

Artificial Intelligence in Dentistry: Current Applications and Future Trajectories with a Focus on Endodontic .

Abdulrhman Alkhaled Chaza Kouchaji

Department of Pediatric Dentistry, Faculty of Dentistry, Damascus University

Abstract:

Artificial intelligence (AI) has significantly enhanced its presence and utility across various sectors, notably in dentistry . By mimicking human cognitive functions, AI facilitates complex predictions and decision-making in healthcare, particularly within endodontic. This scoping review aims to map the existing literature and provide a comprehensive overview of the current and potential applications of artificial intelligence in endodontics, while identifying research gaps and limitations in the field . Models such as convolutional neural networks (CNNs) and artificial neural networks (ANNs) have demonstrated diverse applications in this specialty. These include analyzing root canal system anatomy, predicting dental pulp stem cell viability, determining working lengths, detecting root fractures and periapical lesions, and forecasting the outcomes of retreatment procedures . Future potential extends to scheduling, patient management, drug interaction analysis, prognostic diagnosis, and robotic-assisted surgery. AI has shown commendable accuracy and precision in disease detection, evaluation, and prediction in endodontic, promising to augment diagnostic and therapeutic protocols and improve treatment outcomes . However, prior to the integration of AI models into routine clinical practice, further validation of their cost-effectiveness, reliability, and generalizability remains imperative.

Keywords: Artificial Intelligence, Artificial Neural Networks (ANN) , Convolutional Neural Networks (CNN) , Deep Learning , Machine Learning .

Introduction and Background:

The pursuit of replicating human brain functionality has long captivated scientists[1] . Artificial Intelligence (AI), a field formally introduced by John McCarthy in 1956, represents this endeavor through machines designed to perceive their environment and execute actions to achieve specific goals [2] [3] . In healthcare, AI excels at identifying critical data patterns, aiding in diagnosis, prognosis, and therapeutic decision-making with efficiency and precision often comparable to medical experts . [3] [4]

In dentistry, most applications leverage supervised learning, where algorithms are trained on large datasets comprising various patient features (e.g., images, age, sex) and corresponding ground truth outcomes [3]. In dentistry, most applications leverage supervised learning, where algorithms are trained on large datasets comprising various patient features (e.g., images, age, sex) and corresponding ground truth outcomes (Aminoshariae et al., 2021). A 2024 critical review published in the Journal of Dental Research synthesized recent advances in AI research for clinical endodontics, covering applications ranging from the detection of pulpitis and periapical pathologies to the identification of root fractures, resorptions, and the prediction of treatment outcomes [5]. Tracing the trajectory of AI in dentistry, a 2022 review documented the evolution from early expert systems to modern deep learning applications, highlighting key endodontic applications including root canal anatomy analysis, dental pulp stem cell viability prediction, working length determination, and fracture and periapical lesion detection [6]. ANNs mimic biological neural networks to decipher relationships between these inputs and outputs. While not yet routine, AI's impact is growing in areas like radiographic image analysis, caries detection, and record-keeping. This review synthesizes literature on AI applications across dentistry, with a concentrated focus on endodontic, exploring its role in diagnosis, clinical decision-making, outcome prediction, and current limitations [3].

The rapid evolution of this field is underscored by very recent publications, for instance, a 2025 systematic review encompassing studies up to June 2025 demonstrated that AI systems achieve diagnostic accuracy ranging from 75% to 99% across various endodontic tasks, including periapical lesion detection and fractured instrument identification [7].

However, the rapid proliferation of AI research in endodontics has resulted in a scattered and heterogeneous evidence base. Therefore, this article presents a scoping review designed to systematically map the existing literature, synthesize current knowledge on AI applications in endodontics, and critically appraise the methodological quality and limitations of included studies. This review also seeks to identify knowledge gaps and propose directions for future research to facilitate the responsible integration of AI into endodontic clinical practice.

Methods :

Study Design: This review was conducted as a scoping review in accordance with the Joanna Briggs Institute (JBI) methodology for scoping reviews and adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist.

Search Strategy: A systematic literature search was performed in three electronic databases: PubMed, Scopus, and Web of Science. The search was conducted up to September 2025. The search strategy combined keywords and MeSH terms related to artificial intelligence (e.g., "artificial intelligence," "machine learning," "deep

learning") and endodontics (e.g., "endodontics," "root canal treatment," "apical periodontitis").

Eligibility Criteria: We included original research articles, reviews, and conference proceedings published in English that investigated the application of AI in any aspect of endodontics.

AI Fundamentals and Operational Hierarchy:

AI systems typically operate through a hierarchy of Input, Processing, and Output [8]. In dentistry, input data can be textual (medical records), visual (radiographic images), or auditory. Neural networks process this data to generate outputs such as a diagnosis, treatment plan, or prognosis. [9] [8]. Key AI components include:

- Machine Learning (ML): Algorithms that learn from data to make predictions. [10]
- Neural Networks: Computational models inspired by the human brain.
- Deep Learning (DL): A subset of ML using multi-layered neural networks for advanced pattern recognition. [9]
- Data Science & Big Data: Fields concerned with extracting insights from vast, complex datasets. [11] [12]

AI models function in two phases: training (where parameters are learned from historical data) and testing (where these parameters are applied to new data). [9] Modern AI has moved beyond being a "black box"; techniques like heatmap generation (as visualized in explanatory schematics) now illustrate which input features (e.g., specific pixels in an image) influenced a given prediction, enhancing interpretability and trust. [13]. The methodologies underpinning AI applications in endodontics have been systematically categorized in a 2023 narrative review, which detailed the use of artificial neural networks (ANNs), convolutional neural networks (CNNs), and support vector machines (SVMs) for tasks including apical foramen detection, periapical disease diagnosis, vertical root fracture identification, and assessment of regenerative treatment outcomes [14].

Applications of Artificial Intelligence in Endodontic:

AI is becoming increasingly relevant for endodontic treatment planning and disease diagnosis, capable of detecting minute changes imperceptible to the human eye. [15] [16] [17]

A 2023 comprehensive review analyzing 56 scientific papers confirmed that AI applications in endodontics achieve accuracy rates approaching 90% across various diagnostic and prognostic tasks, underscoring the technology's growing reliability and clinical relevance [18].

Key applications include:

-Detection of Periapical Lesions

Early and accurate detection of apical periodontitis is a cornerstone of successful endodontic treatment [19]. However, conventional diagnostic methods face inherent limitations. While 2D intraoral and panoramic radiographs remain the standard first-line tools, their diagnostic accuracy is compromised by anatomical noise, geometric distortion, and the two-dimensional nature of a three-dimensional pathology (Patel et al., 2009). Cone-beam computed tomography (CBCT) has addressed many of these limitations by providing high-resolution 3D assessment, but it introduces a new challenge: the cognitive burden of interpreting large volumetric datasets, which can lead to inter- and intra-observer variability.

This is where artificial intelligence offers a paradigm shift. AI models are not simply replicating human analysis; they are augmenting it by performing tasks that are difficult for the human eye. For instance, instead of merely detecting the presence of a lesion, AI algorithms have been developed to quantify alveolar bone loss with high precision, providing objective measurements that can track disease progression or healing over time [20] [21]. Furthermore, AI moves beyond simple detection toward differential diagnosis. Studies have demonstrated the ability of machine learning models to classify periapical lesion severity [22] and, more importantly, to differentiate between periapical cysts and granulomas on both radiographic and CBCT images [23]. This distinction has significant treatment implications, as cystic lesions may require surgical intervention whereas granulomas often respond to non-surgical management. The diagnostic accuracy achieved by these AI models in recent studies has been reported as comparable to, or in some cases exceeding, that of human specialists, suggesting that AI can serve as a reliable "second opinion" to reduce diagnostic errors [24] [25]. This trend has been further consolidated by recent evidence. A 2025 systematic review confirmed that AI systems, particularly DenseNet201 for fractured instrument detection (AUC = 0.900) and ChatGPT-4 for diagnostic tasks (99% accuracy compared to 77-80% for dental students), achieve comparable or superior performance to clinicians, offering advantages in speed, reproducibility, and objectivity [7].

-Detection of Root Fractures

Vertical root fractures (VRF) represent one of the most diagnostically challenging conditions in endodontics, often presenting with nonspecific clinical signs and symptoms. The prognosis for a tooth with a VRF is generally poor, making accurate and early diagnosis critical to avoid unnecessary treatment [26]. The fundamental diagnostic dilemma stems from the limitations of conventional 2D radiography, where the fracture line is often obscured by the root canal filling material, the buccal and lingual cortical plates, or simply by the angle of the X-ray beam.

Artificial intelligence, particularly convolutional neural networks (CNNs), has emerged as a powerful tool to address this challenge by learning to recognize the

subtle radiographic signatures of fractures that are imperceptible to the human eye. Research has explored the application of CNNs across various imaging modalities. Studies on panoramic radiography [27] and periapical radiographs [28] have demonstrated that AI can enhance fracture detection on 2D images. However, the most significant impact lies in the analysis of 3D CBCT data. When AI algorithms are applied to CBCT volumes, they can systematically traverse the entire dataset, identifying potential fracture lines slice by slice and in three dimensions. This AI-assisted analysis has consistently shown superior sensitivity, specificity, and overall accuracy compared to unaided assessment of 2D radiographs [28] [29]. This suggests that the true value of AI in VRF detection is not in replacing the clinician's interpretation of a single image, but in unlocking the full diagnostic potential of complex 3D imaging data, effectively acting as a tireless and highly focused assistant that highlights regions of interest for the clinician to review. The application of AI for vertical root fracture detection continues to advance. A 2024 review highlighted that AI models applied to CBCT imaging achieve superior diagnostic accuracy compared to conventional radiographic assessment, with the ability to detect subtle fracture lines that may be overlooked by the human eye. The integration of AI with 3D imaging modalities represents a significant step forward in addressing this diagnostic challenge [30].

-Determination of Working Length

The determination of an accurate working length (WL)—the distance from a coronal reference point to the point where canal preparation and obturation should terminate is arguably one of the most critical steps in determining the outcome of root canal treatment [3]. An incorrect working length can lead to under-instrumentation with residual necrotic tissue or over-instrumentation that damages periapical tissues. Traditional methods for WL determination include radiographic interpretation and electronic apex locators (EALs). While EALs offer high accuracy, they provide no visual confirmation; radiography offers visualization but is subject to interpretation errors, foreshortening, and elongation [31].

Artificial intelligence offers a novel approach that combines the objectivity of an electronic device with the visual confirmation of imaging. By training artificial neural networks (ANNs) on datasets of radiographs with precisely predefined minor apical foramen locations, researchers have developed models that can consistently and automatically identify this anatomical landmark. The key advantage of this approach is its reproducibility and freedom from operator fatigue or subjective bias. In a pioneering study. [31], the ANN not only successfully located the minor apical foramen but did so with an accuracy that surpassed that of a panel of clinical experts. This finding, supported by subsequent research [32], positions AI not merely as an adjunctive tool, but as a potential new standard for objective WL determination. The superiority of AI-based approaches for working length determination has been further corroborated by recent evidence. A 2024 comprehensive review reported that AI models achieved up to 96% accuracy in locating the minor apical foramen,

significantly outperforming the 76% accuracy achieved by expert clinicians. This reinforces the potential of AI to establish a new, objective standard for this critical step in root canal treatment [30]. However, it is important to note that these models are trained on 2D images; future integration with 3D imaging data and real-time video feeds from operative microscopes could represent the next frontier in AI-assisted endodontic treatment.

-Analysis of Root and Root Canal Morphology

Successful endodontic treatment is predicated on a thorough understanding of root and canal anatomy. The presence of untreated canals, isthmuses, or complex morphological variations is a leading cause of persistent apical periodontitis after root canal treatment [3]. Traditionally, the assessment of root morphology has relied on the clinician's interpretation of 2D radiographs, a method that is inherently limited in its ability to capture the full complexity of three-dimensional anatomical variations.

Deep learning algorithms are transforming this aspect of endodontic diagnosis by automating the analysis of complex anatomical structures. For instance, [33] demonstrated that a deep learning-based AI system could classify root morphology of mandibular first molars on panoramic radiographs with high accuracy.

While this represents an important step for large-scale screening and epidemiological studies, the more transformative application lies in the automated segmentation of 3D CBCT data. AI algorithms can now perform precise, pixel-level segmentation of individual teeth from CBCT volumes in a fraction of the time required for manual segmentation. This automation has profound implications: it not only speeds up the analysis process significantly but also enables the creation of detailed 3D models of root canal systems for patient education, preoperative planning, and the design of customized surgical guides. By reducing the time and expertise required for anatomical assessment, AI democratizes access to advanced diagnostic insights, potentially raising the standard of care across diverse clinical settings.

-Predicting Retreatment Outcomes and Stem Cell Viability

Beyond diagnostic imaging, artificial intelligence is beginning to demonstrate utility in predictive analytics, offering insights that extend into the biological and prognostic domains of endodontics. This represents a shift from AI as a "diagnostic tool" to AI as a "clinical decision support system" that can inform treatment planning by forecasting outcomes.

In the context of nonsurgical endodontic retreatment, clinicians must often weigh the risks and benefits of intervention against alternatives such as apical surgery or extraction. Case-based reasoning (CBR) AI systems have been developed to address this clinical dilemma. By drawing on databases of previous cases with known outcomes, these systems can predict the likelihood of success for a given retreatment scenario, effectively providing an evidence-based, personalized risk assessment [34]

[35] . The predictive capability of AI in endodontics has been further validated by a 2025 meta-analysis, which reported a pooled sensitivity of 0.83 for AI models in predicting endodontic treatment outcomes. The analysis emphasized that while AI demonstrates promising diagnostic efficacy, it should serve as an adjunctive tool to enhance clinical decision-making rather than replace comprehensive clinical evaluation [36]

This approach moves beyond generalized success rates from the literature to patient-specific predictions based on similarity to prior cases.

Perhaps even more innovative is the application of AI in regenerative endodontics. The success of regenerative procedures depends critically on the viability of dental pulp stem cells (DPSCs) after exposure to inflammation or disinfecting agents. Traditional methods of assessing cell viability are time-consuming and cannot easily account for the complex interplay of multiple variables. Neuro-fuzzy inference systems, which combine the learning capability of neural networks with the reasoning capability of fuzzy logic, have shown remarkable promise in predicting DPSC viability under various time-concentration conditions of inflammatory stimuli [37] . This application exemplifies how AI can model complex biological systems, potentially guiding the selection of optimal conditions for maximizing stem cell survival in regenerative protocols [3]

Broader Dental Applications of AI:

- Dental Education: AI-powered simulators and intelligent tutoring systems provide risk-free, interactive preclinical training with immediate feedback. [38]
- Patient Management: Virtual dental assistants can aid in scheduling, documentation, and preliminary patient triage.[1]
- Diagnosis & Prognosis: AI assists in detecting oral cancer, classifying mucosal lesions, and formulating tooth-specific prognostic assessments. [1]
- Dental Radiology: AI enhances the analysis of digital radiographs, 3D scans, and CBCT images for faster diagnosis. [4]
- Oral Surgery: Robotic and image-guided surgical systems improve precision in implant placement and complex surgeries. [1] [38]
- Prosthodontics & Orthodontics: AI aids in designing aesthetic prostheses and planning personalized orthodontic treatment with aligners. [1]
- Forensic Odontology: AI is applied for age estimation, gender determination, and bite mark analysis . [39]

- Future Innovations: Potential advancements include intelligent dental chairs with patient monitoring capabilities and bio printing for tissue regeneration . [38] [4]

A 2022 systematic review of 55 studies provided a comprehensive overview of AI applications across all dental specialties, including endodontics, oral surgery, orthodontics, prosthodontics, and forensic dentistry. The review emphasized the transformative potential of AI in enhancing diagnostic accuracy, streamlining workflows, and personalizing patient care across the entire dental profession[40].

Methodological Limitations and Challenges in AI Research

Despite the promising diagnostic and prognostic capabilities of artificial intelligence in endodontics, the translation of these models from research settings to routine clinical practice faces several significant methodological and practical challenges. A critical appraisal of the existing literature reveals recurring limitations that must be addressed to ensure the reliability, generalizability, and ethical implementation of AI technologies.

- Data-Related Limitations

The performance of any AI model is inherently dependent on the quality and quantity of data used for its training. A pervasive limitation across studies in endodontics is the reliance on relatively small, single-center datasets. For instance, many studies on root fracture detection or working length determination have been conducted on samples of extracted teeth or radiographs from a limited patient population [27] [31] . This raises concerns about the generalizability of findings to diverse clinical settings with varying imaging equipment, patient demographics, and disease presentations. Furthermore, the lack of external validation—where a model is tested on an independent dataset from a different institution—means that reported accuracy metrics may be optimistic and may not reflect real-world performance. Another critical issue is annotation bias; the "ground truth" labels used to train models are often determined by human experts whose judgments may be subjective or variable, inadvertently encoding human error into the AI system.

- Model-Related Limitations

Overfitting remains a significant concern, particularly when complex deep learning models are trained on limited datasets. An over fitted model may perform exceptionally well on the training data but fail catastrophically when confronted with novel inputs. Although techniques such as cross-validation are sometimes employed, they do not replace the need for robust external validation. Additionally, while advances in explainable AI—such as heatmap generation—have improved interpretability [13] , many models still function as "black boxes," making it difficult for clinicians to understand the rationale behind a specific prediction. This lack of transparency can hinder clinical trust and acceptance, particularly in complex or borderline cases where clinical judgment is paramount.

- Bias and Generalizability Concerns

Spectrum bias is another methodological challenge. Many studies selectively include high-quality images with clearly defined pathologies, excluding ambiguous or low-quality images that are common in everyday practice. This creates an unrealistic performance expectation and limits the applicability of findings to routine clinical scenarios. Furthermore, the demographic homogeneity of training datasets—often derived from single geographic regions or ethnic groups—raises questions about whether these models will perform equitably across diverse patient populations. Algorithmic bias, if unaddressed, could inadvertently exacerbate healthcare disparities.

- Clinical Implementation Barriers

Beyond methodological considerations, several practical barriers impede the integration of AI into endodontic practice. The computational infrastructure required to run sophisticated AI models may not be readily available in many dental clinics. Interoperability with existing practice management software and electronic health records remains a technical challenge. Moreover, the cost-effectiveness of AI-assisted diagnosis has yet to be demonstrated; it remains unclear whether the additional expense of AI tools translates into improved patient outcomes or reduced treatment times. There is also a need for structured training programs to familiarize clinicians with AI outputs and their appropriate interpretation, ensuring that these tools are used as adjuncts rather than replacements for clinical reasoning.

- Ethical and Regulatory Considerations

The deployment of AI in healthcare raises important ethical and regulatory questions. In the event of a diagnostic error, questions of liability remain unresolved: is the clinician, the software developer, or the institution responsible? Data privacy concerns are paramount, as training robust models requires access to large volumes of patient data, necessitating stringent data governance frameworks. Finally, regulatory approval pathways for AI-based medical devices are still evolving, and clear guidelines are needed to ensure that only validated, safe, and effective tools reach the clinical market.

Addressing these limitations through multi-center collaborative research, prospective clinical validation, and the development of standardized reporting protocols is essential. Only through rigorous and transparent evaluation can the full potential of AI be realized in a manner that is safe, equitable, and beneficial to patients and clinicians alike.

Impact on Dentists, Limitations, and Future Outlook :

Artificial intelligence is not positioned to replace endodontists but to augment their capabilities, serving as a powerful decision-support tool that enhances diagnostic accuracy and treatment planning. By automating routine tasks such as landmark

identification and preliminary image analysis, AI can reduce cognitive load and free clinicians to focus on complex decision-making and patient interaction. However, AI cannot replicate essential human qualities such as clinical intuition, empathy, and the nuanced dynamics of patient-dentist communication[8] .

Future research must prioritize several key areas. First, multi-center prospective studies with diverse patient populations are urgently needed to validate the generalizability of existing models and establish real-world performance benchmarks [41] . Looking ahead, the integration of AI with other transformative technologies promises to reshape endodontic practice. A 2025 review highlighted that beyond AI, technologies such as robotics, augmented reality (AR), virtual reality (VR), and regenerative medicine are converging to create a new paradigm of precision dentistry. These innovations are expected to enhance surgical accuracy, improve training through simulation, and enable minimally invasive interventions[42]. Second, efforts should focus on developing explainable AI systems that provide transparent, interpretable rationales for their predictions, thereby fostering clinical trust. Third, the integration of multimodal data—combining radiographic images with clinical, genomic, and biomarker information—holds promise for more personalized and predictive endodontic care. Fourth, research into the cost-effectiveness and workflow integration of AI tools will be essential to demonstrate tangible value to healthcare systems and practitioners.

The ultimate goal is the seamless, ethical, and responsible integration of AI into endodontic practice, where it functions as a reliable adjunct to clinical expertise, ultimately improving patient outcomes while preserving the irreplaceable human elements of care.

Conclusion :

Artificial intelligence technology has found substantial application in endodontics, with neural network models often matching or exceeding the diagnostic accuracy of dental experts . These tools are particularly beneficial as supportive aids for practitioners and trainees. AI should be viewed as a powerful augmentative tool that can enhance diagnostic precision, streamline clinical processes, and support complex decision-making . However, its integration must complement the irreplaceable human elements of clinical judgment, experience, and patient-centered care . Continued research is essential to overcome existing limitations and fully realize the transformative potential of AI in dentistry and endodontics.

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Authors confirm that all data supporting the findings of the study are available within the article.

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- **C.N.K :** Methodology, Formal analysis, Writing – review & editing .

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