REVIEW ARTICLE

Artificial Intelligence and Its Application in Endodontics: A Review

Zeeshan Heera Ahmed[1], Abdullah Muharib Almuharib[2], Abdulrahman Abdullah Abdulkarim[3], Abdulaziz Hassoon Alhassoon[4], Abdullah Fahad Alanazi[5], Muhannad Abdullah Alhaqbani[6], Mohammed Saif Alshalawi[7], Abdullah Khalid Almuqayrin[8], Mohammed Ibrahim Almahmoud[9]

Abstract

Aim and background: Artificial intelligence (AI) since it was introduced into dentistry, has become an important and valuable tool in many fields. It was applied in different specialties with different uses, for example, in diagnosis of oral cancer, periodontal disease and dental caries, and in the treatment planning and predicting the outcome of orthognathic surgeries. The aim of this comprehensive review is to report on the application and performance of AI models designed for application in the field of endodontics.

Materials and methods: PubMed, Web of Science, and Google Scholar were searched to collect the most relevant articles using terms, such as AI, endodontics, and dentistry. This review included 56 papers related to AI and its application in endodontics.

Result: The applications of AI were in detecting and diagnosing periapical lesions, assessing root fractures, working length determination, prediction for postoperative pain, studying root canal anatomy and decision-making in endodontics for retreatment. The accuracy of AI in performing these tasks can reach up to 90%.

Conclusion: Artificial intelligence has valuable applications in the field of modern endodontics with promising results. Larger and multicenter data sets can give external validity to the AI models.

Clinical significance: In the field of dentistry, AI models are specifically crafted to contribute to the diagnosis of oral diseases, ranging from common issues such as dental caries to more complex conditions like periodontal diseases and oral cancer. AI models can help in diagnosis, treatment planning, and in patient management in endodontics. Along with the modern tools like cone-beam computed tomography (CBCT), AI can be a valuable aid to the clinician.

Keywords: Artificial intelligence, Comprehensive review, Endodontics, Advantages and disadvantages of AI in endodontics, Future of AI in endodontics.

The Journal of Contemporary Dental Practice (2023): 10.5005/jp-journals-10024-3593

Introduction

In 1955, the eminent mathematician John McCarthy, recognized as the founding father of artificial intelligence (AI), introduced the term “artificial intelligence” to encapsulate the groundbreaking concept of machines exhibiting intelligent capabilities (McCarthy).[1] The subsequent year marked a pivotal moment in AI history, as McCarthy took the lead in organizing the influential Dartmouth conference, formally inaugurating an era of flourishing AI research from the 1950s to the 1970s (McCarthy et al.).[2]

By 1978, Richard Bellman, an accomplished applied mathematician, provided a comprehensive characterization of AI as the mechanization of tasks aligned with human cognitive functions, including learning, decision-making, and problem-solving (Bellman).[3] In the contemporary landscape, the term “artificial intelligence” has evolved to encompass any machine or technology capable of emulating human cognitive abilities, particularly in problem-solving contexts. To navigate the complexities of AI, one must grasp fundamental concepts that have propelled substantial advancements, notably within medical imaging and diagnosis methods (AI in Healthcare, 2022).[4]

The integration of AI models into the healthcare industry stands as a significant technological milestone, particularly with the advent of AI algorithms, prominently machine learning algorithms, playing a central role. The efficacy of these algorithms’ hinges on the quality and quantity of datasets employed for training (AI in Healthcare).[5]

[1]Department of Restorative Dental Sciences and Endodontics, College of Dentistry, King Saud University, Riyadh, Saudi Arabia

[2–9]College of Dentistry, King Saud University, Riyadh, Saudi Arabia

Corresponding Author: Zeeshan Heera Ahmed, Department of Restorative Dental Sciences and Endodontics, College of Dentistry, King Saud University, Riyadh, Saudi Arabia, Phone: +966502318766, e-mail: aheera@ksu.edu.sa

How to cite this article: Ahmed ZH, Almuharib AM, Abdulkarim AA, *et al*. Artificial Intelligence and Its Application in Endodontics: A Review. J Contemp Dent Pract 2023;24(11):912–917.

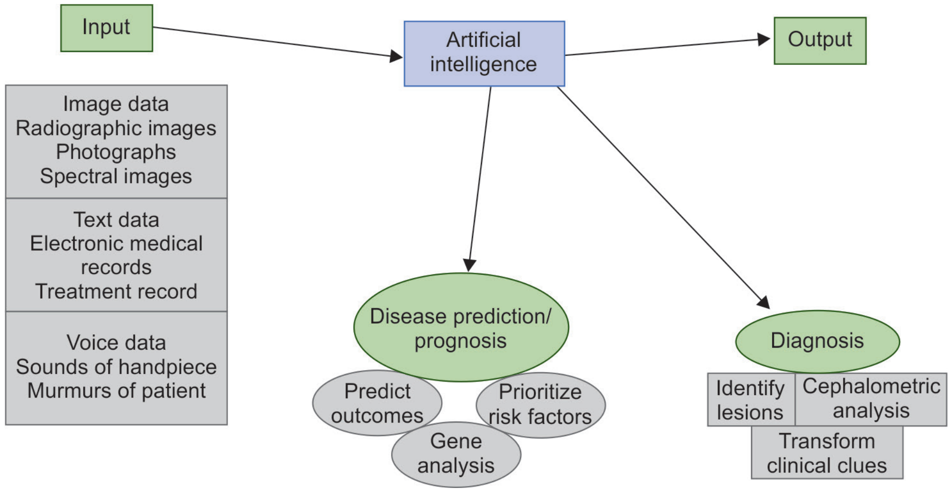
Source of support: Nil

Conflict of interest: None

Among the pioneering AI algorithms, convolutional neural networks (CNNs) have emerged as a solution to complex problems, employing convolutional filtering steps and leveraging extensive datasets to replicate intricate cognitive processes (LeCun et al.).[6]

Within the realm of computer science, AI refers to the exploration of intelligent machines capable of comprehending their environment and optimizing behavior for success. The term is specifically invoked when computers emulate analytical abilities associated with human brains, encompassing learning and problem-solving (Russell and Norvig).

Flowchart 1: Block diagram of artificial intelligence model in dentistry—disease diagnosis and prediction/prognosis



Recent advancements in clinical practice include the application of a static computed tomographic-based stereolithographic drill guide system, reported to enhance precision in both surgical and nonsurgical cavity preparations (Clinical Advances in Endodontics).[7] In the domain of root canal therapy, a critical objective involves the cleaning and reshaping of the root canal system while preserving its original form. Recent market entries, such as various single-file systems for root canal instrumentation, have been subject to numerous research studies evaluating their efficiency and effectiveness (Yared).[8]

Alterations in root canal curvature are commonplace occurrences with pivotal roles in endodontic procedures. Despite their significance, only a limited number of research studies have endeavored into the measurement of canal curvature. Schneider pioneered this field, utilizing X-rays to determine the sharp angle between the canal's long axis and a direct line from the apical foramen to the point where the curve begins. Günday et al. compared different X-ray techniques for curve measurement in mesiobuccal canals.[9] Nagy et al. sought to establish a mathematical representation of the canal's axis based on X-ray findings.[10,11] Schafer et al. proposed mathematically deriving the radius of the canal from X-rays to genuinely capture its curve.[12]

Departing from conventional 2D X-ray methods, Peters et al. introduced a three-dimensional (3D) approach to measuring canal curvature using micro-computed tomography (microCT).[13] This innovation marked a substantial leap forward, providing a more comprehensive and accurate understanding of root canal morphology.

AI found its application in endodontics, promising to enhance various aspects of diagnosis and treatment planning. The subsequent sections of this comprehensive review delve into the specific applications of AI in endodontics, including diagnostic applications, periapical lesion detection, vertical root fracture diagnosis, prediction of postoperative pain, morphology assessment of root and root canal systems, determination of working length, and decision-making for retreatment (Flowchart 1).

Materials and Methods

This review article involved an assessment of published studies discussing AI and its application in Endodontics. Multiple databases, including PubMed, Web of Science, and Google Scholar, were utilized to collect the most relevant articles on this subject. The search used several terms, such as AI, endodontics, and dentistry. By using this method, all the studies discussed AI and its application in endodontics. were obtained. We included all studies that addressed AI and its application, advantages, and disadvantages. Studies with poor methodological quality, outdated data, or insufficient data were excluded. The initial screening elicited 111 studies. After implementing our inclusion criteria, the most relevant articles were selected and included in this review. This review ultimately involved 56 papers related to AI and its application in application in endodontics.

Result and Discussion

Diagnostic Application of AI Endodontics

In the field of dentistry, AI models are specifically crafted to contribute to the diagnosis of oral diseases, ranging from common issues, such as dental caries to more complex conditions like periodontal diseases and oral cancer. Moreover, these advanced models extend their utility to treatment planning for orthognathic surgeries, offering valuable insights into predicting treatment outcomes.[14–16] This aligns with comprehensive systematic reviews within the dental domain, where Mohammad-Rahimi et al. conducted a study evaluating the performance of deep learning models in periodontology and oral implantology. The conclusive findings emphasized the overall high performance of these models, highlighting their potential in enhancing diagnostic accuracy and treatment planning.[17]

Similarly, Albalawi and Alamoud delved into the application of AI models in orthodontics, presenting a diverse range of models. The study affirmed the reliability of these AI models, noting their capacity to autonomously execute tasks with a speed and efficiency comparable to that of seasoned specialists.[18] Another noteworthy contribution comes from Junaid et al., who explored the application and performance of AI models specifically tailored for cephalometric landmark identification. Their findings underscored the significant efficiency gains achieved by orthodontists through the utilization of these models.[19]

Shedding light on the realm of endodontics, Nagendrababu et al. presented a comprehensive report on AI models designed

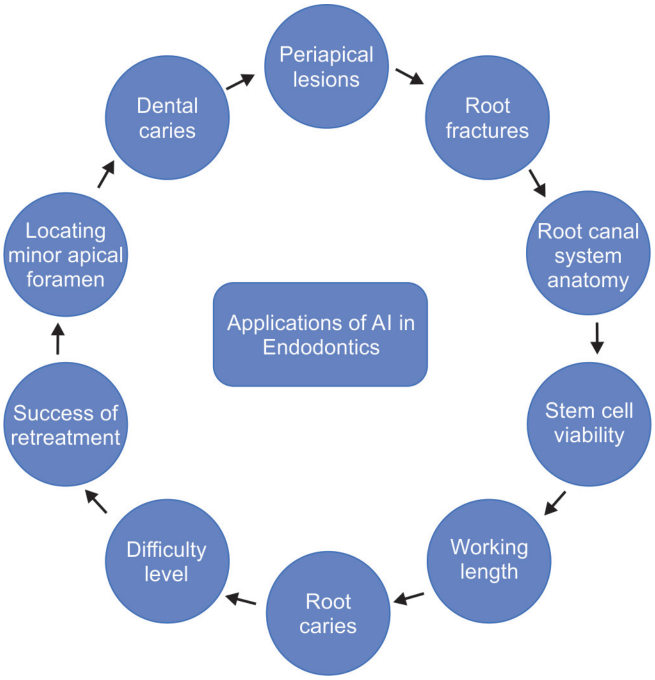


Fig. 1: Applications of artificial intelligence in endodontics

for various tasks, including the study of root canal anatomy, detection and diagnosis of periapical lesions and root fractures, and determination of the working length for planning root canal treatment. The authors concluded that these AI models hold substantial promise in facilitating clinicians with precise diagnosis and treatment planning, ultimately leading to improved treatment outcomes.[20] Umer and Habib further expanded on the application of AI models in endodontics, focusing on diagnosis and treatment planning. Their study revealed impressive accuracy rates exceeding 90% in performing the designated tasks, reinforcing the potential of AI in elevating the standards of endodontic practices.[21] However, a recurring challenge highlighted by these authors is the irregular reporting of AI-related research in the field (Fig. 1).

Periapical Lesions Detection

Clinicians often face challenges in accurately diagnosing and planning treatment for teeth exhibiting periapical lesions and associated symptoms, making the process inherently complex.[20] Apical periodontitis, a prevalent condition, accounts for approximately 75% of cases involving radiolucent jaw lesions.[22] Timely detection becomes paramount in enhancing treatment efficacy, preventing the spread to adjacent tissues, and mitigating potential complications.[23] Common radiographic techniques employed for diagnosing pulp and periapical diseases include intraoral periapical radiographs (IOPA), orthopantomograms, and cone-beam computed tomography (CBCT) imaging.[24] In a meta-analysis, CBCT imaging demonstrated superior accuracy scores for identifying periapical lesions (0.96) compared with traditional IOPA (0.73) and digital IOPA (0.72).[25] Notably, the accuracy of CBCT imaging diminishes in diagnosing apical periodontitis in teeth with filled roots, limiting its use to specific clinical scenarios due to its high cost and radiation exposure.[20]

The distinctive features of periapical radiolucency and alveolar bone resorption provide valuable foundations for developing AI models aimed at detecting periapical pathology and periodontitis.[26] Endres et al. revealed that a deep learning algorithm could accurately detect periapical radiolucencies on panoramic radiographs, matching the proficiency of 24 oral and maxillofacial surgeons.[27] Orhan et al.'s study demonstrated an impressive detection accuracy rate of 92.8%, identifying 142 out of 153 periapical lesions using an AI system.[28] Lee et al. leveraged a deep learning network to develop a model capable of identifying periodontally challenged molars and premolars, predicting the prognosis of these teeth.[29] Additionally, Issa et al. evaluated the diagnostic accuracy of an AI system called Diagnocat in detecting apical pathosis on periapical radiographs. The system displayed a sensitivity of 92.30% in identifying periapical lesions and a specificity of 97.87% in recognizing healthy teeth.[30]

In a comprehensive approach, Li et al. undertook the training, validation, and testing of a deep learning model using 4,129 periapical radiographs. Their findings underscored the potential of deep learning to enhance the accuracy and consistency of evaluating dental caries and periapical periodontitis on periapical radiographs.[29] These advancements in AI applications showcase the transformative potential of technology in augmenting diagnostic capabilities and improving overall outcomes in dental care.

Vertical Root Fracture

Diagnosing vertical root fractures (VRFs) poses a formidable challenge in dental practice, characterized by fractures extending longitudinally from the root apex to the crown.[31] The prevalence of VRFs post-root canal treatment varies widely, ranging from 3.7 to 30.8%.[20,21] Among the array of diagnostic modalities, cone-beam computed tomography (CBCT) has gained prominence for detecting VRFs due to its submillimeter spatial resolution and three-dimensional (3D) visualization capabilities.[32]

Fukuda et al.'s study emphasizes the potential utility of a designed neural network as an effective model for diagnosing VRFs on CBCT images, specifically in endodontically treated and intact teeth.[33] Another research endeavor leveraged periapical radiographs and CBCT images to construct a neural network aimed at identifying VRFs in both intact and root-filled teeth, underscoring the superior effectiveness of CBCT images compared to periapical radiographs.[34]

In a noteworthy exploration by Shah et al., fractures were intentionally induced in second molars, and wavelet analysis applied to synthetic data proved instrumental. Wavelets, as mathematical operations, facilitated the recovery of weak signals in noisy settings within a machine learning framework. Despite a limited sample size, the successful application of steerable wavelets showcased their efficacy in detecting fractures in high-resolution CBCT images.[35] These innovative approaches highlight the evolving landscape of diagnostic methodologies, with neural networks and wavelet analysis offering promising avenues for enhancing the precision of VRF detection in dental imaging.

Predicting Postoperative Pain

The artificial neural network (ANN) has witnessed significant development in the medical field, finding widespread application in disease diagnosis, prognosis, and clinical decision-making.[36,37] Representing one of the latest advancements in nature-inspired algorithms, ANN stands out as a rapidly evolving technology.[38]

Studies indicate that ANN holds the potential to identify crucial variables and predict posttreatment pain with remarkable accuracy.

Notably, researchers have successfully applied this model to predict conditions such as non-ST-elevation myocardial infarction (NSTEMI) and unstable chest pain. In the context of acute pain treatment in sickle cell disease, the integration of mobile health apps and machine learning models demonstrated predictive capabilities.[39,40]

In the realm of dentistry, Gao et al. emphasize the high prediction accuracy of ANN based on the BP algorithm, suggesting potential benefits for dentists and patients in future root canal therapy.[41] Furthermore, with ongoing optimization of measurement methods, the precision of ANN models is expected to continually improve, promising enhanced accuracy in predicting outcomes related to root canal therapy.

Morphology of Root and Root Canal System

Cone-beam computed tomography (CBCT) imaging and periapical radiography serve as crucial tools for comprehending the complexities of various root and root canal systems. When compared with traditional radiography, CBCT imaging has demonstrated superior accuracy in delineating the intricate geometries of roots and root canals. In cases of endodontic retreatment, addressing missed canals becomes imperative, with statistics revealing that 93% of all missed canals are associated with the maxillary first molar and 44% with maxillary second molars.[20]

In a study by Lina et al., 57 deidentified CBCT studies focusing on maxillary molars with clinically confirmed unobturated MB2 canals were collected. The research aimed to explore the potential of AI in detecting and localizing Unobturated second mesial buccal (MB2) canals. The findings suggested that AI holds promise in identifying both obturated and unobturated canals in endodontically treated teeth. However, it is crucial to note that the current AI algorithm is somewhat susceptible to metallic artifacts, variations in canal calcifications, and specific configurations.[42]

Additionally, according to Hiraiwa et al.[43] utilizing CBCT, a deep learning system exhibited a high diagnostic accuracy of 86.9% in determining whether distal roots were single or possessed extra roots. This underscores the potential of deep learning systems to effectively identify and classify complex canal configurations, such as C-shaped canals, offering valuable support to clinicians in both practice and education.[44,45]

Determination of Working Length

The precise identification of the physiological apex of the root canal is a fundamental requirement for the success of endodontic therapy.[46] The minor diameter, representing the narrowest diameter with the least blood supply and innervation, serves as the appropriate apical limit for endodontic treatment.[47] Among the techniques commonly employed by clinical dentists, radiography and electronic apex locators stand out as routine methods.[48]

In a study by Saghiri et al.,[49] it was observed that ANN can function as a valuable second opinion in locating the apical foramen (AF) on radiographs, thereby enhancing the precision of determining the working length through radiography. Another study conducted on human cadaver models by Saghiri et al.[50] compared the accuracy of assessing periapical radiographs to locate the anatomic position of the minor apical constriction between endodontists and ANN. The findings revealed an accuracy of 76% for endodontists and an impressive 96% for the ANN. Additionally, when comparing the ANN with real measurements after extraction, no significant differences were found in root length measurements. This underscores the potential of ANN to contribute significantly to the precision of endodontic procedures.[49,50]

Decision-making for Retreatment

The success rate of endodontic therapy stands at an impressive 90%, leaving a 10% failure rate. In addressing this 10%, the integration of AI techniques holds significant promise for endodontologists, aiding in the analysis of cases to determine whether retreatment or extraction is the more suitable course of action.[51–53]

Campo et al.[54] have contributed to this area by introducing a decision support system grounded in the case-based reasoning (CBR) paradigm. This system is meticulously designed to predict the viability of conducting retreatment. By doing so, it proves instrumental in reducing the occurrence of unsuccessful retreatments, effectively forecasting the likelihood of success or failure, and consequently, averting unnecessary extractions. Impressively, they achieved an 84.4% accuracy in predicting the final treatment or retreatment outcome for the cases under consideration.[54]

For Patient Management

Artificial intelligence-driven virtual dental assistants have revolutionized the landscape of dental offices, demonstrating enhanced accuracy and a reduced margin of error compared with their human counterparts. The utilization of these virtual assistants demands less manpower, optimizing operational efficiency. Their capabilities extend across various crucial tasks, including clinical diagnosis, treatment planning, visit scheduling, insurance and paperwork organization, among others. Notably, these virtual assistants play a pivotal role in furnishing dentists with comprehensive insights into patients' medical histories and relevant habits, such as smoking and drinking. In instances of dental emergencies, particularly when the practitioner is unavailable, patients can access emergency teleassistance as a viable option.[55]

Limitation and Future Application

While the presented AI models showcase promising outcomes, it is crucial to acknowledge certain limitations inherent in the studies. Most notably, these models were developed with a constrained number of datasets for both training and evaluation purposes. The data samples utilized were predominantly sourced from a singular clinic or center and were generated using a single radiographic instrument. Consequently, the outcomes derived from these studies lack the broad applicability and generalizability necessary for broader clinical contexts due to the inherent homogeneity of the samples.

To address these limitations effectively, future research endeavors should prioritize incorporating a more extensive and diverse range of datasets for both training and testing the AI models. The inclusion of samples from multiple centers and diverse radiographic instruments is imperative to enhance the robustness and external validity of the models.[56]

Another notable limitation observed in certain models is the reliance on datasets labeled by operators, introducing the potential for human bias. This reliance on manual labeling can inadvertently influence and compromise the overall performance of the AI models. Future applications in this domain should explore strategies to minimize human bias, potentially through automated or standardized labeling processes, ensuring the models maintain optimal performance integrity. This emphasis on overcoming current limitations lays the foundation for the evolution and broader adoption of AI models in the dynamic landscape of dental diagnostics and treatment planning.

Conclusion

Artificial intelligence has valuable application in the field of modern endodontics with promising results. More studies with larger number of databases need to be applied in the future to overcome the lack of heterogeneity, so the results can be generalized.

Clinical Significance

In the field of dentistry, AI models are specifically crafted to contribute to the diagnosis of oral diseases, ranging from common issues such as dental caries to more complex conditions like periodontal diseases and oral cancer. Future applications in this domain should explore strategies to minimize human bias, potentially through automated or standardized labeling processes, ensuring the models maintain optimal performance integrity. This emphasis on overcoming current limitations lays the foundation for the evolution and broader adoption of AI models in the dynamic landscape of dental diagnostics and treatment planning.

References

1. Rajaraman V. JohnMcCarthy—Father of artificial intelligence. Resonance [Internet] 2014;19(3):198–207. DOI: 10.1007/s12045-014-0027-9.
2. National Research Council. Funding a Revolution [Internet]. Washington, D.C.: National Academies Press; 1999. Available from: http://www.nap.edu/catalog/6323.
3. Bellman RE. Artificial intelligence: Can computers think? San Francisco: Boyd & Fraser Pub. Co., c1978.
4. Allen B Jr, Seltzer SE, Langlotz CP, et al. A Road Map for Translational Research on Artificial Intelligence in Medical Imaging: From the 2018 National Institutes of Health/RSNA/ACR/The Academy Workshop. J Am Coll Radiol 2019;16(9 Pt A):1179–1189. DOI: 10.1016/j.jacr.2019.04.014.
5. Schwendicke F, Samek W, Krois J. Artificial Intelligence in Dentistry: Chances and Challenges. J Dent Res [Internet] 2020;99(7):769–774. DOI: 10.1177/0022034520915714.
6. Burt JR, Torosdagli N, Khosravan N, et al. Deep learning beyond cats and dogs: Recent advances in diagnosing breast cancer with deep neural networks. Br J Radiol 2018;91(1089):20170545. DOI: 10.1259/bjr.20170545.
7. Pinsky H, Champleboux G, Sarment D. Periapical Surgery Using CAD/CAM Guidance: Preclinical Results. J Endod [Internet]. 2007;33(2):148–151. DOI: 10.1016/j.joen.2006.10.005.
8. Stern S, Patel S, Foschi F, et al. Changes in centering and shaping ability using three nickel–titanium instrumentation techniques analysed by micro-computed tomography (μCT). Int Endod J [Internet] 2012;45(6):514–523. DOI: 10.1111/j.1365-2591.2011.02004.x.
9. Günday M, Sazak H, Garip Y. A comparative study of three different root canal curvature measurement techniques and measuring the canal access angle in curved canals. J Endod [Internet] 2005;31(11):796–798. DOI: 10.1097/01.don.0000158232.77240.01.
10. Dobonagy C, Keszthelyi G, Szabo J, et al. A computerized method for mathematical description of three-dimensional root canal axis. J Endod 2000;26(11):639–643. DOI: 10.1097/00004770-200011000-00002.
11. Nagy CD, Szabó J, Szabó J. A mathematically based classification of root canal curvatures on natural human teeth. J Endod 1995;21(11):557–560. DOI: 10.1016/S0099-2399(06)80985-4.
12. Schafer E, Diez C, Hoppe W, et al. Roentgenographic investigation of frequency and degree of canal curvatures in human permanent teeth. J Endod 2002;28(3):211–216. DOI: 10.1097/00004770-200203000-00017.
13. Peters OA, Laib A, Rüegsegger P, et al. Three-dimensional analysis of root canal geometry by high-resolution computed tomography. J Dent Res 2000;79(6):1405–1409. DOI: 10.1177/00220345000790060901.
14. Thomas B. Artificial intelligence: review of current and future applications in medicine. Fed Pract 2021;38(11):527–538. DOI: 10.12788/fp.0174.
15. Shi F, Wang J, Shi J, et al. Review of artificial intelligence techniques in imaging data acquisition, segmentation, and diagnosis for COVID-19. IEEE Rev Biomed Eng 2021;14:4–15. DOI: 10.1109/RBME.2020.2987975./.
16. Kumar Y, Koul A, Singla R, et al. Artificial intelligence in disease diagnosis: A systematic literature review, synthesizing framework and future research agenda. J Ambient Intell Humaniz Comput 2023;14(7):8459–8486. DOI: 10.1007/s12652-021-03612-z.
17. Mohammad-Rahimi H, Motamedian SR, Pirayesh Z, et al. Deep learning in periodontology and oral implantology: A scoping review. J Periodontal Res 2022;57(5):942–951. DOI: 10.1111/jre.13037.
18. Albalawi F, Alamoud KA. Trends and application of artificial intelligence technology in orthodontic diagnosis and treatment planning—A review. Appl Sci 2022;12(22):11864. DOI: 10.3390/app122211864.
19. Junaid N, Khan N, Ahmed N, et al. Development, application, and performance of artificial intelligence in cephalometric landmark identification and diagnosis: A systematic review. Healthcare 2022;10(12):2454. DOI: 10.3390/healthcare10122454.
20. Aminoshariae A, Kulild J, Nagendrababu V. Artificial intelligence in endodontics: current applications and future directions. J Endod 2021;47(9):1352–1357. DOI: 10.1016/j.joen.2021.06.003.
21. Umer F, Habib S. Critical analysis of artificial intelligence in endodontics: A scoping review. J Endod 2022;48(2):152–160. DOI: 10.1016/j.joen.2021.11.007.
22. Becconsall-Ryan K, Tong D, Love RM. Radiolucent inflammatory jaw lesions: a twenty-year analysis. Int Endod J 2010;43(10):859–865. DOI: 10.1111/j.1365-2591.2010.01751.x.
23. Chapman MN, Nadgir RN, Akman AS, et al. Periapical lucency around the tooth: radiologic evaluation and differential diagnosis. RadioGraphics 2013;33(1):E15–E32. DOI: 10.1148/rg.331125172.
24. Velvart P, Hecker H, Tillinger G. Detection of the apical lesion and the mandibular canal in conventional radiography and computed tomography. Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology 2001;92(6):682–688. DOI: 10.1067/moe.2001.118904.
25. Leonardi Dutra K, Haas L, Porporatti AL, et al. Diagnostic accuracy of cone-beam computed tomography and conventional radiography on apical periodontitis: A systematic review and meta-analysis. J Endod 2016;42(3):356–364. DOI: 10.1016/j.joen.2015.12.015.
26. Hung K, Montalvao C, Tanaka R, et al. The use and performance of artificial intelligence applications in dental and maxillofacial radiology: A systematic review. Dentomaxillofacial Radiol 2020;49(1):20190107. DOI: 10.1259/dmfr.20190107.
27. Endres MG, Hillen F, Salloumis M, et al. Development of a deep learning algorithm for periapical disease detection in dental radiographs. Diagnostics 2020;10(6):430. DOI: 10.3390/diagnostics10060430.
28. Orhan K, Bayrakdar IS, Ezhov M, et al. Evaluation of artificial intelligence for detecting periapical pathosis on cone-beam computed tomography scans. Int Endod J 2020;53(5):680–689. DOI: 10.1111/iej.13265.
29. Lee SJ, Chung D, Asano A, et al. Diagnosis of tooth prognosis using artificial intelligence. Diagnostics 2022;12(6):1422. DOI: 10.3390/diagnostics12061422.
30. Issa J, Jaber M, Rifai I, et al. Diagnostic Test Accuracy of Artificial Intelligence in Detecting Periapical Periodontitis on Two-Dimensional Radiographs: A Retrospective Study and Literature Review. Medicina (B Aires) 2023;59(4):768. DOI: 10.3390/medicina59040768.

31. Varshosaz M, Tavakoli MA, Mostafavi M, et al. Comparison of conventional radiography with cone beam computed tomography for detection of vertical root fractures: An in vitro study. J Oral Sci 2010;52(4):593–597. DOI: 10.2334/josnusd.52.593.
32. Baageel T, Allah E, Bakalka G, et al. Vertical root fracture: Biological effects and accuracy of diagnostic imaging methods. J Int Soc Prev Community Dent 2016;6(Suppl 2):S93–S104. DOI: 10.4103/2231-0762.189735.
33. Fukuda M, Inamoto K, Shibata N, et al. Evaluation of an artificial intelligence system for detecting vertical root fracture on panoramic radiography. Oral Radiol 2020;36(4):337–343. DOI: 10.1007/s11282-019-00409-x.
34. Johari M, Esmaeili F, Andalib A, et al. Detection of vertical root fractures in intact and endodontically treated premolar teeth by designing a probabilistic neural network: An ex vivo study. Dentomaxillofacial Radiol 2017;46(2):20160107. DOI: 10.1259/dmfr.20160107.
35. Paniagua B, Shah H, Hernandez-Cerdan P, et al. Automatic quantification framework to detect cracks in teeth. In: Gimi B, Krol A, editors. Medical Imaging 2018: Biomedical Applications in Molecular, Structural, and Functional Imaging [Internet]. SPIE; 2018. p. 55. Available from: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10578/2293603/Automatic-quantification-framework-to-detect-cracks-in-teeth/10.1117/12.2293603.full.
36. Vickram AS, Kamini AR, Das R, et al. Validation of artificial neural network models for predicting biochemical markers associated with male infertility. Syst Biol Reprod Med 2016;62(4):258–265. DOI: 10.1080/19396368.2016.1185654.
37. Esteva A, Kuprel B, Novoa RA, et al. Dermatologist-level classification of skin cancer with deep neural networks. Nature 2017;542(7639): 115–118. DOI: 10.1038/nature21056.
38. Choi HI, Jung SK, Baek SH, et al. Artificial intelligent model with neural network machine learning for the diagnosis of orthognathic surgery. J Craniofac Surg 2019;30(7):1986–1989. DOI: 10.1097/SCS.0000000000005650.
39. Johnson A, Yang F, Gollarahalli S, et al. Use of mobile health apps and wearable technology to assess changes and predict pain during treatment of acute pain in sickle cell disease: Feasibility study. JMIR mHealth uHealth 2019;7(12):e13671. Published 2019 Dec 2. DOI: 10.2196/13671.
40. Wu CC, Hsu WD, Islam MM, et al. An artificial intelligence approach to early predict non-ST-elevation myocardial infarction patients with chest pain. Comput Methods Programs Biomed 2019;173:109–117. DOI: 10.1016/j.cmpb.2019.01.013.
41. Gao X, Xin X, Li Z, et al. Predicting postoperative pain following root canal treatment by using artificial neural network evaluation. Sci Rep 2021;11(1):17243. DOI: 10.1038/s41598-021-96777-8.
42. Albitar L, Zhao T, Huang C, et al. Artificial Intelligence (AI) for Detection and Localization of Unobturated Second Mesial Buccal (MB2) Canals in Cone-Beam Computed Tomography (CBCT). Diagnostics 2022;12(12):3214. DOI: 10.3390/diagnostics12123214.
43. Hiraiwa T, Ariji Y, Fukuda M, et al. A deep-learning artificial intelligence system for assessment of root morphology of the mandibular first molar on panoramic radiography. Dentomaxillofac Radiol 2019;48(3):20180218. DOI: 10.1259/dmfr.20180218.
44. Yang S, Lee H, Jang B, et al. Development and validation of a visually explainable deep learning model for classification of C-shaped canals of the mandibular second molars in periapical and panoramic dental radiographs. J Endod 2022;48(7):914–921. DOI: 10.1016/j.joen.2022.04.007.
45. Sherwood AA, Sherwood AI, Setzer FC, et al. A deep learning approach to segment and classify C-shaped canal morphologies in mandibular second molars using cone-beam computed tomography. J Endod 2021;47(12):1907–1916. DOI: 10.1016/j.joen.2021.09.009.
46. Ricucci D, Langeland K. Apical limit of root canal instrumentation and obturation, part 2. A histological study. Int Endod J 1998;31(6): 394–409. DOI: 10.1046/j.1365-2591.1998.00183.x.
47. Ponce EH, Vilar Fernández JA. The cemento-dentino-canal junction, the apical foramen, and the apical constriction: Evaluation by optical microscopy. J Endod 2003;29(3):214–219. DOI: 10.1097/00004770-200303000-00013.
48. Petersson A, Axelsson S, Davidson T, et al. Radiological diagnosis of periapical bone tissue lesions in endodontics: A systematic review. Int Endod J 2012;45(9):783–801. DOI: 10.1111/j.1365-2591.2012.02034.x.
49. Saghiri MA, Asgar K, Boukani KK, et al. A new approach for locating the minor apical foramen using an artificial neural network. Int Endod J 2012;45(3):257–265. DOI: 10.1111/j.1365-2591.2011.01970.x
50. Saghiri MA, Garcia-Godoy F, Gutmann JL, et al. The reliability of artificial neural network in locating minor apical foramen: A cadaver study. J Endod 2012;38(8):1130–1134. DOI: 10.1016/j.joen.2012.05.004.
51. Jurisica I, Glasgow JI. Applications of case-based reasoning in molecular biology. AI Mag 2004;25(1):86–96. DOI: 10.1609/aimag.v25i1.1749.
52. Canalda Sahli C, Brau Aguade E. Endodoncia técnicas clínicas y bases científicas. 2006. 4th Edition. Carlos Canalda Sahli EBA (Ed)., Elsevier Health Sciences, 2019;2019. p. 432.
53. Suarez-Rivaya J, Ripolles de Ramon MJ, Pradies RG. Restauración del diente endodonciado. Diagnóstico y Opciones Terapéuticas 2006; Available from: https://hdl.handle.net/20.500.14352/52518.
54. Campo L, Aliaga IJ, De Paz JF, et al. Retreatment Predictions in Odontology by means of CBR Systems. Comput Intell Neurosci 2016;2016:7485250. DOI: 10.1155/2016/7485250.
55. Alexander B, John S. Artificial intelligence in dentistry: current concepts and a peep into the future. Int J Adv Res 2018;6(12): 1105–1108. DOI: 10.21474/IJAR01/8242.
56. Khanagar SB, Alfadley A, Alfouzan K, et al. Developments and performance of artificial intelligence models designed for application in endodontics: A systematic review. Diagnostics 2023;13(3):414. DOI: 10.3390/diagnostics13030414