TPM Vol. 32, No. S7, 2025
ISSN: 1972-6325
https://www.tpmap.org/

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ARTIFICIAL INTELLIGENCE AS A PROMISING PATHWAY TO DENTAL EXCELLENCE

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ABSTRACT
In an era of rapid dynamic developments across medicine, technology, and artificial intelligence (AI), lifelong learning is essential for long-term clinical success in dental practice. Artificial intelligence—the simulation of human intelligence processes by machines—has been utilized in healthcare for decades and holds transformational potential for dentistry by solving complex diagnostic challenges and streamlining clinical workflows. AI encompasses diverse subfields, including machine learning (ML), natural language processing (NLP), computer vision, and robotics. Investigating AI applications in periodontics and cariology is particularly critical, as these represent major global oral health burdens. AI algorithms can analyze dental radiographs and detect early structural breakdown or loss that might escape manual clinician screening. Currently, AI algorithms span periodontics, cariology, endodontics, prosthodontics, orthodontics, and oral pathology. Conversely, real-world clinical adoption of AI in dentistry remains modest due to challenges surrounding data quality, standardization, algorithmic bias, high implementation costs, and regulatory compliance.

KEYWORDS: Artificial Intelligence, Machine Learning, Digital Dentistry, Periodontics, Cariology, Endodontics, Prosthodontics, Diagnostic Accuracy.

1. INTRODUCTION

Artificial intelligence (AI) has a rich history in healthcare, with early developments dating back to the mid-20th century. The earliest medical AI applications emerged in the 1950s when researchers utilized computer programs such as the "MIT Programmed Auto-analyzer" to analyze blood and urine samples [1]. In the 1970s, the MYCIN system demonstrated the capabilities of expert systems in guiding the diagnosis and antimicrobial treatment of infectious diseases [2].

During the 1980s, machine learning (ML) algorithms were progressively incorporated into medical image analysis and pharmacological discovery. The 1990s witnessed further expansion with clinical management systems such as "IntelliCare" for mental health disorders and "CardioCom" for cardiac diagnostic support [3]. Subsequent decades, particularly from the 2000s onward, witnessed transformative advancements in natural language processing (NLP) and deep learning, enabling comprehensive AI integration across diagnosis, treatment planning, precision medicine, and continuous patient monitoring [4].

Although digital integration in dentistry was historically perceived as lagging behind general medicine, modern dental clinical workflows have undergone a profound paradigm shift. Historically described as subjective and operator-dependent [5], modern dentistry leverages advanced technologies to maximize diagnostic precision, efficiency, and patient comfort. Key innovations include intraoral digital scanners, 3D additive manufacturing, computer-aided design and computer-aided manufacturing (CAD/CAM), guided surgical robotics, and AI decision-support systems. AI applications are rapidly proliferating across dental radiology, automated caries detection, electronic health record processing, and automated risk stratification.

2. AI Applications in Periodontal Disease

Chronic inflammatory oral conditions, primarily gingivitis and periodontitis, represent significant global health burdens leading to progressive tissue destruction and tooth loss. Early diagnosis is critical to arresting disease progression and mitigating systemic inflammatory risks. Standard periodontal diagnostics rely on clinical probing, visual plaque indexing, radiographic evaluation, quantitative light-induced fluorescence (QLF), and salivary bacterial DNA assays. However, traditional clinical examinations remain inherently subjective and operator-dependent, often constrained by clinical time limits.

Radiographic assessment of early alveolar bone loss remains challenging, as two-dimensional conventional images frequently miss early architectural changes. While QLF and molecular testing offer enhanced diagnostic granularity, they are limited by cost and accessibility [6]. The application of AI systems—particularly convolutional neural networks (CNNs)—provides an objective, highly repeatable methodology for detecting periodontal breakdown. In a systematic review, Revilla-León et al. [7] reported that AI models achieved accuracy rates ranging from 47% to 99% in plaque detection, gingivitis assessment, and marginal alveolar bone loss quantification. Although further validation on diverse clinical datasets is required, AI models show strong potential as robust clinical decision-support tools.

3. AI Applications in Oral Mucosal Disease

Oral mucosal conditions, including Oral Lichen Planus (OLP), represent chronic inflammatory disorders requiring precise differential diagnosis and longitudinal monitoring. OLP manifests as reticular, erosive, or bullous lesions across oral tissues. AI-driven computer vision systems trained on intraoral clinical photographs and histopathological slides offer enhanced automated classification of mucosal lesions, assisting clinicians in differentiating benign inflammatory conditions from dysplastic or pre-malignant lesions.

4. AI Applications in Cariology

Cariology encompasses the prevention, risk assessment, diagnosis, and management of dental caries—one of the most prevalent chronic diseases worldwide [8]. Standard diagnostic methods include visual-tactile inspection, bitewing/periapical radiography, fluorescence-based detection devices (e.g., DIAGNOdent, Spectra), and caries indicator dyes. Early-stage carious lesions remain difficult to diagnose consistently due to variable clinical presentations and intra-observer variability.

To address diagnostic variability, deep learning models have been extensively applied to dental radiography. Lee et al. [9] evaluated deep learning models for detecting early proximal caries on bitewing radiographs, demonstrating that AI assistance significantly enhanced clinician sensitivity for detecting subtle enamel and early dentinal caries. However, overlap of proximal tooth contacts and variations in image contrast can increase false-positive rates. In risk assessment, Hung et al. [10] utilized support vector machine (SVM) algorithms on national survey datasets to construct accurate predictive risk models for root caries. Despite these promising results, systematic reviews caution that many current caries-detection algorithms carry an unclear or high risk of bias due to reliance on retrospective in vitro datasets [11].

5. AI Applications in Endodontic Disease

Endodontics focuses on the etiology, diagnosis, prevention, and treatment of diseases affecting the dental pulp and periradicular tissues. Accurate diagnostic classification of pulpal status and periapical pathosis is critical for preserving pulp vitality or executing definitive root canal therapy [12]. Deep learning models trained on periapical radiographs have evolved from single-disease identification to multi-disease classification. For instance, Li et al. [13] developed a unified deep learning model capable of simultaneous detection of carious lesions and periapical radiolucencies with diagnostic performance comparable to experienced endodontists.

Determining accurate working length and navigating complex root canal morphology represent vital steps in endodontic therapy. Traditional radiographic working length determination is prone to geometric distortion and anatomical superimposition. Cone-Beam Computed Tomography (CBCT) offers superior three-dimensional visualization but carries higher radiation exposure and costs [14]. To assist standard radiography, Saghiri et al. [15, 16] demonstrated that artificial neural networks (ANNs) accurately locate the minor apical foramen with up to 93% accuracy. Furthermore, convolutional neural networks have been successfully applied to detect anatomical variations; Jeon et al. [17] demonstrated high CNN accuracy in classifying complex C-shaped canal configurations in mandibular molars using panoramic radiographs.

6. AI Applications in Prosthodontics

Prosthodontics involves the restoration and replacement of missing intraoral and maxillofacial structures. AI integration in prosthodontics enhances automated restoration design, margin detection, shade matching, and implant surgical planning [18].

6.1 Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM)

CAD/CAM technology has revolutionized indirect restorative workflows. Intraoral optical scanners generate high-resolution 3D digital impressions, eliminating physical impression materials and reducing chairside processing time [19, 20]. Integrating AI into CAD/CAM software allows for dynamic learning from extensive clinical shape databases. AI-driven restorative software automatically proposes optimized occlusal anatomy, identifies preparation margin lines, and predicts dynamic occlusal wear and material performance prior to subtractive milling or additive 3D printing [21].

6.2 Tooth-Supported Fixed and Removable Prosthodontics

Achieving optimal esthetics and biomechanical stability requires accurate integration of prostheses with existing oral structures [22]. AI tools assist clinicians in automated shade selection, facial aesthetic profile simulation, and removable partial denture framework design [23]. Furthermore, 3D Generative Adversarial Networks (GANs) represent a significant breakthrough, learning natural tooth morphology to automatically design patient-specific anatomical crowns. Chau et al. [24, 25] validated GAN-based workflows for single-molar crowns, demonstrating high biomimetic fidelity and structural precision.

6.3 Implantology

Dental implant therapy demands accurate preoperative planning to ensure long-term osseointegration and avoid vital anatomical structures. Combining AI with CBCT and optical scan data enables automated 3D tooth segmentation [26], guided implant surgical planning [27, 28], automated osteotomy site mapping [29], and prosthetic-driven implant positioning [30]. Additionally, machine learning algorithms assist in evaluating long-term implant success and detecting early signs of peri-implantitis or mechanical hardware failure [31].

6.4 Maxillofacial Prosthetics

Reconstructing complex maxillofacial defects resulting from oncological resection, trauma, or congenital anomalies presents unique clinical challenges [32]. AI algorithms facilitate the automated synthesis of 3D facial models, optimize material density and mechanical distribution, and match silicone prosthetic pigmentation to the patient's exact skin tone under varying lighting conditions [33, 34, 35].

7. AI Applications in Orthodontics and Dentofacial Orthopedics

Orthodontics addresses the diagnosis, prevention, and correction of malocclusion and dentofacial skeletal discrepancies. AI technologies are widely integrated into orthodontic workflows, including automated image archiving and classification [36, 37], automated 2D and 3D cephalometric landmark identification [38], treatment outcome prediction and soft tissue profiling [39], clear aligner staging and digital impression processing [40, 41], and remote patient compliance monitoring via conversational chatbots and smartphone-based tracking platforms [42].

8. AI Applications in Oral Medicine and Pathology

Oral squamous cell carcinoma (OSCC) and potentially malignant disorders (OPMDs) carry high morbidity and mortality when diagnosed at advanced stages. Early detection is paramount for patient survival. AI systems analyze clinical photographs, autofluorescence images, and histopathological tissue slides to identify subtle dysplastic features and malignant transformations [43, 44]. Furthermore, predictive algorithms integrate patient demographic, lifestyle, and genomic data to construct personalized oral cancer risk profiles, aiding early targeted screening [45, 46, 47].

9. Summary of AI Clinical Applications in Dentistry

The operational roles and underlying AI modalities across major dental disciplines are summarized in Table 1 below:

Dental Specialty	Primary AI Modality	Clinical Applications
Periodontics	CNNs, Computer Vision	Detection of dental plaque, diagnosis of gingivitis, quantification of marginal alveolar bone loss.
Cariology	Deep Learning, SVM	Early proximal caries detection on bitewings, caries risk prediction, non-invasive lesion tracking.
Endodontics	ANNs, CNNs	Simultaneous detection of caries and periapical lesions, apical foramen localization, C-shaped canal classification.
Prosthodontics	3D GANs, CAD/CAM AI	Automated crown morphological design, margin identification, digital shade selection, maxillofacial prosthetic color matching.
Implantology	Machine Learning, CBCT AI	Automated 3D tooth segmentation, guided implant placement planning, risk assessment for peri-implant failure.
Orthodontics	Deep Learning, Chatbots	Automated cephalometric landmarking, treatment outcome simulation, remote aligner monitoring.
Oral Pathology	Computer Vision, Predictive Algorithms	Histopathological classification of OPMDs and OSCC, automated autofluorescence image screening, risk profiling.

10. DISCUSSION

The integration of AI across dental disciplines offers unmatched capabilities in improving diagnostic precision, streamlining clinical workflows, and personalizing treatment planning. However, several critical barriers impede universal clinical adoption. The primary challenge remains the availability of standardized, high-quality, diverse, and multi-center annotated datasets required for training robust models. Existing dental datasets are predominantly small, fragmented, and retrospective, raising concerns regarding algorithmic generalizability and bias. Furthermore, legal and regulatory frameworks surrounding data privacy (e.g., HIPAA compliance), dynamic model updates, and liability for AI-assisted diagnostic errors remain evolving topics [48]. High implementation costs and practitioner unfamiliarity further necessitate enhanced educational initiatives and interdisciplinary collaboration between clinicians and data scientists.

11. CONCLUSION

Artificial intelligence serves as a highly capable clinical decision-support tool in modern dentistry, elevating diagnostic accuracy and treatment planning efficiency. Nevertheless, AI cannot replace human clinical judgment, empathetic patient communication, or comprehensive holistic care. Future developments must focus on robust prospective validation, ethical algorithm development, data security, and comprehensive educational integration into dental curricula.

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