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Odontogenic Maxillary Sinusitis: A Multidisciplinary Approach

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ABSTRACT

Background

Oral biofilms are complex microbial ecosystems that drive the initiation and progression of dental caries, gingivitis, and periodontitis. Traditional biofilm control has relied heavily on mechanical plaque removal and pharmacological agents such as chlorhexidine. However, limitations including microbial dysbiosis, adverse effects, and incomplete long - term effectiveness have encouraged the development of biologically guided therapies and computational diagnostic approaches.

Objective

This review summarizes the evolution of oral biofilm management from conventional antimicrobials to emerging strategies including probiotics, targeted antimicrobial agents, and artificial intelligence (AI)-assisted biofilm detection and risk prediction.

Methods

A narrative review approach was used to synthesize key evidence on oral biofilm pathogenesis, conventional and emerging therapeutic strategies, and recent advances in biofilm detection using imaging, computer-assisted analysis, and machine learning.

Results

Chlorhexidine remains the most widely used chemical plaque control agent, yet its side effects and limited suitability for prolonged use restrict clinical application. Novel therapeutic approaches, including probiotics, host-modulation, and anti-biofilm molecules, aim to control biofilms while preserving microbial homeostasis. AI-driven diagnostics have demonstrated increasing accuracy in plaque detection, periodontal risk assessment, and chairside decision support. Image-based deep learning models offer consistent plaque scoring and may improve patient motivation and clinician calibration.

Conclusion

Oral biofilm management is shifting toward personalized, minimally disruptive approaches supported by computational diagnostics. While AI-assisted detection tools show promise, robust multicenter validation and clinical integration are essential before routine adoption.

Keywords

Oral biofilm; Dental plaque; Chlorhexidine; Probiotics; Antimicrobial agents; Artificial intelligence; Deep learning; Periodontal diagnosis

INTRODUCTION

Oral biofilms, commonly referred to as dental plaque, are structured microbial communities embedded in an extracellular polymeric matrix adherent to oral surfaces. Rather than representing random microbial accumulation, plaque is a highly organized ecosystem shaped by nutrient availability, host factors, and microbial interactions. Biofilm-mediated dysbiosis plays a central role in caries and periodontal diseases, making biofilm control fundamental to preventive and therapeutic dentistry (1,2).

For decades, clinical biofilm management has been based on mechanical plaque control and adjunctive pharmacological agents. Although antiseptics and antibiotics can suppress bacterial load, complete eradication of oral biofilms is unrealistic and often undesirable due to the ecological role of commensal microbiota (3). Contemporary research has therefore moved toward strategies that modulate biofilm composition, disrupt virulence, and support host defences rather than broadly eliminating microorganisms (4,5).

In parallel, diagnostic dentistry has entered an era of digital transformation. Advances in image processing and artificial intelligence (AI) have enabled computer-assisted plaque detection, automated scoring, and risk prediction. These developments have the potential to improve diagnostic consistency, patient engagement, and personalized care planning (6–8).

This review discusses the evolution of oral biofilm research and management, focusing on conventional pharmacological agents, emerging therapies, and AI-driven diagnostic tools.

BIOLOGY OF ORAL BIOFILMS

Biofilm development begins with the formation of the acquired pellicle, followed by bacterial adhesion and co-aggregation. Early colonizers such as streptococci and actinomyces facilitate attachment, while bridging organisms enable late colonizers to integrate into a mature biofilm. The extracellular matrix contributes to

structural stability and provides protection from antimicrobials and host immune responses (1,2,9).

Oral diseases are increasingly explained through the ecological plaque hypothesis, in which environmental changes (e.g., frequent sugar intake, reduced salivary flow, or inflammation) shift the biofilm toward a pathogenic profile (4). In periodontitis, dysbiosis is characterized by increased proteolytic anaerobes and altered host-microbe interactions. In caries, acidogenic and aciduric organisms dominate under frequent carbohydrate exposure (2,4). Because biofilms function as communities rather than isolated species, strategies targeting only one organism often fail. This understanding has influenced the shift toward biofilm disruption, virulence inhibition, and microbial balance restoration (5).

CONVENTIONAL BIOFILM CONTROL STRATEGIES

Mechanical plaque removal remains the foundation of oral biofilm management. Toothbrushing, interdental cleaning, and professional scaling disrupt biofilm architecture and reduce microbial load. However, mechanical control is dependent on patient compliance and manual dexterity, making adjunctive chemical methods clinically valuable (3,10).

Chlorhexidine (CHX) is considered the gold standard chemical plaque control agent due to its broad antimicrobial spectrum and substantivity. CHX mouth rinses reduce plaque accumulation and gingival inflammation, especially in short-term use such as post-surgical care or acute gingivitis management (3,10). Despite proven effectiveness, CHX is limited by adverse effects including tooth staining, taste alteration, mucosal irritation, and potential disruption of normal oral microbiota with prolonged use (3,10).

Systemic antibiotics are not indicated for routine plaque control. In periodontitis, antibiotics may be prescribed in selected cases such as aggressive periodontitis, refractory disease, or acute infections. However, biofilm-associated resistance mechanisms and global antimicrobial stewardship concerns have restricted widespread antibiotic use (11). Local drug delivery systems provide targeted antimicrobial effects with reduced systemic exposure; nevertheless, their benefits are adjunctive rather than curative and must accompany mechanical debridement (11).

EMERGING THERAPEUTIC STRATEGIES

Probiotics have been proposed as an ecological strategy to support beneficial microbial communities. Lactobacillus and Bifidobacterium strains have been investigated for their ability to reduce cariogenic bacteria, inhibit periodontal pathogens, and modulate inflammatory responses (12,13). Clinical studies show variable results due to differences in strains, dosing, delivery vehicles, and outcome measures. Current evidence supports probiotics as an adjunct rather than a replacement for mechanical plaque control (12,13).

Targeted approaches aim to suppress pathogenic organisms or biofilm virulence while preserving commensals. Strategies include quorum sensing inhibitors, enzymes degrading extracellular matrix components, antimicrobial peptides, and light-activated approaches such as photodynamic therapy (PDT) (5,14). Photodynamic therapy has shown promise as an adjunct in periodontal therapy, especially in patients where antibiotic use is undesirable. However, the evidence remains mixed, and standardization of protocols is needed (14).

Host modulation therapy aims to reduce periodontal tissue destruct ion by modifying inflammatory

mediators. Sub-antimicrobial dose doxycycline is a recognized example, acting as a matrix metalloproteinase inhibitor (15). Newer approaches include cytokine modulation, antioxidant therapies, and pro-resolving lipid mediators; however, many remain in experimental stages (15).

DIAGNOSTIC EVOLUTION: FROM CLINICAL INDICES TO DIGITAL BIOFILM ANALYSIS

Plaque indices remain widely used in clinical practice, but they are limited by subjectivity, inter-examiner variability, and dependence on clinician training (10). In addition, plaque scoring often requires disclosing agents, which can be time-consuming in busy clinical settings.

Digital dentistry has introduced the ability to capture intraoral photographs and analyze plaque using software-based image processing. Disclosed plaque can be quantified through segmentation techniques, providing objective measures of plaque distribution and intensity (6,7). Computer-assisted plaque analysis offers standardized scoring, improved patient education through visual feedback, and monitoring of plaque control over time (6,7).

AI-DRIVEN DIAGNOSTICS IN ORAL BIOFILM MANAGEMENT

AI systems, particularly machine learning and deep learning, have shown increasing capability in pattern recognition tasks. In dentistry, AI has been applied to radiographic interpretation, caries detection, periodontal bone loss assessment, and oral lesion screening (8,16). Biofilm detection is a logical extension because plaque can be visually captured and quantified.

Deep learning systems trained on labelled intraoral images can identify disclosed plaque areas and generate automated plaque scores. Studies suggest that AI can achieve high agreement with expert clinicians, potentially reducing examiner bias and improving reproducibility (6–8). AI-based plaque detection may be valuable in tele-dentistry, community screening programs, monitoring oral hygiene in orthodontic patients, and patient self-assessment using smartphone images (7,8).

Visualizing plaque accumulation is known to improve patient compliance. AI-based plaque mapping could provide real-time feedback, allowing patients to recognize missed areas and improve brushing technique. This approach aligns with personalized preventive dentistry and could reduce the long-term burden of biofilm-associated disease (7,8).

CLINICAL VALIDATION AND LIMITATIONS

Although AI-driven diagnostics show promise, several challenges remain. AI models depend heavily on the quality and diversity of training data, and images collected under standardized conditions may not generalize to routine clinical environments (8,16). Most AI studies remain single-center or pilot investigations; multicenter validation is essential before widespread adoption (8).

Clinical AI tools require validation, regulatory approval, and clear accountability frameworks. The dentist remains responsible for clinical decision-making, and AI should be viewed as decision support rather than replacement (16). Not all clinically significant biofilms are visible; subgingival biofilms and microbial virulence cannot be fully assessed by imaging alone. Future diagnostics may integrate imaging with salivary biomarkers, microbiome sequencing, and chairside inflammatory tests (5,16).

FUTURE DIRECTIONS

The future of oral biofilm management is likely to combine minimally disruptive therapeutic strategies, microbiome-supportive interventions, targeted anti-biofilm technologies, and AI-assisted diagnostics with personalized risk prediction (5,8,16). Integration of AI into routine dental workflows may improve standardization of preventive care and support early intervention. However, clinical adoption will depend on affordability, usability, and evidence demonstrating improved patient outcomes.

CONCLUSION

Oral biofilm management has evolved from broad pharmacological suppression toward biologically informed, personalized strategies that aim to preserve microbial balance while reducing disease risk. Chlorhexidine remains a valuable short-term agent, but its limitations highlight the need for alternative approaches such as probiotics, anti-biofilm molecules, and host modulation therapies. Concurrently, AI-driven diagnostics represent a major advancement in plaque detection and monitoring, offering objective scoring and enhanced patient engagement. Continued research, clinical validation, and ethical implementation are essential to translate these technologies into routine dental practice.

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