

EVALUATION OF 3D IMAGING INTEGRATION WITH AI ALGORITHMS FOR AUTOMATED ENDODONTIC CANAL MORPHOLOGY ANALYSIS

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ABSTRACT

Combination of the three-dimensional imaging technologies with algorithms of the artificial intelligence proved to be a groundbreaking trend in modern endodontic practice that is essentially groundbreaking in terms of analysing the morphology of root canals and increasing the accuracy of the diagnosis. This is comprehensive research that assesses the effectiveness of using combination of cone-beam computed tomography with more advanced machine learning models, especially convolutional neural networks and deep learning models, to perform automated segmentation and endodontic canal system analysis. The research method included an analytical approach of the CBCT data that were subjected to artificial intelligence-based segmentation systems, and the performance indicators were compared to manual segmentation of the data by trained endodontists. The results show that AI-based 3D imaging systems can identify anatomical variations on roots canals with diagnostic accuracy rates that surpass ninety percent with regard to identifying complex morphological structures such as accessory canals, isthuses, apical deltas, and C-shaped canal designs. The automated segmentation process also greatly decreased the time that took to analyze a case of about forty five minutes when using the traditional manual methods to less than five minutes and still yielded similar or better accuracy levels. Moreover, the combination of artificial intelligence and three-dimensional imaging proved to be remarkably effective in the detection of canals with the presence of calcification, the occurrence of vertical root fracture, and the prognosis of treatment with high sensitivity and specificity rates. The paper demonstrates that deep learning models with U-Net architecture are stable in the performance of different demographic groups and tooth types with dice similarity coefficients between zero point seven three six and zero point seven six eight on complex canal structures. These findings highlight the potential transformative power of the AI-enhanced 3D imaging to simplify the endodontic processes and minimize operator-specific variability and eventually enhance the patient outcome with more accurate treatment planning. Clinical implications of this integration are not limited to the diagnostic accuracy only, but include improved educational training, standardized assessment protocols and possibilities of the large scale epidemiological studies on root canal anatomy variations between world populations.

Keywords

Three-dimensional imaging, cone-beam computed tomography, artificial intelligence, deep learning, convolutional neural networks, endodontic canal morphology.

INTRODUCTION

Endodontic treatment is one of the most significant procedures in modern dentistry, which is concerned with the conservation of natural dentition by controlling pulpal and periapical pathologies very accurately. The effectiveness of endodontic therapy is essentially relying on the overall knowledge of the clinician of the root canal structure that is exceptionally complex and diverse in diverse populations of the society and in diverse individuals. Although the traditional two-dimensional radiographic imaging still remains the foundation of dental diagnosis over decades, it has serious drawbacks that limit its ability to clearly represent the three-dimensionality of root canal systems, which commonly leads to the absence of canals, incomplete debridement, and consequent treatment failure. With the emergence of cone-beam computed tomography, endodontic imaging radically changed as high-resolution three-dimensional imaging of the tooth determined the morphology of a root canal in multiple planes without needing to superimpose the existing images like in traditional radiography. In spite of these technological developments, the interpreting of CBCT images is still very reliant on operator experience and prone to human error, inconsistency of diagnostic consistency and manual interpretation, which is time-consuming. The advent of artificial intelligence, especially deep learning methods and convolutional neural networks has presented the medical field with more opportunities than ever before to apply AI to

complex diagnosis tasks, and dentistry, in particular, may be seen as a highly promising field to implement AI. The recent advancements in the computing technology have enabled the development of advanced AI-powered machines that can automatically subdivide anatomical structures, identify pathological conditions, and can predict treatment outcomes with a level of accuracy that is in many cases more than a match of human capacity.(Singh, 2018). The availability of three-dimensional imaging technology, combined with the application of artificial intelligence algorithms, offers a rare chance to solve the inherent shortcomings of the existing endodontic diagnostic process, as well as to increase the level of accuracy, efficiency, and standardization in the analysis of canal morphology. This study will provide a thorough assessment of the combination of CBCT imaging and AI procedures to analyze the morphology of endodontic canals automatically, assessing the precision of diagnoses, time spent, and clinical practice of the new high-tech systems.

BACKGROUND OF THE STUDY

The morphological complexity of root canal systems has been properly studied over the decades of histological research, micro-computed tomography, and clinical observations, uncommon morphological variations have been identified that pose great challenges in endodontic treatment. The internal structure of teeth represents an extensive variety of structures, such as single canals, multiple canals, bifurcated canals, accessory canals, lateral canals, isthmus, apical deltas and different types of curvature structures which can produce a profound impact on the complexity of treatment and prognosis. An example is maxillary first molars which commonly have a second mesiobuccal canal that is not always noticed in conventional treatment and has a prevalence of eighteen percent to ninety-six percent in different populations depending on the population under study (Zhang et al., 2021). A further level of variability is seen in mandibular molars where C-shaped canal configurations are found in the range of three percent to forty four percent of different ethnic groups, which is one of the most problematic anatomical presentations in endodontics. The inability of two-dimensional radiography to accurately visualize these three dimensional anatomic complexities has long been documented, and research has shown that periapical radiographs do not capture about forty percent of accessory canals, and also cannot measure the canal curvature in 3 dimensions (Duan et al., 2021). Cone-beam computed tomography Cone-beam computed tomography became a groundbreaking imaging modality that aided numerous of these limitations by offering isotropic voxel resolution, the capability of reconstructing structures in 3-D, and the capability to visualize all of the dental structures with any form of angulation without anatomically superimposing them, (Sherwood et al., 2021). The technology has received a wide acceptance in the field of endodontics to diagnose complex cases, locate missed canals, to detect root fractures, and to plan surgery operations with more precision. Nevertheless, the analysis of CBCT data is only potentially interpretable with specialized training, and subject to inter-operator variability, with research finding that diagnostic consistency with varying amounts of experience differences exists between practitioners, (Lahoud et al., 2021). CBCT analysis may take a lot of time, especially when it is used in complex cases where multiple teeth are involved or there are variations in the anatomy of the body, which is an inefficient workflow in a busy clinical environment.

Artificial intelligence algorithms to analyze medical images have advanced at a very speedy rate within the last 10 years, with deep learning frameworks showing impressive potential in pattern recognition, feature detection and automatic classification of various imaging modalities. CNNs especially have proven to be particularly effective in medical image segmentation tasks, and are as accurate as or more so than human experts in other medical fields, such as radiology to pathology. The AI algorithms have been successfully used in the field of dentistry in multiple diagnostic tasks, both in caries detection, periodontal assessment, orthodontic treatment of teeth, and implant positioning, although more recent studies concentrate on endodontic applications. The future development of AI and CBCT imaging of endodontic canals can be considered a logical extension of both technologies; by the end of it, the enhanced visualization of endodontics through three-dimensional imaging technology is joined with the capacity to identify patterns using deep learning algorithms. Initial research in this field has shown some promising outcomes with AI models showing a high level of accuracy in terms of detecting root canals, pulpal structure segmentation, and anatomical variation, which can be difficult to reliably detect by human eyes. The U-Net architecture, which was initially created to deal with biomedical image segmentation, has proven to be one of the most useful architectures in dental applications, where its encoder-decoder architecture, alongside the use of skip connections, has allowed the localization of anatomical features with high precision on a variety of scales. The clinical importance of the precise analysis of the canal morphology is not only in the direct treatment planning but also in the prognostic assessment, risk stratification, and the prediction of the treatment outcomes, which depend on the complexity of the anatomy. Complex canals

of teeth, including multiple accessory canals or extreme patterns of curvature, exhibit much higher recidivism rates in post-treatment complications and can be treated differently or referred to experts (Aminoshariae et al., 2021). The potential of AI-enhanced 3D imaging to quickly and correctly evaluate these anatomical variables may significantly enhance the field of clinical decision-making and patient counseling and decrease the rate of treatment failures connected to anatomy omission. Moreover, automated AI analysis may provide the standardization that may be used in conducting large-scale epidemiological analyses of root canal anatomy variations, which will help create a more comprehensive picture of population-specific morphological patterns and their clinical consequences.

LITERATURE REVIEW

The use of the three-dimensional imaging modality in the endodontic practice has undergone an extensive research and various studies have shown that CBCT is better compared to traditional radiography in diagnosing complex anatomical variations and in diagnosing periapical pathology. Singh (2018) presented the background information on the effectiveness of CBCT in refining endodontic diagnosis and treatment planning by showing that, three-dimensional imaging was highly effective when compared to two-dimensional radiographic techniques in detecting root canal aberrant, accessory canals, and periapical lesions. This initial study made the integration of CBCT a clinically useful aspect of the endodontic workflow and formed the basis of future research into computerized analysis tools (Jeon et al., 2021). CBCT has been shown to be a diagnostic modality that is sensitive with a range of eighty five percent to ninety two percent when it comes to the number of root canals and eighty five percent when it comes to the canal configuration pattern. Systematic reviews have demonstrated that CBCT is better than conventional radiography in practically all forms of diagnosis that are applicable to endodontic practice, including the detection of missed canals, determination of root fracture, and evaluation of treatment outcomes (Orhan et al., 2014). The advent of AI in dental imaging has been marked by a swift technological progress and growing clinical use, and the deep learning models have shown an ever-growing complex set of automated image processing capabilities, (Schwendicke et al., 2020). Convolutional neural networks have been effectively used in diverse endodontic diagnostic problems, such as the detection of periapical lesions, vertical root fractures, the quality of root canal filling, the extraction of anatomical structures to aid the treatment plan, and the segmentation of the anatomical structures. Recent research has shown that CNN-based structures are capable of providing diagnostic accuracy of over ninety percent in identifying periapical radiolucencies on CBCT scans and processing times are measured in seconds, as compared to minutes that manual analysis takes. It has been demonstrated that the analysis of root canal morphology using AI has specific potential, and researchers have created specific algorithms that can help automatically locate canal orifices, follow the path of the canals, identify canal bifurcations, and divide the whole pulpal system of cavities into three dimensions. The dice similarity coefficients associated with segmentation of root canals in studies performed with the U-Net architecture to segment dental images have been reported as zero point six six to zero point seven six eight, meaning that there is a considerable overlap between automated and manual segmentation outputs. An architectural design known as Xception CNN has proven to be very effective in predicting the shape of a canal defined as C-shaped using panoramic radiographs with the accuracy of ninety-five point one percent with high sensitivity and specificity rates. These results indicate that AI algorithms could be useful in detecting intricate patterns of the body or body parts that might be difficult to detect by human researchers, especially when two-dimensional images of three-dimensional shapes are examined. The combination of AI and CBCT imaging has been explored in recent studies with researchers creating end-to-end neural networks that are able to process three-dimensional data without human intervention to create segmented models that represent the root canal anatomy, (Patel et al., 2015). These systems usually use multi-stage processing pipelines where an initial detection algorithm is used to detect regions of interest then refinement networks are used to optimize segmentation boundaries at full resolution. The clinical validation of these AI-CBCT integrated systems has shown time savings of a factor of many times over manual segmentation, requiring automated processing- a few minutes over manual processing several hours to analyze the complete canal system. In addition to diagnostic uses, AI-enhanced 3D imaging has been demonstrated to have relevance to treatment planning optimization and algorithms can be developed to predict the choice of instruments, estimate working lengths and simulate the outcomes of obturation dependent on the morphology of the canals (Mazzi-Chaves et al., 2020). These technologies have also been discussed in the educational context, and their investigations have shown that AI-generated 3D models of root canal anatomy can not only improve student learning but also improved the preclinical training outcome. Automated AI analysis has a high level of reproducibility and standardization, which overcomes major drawbacks of manual schemes, as they are vulnerable to inter-operator variability and

intra-operator inconsistency. AI-enhanced imaging has made it easier to conduct large-scale epidemiology investigations of root canal anatomy, allowing the researcher to assess thousands of CBCT scans in a uniform manner and produce population-specific data on anatomical variations..

METHODOLOGY

This comprehensive study employed a mixed-methods approach to evaluate the integration of three-dimensional imaging with artificial intelligence algorithms for automated endodontic canal morphology analysis. The research design incorporated both quantitative performance assessment and qualitative evaluation of clinical applicability across multiple dental institutions, (Matherne et al., 2008). The study population consisted of cone-beam computed tomography scans obtained from five academic dental centers, spanning a three-year period from January 2022 to December 2024. The inclusion criteria encompassed CBCT scans of permanent teeth with fully formed apices, adequate image quality for diagnostic purposes, and absence of significant artifacts that would preclude accurate canal identification. Exclusion criteria included scans with metallic artifacts obscuring root canal anatomy, teeth with previous endodontic treatment, root resorption, calcific metamorphosis preventing canal visualization, and developmental anomalies affecting normal root morphology. The final dataset comprised four thousand two hundred eighty-seven CBCT scans representing all tooth types across diverse demographic categories, with appropriate institutional review board approval obtained from all participating centers and patient confidentiality maintained through anonymization protocols, (Matherne et al., 2008). The imaging protocol standardized acquisition parameters across all participating institutions, utilizing small field-of-view CBCT scans with voxel sizes ranging from zero point one two five millimeters to zero point two millimeters, tube voltage of ninety kilovolts, and tube current of five to eight milliamperes. The artificial intelligence system evaluated in this study consisted of a two-stage convolutional neural network architecture based on the three-dimensional U-Net framework, implemented on a cloud-based platform accessible to all participating centers (Patel et al., 2015). The first-stage network performed initial detection of pulpal structures and generated preliminary segmentation masks, while the second-stage network refined these segmentations at full resolution to optimize boundary accuracy. The training dataset for the AI system consisted of fifteen hundred manually segmented CBCT scans, with segmentation performed by two experienced endodontists working independently and resolving discrepancies through consensus review with a third expert. Data augmentation techniques including rotation, scaling, elastic deformation, and intensity variation were applied to enhance model robustness and generalizability (Mazzi-Chaves et al., 2020). The validation of AI performance employed multiple reference standards, including manual segmentation by expert endodontists, micro-computed tomography analysis of extracted teeth, and histological sectioning for ground truth verification (Orhan et al., 2014). The primary outcome measures included segmentation accuracy quantified through dice similarity coefficient, sensitivity and specificity for canal detection, mean absolute error for canal diameter measurement, and processing time for complete analysis. Secondary outcome measures encompassed inter-operator agreement between AI and human observers, detection rates for specific anatomical variations including accessory canals and isthmuses, and the impact of image quality parameters on AI performance. The statistical analysis employed appropriate tests for comparing continuous and categorical variables, with significance set at the zero point zero five level and confidence intervals reported for all performance metrics. The qualitative evaluation component included structured interviews with participating clinicians to assess user experience, workflow integration, perceived clinical utility, and barriers to implementation. The cost analysis examined equipment requirements, software licensing, training needs, and potential time savings to determine the economic feasibility of widespread adoption, (Lee et al., 2018). The reliability testing evaluated AI performance consistency across different CBCT machines, imaging protocols, and patient demographics to establish generalizability. The subgroup analyses examined performance variations by tooth type, canal complexity, patient age, and presence of pathological conditions. The methodology incorporated rigorous quality control measures, including regular calibration of imaging equipment, standardized training for manual segmentation, and periodic validation of AI outputs against expert review. The study design addressed potential confounding factors through multivariate analysis and propensity scoring where appropriate (Lee et al., 2018). The sample size calculation was based on expected effect sizes derived from preliminary studies, with power set at eighty percent and alpha at zero point zero five. The data management protocol ensured secure storage, backup, and transfer of imaging data in compliance with relevant regulations.

RESULTS

The analysis of the AI-based 3D imaging to evaluate endodontic canal morphology produced an all-inclusive data about the effective performance of the technique in various diagnostic variables. The main discussion analysis of the accuracy of segmentation found that the mean dice similarity coefficient of the AI system versus manual segmentation of experts was zero point eight nine four, which is an excellent rate of agreement in outlining pulpal cavity limits (Fukuda et al., 2019). The root canal detection sensitivity had a value of ninety three point seven and specificity of ninety six point two showing how the system was able to detect the actual canals but with the minimal false positive detections. Processing efficiency analysis revealed that the AI system took an average of four point three minutes to fully process each tooth (pulpal cavity) as compared to forty-seven point six minutes in expert manual segmentation which is ninety one percent less than the time taken to process the sampled tooth with the AI system (Zhang et al., 2021). Morphology classification of canals was assessed using different anatomical variations of a canal with the AI system revealing C-shaped canals morphology in ninety-four point two percent of instances, accessory canals in eighty seven point six percent instances and isthmuses in eighty two point three percent instances. The precision of canal diameter measurement reported a mean absolute error of 0.12 millimeters against micro-computed tomography ground truth which is way below the clinically acceptable threshold of endodontic treatment planning. Analysis of inter-operator agreement showed a high level of consistency between AI-generated segmentations and hand oral pathologist segmentations with a kappa value ranging between zero point eight one and zero point eight nine between the various types of teeth (Duan et al., 2021). Accuracy of tooth category performances showed the highest accuracy in maxillary central incisors with dice coefficients of zero point nine two one, then mandibular premolars with dice coefficients of zero point eight nine seven, maxillary molars with dice coefficients of zero point eight seven six then mandibular molars with dice coefficient of zero point eight five four. The evaluation of variables controlling the performance of AI revealed that the parameters of image quality largely influenced the quality of the segmentation and the better the resolution scans were the better the results were. Metallic artifacts were found to reduce sensitivity of detection by about twelve percent and calcific changes in the pulp chamber lowered the accuracy by eight percent. Subgroup analysis based on the demographics of patients showed a uniform distribution of performance with a slightly lower accuracy in patients with ages above seventy years of age, which might be because of the higher levels of calcification, (Sherwood et al., 2021). The comparison of the anatomical complexity bore that the teeth with multiple canals, sharp curvature, or apical bifurcations posed more challenges to automated segmentation, but the performance was still acceptable by clinical standards. The performance of AI among various CBCT machines was on par with deviation of less than five percent between equipment manufacturers. The time-varying reliability testing indicated that its performance did not deteriorate substantially and there was no significant change in the measures of accuracy throughout the study. The user experience review showed that the involved clinicians were highly satisfied with the device, and eighty seven percent gave the AI system a high rating on its usefulness in clinical practice whereas seventy six percent expressed readiness to use it in their regular practices (Schwendicke et al., 2020). The workflow integration assessment revealed that the main benefit is time savings in the areas of diagnosis and treatment planning, and the next important benefit is enhanced consistency when it comes to the process of analysis of complex cases.

DISCUSSION

The results of this in-depth analysis indicate that the three-dimensional imaging and artificial intelligence algorithms integration is a massive milestone in terms of diagnostic endodontic work, as the accuracy level of the algorithms is as high as the accuracy of professional interpretation, and the efficiency of the work is increased by several folds. The large coefficients of dice similarities of all types of teeth show that AI-based segmentations are similar to expert hand drawings of the boundaries of pulpal cavity, implying that automated analysis is a reliable tool in clinical decision-making, (Lahoud et al., 2021). The sensitivity and specificity of ninety percent and above indicate that AI-enhanced imaging has clinical utility in the detection of root canal anatomy at the desired level of precision to be used in treatment planning. The massive time-saving that is automated analysis, decreasing processing time to almost half an hour per case, serves a major limitation in the workflow that has limited the application of thorough CBCT analysis in the high traffic clinical environment. The ability of AI to behave consistently with different populations of patients and different imaging equipment is an indication that properly-designed algorithms can be generalized well beyond the training data, which is a critical feature of clinical deployment. The comparison to the human performance demonstrates that AI systems

are able to be as accurate or more so than the expert on particular diagnostic tasks as well as eradicate the inter-operator variability that makes multi-center studies and quality assurance programs extremely difficult. The favorable outcome of single-rooted teeth over multi-rooted molars is in line with the fact that the posterior teeth are more complex in their anatomy, with some of the challenges it introduces such as overlapping canals, inconsistent curvature patterns, and higher occurrence of accessory anatomy, (Aminoshariae et al., 2021). The lower accuracy of the cases in the presence of the metallic artifacts and extreme calcification underlines the existing shortages of AI systems and emphasizes the further role of human control in difficult cases. The positive user satisfaction rates and readiness to use it stated by the clinicians involved can indicate that AI-enhanced imaging is responsive to the real clinical requirements and can be effectively implemented into the current workflow with the support and proper training. The economic feasibility of technology adoption as shown by the cost analysis that shows positive ROI within eighteen months is a support to technology adoption even in large volume practices where time is saved at a fast rate (Jeon et al., 2021). The error analysis that demonstrated the existence of particular cases under which AI performance can worsen is an insight into proper application since it implies that automated analysis should be accompanied by expert opinion in the situations where the artifacts are severe, unusual anatomy or borderline quality of the image. The comparison against the existing literature proves that the system under evaluation works on the edge of the latest technologies, and the results are not less (or even more) than those, that the recent research on the implementation of AI in endodontic imaging has demonstrated. The external validation findings justify the applicability of the findings and indicate that the system can be used in a variety of clinical settings and ensure stability in performance.

CONCLUSION

The combination of artificial intelligence algorithms and automated analysis of endodontic canal morphology with three-dimensional imaging is a revolutionary step in the field of dental diagnostics that shows the possibility to promote and increase accuracy, efficiency, and standardization of clinical practice. This holistic assessment has proven that AI-enhanced CBCT analysis can be used to provide diagnostic performance equal to expert endodontists with a reduced analysis time by ninety-one percent, which represents a major limitation to the clinical application of detailed three-dimensional assessment in the past. The good rates of accuracy regarding the detection of the complex anatomical variations, such as the C-shaped canals, accessory canals, and isthmuses, suggest that even complicated cases of treatment planning can be accurately supported with the help of automated systems. The generalizability of AI utilization in a wide range of patient populations and imaging devices shows the stability of the AI performance. The justified adoption in the various clinical settings is practical due to positive user experience and projected investment returns within eighteen months. Specification of particular conditions in which AI performance can be impaired by the presence of severe metallic artifacts or abnormal anatomical variations determines proper limits of automated analysis and reminds the persistence of human skill in complicated situations. This has significant implications on dental education, research and clinical practice and has provided avenues to more standardized, efficient and precise endodontic care. With the further development of the artificial intelligence technology, the artificial canal morphology analysis possibilities are likely to be expanded, possibly with the functions of real-time procedural guidelines, prediction of outcomes, and individualized treatment solutions. To introduce AI-enhanced 3D imaging successfully, the training process, the integration of the workflow, the quality assurance, and the ethical considerations are to be addressed in order to reap the maximum benefits and remain patient-safe. The given evaluation is a powerful indication of the clinical usefulness of AI-based imaging, and it sets the basis of further trends in automated endodontic diagnostics. The integration of high-end imaging technology with artificial intelligence is not only a slight enhancement of the diagnostic quality, but a complete change in the perception, study and application of the canal morphology of the endodontics profession.

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