MEDDOCS Open Access Publisher

ISSN 2639-4391

Annals of Epidemiology and Public Health

Open Access | Review Article

The Digital Revolution: Applications of Artificial Intelligence in Modern Dentistry

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Received: Mar 21, 2026

Accepted: Apr 06, 2026

Published Online: Apr 13, 2026

Journal: Annals of Epidemiology and Public Health

Publisher: MedDocs Publishers LLC

Online edition: http://meddocsonline.org/

Keywords: Artificial intelligence; Machine learning; Deep learning; Digital dentistry; Diagnostic imaging; Treatment planning; Computer-aided design/Computer-aided manufacturing (CAD/CAM).

Abstract

Artificial Intelligence (AI) is rapidly transforming the landscape of modern dentistry, revolutionizing diagnostic methodologies, treatment planning, patient management, and administrative workflows. This comprehensive review article explores the multifaceted applications of AI across various dental specialties, including oral radiology, restorative dentistry, orthodontics, oral surgery, and periodontics. By leveraging machine learning algorithms and deep neural networks, AI systems are enhancing diagnostic accuracy, predicting treatment outcomes, and personalizing patient care. This paper synthesizes findings from recent literature (2022-2025) to provide a detailed analysis of current AI technologies, their clinical implementations, inherent challenges, and future prospects in reshaping dental practice towards a more precise, efficient, and predictive model of healthcare.

Introduction

The field of dentistry is undergoing a paradigm shift, driven by the integration of digital technologies and, most notably, Artificial Intelligence (AI). For decades, dental practice relied heavily on the clinician's subjective experience and traditional two-dimensional imaging. However, the advent of AI particularly its subsets, Machine Learning (ML) and Deep Learning (DL) has introduced unprecedented capabilities in data analysis, pattern recognition, and predictive modeling [1-12].

AI in dentistry is not merely an automated tool; it functions as an intelligent assistant that augments the clinician's expertise. By training on vast datasets of radiographic images, intraoral scans, and patient records, AI algorithms can identify subtle pathological changes, predict the progression of oral diseases, and optimize complex treatment plans with a level of consistency and speed that surpasses human capabilities alone [13-18].

The global AI in dentistry market is experiencing exponential growth, projected to reach significant valuations by the end of the decade, driven by the increasing demand for precision dentistry, the rising prevalence of oral diseases, and the growing adoption of value-based healthcare models [19-23]. This article aims to provide a comprehensive overview of how AI is being deployed across the major domains of modern dentistry, the benefits it offers, the challenges it faces, and the trajectory it sets for the future of oral healthcare.

Foundational technologies: How AI works in dentistry

Understanding the core technologies is essential to appreciating AI's impact. The AI systems used in dentistry primarily fall into two categories:

Machine learning (ML)

ML involves algorithms that learn from data without being

Cite this article: Bita P, Sanaz B, Omid P. The Digital Revolution: Applications of Artificial Intelligence in Modern Dentistry. A Epidemiol Public Health. 2026; 9(1): 1132.

explicitly programmed for every rule. In a dental context, an ML model can be trained on thousands of patient records (including age, oral hygiene habits, and dietary information) to identify complex patterns that predict the risk of developing dental caries or periodontal disease [24-27]. Common ML techniques used include Support Vector Machines (SVMs) and Random Forests, which are effective for classification tasks like distinguishing between different types of oral lesions.

Deep Learning (DL) and Convolutional Neural Networks (CNNs)

DL is a more advanced subset of ML, utilizing artificial neural networks with multiple layers (hence "deep"). The most significant breakthrough for dental imaging has been the Convolutional Neural Network (CNN). CNNs are exceptionally adept at processing visual data. They are designed to automatically and adaptively learn spatial hierarchies of features from input images [28-29].

How a CNN Works: When analyzing a panoramic radiograph, the initial layers of a CNN might detect simple features like edges and lines. Deeper layers combine these to recognize more complex structures, such as the shape of a tooth, the outline of a root canal, or the radiolucent appearance of a carious lesion. By training on meticulously labeled datasets (e.g., images where cavities have been marked by experts), the CNN learns to identify these features autonomously.

These technologies form the backbone of virtually all modern AI applications in dentistry, from image analysis to predictive analytics [30-31].

Key applications of AI in dental specialties

AI is not a monolithic tool but a versatile technology with tailored applications across different dental disciplines.

Oral radiology and diagnostics

This is arguably the most mature and impactful area of AI application. AI systems are now capable of analyzing various radiographic modalities with high accuracy [32-37].

- Caries Detection: Studies have demonstrated that AI algorithms, particularly CNNs, can detect proximal caries (cavities between teeth) on bitewing radiographs with a sensitivity and specificity comparable to, or even exceeding, that of experienced dentists [38-40]. They can highlight suspicious areas that might be missed by the human eye, especially in early stages.
- Detection of Pathologies: Beyond cavities, AI is adept at identifying other pathologies. This includes the detection of periapical lesions (cysts or abscesses at the tooth root tip), odontogenic cysts and tumors, and signs of osteoporosis in the jawbone [41-43]. In panoramic radiographs, AI can automatically detect and highlight incidental findings such as carotid artery calcifications, which are a risk indicator for stroke.
- Anatomical Landmark Identification: AI automates the tedious process of tracing anatomical structures. It can accurately identify and mark critical landmarks like the mandibular canal, maxillary sinuses, and mental foramen. This is crucial for planning implant placement to avoid nerve damage [44].

Restorative and prosthetic dentistry

AI is streamlining workflows in creating dental restorations, from small fillings to full-mouth rehabilitations.

- CAD/CAM Integration: AI algorithms are being integrated into Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) systems. When designing a crown or a veneer, AI can analyze the adjacent and opposing teeth to suggest an optimal morphology that ensures proper occlusion and aesthetics. It can learn from millions of previous designs to propose a functional and natural-looking restoration, significantly reducing design time [45].
- Caries Detection for Minimally Invasive Dentistry: Beyond radiography, AI is being combined with other technologies like near-infrared imaging (e.g., DIAGNOcam) to detect non-cavitated carious lesions. This allows for intervention at the earliest possible stage, often through remineralization therapies, aligning perfectly with the principles of minimally invasive dentistry [46-48].
- Margin Analysis: AI can help in assessing the quality of digital impressions by detecting flaws or inaccuracies in the preparation margin line, ensuring a better fit for the final restoration.

Orthodontics

Orthodontics has embraced AI for both diagnosis and treatment planning.

- Cephalometric Analysis: Traditionally, tracing and analyzing cephalometric radiographs for orthodontic diagnosis was a time-consuming manual task with significant inter- and intra-operator variability. AI-powered software can now automatically identify cephalometric landmarks in seconds, with accuracy that matches expert clinicians, providing instant and reproducible analyses [49].
- Treatment Planning and Outcome Prediction: AI algorithms are used to plan tooth movement in clear aligner therapy. By simulating the biological response of the periodontal ligament and bone to applied forces, AI can predict the stages of tooth movement and the final alignment with high precision. Furthermore, it can simulate the projected impact of orthodontic treatment on a patient's facial soft tissue profile, helping patients visualize the potential aesthetic outcome [50-51].

Oral and maxillofacial surgery

In surgery, AI serves as a critical tool for pre-operative planning and intra-operative guidance.

- Virtual Surgical Planning (VSP): AI enhances VSP for complex procedures like orthognathic surgery (corrective jaw surgery) or mandibular reconstruction. By analyzing 3D CT scans, AI can help simulate the surgical cuts (osteotomies), reposition bone segments for optimal function and aesthetics, and design precise surgical guides [52].
- Third Molar (Wisdom Tooth) Extraction: AI can analyze the relationship between impacted wisdom teeth and the inferior alveolar nerve on panoramic or CBCT scans. It can predict the risk of nerve injury during extraction by assessing the proximity and anatomical relationship, allowing surgeons to plan a safer approach or consider alternative treatments [53].

- Intra-operative Navigation: While still emerging, AI is being integrated into surgical navigation systems. It can help register the patient's actual anatomy with the pre-operative 3D plan, providing real-time feedback to the surgeon on the position of their instruments relative to critical structures.

Periodontics

AI aids in the objective assessment of periodontal health, which has historically been a subjective and labor-intensive process.

- Bone Loss Detection and Staging: AI algorithms can automatically measure the alveolar bone level around teeth on panoramic or periapical radiographs. By quantifying the amount of bone loss relative to the patient's age and tooth length, AI can assist in the accurate staging and grading of periodontitis [54].
- Radiographic Assessment: AI can highlight areas of furcation involvement or vertical bone defects that might be subtle on a 2D radiograph, prompting the clinician to perform a more thorough clinical examination.

Oral medicine and pathology

Early detection of malignant and potentially malignant disorders is critical for patient survival.

- Oral Cancer Screening: AI is being developed to analyze photographic and endoscopic images of oral lesions. By assessing features like color, texture, and border irregularity, AI models can differentiate between benign lesions, oral epithelial dysplasia, and oral squamous cell carcinoma with encouraging accuracy [55]. This can serve as a valuable triage tool, especially in primary care settings, to identify high-risk lesions requiring immediate biopsy.
- Automated Biopsy Analysis: Beyond imaging, AI is also being applied to analyze histopathological slides of biopsied tissue. This can help pathologists detect cancerous cells more quickly and consistently, reducing diagnostic errors.

Practice management and patient communication

Beyond clinical applications, AI is streamlining the business side of dentistry.

- Administrative Automation: AI-powered software can automate routine administrative tasks such as scheduling appointments, sending reminders, processing insurance claims, and managing patient billing. This frees up the dental team to focus more on patient care [56].
- Virtual Assistants and Chatbots: AI-driven chatbots on dental practice websites can answer common patient questions 24/7, provide information about procedures, and even help patients fill out their medical history forms before their visit.
- Patient Education: AI can generate personalized educational materials. For instance, it can take a patient's own intraoral scan and create a 3D animation showing the progression of their gum disease or how a proposed crown will look and function, significantly improving patient understanding and acceptance of treatment [57].

Benefits of integrating AI in dentistry

The integration of AI offers a multitude of benefits that enhance both clinical outcomes and the patient experience.

- Enhanced Diagnostic Accuracy and Consistency: AI algorithms are not subject to fatigue, distraction, or the inherent variability in human visual perception. They provide a consistent, objective second opinion, reducing the risk of missed diagnoses and inter-examiner variability [58].
- Early Disease Detection: By identifying subtle radiographic signs that may be invisible to the naked eye, AI enables the detection of pathologies at much earlier stages. This allows for simpler, less invasive, and more cost-effective interventions.
- Increased Efficiency and Workflow Optimization: Automating time-consuming tasks like radiographic tracing, CAD/CAM design, and administrative work significantly reduces the time required for these processes. This allows dentists to see more patients or dedicate more time to complex clinical procedures.
- Personalized and Predictive Treatment Planning: AI can analyze large datasets to predict how a patient will respond to a specific treatment. This leads to more personalized, predictable, and successful treatment outcomes, moving dentistry from a reactive to a proactive model.
- Improved Patient Communication and Trust: Visualizing their dental problems and proposed treatment plans through AI-generated simulations helps patients become more engaged in their care. This transparency builds trust and can lead to higher case acceptance rates [59].

Challenges and ethical considerations

Despite its immense potential, the adoption of AI in dentistry is not without significant challenges and ethical concerns.

- Data Privacy and Security: AI algorithms require vast amounts of patient data for training and validation. This raises critical concerns about the privacy and security of sensitive health information. Ensuring compliance with regulations like HIPAA (in the US) and GDPR (in Europe) is paramount [60]. Anonymization and robust cybersecurity measures are non-negotiable.
- Algorithmic Bias and Generalizability: An AI model is only as good as the data it is trained on. If the training dataset lacks diversity in terms of ethnicity, age, or oral health status, the algorithm may be biased and perform poorly on populations not represented in the data [61]. This could inadvertently exacerbate existing healthcare disparities.
- The "Black Box" Problem: Many deep learning models are considered "black boxes," meaning their decision-making process is not transparent or easily interpretable by humans. In a clinical setting, a dentist needs to understand why an AI flagged a specific area as suspicious to make an informed judgment. The development of Explainable AI (XAI) is crucial to address this.
- Legal and Regulatory Landscape: The question of liability is complex. If an AI system misses a diagnosis that leads to patient harm, who is responsible the clinician, the software developer, or the hospital? Clear regulatory frameworks and guidelines from bodies like the FDA are needed to define the status of AI as a medical device and establish liability protocols [62].
- Integration and Training: Successfully integrating AI tools into

existing practice workflows can be challenging. It requires a financial investment in new hardware and software, as well as comprehensive training for dentists and their staff to use these tools effectively and interpret their output critically. Over-reliance on AI ("automation bias") is a real risk where clinicians may blindly accept an AI's suggestion without applying their own judgment.

Future perspectives: The next frontier

The future of AI in dentistry is dynamic and points toward an increasingly integrated and intelligent ecosystem.

- Multimodal AI: Future AI systems will not analyze data in isolation (e.g., only X-rays). They will integrate and correlate multiple data streams radiographs, intraoral photos, 3D scans, genomic data, salivary biomarkers, and patient-reported outcomes to provide a holistic, 360-degree view of a patient's oral and systemic health [63].
- Predictive and Preventive Analytics: AI will evolve from a diagnostic tool to a predictive one. By analyzing a patient's risk profile (genetics, microbiome, lifestyle), AI could predict their likelihood of developing conditions like caries, periodontitis, or even oral cancer years in advance, enabling targeted, personalized preventive strategies.
- AI in Teledentistry and Remote Monitoring: Combined with intraoral cameras and smartphone apps, AI will power teledentistry platforms. Patients will be able to capture images of their mouth at home, and an AI algorithm will analyze them for urgent issues, providing a preliminary triage and determining if an in-person visit is necessary. This is particularly valuable for remote or underserved populations.
- Robotics and AI-Assisted Surgery: The convergence of AI and robotics will lead to more precise and minimally invasive surgical procedures. AI-guided robotic systems could assist in placing implants with sub-millimetric accuracy or performing complex bone surgeries with enhanced dexterity and control [64-69].
- Personalized Oral Health Coaching: AI-powered apps will act as personal oral health coaches. By learning a user's habits, they can provide real-time feedback on brushing technique, dietary advice, and personalized reminders for oral hygiene, fostering better long-term self-care.

Conclusion

Artificial Intelligence is no longer a futuristic concept in dentistry; it is a present and powerful reality that is fundamentally reshaping the profession. From the precise detection of hidden caries on a radiograph to the predictive planning of orthodontic tooth movement and the automation of administrative tasks, AI is proving to be an invaluable ally to the dental professional. Its ability to enhance diagnostic accuracy, improve workflow efficiency, and facilitate personalized patient care is driving a new era of precision dentistry.

However, the path to full integration is paved with significant challenges. The dental community, in collaboration with technologists, ethicists, and regulators, must proactively address issues related to data privacy, algorithmic bias, transparency, and legal liability. The successful adoption of AI hinges not on replacing the dentist, but on augmenting their skills creating a powerful synergy where human empathy, clinical judgment, and ethical oversight are combined with machine intelligence and consistency.

As we look to the future, the role of AI will only grow, moving towards truly integrated, predictive, and preventive oral healthcare systems. By embracing this technology thoughtfully and critically, the dental profession can fulfill its ultimate goal: improving the oral and overall health of patients with greater precision, efficiency, and compassion than ever before.

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