

Artificial Intelligence Applications in Dentistry: Transforming Clinical Practice, Challenges, and Future Perspectives

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Abstract

Artificial intelligence (AI) is revolutionizing modern dentistry by enhancing diagnostic accuracy, streamlining workflows, and enabling personalized patient care. Leveraging advanced computational models, including machine learning and convolutional neural networks (CNNs), AI applications span across dental specialties such as surgical dentistry, orthodontics, endodontics, orthodontics, and oral pathology. These technologies facilitate early disease detection, precise treatment planning, predictive modeling of restorative success, and improved clinical outcomes and patient satisfaction. Despite its transformative potential, the integration of AI into dentistry faces challenges such as data bias, limited interpretability, and ethical concerns surrounding patient privacy. This review explores the applications, limitations, and future prospects of AI in dentistry.

Keywords: Dentistry, Artificial Intelligence, Dental Technologies, Diagnostic Accuracy, Personalized Treatment

Introduction

In the modern dental landscape, artificial intelligence (AI) is emerging as a transformative force that is helping to improve dentistry, clinical practice, and patient outcomes [1]. AI enables systems to process vast amounts of data, identify complex patterns, and aid clinical decision-making with unprecedented accuracy by leveraging advanced computational models such as machine learning and deep learning [2]. This integration of AI in dentistry aligns with the broader shift toward digitalization and evidence-based healthcare, where personalized and proactive approaches are increasingly prioritized [3].

Dentists' practices and tasks that include radiography, early detection, diagnosis, patient-tailored treatment plans, and collaborative dental teams create an ideal environment for AI tools in dentistry [4]. AI applications range from early detection of diseases, such as tooth decay and periodontal disease, to assisting in orthodontic treatment planning, endodontic procedures, and prosthetic design [4,5]. Convolutional neural networks (CNNs), a subset of deep learning algorithms, have demonstrated remarkable capabilities in analyzing dental X-rays, identifying lesions, and segmenting anatomical structures [6].

AI in dentistry contributes to improving diagnostic efficiency and accuracy, helping in early detection of tooth decay, gum disease or subtle periodontal bone loss compared to traditional diagnostic methods [7]. In orthodontics, AI systems support automated analysis of head x-rays and simulation of treatment outcomes, streamlining workflow and improving communication with patients [8]. AI also contributes to the design of dentures using computer-aided design and

manufacturing (CAD/CAM) systems and predicting the longevity and success of dental restorations and implants [9].

However, the integration of AI in dentistry faces several challenges related to data bias, interpretability of AI algorithms, and ethical concerns, such as patient privacy and accountability for AI-driven decisions. Addressing these challenges requires collaboration between clinicians, researchers and technology experts to ensure that AI systems are reliable, unbiased and effectively integrated into dental practices [10].

Accordingly, this review explores the applications, challenges and future prospects of AI in modern dentistry.

Applications of Artificial Intelligence in Dentistry

Artificial Intelligence in Operative Dentistry

Artificial intelligence, especially convolutional neural networks (CNNs), has revolutionized the field of Operative dentistry by enhancing diagnostic accuracy and streamlining clinical workflows [11]. CNNs are highly effective in analyzing dental radiographs to detect conditions such as dental caries, vertical root fractures, and apical lesions. These algorithms can identify cavities at an early stage with remarkable accuracy, often outperforming traditional diagnostic methods. This enables early intervention and reduces reliance on subjective assessments by clinicians. Additionally, AI models have proven their value in analyzing volumetric changes in the pulp space, which aids in treatment decisions through accurate assessment of the extent of pulpal involvement [12]. AI tools enhance diagnostic accuracy, achieve more efficient treatment outcomes, and predict prognosis in restorative dentistry [13].

Artificial Intelligence in Periodontics

The integration of AI technologies into dentistry has improved the treatment of periodontal diseases, early detection of periodontal diseases, and their effective management. AI-powered CNNs have shown exceptional accuracy in detecting periodontal bone loss from panoramic radiographs more efficiently and accurately than traditional methods [14]. AI applications also help classify the severity of periodontal diseases, enabling more targeted and personalized treatment plans. In addition, AI algorithms are increasingly being used to predict disease progression by analyzing systemic health factors, allowing clinicians to implement preventive measures. The predictive approach offered by AI technologies contributes to improving patient outcomes and reducing the long-term impact of periodontal diseases [15].

Artificial Intelligence in Orthodontics

In modern dentistry, especially orthodontics, AI technologies have contributed to improving the accuracy and efficiency of treatment planning and the ability to simulate interventional procedures. AI algorithms in analyzing head measurements simplify the process of identifying anatomical landmarks, significantly reducing the time and effort required for diagnostic assessments [16]. Furthermore, AI systems can simulate the facial and skeletal changes resulting from orthodontic interventions, providing patients with a clear visualization of the expected outcomes. This enhances patient communication and satisfaction while supporting informed decision-making and patient-centered care. Decision support systems based on virtual networks and artificial neural networks (ANNs) help orthodontists determine optimal treatment strategies, including whether tooth extractions are necessary. These tools improve the predictability of orthodontic treatments while maintaining a high standard of oral health care [17].

Artificial Intelligence in Endodontics

In endodontics, AI applications have greatly enhanced diagnostic accuracy and procedural efficiency [18]. CNNs have been used to detect periapical lesions on cone-beam computed tomography (CBCT) scans with similar accuracy to endodontists. Such tools enable lesions to be identified more consistently and reliably, reducing the risk of misdiagnosis [19]. Additionally, AI models are being used to predict the viability of dental pulp stem cells, an

innovation that holds promise for the development of regenerative endodontic treatments. Furthermore, automated systems for measuring working lengths in root canal treatments have improved procedural accuracy, reduced errors and contributed to successful clinical outcomes. These developments highlight the transformative potential of AI in improving endodontic care interventions [20].

Artificial Intelligence in Prosthetic Dentistry

Prosthetic dentistry has benefited greatly from the integration of AI, particularly in the design and optimization of dentures. AI tools through generative adversarial networks automate the design of dental crowns, enabling faster and more personalized solutions that meet individual patient needs [21]. Predictive AI models have also proven useful in estimating the longevity and debonding probability of dental restorations, supporting clinicians in material selection and long-term treatment planning. Furthermore, ontology-based decision support systems have been used to improve the design of removable partial dentures, achieving both aesthetic and functional benefits [3,21]. AI is redefining the landscape of dental prosthetics practice by simplifying the design process and improving predictive accuracy [22].

Artificial Intelligence in Oral and Maxillofacial Pathology

Artificial intelligence is revolutionizing oral and maxillofacial pathology by enhancing the accuracy, efficiency, and objectivity of diagnostic procedures. Through advanced algorithms, AI systems can analyze radiographic images to identify abnormalities and help classify different diseases. This level of accuracy reduces the potential for human error and ensures consistent diagnostic results [23]. Additionally, AI speeds up the diagnostic process, enabling clinicians to make timely decisions that are critical in the management of conditions such as oral cancer and other serious diseases. AI is reshaping the practice of oral and maxillofacial pathology by streamlining workflows and supporting evidence-based decision-making, ultimately improving patient care and outcomes [24].

Training and Education for Dental Professionals

The successful integration of AI into dental practice requires comprehensive training programs for dental professionals [25].

- **Understanding AI fundamentals:** Dental professionals need a basic understanding of AI technologies, including machine learning and deep learning, to appreciate how these systems analyze data and make recommendations.
- **Clinical application:** Workshops and hands-on sessions should be integrated into dental education to familiarize dentists and dental assistants with AI-based diagnostic tools, treatment planning software, and predictive models.
- **Interpreting decision support:** Dentists must learn how to critically evaluate AI-driven suggestions, ensuring that they complement rather than replace their expertise.
- **Continuing education:** continuing professional development programs are critical to keeping dentists up to date with the latest developments and applications.

Dental Patient-Centric Care with AI

AI has the potential to transform patient care into dentistry by improving the quality and efficiency of interventions. AI reduces waiting times and ensures patients receive timely interventions by enabling faster and more accurate diagnoses. AI-powered tools customize treatment plans based on individual patient data, ensuring accuracy and tailoring care to specific needs [26]. Furthermore, these technologies reduce the need for surgical or repetitive procedures [27]. AI-powered visual simulations also enhance communication between dentists and patients, allowing for a better understanding of treatment options and building trust [28].

Integrating AI with Emerging Technologies

The future of AI in dentistry lies in its integration with other advanced technologies, creating a synergistic ecosystem that enhances clinical capabilities and patient care:

- **3D Printing:** AI algorithms are improving the design of dentures, ensuring a precise fit that complements 3D printing technologies. For example, AI can improve crown designs, improve manufacturing accuracy, and reduce material waste [29].
- **Robotics:** Robotic-assisted, AI-guided dental surgeries can achieve unprecedented precision, reducing complications and recovery times for procedures such as implant placement and orthodontic adjustments [30].
- **Augmented and Virtual Reality (AR/VR):** AI is driving AR and VR applications in medical education and patient consultations. Simulated procedures and treatment visualizations provide valuable insights for both clinicians and patients [31].
- **Advanced imaging technologies:** AI-powered imaging systems, such as cone-beam CT and intraoral scanners, seamlessly integrate with cloud computing to generate comprehensive, real-time analytics [31].
- **Teledentistry:** AI-powered diagnostics combined with teledentistry platforms enable remote consultations and follow-ups, expanding access to high-quality dental care [32].

Challenges and Limitations for AI in Dentistry

The integration of AI technologies into dentistry faces several challenges. These challenges must be addressed to benefit from the integration of AI into dentistry [10].

- **Data acquisition and quality** The effectiveness of AI models in dentistry is highly dependent on the quality and consistency of the data they are trained on. A major challenge arises from the lack of standardization in imaging methods and data annotation practices, leading to variations that can hinder the generalizability of AI applications across different clinical settings. Additionally, concerns about patient privacy and data security limit access to comprehensive datasets, which are essential for robust model training and validation.
- **Interpretability:** Many AI models, especially those using deep learning techniques, operate as black boxes, providing outputs without a transparent view of the decision-making process. This causes dentists to be skeptical about the accuracy and reliability of the recommendations provided by AI technologies. Enhancing the interpretability of AI systems is critical to building trust and facilitating their integration into dental practice and ensuring that dentists are able to effectively understand and use the insights AI provides in patient care.
- **Computational Power:** Implementing AI algorithms requires a robust technology architecture and significant computational resources. Dental facilities in resource-constrained settings lack advanced computing infrastructure, which can hamper the adoption of AI technologies. Therefore, having a technological architecture is essential to ensure access to, application of, and utilization of AI-led advances in dentistry.
- **Ethical and Legal Issues:** Integrating AI into dental practice faces a number of ethical and legal considerations. These include ensuring the confidentiality of patient data, which requires robust data governance frameworks to protect sensitive information. Furthermore, AI models suffer from data bias arising from training data, which requires clear policies and strategies to delineate accountability between technology developers and dentists.

Future Directions for AI in Dentistry

Improving Data Sharing

The development of standardized, open-source dental datasets will enhance the training and validation of AI models, ensuring greater reliability and generalizability across clinical settings. Collaborative efforts between dentists, technology developers, and health systems will accelerate innovation and improve AI applications in dentistry.

Explainable AI

Explainable AI models are essential to fostering trust and adoption among dentists. These systems will allow dental professionals to confidently evaluate and integrate AI recommendations into their clinical workflow by providing transparent and consistent insights into the predictions made by AI applications.

Integration with Clinical Workflow

Seamless integration of AI tools into everyday dental practice requires user-friendly systems and comprehensive training programs for clinicians. This ensures that AI complements existing workflows, enhances diagnostic accuracy, and supports informed, patient-centered decision-making.

Ethical Frameworks

Ethical guidelines should address patient privacy, accountability, and equitable access to AI technologies. Clear standards for data use and accountability will ensure dentists embrace AI technologies, foster trust, and reduce disparities in dental care delivery.

Conclusion

AI technologies are shaping the modern dental landscape by improving diagnostic accuracy, enhancing clinical efficiency, and delivering patient-centered care. AI applications in specialties such as orthodontics, prosthetic dentistry, and periodontics have shown significant benefits, from early disease detection to personalized treatment planning. However, successful integration of AI requires overcoming challenges related to data quality, algorithm interpretability, and ethical considerations. Future advances in explainable AI, standardized data sharing, and the integration of AI with other advanced technologies will further improve dental practice. Collaboration between clinicians, researchers, and technology developers is essential to ensure that AI technologies are ethical, reliable, and accessible, ultimately transforming dental care into a more efficient, evidence-based, and patient-centered specialty.

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