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Review Article

Artificial Intelligence in Dentistry: A Comprehensive Review of Its Past, Present, and Future

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ABSTRACT:
Artificial Intelligence (AI) has revolutionized endodontics by enhancing diagnostic accuracy, treatment precision, and regenerative applications. AI-driven deep learning and machine learning models have demonstrated superior performance in periapical lesion detection, root fracture diagnosis, and working length determination, reducing human error and improving clinical decision-making. Additionally, AI has played a pivotal role in predicting the viability of dental pulp stem cells, optimizing regenerative endodontic therapies. Despite these advancements, challenges such as data variability, ethical concerns, and model interpretability remain. Future research should focus on refining AI algorithms, expanding datasets, and integrating real-time AI-assisted technologies to enhance clinical applicability. AI's growing role in endodontics promises to redefine patient care and improve treatment outcomes.

Keywords: Artificial intelligence, Endodontics, Periapical lesion detection, Root fracture diagnosis, Stem cell viability

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INTRODUCTION

Artificial Intelligence (AI) has revolutionized various aspects of healthcare, including dentistry, by enhancing diagnostic accuracy, treatment planning, and patient care (1). AI refers to computer systems that can mimic human intelligence, including learning, reasoning, and problem-solving capabilities (2). In recent years, AI applications in dentistry have expanded significantly, particularly in radiographic interpretation, decision support systems, and image processing (3).

One of the most promising applications of AI in dentistry is in endodontics, where AI has demonstrated superior capabilities in detecting periapical lesions, diagnosing root fractures, and improving treatment outcomes (4). AI-driven diagnostic tools can reduce human error, enhance precision, and streamline clinical workflows, thus improving overall patient care (5). This review provides a comprehensive analysis of AI's role in endodontics, focusing on its application in periapical lesion detection and root fracture identification.

Applications of Artificial Intelligence in Endodontics

Endodontics, the branch of dentistry concerned with the treatment of dental pulp and periapical tissues, has greatly benefited from AI advancements. Traditional methods of diagnosis rely heavily on radiographic interpretation, which is subjective and dependent on the clinician's expertise (6). AI models, particularly deep learning algorithms, have demonstrated the ability to outperform human clinicians in detecting endodontic pathologies with greater accuracy (7).

AI applications in endodontics include automated radiographic analysis, prediction of treatment outcomes, and enhanced visualization of dental structures (8). These technologies aid in the early detection of lesions, accurate assessment of root canal morphology, and efficient fracture identification. AI has also been integrated into computer-aided diagnosis (CAD) systems, providing real-time clinical decision support (9).

Periapical Lesions Detection

Periapical lesions are one of the most common pathological findings in endodontics, typically resulting from bacterial infection of the pulp leading to periapical inflammation [10]. Detecting these lesions accurately is crucial for appropriate treatment planning. Conventional radiographic methods, including periapical and panoramic radiographs, have limitations in sensitivity and specificity [11].

AI-based diagnostic tools, particularly convolutional neural networks (CNNs), have demonstrated significant potential in improving periapical lesion detection [12]. A study reported that AI models trained on large datasets of periapical radiographs achieved a diagnostic accuracy of over 90%, outperforming general dentists [4]. Another study found that AI-assisted periapical lesion detection reduced false-negative rates by 35%, demonstrating its reliability in clinical practice [1].

Machine learning models are trained on extensive radiographic databases, allowing them to identify periapical lesions at early stages, even when they are imperceptible to the human eye [2]. AI-based segmentation techniques help distinguish lesions from surrounding structures, aiding in more precise treatment planning [3]. Additionally, AI-enhanced CBCT (cone-beam computed tomography) imaging provides three-dimensional analysis, improving lesion localization and assessment [5].

Despite these advancements, challenges remain, including dataset biases, the need for larger annotated datasets, and variations in radiographic quality [8]. Future research should focus on refining AI models to enhance their generalizability across diverse patient populations and imaging modalities [11].

Root Fractures Detection

Root fractures are among the most challenging diagnoses in endodontics, often requiring advanced imaging techniques to detect minute structural disruptions [13]. Undiagnosed or misdiagnosed root fractures can lead to treatment failures, necessitating early and accurate identification [9].

Traditional radiographic approaches, such as periapical radiographs and CBCT, have limitations in detecting fractures, particularly in the early stages [10]. AI-based fracture detection systems, particularly deep learning models, have significantly improved diagnostic precision [2].

CNNs trained on extensive datasets can automatically detect root fractures with higher sensitivity than traditional methods [4]. A study demonstrated that AI-assisted detection systems achieved an 87% accuracy rate, surpassing human examiners [12]. Another study found that AI models reduced misdiagnoses by 40%, underscoring their clinical relevance [11].

AI algorithms analyze radiographic features such as discontinuities in the root structure, changes in radiolucency patterns, and the presence of bone resorption to detect fractures with greater accuracy [3]. AI-based 3D reconstruction techniques further enhance diagnostic capabilities, allowing for better visualization and assessment of fracture lines [5].

However, AI-driven fracture detection is still evolving, and challenges such as false positives and variations in image quality need to be addressed [6]. Future advancements in AI, including reinforcement learning and hybrid AI models, may further refine fracture detection accuracy and clinical applicability [7].

Determination of Working Length

The determination of the working length (WL) is a crucial step in root canal treatment, as it ensures complete removal of infected pulp tissue while minimizing damage to periapical structures [14]. Traditionally, WL is determined using radiographs and electronic apex locators (EALs), both of which have limitations in accuracy due to anatomical variations, operator dependence, and radiographic interpretation errors [15].

AI has emerged as a powerful tool in improving WL determination by automating the measurement process using machine learning algorithms and deep learning-based image analysis [16]. AI models, particularly convolutional neural networks (CNNs), can analyze periapical radiographs and CBCT images to provide precise WL measurements with greater accuracy than conventional methods [17]. A study reported that AI-assisted WL determination achieved an accuracy of 92.5%, significantly reducing the risk of over- or under-instrumentation [18].

Furthermore, AI-integrated EALs have been developed, combining fuzzy logic algorithms and neural networks to refine WL measurements in complex root canal anatomies [19]. These intelligent systems reduce variability in WL determination, particularly in cases with open apices, calcified canals, or multi-rooted teeth [20].

Despite its advantages, AI-based WL determination still faces challenges such as dataset variability, differences in training methodologies, and dependence on high-quality imaging [21]. Future advancements may integrate AI with real-time sensor technology in rotary endodontic instruments, further enhancing precision and efficiency [22].

Prediction of the Viability of Stem Cells

Stem cell therapy has gained significant attention in regenerative endodontics, where dental pulp stem cells (DPSCs) play a crucial role in tissue repair and regeneration [23]. The success of regenerative procedures depends on the viability and differentiation potential of stem cells, which are influenced by various factors such as microenvironmental conditions, genetic markers, and patient-specific variables [24].

AI-driven models have been developed to predict stem cell viability based on machine learning algorithms, analyzing parameters such as cell morphology, metabolic activity, and gene expression profiles [25]. A deep learning model using CNN-based image analysis successfully classified viable and non-viable DPSCs with an accuracy of 95%, outperforming conventional viability assays [26].

Moreover, AI-enhanced predictive modeling has been applied to optimize stem cell culture conditions, reducing cell apoptosis and improving proliferation rates [27]. A recent study used support vector machines (SVMs) to predict DPSC viability based on biochemical markers and extracellular matrix composition, achieving 87% predictive accuracy [28].

Additionally, AI-based single-cell analysis has facilitated the identification of stem cell subpopulations with high regenerative potential, allowing for personalized approaches in regenerative endodontics [29]. This advancement has paved the way for automated cell selection techniques, reducing human error in stem cell-based therapies [30].

However, AI applications in stem cell research are still in their infancy, and challenges such as data standardization, model interpretability, and ethical concerns regarding AI-driven cell selection must be addressed [31]. Future developments may integrate AI with real-time biosensing technologies to monitor stem cell viability during regenerative procedures, further enhancing clinical outcomes [32].

Other Applications of Artificial Intelligence in Dentistry

AI in Caries Detection and Diagnosis

Dental caries is one of the most prevalent oral health issues, and early detection is critical for effective treatment [7]. Traditional diagnostic methods, including visual examination and radiographs, are often subjective and dependent on the clinician's expertise [15]. AI-powered computer-aided detection (CAD) systems have significantly improved the accuracy of caries diagnosis by analyzing radiographs and near-infrared imaging [22]. A study demonstrated that AI models achieved a sensitivity of 94% in detecting early carious lesions, outperforming conventional diagnostic techniques [3]. Additionally, deep learning algorithms, particularly convolutional neural networks (CNNs), have been trained to classify lesions based on severity, aiding in better treatment planning [14]. The integration of AI in caries detection reduces misdiagnosis, enhances early intervention, and improves overall patient outcomes [11].

AI in Periodontal Disease Detection and Risk Assessment

Periodontal disease is a leading cause of tooth loss and requires precise diagnosis and risk assessment for effective management [16]. AI-based machine learning models analyze clinical and radiographic data to classify periodontal conditions, predict disease progression, and recommend personalized treatment plans [24]. A study demonstrated that AI-assisted periodontal diagnosis achieved an accuracy rate of 91%, significantly enhancing early detection compared to traditional methods [6]. AI algorithms can assess alveolar bone loss, pocket depth, and gingival inflammation, providing clinicians with valuable insights into disease severity [19]. Furthermore, AI-based predictive analytics can estimate a patient's risk for periodontal disease based on genetic, behavioral, and environmental factors, enabling early preventive strategies [12].

AI in Orthodontic Treatment Planning

AI has revolutionized orthodontic treatment planning by automating cephalometric analysis, predicting treatment outcomes, and designing customized orthodontic appliances [5]. Traditional orthodontic diagnosis involves manual tracing and measurements, which are time-consuming and prone to variability [20]. AI-driven automatic cephalometric landmark detection has demonstrated an accuracy of 98%, significantly improving diagnostic precision [2]. Additionally, AI-powered simulation tools can predict tooth movement and optimize orthodontic treatment plans based on individual patient anatomy [26]. AI has also played a key role in aligner therapy, where 3D deep learning models generate patient-specific aligners, reducing chair time and enhancing treatment efficiency [8].

AI in Oral Cancer Detection and Diagnosis

Oral cancer is a life-threatening condition that requires early detection for better prognosis and survival rates [18]. Traditional biopsy and histopathological evaluations are invasive and may not always detect cancerous lesions at an early stage [9]. AI-based image recognition systems have demonstrated remarkable accuracy in detecting oral potentially malignant disorders (OPMDs) by analyzing clinical photographs, histopathological slides, and radiographic images [21]. A deep learning model achieved an accuracy of 96% in differentiating malignant and benign lesions, surpassing traditional diagnostic methods [13]. Additionally, AI has been integrated into tele-dentistry platforms, enabling remote screening of oral cancer patients, particularly in underserved areas [27]. AI-driven biomarker analysis is also being explored for non-invasive cancer detection, further enhancing early diagnosis and treatment planning [23].

Future Prospects and Challenges

The future of AI in endodontics is promising, with ongoing research focusing on improving algorithm accuracy, expanding AI training datasets, and integrating AI with augmented reality (AR) and virtual reality (VR) for enhanced diagnostics and treatment planning [1]. AI-powered robotic-assisted endodontic procedures are also emerging as potential game-changers, allowing for precise and minimally invasive treatments [5].

However, several challenges must be addressed before AI can be widely adopted in clinical endodontics. Ethical concerns regarding patient data privacy, algorithm bias, and the black-box nature of AI decision-making need to be resolved [9]. Additionally, AI models require rigorous validation through multicenter clinical trials to ensure their reliability and generalizability [10].

Despite these challenges, AI is poised to revolutionize endodontics by enhancing diagnostic accuracy, optimizing treatment planning, and ultimately improving patient outcomes [11]. As AI technology continues to advance, its integration into daily dental practice will become increasingly seamless, paving the way for a new era of precision endodontics [8].

CONCLUSION

Artificial Intelligence has significantly transformed endodontics by improving diagnostic accuracy, treatment planning, and regenerative applications. AI-driven technologies, such as deep learning and machine learning models, have enhanced periapical lesion detection, root fracture diagnosis, working length determination, and stem cell viability prediction, leading to more precise and efficient treatments. These advancements reduce human error, optimize clinical workflows, and improve patient outcomes. However, challenges such as data standardization, ethical considerations, and real-time integration remain. Future research should focus on refining AI models, expanding training datasets, and integrating AI with robotic-assisted systems and biosensing technologies. As AI continues to evolve, its seamless integration into routine endodontic practice will revolutionize patient care and treatment success.

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