesion's presence and extent [46].

Conclusion

The journey through the science, technology, and clinical evidence of fluorescence-based imaging techniques unequivocally demonstrates their transformative role in modern dentistry. This research has detailed the compelling necessity for this shift, rooted in the staggering global burden of dental caries and the profound limitations of conventional diagnostic methods. Visual-tactile examination and radiography, while foundational to dental practice, are inherently inadequate for detecting the disease at its earliest, reversible stage. Their subjectivity, insensitivity to initial demineralization, and reliance on significant mineral loss create a diagnostic gap that perpetuates a restorative, rather than a preventive, approach to patient care.

Fluorescence technologies, including Quantitative Light-induced Fluorescence (QLF), Laser Fluorescence (LF) like DIAGNOdent, and Near-Infrared Transillumination (NIRT) like DIAGNOcam, have successfully bridged this gap. By leveraging the fundamental biophysical changes that occur during the caries process—specifically, the reduction in natural enamel autofluorescence and the fluorescence from bacterial metabolites—these devices provide an objective, sensitive, and quantitative means of diagnosis. The evidence consolidated in this paper confirms that these methods offer superior sensitivity for detecting non-cavitated occlusal and proximal lesions compared to traditional techniques. QLF, in particular, stands out for its unique ability to monitor lesion activity over time, providing invaluable data on the success of non-operative interventions and empowering truly preventive caries management.

However, the adoption of these technologies is not without its challenges. No single device is a perfect panacea. Laser fluorescence can be prone to false positives, QLF requires a specific setup and analysis time, and NIRT can face positioning limitations. Therefore, these tools are best viewed not as replacements for clinical judgment, but as powerful adjuncts that augment it. The optimal diagnostic strategy likely involves a synergistic approach, where a visual examination (using ICDAS criteria) is enhanced by the selective use of these advanced devices to confirm uncertain diagnoses, assess lesion activity, and monitor high-risk patients.

References

1. Bakhshandeh A., Floriano I., Braga M.M., Thorlacius K.A., Ekstrand K.R. Relationship between depth of approximal caries lesions and presence of bacteria in the dentine in primary and permanent posterior teeth: A radiographic examination with microbiological evaluation. Acta Odontol. Scand. 2018;76:509–514.
2. Nyvad B., Fejerskov O. Assessing the stage of caries lesion activity on the basis of clinical and microbiological examination. Community Dent. Oral Epidemiol. 1997;25:69–75.
3. Applebaum E. The Radiopaque Surface Layer of Enamel and Caries. J. Dent. Res. 1940;19:41–46.
4. Mertz-Fairhurst E.J., Curtis J.W., Ergle J.W., Rueggeberg F.A., Adair S.M. Ultraconservative and Cariostatic Sealed Restorations: Results at Year 10. J. Am. Dent. Assoc. 1998;129:55–66.
5. Frencken J.E., de Amorim R.G., Faber J., Leal S.C. The Caries Assessment Spectrum and Treatment (CAST) index: Rational and development. Int. Dent. J. 2011;61:117–123.
6. Meyer-Lueckel H., Paris S. When and How to Intervene in the Caries Process. Oper. Dent. 2016;41:S35–S47.
7. Machiulskiene V., Nyvad B., Baelum V. Prevalence and severity of dental caries in 12-year-old children in Kaunas, Lithuania 1995. Caries Res. 1998;32:175–180.
8. Pitts N.B., Rimmer P.A. An in vivo comparison of radiographic and directly assessed clinical caries status of posterior approximal surfaces in primary and permanent teeth. Caries Res. 1992;26:146–152.
9. Bader J.D., Shugars D.A., Bonito A.J. Systematic reviews of selected dental caries diagnostic and management methods. J. Dent. Educ. 2001;65:960–968.

10. Nyvad B., Kilian M. Comparison of the initial streptococcal microflora on dental enamel in caries-active and in caries-inactive individuals. Caries Res. 1990;24:267–272.
11. Fejerskov O., Nyvad B., Kidd E.A.M. Dental Caries the Disease and Its Clinical Management. Wiley-Blackwell; Chichester, UK: Ames, IA, USA: 2015.
12. GV B. Operative Dentistry, Pathology of the Hard Tissues of the Teeth. Volume 1 Claudius Ash; London, UK: 1914.
13. Ekstrand K.R., Ricketts D.N., Kidd E.A., Qvist V., Schou S. Detection, diagnosing, monitoring and logical treatment of occlusal caries in relation to lesion activity and severity: An in vivo examination with histological validation. Caries Res. 1998;32:247–254.
14. Thewlis J. The X-ray Examination of Enamel: (Section of Odontology) Proc. R. Soc. Med. 1940;33:387–398.
15. Dorri M., Dunne S.M., Walsh T., Schwendicke F. Micro-invasive interventions for managing proximal dental decay in primary and permanent teeth. Cochrane Database Syst. Rev. 2015;2015:CD010431.
16. Nyvad B., Machiulskiene V., Baelum V. Reliability of a new caries diagnostic system differentiating between active and inactive caries lesions. Caries Res. 1999;33:252–260.
17. Pitts N.B. Monitoring of caries progression in permanent and primary posterior approximal enamel by bitewing radiography. Community Dent. Oral Epidemiol. 1983;11:228–235.
18. Baelum V., Heidmann J., Nyvad B. Dental caries paradigms in diagnosis and diagnostic research. Eur. J. Oral Sci. 2006;114:263–277.
19. Schwendicke F., Frencken J.E., Bjorndal L., Maltz M., Manton D.J., Ricketts D., Van Landuyt K., Banerjee A., Campus G., Domejean S., et al. Managing Carious Lesions: Consensus Recommendations on Carious Tissue Removal. Adv. Dent. Res. 2016;28:58–67.
20. Nyvad B., Kilian M. Microbiology of the early colonization of human enamel and root surfaces in vivo. Scand. J. Dent. Res. 1987;95:369–380.
21. Machiulskiene V., Campus G., Carvalho J.C., Dige I., Ekstrand K.R., Jablonski-Momeni A., Maltz M., Manton D.J., Martignon S., Martinez-Mier E.A., et al. Terminology of Dental Caries and Dental Caries Management: Consensus Report of a Workshop Organized by ORCA and Cariology Research Group of IADR. Caries Res. 2020;54:7–14.
22. Silverstone L.M., Hicks M.J., Featherstone M.J. Dynamic factors affecting lesion initiation and progression in human dental enamel. II. Surface morphology of sound enamel and carieslike lesions of enamel. Quintessence Int. 1988;19:773–785.
23. Pitts N.B., Zero D.T., Marsh P.D., Ekstrand K., Weintraub J.A., Ramos-Gomez F., Tagami J., Twetman S., Tsakos G., Ismail A. Dental caries. Nat. Rev. Dis. Primers. 2017;3:17030.
24. Kidd E.A., Pitts N.B. A reappraisal of the value of the bitewing radiograph in the diagnosis of posterior approximal caries. Br. Dent. J. 1990;169:195–200.
25. Luan W., Baelum V., Fejerskov O., Chen X. Ten-year incidence of dental caries in adult and elderly Chinese. Caries Res. 2000;34:205–213.
26. Innes N.P., Evans D.J., Stirrups D.R. Sealing caries in primary molars: Randomized control trial, 5-year results. J. Dent. Res. 2011;90:1405–1410.
27. Paddick J.S., Brailsford S.R., Kidd E.A., Beighton D. Phenotypic and genotypic selection of microbiota surviving under dental restorations. Appl. Env. Microbiol. 2005;71:2467–2472.
28. Gustafsson B.E., Quensel C.E., Lanke L.S., Lundqvist C., Grahnen H., Bonow B.E., Krasse B. The Vipeholm dental caries study; the effect of different levels of carbohydrate intake on caries activity in 436 individuals observed for five years. Acta Odontol. Scand. 1954;11:232–264.

29. Nyvad B. Diagnosis versus detection of caries. Caries Res. 2004;38:192–198.
30. Boston D.W., Jefferies S.R. Physical effects of non-cavitated explorer probing on enamel smooth-surface carious lesions. Am. J. Dent. 2015;28:183–189.
31. Thylstrup A., Bruun C., Holmen L. In vivo caries models—Mechanisms for caries initiation and arrestment. Adv. Dent. Res. 1994;8:144–157.
32. Innes N.P.T., Chu C.H., Fontana M., Lo E.C.M., Thomson W.M., Uribe S., Heiland M., Jepsen S., Schwendicke F. A Century of Change towards Prevention and Minimal Intervention in Cariology. J. Dent. Res. 2019;98:611–617.
33. de Assuncao I.V., da Costa Gde F., Borges B.C. Systematic review of noninvasive treatments to arrest dentin non-cavitated caries lesions. World J. Clin. Cases. 2014;2:137–141.
34. Akpata E.S., Farid M.R., al-Saif K., Roberts E.A. Cavitation at radiolucent areas on proximal surfaces of posterior teeth. Caries Res. 1996;30:313–316.
35. Pitts N. "ICDAS"—An international system for caries detection and assessment being developed to facilitate caries epidemiology, research and appropriate clinical management. Community Dent. Health. 2004;21:193–198.
36. Tellez M., Gomez J., Kaur S., Pretty I.A., Ellwood R., Ismail A.I. Non-surgical management methods of noncavitated carious lesions. Community Dent. Oral Epidemiol. 2013;41:79–96.
37. Hollander F.S.E. The apparent radiopaque surface layer of the enamel. Dent. Cosm. 1935;77:1187–1197.
38. Marggraf T., Ganas P., Paris S., Schwendicke F. Bacterial reduction in sealed caries lesions is strain- and material-specific. Sci. Rep. 2018;8:3767.
39. Ismail A.I., Pitts N.B., Tellez M., Authors of International Caries Classification and Management System (ICCMS) Management S., Banerjee A., Deery C., Douglas G., Eggertsson H., Ekstrand K., et al. The International Caries Classification and Management System (ICCMS) An Example of a Caries Management Pathway. BMC Oral Health. 2015;15:S9.
40. Nyvad B., Baelum V. Nyvad Criteria for Caries Lesion Activity and Severity Assessment: A Validated Approach for Clinical Management and Research. Caries Res. 2018;52:397–405.
41. Zero D.T., Fontana M., Martinez-Mier E.A., Ferreira-Zandona A., Ando M., Gonzalez-Cabezas C., Bayne S. The biology, prevention, diagnosis and treatment of dental caries: Scientific advances in the United States. J. Am. Dent. Assoc. 2009;140:25S–34S.
42. Ekstrand K., Qvist V., Thylstrup A. Light microscope study of the effect of probing in occlusal surfaces. Caries Res. 1987;21:368–374.
43. Pitts N.B., Ekstrand K.R., Foundation I. International Caries Detection and Assessment System (ICDAS) and its International Caries Classification and Management System (ICCMS)—Methods for staging of the caries process and enabling dentists to manage caries. Community Dent. Oral Epidemiol. 2013;41:e41–e52.
44. Hintze H., Wenzel A., Danielsen B., Nyvad B. Reliability of visual examination, fibre-optic transillumination, and bite-wing radiography, and reproducibility of direct visual examination following tooth separation for the identification of cavitated carious lesions in contacting approximal surfaces. Caries Res. 1998;32:204–209.
45. Gomez J. Detection and diagnosis of the early caries lesion. BMC Oral Health. 2015;15:S3.
46. Giacaman R.A., Fernández C.E., Muñoz-Sandoval C., León S., García-Manríquez N., Echeverría C., Valdés S., Castro R.J., Gambetta-Tessini K. Understanding dental caries as a non-communicable and behavioral disease: Management implications. Front. Oral Health. 2022;3:764479.