Advances in Early Diagnosis and Management of Dental Caries: A Clinical Review

Dr. Neha R. Kulkarni

Department of Conservative Dentistry and Endodontics, Shantideep Dental College & Hospital, Pune, India

ABSTRACT

Dental caries remains one of the most prevalent chronic diseases worldwide, affecting individuals across the lifespan and placing a significant burden on healthcare systems. Contemporary understanding of caries as a dynamic, biofilm-mediated, and behaviorally driven disease has shifted the clinical focus from operative intervention to early diagnosis and minimally invasive management. Over the past two decades, major advances have been made in standardized visual criteria, optical and radiographic adjunctive technologies, and risk-based management strategies, alongside novel therapeutic agents and artificial intelligence–driven diagnostic tools. This clinical review synthesizes current evidence on early diagnosis of dental caries and translates technological and therapeutic advances into practical recommendations for daily practice. The review discusses epidemiology and pathophysiology, outlines conventional and advanced diagnostic methods, and examines non-operative, micro-invasive, and minimally invasive management of early lesions. Special attention is given to standardized systems such as ICDAS/ICCMS, optical methods including quantitative light-induced fluorescence (QLF) and near-infrared transillumination (NIRT), resin infiltration, silver diamine fluoride, and artificial intelligence (AI)–based systems for radiographic interpretation. The paper concludes with an integrated clinical decision-making framework for early caries detection and management and highlights future directions in personalized, data-driven caries care.

Keywords: *dental caries; early diagnosis; caries detection; quantitative light-induced fluorescence; near-infrared transillumination; ICDAS; silver diamine fluoride; resin infiltration; caries risk assessment; artificial intelligence.*

1. INTRODUCTION

Dental caries is a chronic, biofilm-mediated, sugar-driven disease that affects the hard tissues of teeth. It remains the most common non-communicable disease globally and is a major public health problem in both industrialized and developing countries. Early diagnosis and appropriate management are crucial to prevent progression to cavitation, pulpal involvement, pain, infection, and tooth loss. Historically, caries management focused on surgical intervention, guided largely by the "extension for prevention" philosophy. However, current concepts emphasize early detection, risk assessment, preservation of tooth structure, and control of the disease process through minimally invasive and non-operative approaches.

The rationale for early diagnosis is multifold. First, initial caries lesions are reversible if the balance between demineralization and remineralization is favorably modified. Second, early lesions are often asymptomatic and may remain undetected by conventional methods until significant structural damage occurs. Third, early detection enables targeted preventive interventions, which are more cost-effective and acceptable to patients, particularly children, older adults, and medically compromised individuals. Technological advances in diagnostic devices and imaging, as well as new materials and preventive strategies, have expanded the clinician's arsenal for managing early lesions.

This review aims to provide clinicians, postgraduate students, and researchers with a comprehensive yet clinically focused synthesis of advances in early diagnosis and management of dental caries. Emphasis is placed on practical applications, strengths and limitations of various methods, and integration of diagnostic information into decision-making.

2. EPIDEMIOLOGY AND PATHOBIOLOGY OF DENTAL CARIES

2.1 Global burden

Despite improvements in oral health awareness and fluoridation, dental caries remains highly prevalent in both primary and permanent dentitions. Untreated caries of permanent teeth is consistently ranked among the most prevalent health conditions worldwide. Caries prevalence often exhibits social gradients, with higher levels in socioeconomically disadvantaged communities and in populations with limited access to dental care, fluoridated water, and preventive programs. Furthermore, caries patterns are changing, with an increasing burden among older adults due to root caries and retained dentitions, and in certain vulnerable pediatric populations.

2.2 Caries as a dynamic process

Caries is now recognized as a dynamic process characterized by alternating episodes of demineralization and remineralization at the tooth–biofilm interface. Frequent intake of fermentable carbohydrates leads to acid production by cariogenic bacteria within the dental biofilm, resulting in a drop of pH below the critical threshold for enamel and dentin. Repeated acid challenges cause net mineral loss when the remineralizing capacity of saliva and fluoride is overwhelmed. Early in the disease, mineral loss is confined to the subsurface enamel, manifesting clinically as a white spot lesion with intact surface. At this stage, lesions are potentially reversible with appropriate preventive measures. Progression leads to surface breakdown, cavitation, and eventual involvement of dentin and the pulp.

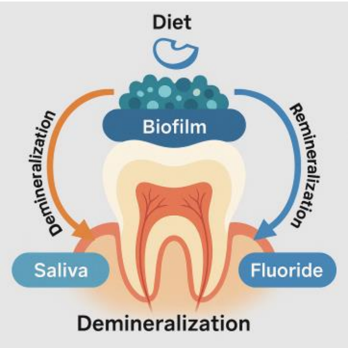

Figure 1 — Schematic representation of the caries process

2.3 Risk factors and risk assessment

Caries risk is determined by complex interactions among biological, behavioral, environmental, and social factors. Key risk indicators include past caries experience, dietary habits (especially frequency of sugar intake), oral hygiene and biofilm accumulation, salivary flow and buffering capacity, fluoride exposure, socio-economic status, and medical conditions such as xerostomia or special care needs. Caries risk assessment tools, such as CAMBRA-based protocols or Cariogram-type models, help categorize patients into low, moderate, high, or extreme risk based on these factors. Risk assessment is crucial for tailoring recall intervals, preventive interventions, and thresholds for operative care. It also underpins contemporary systems such as the International Caries Classification and Management System (ICCMS), which integrates lesion staging with risk level to guide management.

3. CONVENTIONAL DIAGNOSTIC APPROACHES AND THEIR LIMITATIONS

3.1 Visual–tactile examination

Visual–tactile inspection under good lighting, with clean and dry tooth surfaces, is the cornerstone of caries diagnosis. Traditional methods relied on blunt probes or explorers to detect "stickiness" on occlusal surfaces. However, this approach has been criticized because it may inadvertently damage fragile demineralized enamel, predispose to cavitation, and lacks sensitivity for early non-cavitated lesions. Current guidelines advocate a careful visual examination aided by air-drying, magnification when available, and the use of a ball-ended probe mainly to remove debris and gently assess surface roughness instead of "catching" in pits and fissures.

3.2 Radiographic examination

Bitewing radiographs remain a mainstay for detection of proximal and occlusal dentin caries. They are particularly useful for estimating lesion depth and guiding operative decisions. However, conventional radiographs have limited sensitivity for early enamel lesions and for occlusal lesions that are confined to the enamel. Overlapping contacts, image distortion, and observer variability further compromise diagnostic accuracy. Moreover, radiation exposure, although low per examination, requires adherence to the ALARA (As Low As Reasonably Achievable) principle, especially in children and pregnant patients. As a result, interest has grown in adjunctive imaging technologies that can visualize early demineralization without ionizing radiation.

3.3 Who criteria and their evolution

Historically, epidemiological surveys have used the WHO criteria, which record dentinal cavitation as the threshold for caries detection. While useful for population-level assessments, these criteria underestimate the prevalence of early lesions and offer limited guidance for preventive management. Recognizing the need to capture the full spectrum of caries severity, more detailed visual scoring systems such as ICDAS were developed, which allow clinicians and researchers to document and monitor non-cavitated as well as cavitated lesions.

4. STANDARDIZED VISUAL CRITERIA: ICDAS AND ICCMS

4.1 International Caries Detection and Assessment System (ICDAS)

The International Caries Detection and Assessment System (ICDAS) was developed to provide a unified, evidence-based visual scoring system for caries across different surfaces and tooth types. The ICDAS codes range from 0 (sound) to 6 (extensive distinct cavity) and emphasize early detection of non-cavitated lesions. Codes 1 and 2 represent initial changes in enamel visible only after air-drying or as distinct white/brown discolorations, while codes 3 to 6 reflect increasingly severe surface breakdown and dentin involvement. The ICDAS framework also accounts for lesion location (smooth surfaces, pits and fissures, root surfaces) and presence of restorations or sealants.

The adoption of ICDAS in research and clinical practice has improved the ability to detect and monitor early lesions, evaluate preventive interventions, and standardize communication among clinicians, researchers, and public health professionals. However, its use requires training and calibration to ensure reproducible scoring.

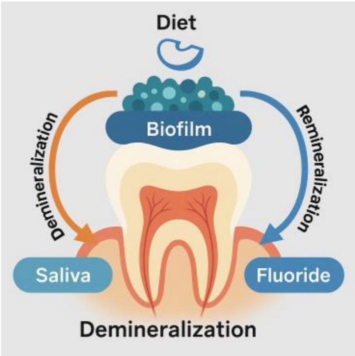

Figure 2 — ICDAS visual scoring for occlusal caries (codes 0–6)

4.2 International Caries Classification and Management System (ICCMS)

Building upon ICDAS, the International Caries Classification and Management System (ICCMS) integrates lesion staging with caries risk assessment and individualized management options. ICCMS emphasizes that diagnosis of the disease (caries activity and risk) should precede the diagnosis of individual lesions. It proposes treatment plans that combine preventive, non-operative, micro-invasive, and operative measures tailored to both lesion severity and patient risk profile. For example, an initial proximal enamel lesion in a low-risk adult may be monitored and managed with intensified home care and fluoride, while a similar lesion in a high-risk child with multiple active lesions may warrant more frequent recalls, professional fluoride applications, or micro-invasive intervention such as resin infiltration.

5. ADVANCES IN OPTICAL AND ADJUNCTIVE DIAGNOSTIC TECHNOLOGIES

The limitations of conventional visual and radiographic methods have driven the development of adjunctive technologies that enhance early detection and quantification of demineralization. Among these, quantitative light-induced fluorescence, laser fluorescence devices, fiber-optic and digital transillumination, and near-infrared transillumination are the most widely studied.

5.1 Quantitative light-induced fluorescence (QLF)

Quantitative light-induced fluorescence is an optical method that exploits the natural fluorescence of tooth tissues. When teeth are illuminated with blue light of specific wavelength, sound enamel fluoresces more strongly than demineralized enamel. Demineralization leads to increased scattering, resulting in a loss of fluorescence (ΔF) that can be captured and quantified using digital cameras and software. QLF systems provide pseudo-color images and numerical outputs corresponding to lesion depth and area, which can be used to monitor progression or regression over time.

Over three decades of research have validated QLF for detecting early enamel lesions on smooth and occlusal surfaces, as well as monitoring the effects of remineralizing agents. Recent systematic reviews have concluded that QLF has moderate-to-high sensitivity for early lesions, especially when used as an adjunct to visual examination. QLF is particularly valuable in clinical trials to quantify changes in lesion fluorescence and area in response to fluoride, casein phosphopeptide–amorphous calcium phosphate (CPP-ACP), and other agents. Nevertheless, factors such as plaque, stains, dehydration, and lighting conditions can affect readings, necessitating standardized protocols.

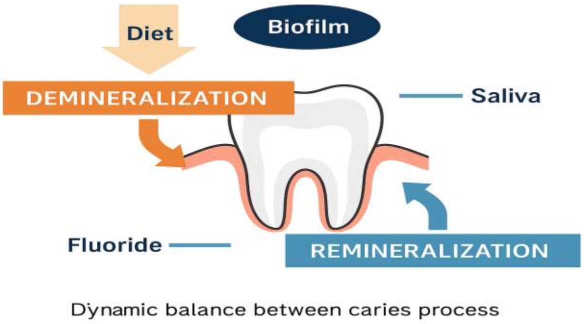

Figure 3 — QLF images comparing sound vs. early enamel lesions

5.2 Laser fluorescence devices

Laser fluorescence devices, such as DIAGNOdent, use a diode laser to induce fluorescence in bacterial metabolites and demineralized tissues. The reflected fluorescence is converted into numerical values that approximate lesion severity. These devices are primarily used on occlusal pits and fissures and have demonstrated good sensitivity but lower specificity, with a risk of false positives due to staining or plaque. They should therefore be used as adjuncts rather than stand-alone diagnostic tools and interpreted in conjunction with visual and radiographic findings.

5.3 Fiber-optic and digital transillumination

Fiber-optic transillumination (FOTI) and digital imaging fiber-optic transillumination (DIFOTI) utilize visible light transmitted through tooth structures. Demineralized enamel and dentin scatter light differently, appearing as dark shadows against a lighter background. DIFOTI systems capture these images for documentation and monitoring. Transillumination is particularly useful for proximal and occlusal lesions and offers the advantage of no ionizing radiation. However, its diagnostic accuracy is operator-dependent, and standardized interpretation criteria are still evolving.

5.4 Near-infrared transillumination (NIRT)

Near-infrared transillumination employs near-infrared wavelengths, which penetrate enamel more deeply than visible light and provide higher contrast between sound and demineralized tissues. Devices using NIRT can visualize early proximal and occlusal lesions without radiation. Clinical and in vitro studies suggest that NIRT has comparable or higher sensitivity for early proximal caries compared with bitewing radiographs, especially in low-to-moderate caries risk populations. However, specificity can vary, and NIRT cannot reliably assess lesion depth into dentin in all cases. Consequently, it is best integrated with traditional radiography, where NIRT may reduce the frequency of radiographic examinations in selected low-risk patients, but does not replace them entirely.

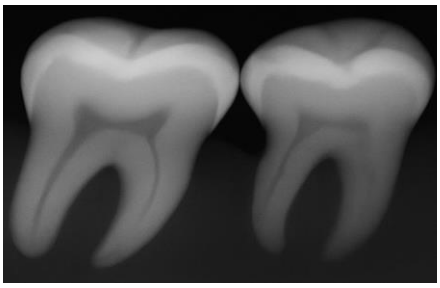

Figure 4. Near-infrared transillumination (NIRT) image of proximal caries, showing increased contrast between sound and demineralized enamel.

5.5 Micro-computed tomography as a validation standard

Micro-computed tomography (micro-CT) is not a clinical diagnostic tool but serves as a high-resolution reference standard for caries research. Its use has allowed precise correlation between optical measurements (e.g., QLF or NIRT) and actual lesion depth and mineral density in extracted teeth. Such studies have supported the validity of optical methods for quantifying early demineralization and informed the calibration of novel devices. In the clinical context, however, micro-CT remains a research tool due to radiation dose and practical constraints.

6. ARTIFICIAL INTELLIGENCE AND DIGITAL DIAGNOSTICS

6.1 AI-assisted radiographic caries detection

Artificial intelligence, particularly deep learning using convolutional neural networks (CNNs), has emerged as a powerful tool for image recognition. In dentistry, AI systems have been developed to detect caries on bitewing, periapical, panoramic, and cone-beam CT images. Numerous studies and systematic reviews report that AI models can achieve sensitivity and specificity comparable to, or in some cases exceeding, those of general dentists for detection of proximal and occlusal caries. AI-assisted software can highlight suspected lesions, quantify lesion size, and prompt the clinician to review specific regions, thereby reducing oversight and inter-observer variability.

6.2 Benefits and limitations

Potential benefits of AI-based caries detection include improved diagnostic consistency, time efficiency, and support for less experienced clinicians. AI tools can also serve as educational aids, enabling students to compare their interpretations with algorithm outputs. However, limitations include dependence on training data quality and representativeness, potential bias across populations, and reduced performance for certain lesion types or image qualities. AI systems should therefore be viewed as decision-support tools that augment, but do not replace, the clinical judgment of dentists. Regulatory, ethical, and data protection considerations must also be addressed before widespread implementation.

6.3 Integration with clinical workflows

Successful integration of AI into clinical practice requires seamless embedding within existing radiographic software, intuitive user interfaces, and minimal disruption to workflow. Real-time analysis of images, automatic generation of reports, and integration with electronic health records may help clinicians track lesions longitudinally and evaluate outcomes of preventive interventions. In the longer term, AI may fuse data from radiographs, optical scans, intraoral photographs, and patient risk factors to provide comprehensive, personalized caries risk predictions.

7. ADVANCES IN NON-OPERATIVE AND MINIMALLY INVASIVE MANAGEMENT

7.1 Principles of modern caries management

Modern caries management is grounded in minimal intervention dentistry. The goals are to control the disease process by modifying etiologic factors, preserve as much sound tooth structure as possible, and restore function and aesthetics only when necessary. Early, non-cavitated lesions can often be arrested or reversed through improved biofilm control, dietary modification, and enhanced fluoride exposure. Decisions about when to intervene operatively depend on lesion activity, depth, patient risk status, and the likelihood of compliance with preventive measures.

7.2 Fluoride therapies and remineralizing agents

Topical fluoride—in the form of toothpaste, mouthrinses, gels, and varnishes—remains the cornerstone of caries prevention. High-fluoride toothpastes (e.g., 5,000 ppm fluoride) may be indicated for high-risk adolescents and adults, while fluoride varnishes are effective for both coronal and root caries, particularly in children and older adults with exposed root surfaces or xerostomia. Contemporary meta-analyses support the efficacy of fluoride varnishes in reducing caries incidence in primary and permanent teeth.

Other remineralizing agents, such as CPP-ACP complexes, bioactive glass particles, and calcium–phosphate-based technologies, have been developed to supplement fluoride or target patients with specific needs (e.g., those with high caries risk or orthodontic appliances). Although evidence supports improvements in surrogate outcomes such as enamel hardness and visual lesion regression, long-term clinical effectiveness data are still evolving. Clinicians should consider cost, availability, and patient preference when incorporating such products into preventive regimens.

7.3 Silver diamine fluoride (SDF)

Silver diamine fluoride has gained attention as a non-invasive, low-cost agent for arresting active caries lesions, particularly in young children, older adults, and medically compromised patients who may not tolerate conventional restorative procedures. SDF combines the antimicrobial effects of silver ions with the remineralizing action of fluoride. Clinical trials and systematic reviews demonstrate high caries arrest rates on primary and permanent teeth, including root caries, when SDF is applied at regular intervals. Its main drawbacks are the permanent black staining of arrested lesions and potential, though rare, adverse effects such as mild mucosal irritation.

From a public health perspective, SDF is especially valuable in community and outreach settings, as it can be applied quickly without anesthesia or rotary instruments. In individual patient care, SDF may be used as a definitive treatment for certain lesions or as an interim measure (e.g., within an "ultra-conservative treatment" or "silver-modified atraumatic restorative technique" approach) until more definitive restorative care can be provided.

7.4 Sealants and micro-invasive techniques

Pit and fissure sealants are a well-established preventive measure for occlusal surfaces at high risk of caries. Resin-based sealants, when placed with proper isolation and technique, provide a physical barrier that prevents biofilm colonization and carbohydrate diffusion into pits and fissures. Glass ionomer sealants, although less durable, may

be advantageous in partially erupted teeth or in settings where moisture control is limited. Sealing non-cavitated occlusal lesions is an evidence-based strategy for arresting lesion progression without removing tooth tissue.
Micro-invasive techniques, such as resin infiltration, bridge the gap between non-operative care and conventional restorative treatment. Resin infiltration involves etching the surface of a non-cavitated proximal or smooth-surface lesion, drying, and applying a low-viscosity resin that penetrates the lesion body. The infiltrant occludes the pores within demineralized enamel, thereby impeding diffusion pathways for acids and dissolved minerals. Systematic reviews indicate that resin infiltration can significantly reduce the progression of proximal and smooth-surface lesions compared with non-invasive strategies alone, with additional benefits for masking white spot lesions in aesthetic areas. However, the technique is technique-sensitive and requires meticulous isolation, as well as appropriate case selection (lesions limited to enamel or outer dentin and without cavitation).

7.5 Minimally invasive restorative approaches

When cavitation or structural compromise necessitates restorative treatment, minimally invasive techniques should be employed. These include small conservative preparations confined to infected dentin, selective caries removal to firm dentin near the pulp, and use of adhesive restorative materials that permit maximum preservation of sound tissue. Atraumatic restorative treatment (ART), involving hand instruments and high-viscosity glass ionomer cements, is particularly useful in community settings and for uncooperative patients. Selective caries removal and stepwise excavation strategies reduce the risk of pulp exposure while maintaining pulp vitality.

8. INTEGRATING DIAGNOSIS AND MANAGEMENT: A CLINICAL DECISION FRAMEWORK

8.1 From detection to decision

Effective caries management requires moving systematically from detection and assessment to diagnosis and decision-making. The following steps summarize an integrated approach:

1. Comprehensive risk assessment: Identify patient-level risk factors, including past caries experience, dietary habits, oral hygiene, fluoride exposure, medical conditions, and socio-behavioral determinants.
2. Lesion detection and staging: Perform meticulous visual–tactile examination with drying, supplemented by radiographs where indicated and by optical adjuncts (QLF, NIRT, transillumination) depending on availability and patient needs. Use standardized criteria (e.g., ICDAS) to stage lesions.
3. Lesion activity assessment: Evaluate signs such as lesion location (plaque stagnation areas), surface roughness, opacity, and proximity to the gingival margin to distinguish active from inactive lesions.
4. Treatment planning: Integrate lesion stage and activity with patient risk status and preferences. For each lesion, decide whether non-operative, micro-invasive, or restorative management is appropriate, considering potential for lesion arrest and the consequences of non-intervention.
5. Monitoring and recall: Establish individualized recall intervals and monitoring strategies, using clinical photographs, radiographs, and optical imaging where available to document lesion behavior over time.

8.2 Practical clinical scenarios

For example, in a low-risk adult with an initial proximal enamel lesion identified on bitewing radiograph and corroborated by NIRT imaging, non-operative management with intensified home care, fluoride toothpaste, and possibly fluoride varnish may be appropriate, with periodic radiographic and clinical monitoring. In contrast, a high-risk adolescent with multiple initial proximal lesions and poor compliance may benefit from professional fluoride varnish, dietary counseling, sealants on occlusal surfaces, and resin infiltration of selected proximal lesions to prevent progression.

Similarly, in frail older adults with root caries and limited manual dexterity, SDF application combined with tailored oral hygiene support and dietary counseling may arrest lesions effectively without the need for complex restorative procedures. For young children with severe early childhood caries, SDF may be used to stabilize disease before or instead of comprehensive treatment under general anesthesia, depending on the clinical and social context.

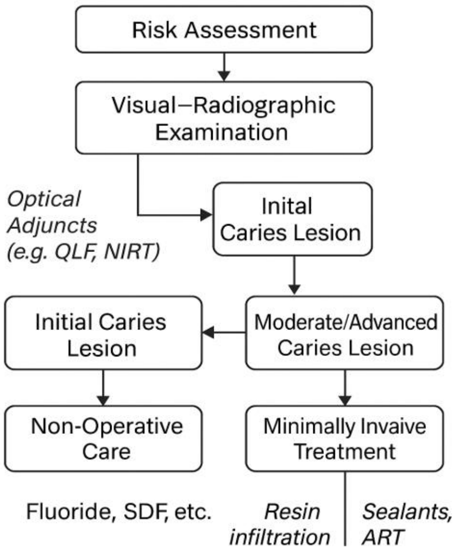

Figure 5. Clinical workflow for early caries diagnosis and management, integrating risk assessment, visual–radiographic examination, optical adjuncts, and decision pathways for non-operative, micro-invasive, and minimally invasive treatments.

8.3 Role of patient engagement and behavioral interventions

Technological advances alone cannot control caries if patient behaviors and social determinants are not addressed. Motivational interviewing, individualized dietary counseling, and co-creation of realistic home-care plans are essential components of successful caries management. Digital tools, such as mobile applications and remote monitoring, may support behavior change by enabling patients to track their brushing, diet, and appointments. AI-driven risk prediction tools, when integrated with patient education, could provide personalized feedback and enhance adherence.

9. FUTURE DIRECTIONS

9.1 Personalized and precision caries care

Future developments in caries diagnosis and management are likely to emphasize personalized, precision approaches that integrate clinical, microbiological, genetic, behavioral, and socio-environmental data. Salivary biomarkers, microbiome profiling, and genomics may help identify individuals at particularly high risk or those who respond differently to preventive interventions. Coupling these data with AI-based analytics and decision-support systems could yield dynamic, individualized caries risk scores and tailored intervention pathways.

9.2 Advances in imaging and optical technologies

Imaging technologies will continue to evolve, with improvements in resolution, speed, and patient comfort. Multispectral and hyperspectral imaging, optical coherence tomography (OCT), and novel fluorescence techniques are being explored for their potential to visualize early mineral changes in three dimensions and in real time. Integration of intraoral scanners with caries-detection algorithms may allow clinicians to monitor demineralization and erosion longitudinally using digital models, supporting minimally invasive interventions.

9.3 Novel materials and therapeutics

On the therapeutic side, bioactive restorative materials that release calcium, phosphate, and fluoride, as well as antimicrobial compounds, hold promise for both restoring form and function and modulating the disease process. Smart materials responsive to pH changes, slow-release antimicrobial agents, and nanotechnology-based remineralizing systems are being investigated. Further high-quality clinical trials are needed to substantiate their long-term benefits and cost-effectiveness compared with existing preventive measures.

9.4 Education, policy, and implementation science

Widespread adoption of early diagnostic technologies and minimally invasive management requires appropriate training of dental students and continuing professional development for practitioners. Curricula should emphasize caries as a preventable, controllable disease, the use of standardized criteria, and proficiency with optical and digital diagnostic tools. From a policy perspective, reimbursement models that incentivize prevention and non-operative care are crucial to support the shift from surgical to medical management of caries. Implementation science approaches can identify barriers and facilitators to integrating new technologies and protocols in diverse practice settings, ensuring that advances translate into improved population oral health.

10. CONCLUSIONS

Early diagnosis and contemporary management of dental caries are central to modern, patient-centered dental care. Advances in standardized visual criteria, optical and digital diagnostic technologies, artificial intelligence, and non-operative and micro-invasive treatment modalities have transformed the diagnostic and therapeutic landscape. Clinicians now have a wide array of tools to detect and monitor early lesions, assess risk, and choose conservative interventions that preserve tooth structure and maintain pulp vitality.

However, technology should not overshadow fundamental principles: meticulous clinical examination, sound risk assessment, effective communication, and patient-centered care remain paramount. The greatest benefits from new diagnostic and management strategies will be realized when they are integrated into comprehensive, preventive-oriented care pathways that address behavioral and social determinants of oral health. Continued research, education, and supportive health policies will be essential to ensure that advances in early diagnosis and management of dental caries translate into tangible improvements in clinical outcomes and quality of life for patients worldwide.

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