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Salivary Biomarkers and Digital Screening Tools in Predictive Pediatric Dentistry: A Comprehensive Review of Early Caries Diagnosis and Risk Assessment

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Abstract: Early childhood caries (ECC) remains a prevalent chronic disease affecting pediatric populations worldwide. Traditional visual-tactile diagnostic criteria often detect enamel lesions only after structural destruction has occurred, limiting the scope for non-invasive biological intervention. The paradigm shift toward predictive, personalized, and preventive dentistry necessitates the integration of early diagnostic biomarkers and automated digital risk-assessment tools. This review synthesizes current evidence on salivary physicochemical parameters (flow rate, buffering capacity, pH, and electrolyte composition), biochemical and immunological biomarkers (matrix metalloproteinases, secretory IgA, total antioxidant capacity), and their synergy with digital risk-stratification software. Furthermore, the role of advanced optical diagnostic technologies, such as laser fluorescence and quantitative light-induced fluorescence, is evaluated. Combining salivary biomarker profiling with automated digital scoring matrices enhances diagnostic precision, eliminates subjective clinician bias, and enables the timely deployment of biomimetic remineralization therapies.

Keywords: Early Childhood Caries, Salivary Biomarkers, Predictive Dentistry, Digital Risk Assessment, Remineralization, Pediatric Oral Health.

1. Introduction

Early childhood caries (ECC) is defined as the presence of one or more decayed, missing (due to caries), or filled tooth surfaces in any primary tooth in a child under six years of age [1]. Despite extensive public health initiatives, ECC remains a major global disease, exhibiting prevalence rates between 30% and 85% in developing regions [2]. Beyond immediate oral pain and masticatory dysfunction, untreated ECC severely impacts a child's systemic growth, speech development, nutritional status, and overall health-related quality of life [3].

Historically, pediatric dental diagnostics relied almost exclusively on visual inspection, often structured via the International Caries Detection and Assessment System (ICDAS), and tactile exploration using dental probes. However, these conventional modalities primarily identify macroscopic structural alterations after significant subsurface mineral loss has taken place [4]. Once cavitation occurs, surgical restorative treatment becomes inevitable. To preserve natural tooth structure, modern pediatric dentistry is shifting toward predictive and biomimetic approaches designed to detect

subclinical demineralization and arrest lesion progression before irreversible tissue loss occurs [5].

The pathogenesis of ECC is inherently multifactorial, driven by prolonged interactions among acidogenic microorganisms, fermentable dietary carbohydrates, host susceptibility, and socio-environmental determinants [6]. Given this complex etiology, accurate risk prediction requires synthesizing multiple biological and behavioral parameters. Saliva, often referred to as the "mirror of oral and systemic health," serves as a non-invasive fluid rich in biological markers that reflect real-time dynamics of enamel demineralization and remineralization [7]. Simultaneously, the integration of digital screening software and automated risk-assessment algorithms allows clinicians to aggregate biological biomarker data with behavioral vectors, establishing precise, reproducible risk profiles [8].

This comprehensive review examines the diagnostic utility of salivary biomarkers, optical detection methods, and digital risk-assessment systems in advancing predictive pediatric dentistry.

2. Materials and Methods

This article is structured as a comprehensive narrative review, appropriate for synthesizing a biologically and technologically heterogeneous evidence base, spanning salivary biochemistry, optical physics-based diagnostics, and clinical decision-support software, that would not be amenable to the narrower inclusion criteria of a systematic review or meta-analysis.

A literature search was conducted across PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar, using combinations of the following terms: "early childhood caries," "salivary biomarkers," "salivary flow rate," "buffering capacity," "matrix metalloproteinases," "secretory IgA," "total antioxidant capacity," "laser fluorescence," "DIAGNOdent," "quantitative light-induced fluorescence," "caries risk assessment," and "digital/predictive pediatric dentistry." The search prioritized peer-reviewed articles published within approximately the last two decades, with emphasis on the most recent ten years to capture developments in digital risk-assessment software and optical diagnostic technology.

Eligible sources included clinical and laboratory studies, systematic reviews, and authoritative narrative reviews addressing salivary physicochemical or biochemical parameters, optical caries-detection devices, or automated caries risk-assessment tools in pediatric or ECC-relevant populations. Studies were excluded if they were not peer-reviewed, were unavailable in English, or addressed adult-only caries risk without applicability to pediatric physiology or ECC pathogenesis. In vitro and mechanistic studies were retained where they clarified the biochemical rationale for a given biomarker (for example, the pH-dependent activation of matrix metalloproteinases), even where pediatric clinical outcome data were limited.

Extracted findings were organized thematically rather than chronologically, around three domains: physicochemical and biochemical salivary biomarkers; advanced optical and digital diagnostic technologies; and the integration of salivary and clinical-behavioral data into automated digital risk-stratification systems. This thematic synthesis structure, rather than a study-by-study summary, was chosen to reflect how these evidence streams are combined in contemporary predictive-dentistry practice.

3. Results and Discussion

3.1 Physicochemical and Biochemical Salivary Biomarkers

Saliva provides primary innate defense against dental caries through mechanical cleansing, chemical buffering, and ion delivery. Unstimulated and stimulated salivary flow rates directly influence the clearance speed of fermentable carbohydrates and cariogenic organic acids from the oral cavity [9]. A reduced salivary flow rate significantly compromises oral clearance, creating an environment favorable for aciduric bacteria such as *Streptococcus mutans* and *Lactobacillus* species.

Salivary pH and buffering capacity represent critical physicochemical markers of caries susceptibility. Under normal physiological conditions, resting salivary pH ranges between 6.7 and 7.3. When dietary carbohydrates are metabolized by cariogenic plaque biofilms, organic acids (primarily lactic, acetic, and propionic acids) are produced, causing a rapid drop in plaque and salivary pH. When pH drops below the critical threshold of 5.5, hydroxyapatite crystals within the enamel structure begin to dissolve [10]. The bicarbonate buffering system, supported by phosphate and protein buffers, acts as the primary mechanism neutralizing intraoral acidity, and quantifying a pediatric patient's salivary buffering capacity provides vital baseline data regarding physiological resilience against acid challenges. In patients with low buffering capacity and reduced salivary flow, this cascade leads directly to enamel demineralization and ECC progression; conversely, in patients with high buffering capacity and adequate salivary flow, rapid acid neutralization occurs, facilitating continuous enamel remineralization.

Saliva is naturally supersaturated with calcium and phosphate ions relative to enamel hydroxyapatite, a chemical supersaturation that maintains thermodynamic equilibrium, prevents spontaneous enamel dissolution, and facilitates continuous remineralization of subclinical microscopic lesions [11]. Fluoride ions present in saliva significantly accelerate this process by replacing hydroxyl groups to form fluorapatite, which exhibits a lower critical pH threshold (approximately 4.5), making enamel markedly more resistant to subsequent acid attacks. Measuring salivary calcium, phosphate, and fluoride concentrations therefore yields crucial diagnostic insight into the intrinsic remineralization potential of the oral fluid.

Beyond inorganic constituents, saliva contains proteins, immunoglobulins, and enzymes that actively participate in oral defense. Secretory Immunoglobulin A (sIgA), the predominant antibody class in mucosal secretions, inhibits bacterial adherence to tooth surfaces, neutralizes bacterial enzymes, and promotes microbial agglutination and clearance [12]; children with congenital or transient sIgA deficiencies frequently demonstrate heightened ECC susceptibility. Matrix metalloproteinases (MMPs), particularly MMP-2, MMP-8, and MMP-9, play a dual role in dentin caries progression: activated by low-pH environments during bacterial acid production, these host enzymes degrade the organic dentin matrix after inorganic mineral dissolution, facilitating deep lesion advancement [13], and elevated salivary MMP levels correlate directly with active, rapidly progressing carious lesions. Total antioxidant capacity (TAC) reflects the overall oxidative stress status within the oral cavity, and fluctuations in TAC correlate with active inflammatory responses and extensive cariogenic activity, serving as an auxiliary biochemical marker of disease severity [14].

3.2 Advanced Optical and Digital Diagnostic Technologies

While salivary biomarkers provide systemic and biological risk data, accurate localization and quantification of early enamel demineralization require sensitive, objective diagnostic instruments. Traditional bite-wing radiography exhibits limited sensitivity for detecting non-cavitated occlusal and smooth-surface enamel lesions and involves ionizing radiation, making frequent use undesirable in young children. To overcome these constraints, advanced optical diagnostic technologies have been integrated into clinical practice.

Laser fluorescence devices (e.g., DIAGNOdent) use a diode laser operating at 655 nm. When the laser light encounters bacterial porphyrins and metabolic end-products within demineralized tooth structure, it emits fluorescent light in the near-infrared spectrum [15]; the system converts this fluorescence into a quantitative numerical scale (0 to 99), allowing clinicians to precisely monitor subtle changes in lesion depth and density over time. Quantitative light-induced fluorescence (QLF) uses blue light (around 405 nm) to excite intrinsic enamel autofluorescence: healthy enamel fluoresces brightly, whereas demineralized areas show fluorescence loss due to increased light scattering within porous enamel. QLF software quantifies mineral loss and lesion area, offering an objective tool for assessing the efficacy of remineralization therapies. Together, these optical technologies address the central limitation of radiographic and visual-tactile diagnosis: they detect and quantify subsurface, pre-cavitation demineralization, the stage at which biomimetic remineralization is still a viable alternative to restorative intervention.

3.3 Integration of Salivary Profiling into Automated Digital Risk Screening

Evaluating individual risk factors in isolation provides limited prognostic value, because ECC is driven by complex interactions among biological, environmental, and behavioral variables. A child might present with high salivary buffering capacity but still develop severe caries due to frequent nocturnal consumption of free sugars combined with poor oral hygiene. To address this diagnostic challenge, pediatric dentistry is adopting automated digital risk-assessment software and clinical decision-support systems that process multiple input parameters, salivary flow, pH, buffering capacity, plaque indices, dietary frequency, maternal oral health, and socio-economic status, converting complex clinical data into standardized, reproducible risk scores.

The input parameters processed by such software typically include:

- Salivary biomarkers: flow rate, pH, buffering capacity, calcium and phosphate concentrations.
- Clinical examination: ICDAS scores, plaque index, DIAGNOdent laser fluorescence values.
- Behavioral/socioeconomic vectors: dietary sugar frequency, nocturnal feeding practices, maternal oral health status.

Upon entering these variables, the automated risk computation engine calculates a comprehensive risk score and stratifies the patient into one of three categories: low risk, managed with standard bi-annual monitoring and general oral hygiene optimization; moderate risk, managed with quarterly remineralization therapies and targeted fluoride applications; and high risk, managed with intensive bio-targeted protocols, including CPP-ACP complexes, silver diamine fluoride (SDF), and strict clinical surveillance.

This integrated approach offers several clinical advantages. It improves objectivity and consistency, since automated algorithms eliminate clinician subjectivity and provide consistent, evidence-based risk categorization across clinical settings. It enables personalized protocol generation, as software automatically generates customized preventive protocols once a patient is categorized into a given risk tier. It strengthens patient and parental engagement, since visual risk graphs, color-coded scorecards, and interactive digital interfaces improve parental understanding, compliance, and commitment to home-care regimens. And it supports resource optimization, ensuring high-risk children receive intensive, bio-targeted preventive interventions while low-risk patients avoid unnecessary, costly procedures.

4. Conclusion

The integration of salivary biomarker profiling, quantitative optical technologies, and automated digital risk screening marks a major evolution in pediatric dentistry, transitioning practice from reactive, restorative care to proactive, predictive management.

Salivary markers provide critical insights into the biological dynamics of the oral cavity, while digital software synthesizes these biological parameters alongside clinical and behavioral variables to create precise risk profiles.

Future research should focus on developing point-of-care microfluidic diagnostic devices ("lab-on-a-chip" systems) capable of rapidly quantifying salivary proteins, electrolytes, and cariogenic pathogens chairside within minutes. Incorporating machine learning and artificial intelligence into digital risk software will further refine predictive models, enabling clinicians to identify caries susceptibility at subclinical stages and deliver personalized, minimally invasive oral healthcare for every child.

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