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REVIEW ARTICLE

Artificial Intelligence in Endodontics

ABSTRACT

Recent development in the field of artificial intelligence has influenced dentistry, and particularly endodontics. Such AI-driven algorithms show great promise in improving the accuracy of diagnostics, treatment planning, and the actual conduct of endodontic treatment, as well as predicting treatment outcomes. AI has already started to prove itself useful in endodontics by improving the detection of periapical pathologies and root fractures, the estimation of root canal anatomy, the determination of working lengths, and the prediction of treatment outcomes. Further development and dissemination of this technology could significantly enhance endodontic practice and contribute to natural dentition conservation. However, despite AI bringing a better success rate and efficiency in the field of endodontic treatments, further studies are still needed to keep on validating their reliability and practicality for wider clinical integrations. This review is undertaken with the purpose of discussing recent advances in AI and describing their applications in the field of endodontics.

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Introduction

Artificial Intelligence-A cutting-edge technology that mimics human cognitive functions-became another crucial breakthrough of the century in most medical streams. Conceived by John McCarthy in 1956, AI has undergone various metamorphoses such as neural network architecture adaptations based on the functionality and operation of the human brain, hence allowing to manipulate complex data and problems to find a solution (1, 2).
In this narrow, high-precision, diagnostic field of endodontics, AI is especially transforming. The usual ways cannot catch the fine tune of the root canal anatomy and variability in the responses of the patients. This gets very much heightened with the use of AI and its advanced data processing and learning to achieve unparalleled accuracy in diagnosing periapical pathologies and root fractures, treatment planning, and prognostication (3). Besides, AI utilizes multimodal data where various forms of data are utilized in learning to diagnose conditions not achievable by human intelligence (4). The growth in computer technology with advancements in special algorithms has enabled the increasing application of machine learning and deep learning, subsets of AI. Machine learning applies statistical learning algorithms in the development of intelligent systems that improve on their own without explicit programming (5). Contrarily, DL handles information like the filtering process of the human brain by using examples to learn through artificial neural networks. As such, these models can classify and predict multiple layers of data without necessarily requiring domain experts to do so manually.
This article discusses in detail the applications of AI in endodontics and how different models of AI improve the accuracy of diagnosis, treatment planning, and its execution. Further, by citing examples of current technologies and results, the article describes the tremendous potential impact AI is going to make on future endodontic practice in terms of improved patient outcomes and the maintenance of natural dentition.

Review

Key features of AI

1. Types of AI

Applications of artificial intelligence can broadly be divided into two categories: physical and virtual. Physical AI involves robotics and automated systems that are employed clinically, while virtual AI refers to the algorithms used in clinical decision-making (6). In the broader medical and dental contexts, AI is further divided into weak AI-or narrow AI-and strong AI. Weak AI is specialized and designed to solve specific tasks or problems. In contrast, strong AI, which remains largely theoretical at this stage, aims to perform tasks across multiple domains with human-like intelligence and capabilities (7, 8).

2. Machine Learning and Deep Learning

Both ML and DL are subsets of AI, and they have really revolutionized data handling and analysis. ML utilizes statistical algorithms for model building, which glean from data for better decision-making without direct human intervention. It includes various learning types like supervised, unsupervised, and semi-supervised learning, each with unique applications and capabilities (9). Deep learning, a more advanced form of machine learning, incorporates multi-layered neural networks into operation and enables deeper learning and recognition capabilities than any other type of machine learning, hence being closely related to complex human thought processes (10).

3. Application in Dentistry

Various ML and DL algorithms are utilized in dentistry to analyze big data sets for extracting useful information for diagnosis, prognosis, and treatment planning and have significantly streamlined various clinical work processes (11). It finds its application in the field of clinical diagnosis, radiology, histopathology, among many others, and does hold promises of changing dental practices by improving the precision and speed of work (12, 13).

Role of AI in pulpal diagnosis

Precise pulpal diagnosis is the very basis of ideal treatment planning in endodontics. Differentiation of reversible from irreversible pulpitis and pulp necrosis is imperative but challenging because of diagnostic signs and symptoms that are usually ambiguous (14, 15).

Advances with AI
Artificial Intelligence integrated into pulpal diagnosis has uplifted the study field significantly. It has been shown that all the stages of pulpitis, starting from early pulpitis to extensive pulpitis, can be diagnosed highly sensitively by the AI models (15, 16). Recently, in a study conducted on digital radiographs, Tumbelaka et al. proved that AI can diagnose both reversible and irreversible pulpitis, which is very useful for further validation (17).

Role of AI in Clinical Practice
Other applications of AI range from diagnosis itself to predicting the course of a disease and the outcome after treatment. Multimodal deep learning models, including ResNet, combined with clinical parameters, have considerably improved diagnostic precision in diseases like deep caries and pulpitis. This is based on comprehensive analysis of datasets that include training and testing phases for refining the predictive capabilities of the AI.

Limitations and Integrative Approach
Although these results seem promising, it is also important to take into consideration that a pulpal diagnosis based exclusively on radiographic examination has several shortcomings. AI should support, but not replace, classic clinical and radiographic examinations and other diagnostic techniques, such as pulp vitality tests, in order to ensure an overall assessment and enhance the accuracy and reliability of diagnoses made within the clinical setting (18).
The use of artificial intelligence is a game-changing event in pulpal diagnosis, providing valid diagnostic tools for accurate decision-making by clinicians. Further development of this will promise finer tuning of diagnostic procedures, advances in patient care for endodontics (19).

Diagnosis of Periapical Lesions: Enhancing Accuracy with AI
Overview
Originally, Peri-apical lesions occurred due to untreated caries, in addition to post treatment diseases which represent a significant portion of jaw lesions, characterized by necrosis of the dental pulp and subsequent inflammatory diseases around the tooth root apex. These lesions, which constitute approximately 75% of jaw radiolucencies, critically influence both treatment planning and outcomes (20).

Diagnostic Techniques
Traditional image modalities such as panoramic and two-dimensional periapical radiographs have commonly been used for their detection (21). The visibility of periapical radiolucency closely depends on the degree of mineral bone loss, estimated at typically an average of 7.1%, but also from the location of the lesion confined to cancellous bone or incoming cortical bone (22). These traditional approaches, however, are insufficient to reveal precisely the complete extent of such lesions.

Imaging with CBCT
Advanced cone beam computed tomography affords the three-dimensional view of the maxillofacial skeleton. Consequently, this resource largely outperforms conventional radiography in diagnosing the periapical lesions. Systematic reviews and meta-analysis studies established that CBCT obtains higher accuracy bringing detection scores decisively higher than traditional and digital intraoral periapical radiography systems (23).
Recent developments have also seen AI models being created that further enhance the detection of periapical pathology from CBCT images (24).
Deep learning segmentation-based models have high accuracy in the detection of periapical radiolucencies, sometimes as high as 93% accuracy with 88% specificity (25). Because AI can investigate minute changes even at the pixel level, it enables a very fine-grained understanding of the various pathologies around the periapical region, which might further help in differentiating between granulomas and cysts, thus aiding clinical decisions on treatment like root canal therapy without surgical interventions (26).
The integration of AI into the diagnostics of endodontics heralds a quantum leap in our efforts at diagnosis and treatment of the perplexing dilemma of the periapical lesions and

further emphasizes the transformative impact of AI on enhanced clinical outcomes in dentistry.

Detection of Vertical Root Fractures (VRF)
VRFs can frequently be found in teeth that have undergone endodontic treatment, though they mostly occur in upper premolars and molars (27). Since these fractures are subtle, the use of conventional diagnostic methodology can hardly clinically detect them (28, 29).

Advanced Imaging Techniques
While conventional radiographs have been the standard, Cone Beam Computed Tomography has been able to outperform in the detection of VRFs, thus providing a clearer and more detailed view of the structure of the tooth (29, 30).

Innovations of AI in VRF Detection
Recent development in AI has greatly supported the ability to trace VRFs. There have been several studies done using AI models on VRFs for better detection accuracy: Machine Learning, Convolutional Neural Networks, and Probabilistic Neural Networks (31, 32). In one of these studies, Johari et al. reported that PNN models have more potential in identifying VRFs in CBCT images, and the results are significantly more satisfying than those obtained from radiographic images in a 2D format (33).

Improved diagnosis using AI
Further work by Vicory et al. presented the usage of an AI algorithm with wavelet features in the detection of microfractures. This points out the ability of AI in detecting even minute details about fractures (34). A study conducted by Hu et al. compared the performance of DLMs, which was till date performed by ResNet50 in VRF in vivo diagnosis using CBCT images (35). Whereas the introduction of AI into the detection of vertical root fractures significantly improves diagnostic accuracy and treatment planning, it provides the clinician with valuable tools for better management of such endodontic complications (36).

Morphology of Root and Root Canal System
Successful non-surgical root canal therapy relies on detailed knowledge of the morphology of the root canal system. Although CBCT imaging is more accurate than 2D radiography, its use as a routine examination in daily practice is still limited due to radiation concerns (32).

Complex Canal Configurations
The C-shaped canal configuration, particularly when it is present in the lower second molar, represents one of the most complicated endodontic configurations. These canal configurations are very challenging to deal with during root canal treatment because of their highly complex anatomy (36).

Advancements in AI Detection
Recent studies have highlighted the effectiveness of AI systems in enhancing the detection and treatment planning for complicated canal shapes. Studies like Jeon et al. and Yang et al. demonstrated that Deep Learning systems significantly outperformed classic CNNs in identifying C-shaped canals on panoramic and periapical images (37, 38). Besides, Hiraiwa et al. presented 87% accuracy using algorithms with DL when diagnosing roots in mandibular first molars (39).
While assessing the morphology of roots and canals, the integration of AI significantly enhances the precision and efficiency of endodontic diagnosis and helps in complicated cases where traditional methods cannot yield an effective outcome.

Determination of Working Length in Endodontics
Accurate determination of the working length is essential in the root canal treatment for the success of the treatments. It helps to be certain that the canal will be sufficiently cleaned, prevent the extrusion of debris, reduce post-operative pain, and affect the treatment outcome as a whole.

Current Techniques
WL is usually determined by using electronic apex locators in combination with the periapical radiographs. These methods,

despite their effectiveness, are highly dependent on the clarity of the digital radiographs and are bound to have their share of errors due to wet canals or metallic restorations of teeth among other conditions (40).

Limitations and Challenges
The position of the cementodentinal junction, the place where instrumentation should ideally terminate, lies 0.5 to 2 mm from the radiographic apex. Misinterpretation of this very important point may result in suboptimal cleaning or overextension of the canal filling materials, resulting in treatment failure.

Advances in AI
Artificial Intelligence, especially using Artificial Neural Networks, has transformed the determination of working length by guaranteeing higher accuracy and reliability. Saghiri et al. reported that for the detection of minor anatomical constrictions, ANN models provided an accuracy rate of 96%, while with traditional radiographic approaches, the accuracy was 76% for endodontists (27). It therefore not only supports traditional methods but adds more accuracy to them by reducing human error and hence gives more precise diagnostic output in working length determination. This makes AI very vital in contemporary endodontic practices (41).

AI in Endodontic Retreatment Prediction
The improvements made in the field of AI have opened new avenues in endodontics, one of which is the predictability in the outcome of retreatment. Artificial intelligence models combine clinical symptoms, patient history, demographic, lifestyle, and genetic factors comprehensively into the planning of treatment (42).

Applications of Predictive Modeling by AI
AI can process large volumes of information. It therefore holds the capability to discover patterns and risk factors not easily attainable or noticeable through conventional means (43). Works like that of Lee et al. and Hung et al. illustrate how AI has advanced diagnosis and treatment (19, 24). Lee et al. employed a case-based reasoning paradigm and achieved prognostic results equal to multi-disciplinary clinical teams. Using machine learning algorithms like SVM and RF, Hung et al. developed AI predictive models which were likely to perform better in identifying patients at risk for tooth surface loss and root caries (19).
Campo et al. also reported the usage of AI in the non-surgical endodontic retreatment through the case-based reasoning approach, which relies on statistical probability and performance recall (43). This technique predicts the outcome of a treatment based on historical data from similar treatments and, therefore, holds a great promise for accurate forecasting of retreatments.

AI in Endodontic Microsurgery
AI also demonstrated effectiveness in predicting the outcomes of endodontic microsurgery. Qu et al. indicated that a GBM model showed an ultra-high sensitivity of 91.39% and hence might be of significant impact on clinical decision-making in complicated surgical situations. The inclusion of AI in endodontic retreatment proposes a revolutionary strategy toward dental care; precision medicine is facilitated through in-depth analysis and improvement in predictability (44).

Regenerative Endodontic Procedures
Regenerative endodontics is a new area of research in which the lost or pathologically damaged physiological tissues of dentine, root, and cells from the pulp-dentin complex are restored. These biologically-based methodologies further promote the morphological and functional development of teeth (43).

Important Factors Involved in REPs
Three factors are considered to be crucial for successful REPs. These factors involve the triad of: Stem Cells, Scaffolds, and Activators. These factors allow the differentiation of cells or secretion of enzymes for the regeneration of tissues of teeth (44).

Technological Integration into REPs
Advanced technologies involved, such as the neuro-fuzzy inference technique increase the percentage of accuracy in treatment. For example, researchers in previous experimental studies had used this neuro-fuzzy infer-

ence technique to assess the vitality of the dental pulp stem cells against various variables and forecasted the results with a high percentage of accuracy (44).

Application and Results
REPs have shown promise in treating teeth with pulp necrosis by using vital adult stem cells in the apical region to drive tissue regeneration. This, therefore, promises great structural and functional recovery of teeth and thus improves the predictability and outcomes of endodontic treatments.
Regenerative endodontics represents a paradigm shift toward more natural and sustainable dental therapies, leveraging biological processes in concert with advanced computational techniques to further enhance treatment efficacy and patient outcomes.

Ethical Considerations and Limitations of AI in Dentistry
While the greater inclusion of AI within dentistry means significant strides are made forward, there are many challenges that accompany this action and have to be resolved in order to further strengthen the reliability, performance, and applicability of AI-based models (45).

Availability and Validity of Data
The application of AI in dentistry faces several key challenges, where the datasets need to be complete and well-structured. Dental data is fundamentally complex, sensitive, and multivariate; hence, it really needs to be supported with strong systematic algorithms in handling and validation.

Reliability and Generalizability
Special attention is usually given to the reliability of AI models used in the clinical setting, which indeed has been found wanting on most occasions regarding clarity in the sample sizes used for both training and testing of the model. Beyond that, however, are the issues associated with generalizability of models-very serious concerns about adherence to clinical guidelines (46). Continuous improvements are needed to enhance the accuracy of the AI systems and increase patient trust.

Ethical and Legal Considerations
There is, however, a possible ethical dilemma with the integration of AI in dental care: taking over long-established dental services and considerations on healthcare privacy. One needs to be very careful regarding the privacy and confidentiality issues arising from AI algorithms once these become integrated into medical practice (45). The accountability issue is another legal consequence, since AI applications-currently both supervised and unsupervised-do not have any accountability whatsoever. Where AI promises the next revolution in dental care, it is the development of clear guidelines and ethical standards regarding its use that will play a crucial role in guaranteeing its safety and effectiveness, while protecting the patients and the integrity of the dental profession (47).

Future Considerations
Nevertheless, apart from the promising outlook, further studies are being called for in terms of reliability, relevance, and cost-effectiveness with regard to these models of AI. Indeed, such characteristics must be critically scrutinized if AI is to be accepted into routine clinical practices that would make the technology practical and effective in managing patients.

Conclusion

Artificial Intelligence, or AI, has increasingly been a pivotal tool in the area of endodontics. Quite a large number of studies have demonstrated its high degree of accuracy in both diagnostic and prognostic assessments. This makes AI an enabling technology that further improves treatment planning and, therefore, probably the success rate of endodontic treatments. Adoption in endodontics is minimal when put in comparison with other dental specialties; however, AI's capability for processing and extracting significant information from voluminous data sets tells about the growing importance of the role of this technology in this sector. Since the technology excels at applying structured knowledge, hence promising applications can be realized which might extend its adoption in the field. AI embodies a transformative factor in endodontics, whose wider dissemination requires caution and validation. Advances and rigorous testing continue to define its role in the reformation of endodontic procedures and outcomes.

Clinical Relevance

Endodontics faces a paradigm shift with AI which enhances diagnostic capabilities and streamlines both treatment planning and procedural execution. The system provides more consistent results by locating periapical lesions along with root fractures and complex canal anatomy. The technology serves to determine working lengths as well as predict retreatment success rates and optimize outcomes in microsurgery procedures. To validate its reliability and clinical integration research must continue beyond current developments. Evidence-based clinical decisions become more robust because of AI which improves patient outcomes thereby helping maintain natural dentition.

Conflict of Interest

None.

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None.

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