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AI FOR ASSESSING CANAL TRANSPORTATION DURING INSTRUMENTATION

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ABSTRACT

Root canal instrumentation is aimed at cleaning and shaping canals, maintaining the original root's anatomy. Canal transportation is an alteration of the canal shape during preparation, leading to undesired deviation from the tooth's natural course. Such alterations can produce untoward results in root canal treatment as they can weaken the tooth structure and increase the chances of procedural errors. Conventional methods of assessing canal transportation involve the use of radiographs or micro-CT, time-consuming analyses, dependent on operator skills, and subjective in nature. Artificial intelligence (AI) techniques specifically of machine learning (ML) and deep learning (DL) are proposed to automate and improve diagnostic and evaluative procedures in endodontics. This study investigates the use of AI in canal transportation assessment during root canal instrumentation with a focus on providing accurate, objective, and reproducible measurements. By merging recent imaging technologies and AI algorithms, canal deviations can be detected and measured in a very efficient manner on the procedural level, enhancing procedural accuracy and patient outcomes. The study's findings offer support for AI-based assessment as a promising adjunctive technique for contemporary endodontic practice.

KEYWORDS: *Artificial Intelligence, Canal Transportation, Root Canal Instrumentation, Machine Learning, Deep Learning, Endodontics, Procedural Accuracy.*

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INTRODUCTION

A successful root canal treatment involves the meticulous cleaning and shaping of the canal, keeping its original anatomical shape intact. One commonly encountered difficulty during instrumentation is canal transportation, which occurs when the prepared canal is deviated from its original pathway. This deviation results in procedural complications such as ledging, zipping, or perforation, and could jeopardize the long-term success of endodontic therapy. Although radiographic or micro-CT methods may provide insight into canal transportation in the past, disadvantages have been observer bias, time consumption, and the large set of advanced equipment needed. More recently, artificial intelligence has come forward with solutions that could be used to improve canal transportation measurement. ML and DL algorithms deal with huge imaging data sets with infinite precision-aided along with automated detection and quantification of canal deviations. This approach reduces human subjectivity and increases objectivity; as such, clinicians come to make more informed decisions while doing instrumentation. The combination of AI can also provide real-time feedback to minimize canal deviation and thus bring about better outcomes. Hence, current research aims towards establishing reliable AI models that will detect canal transportation for different canal morphologies and various instrumentation techniques with precision. Endodontics, through the utilization of AI, is thus heading into a more standardized, and more objective way of viewing and improving root canal preparations.

IMPORTANCE OF MAINTAINING CANAL ANATOMY DURING ROOT CANAL INSTRUMENTATION

Long-term success in endodontic therapy is largely dependent on maintaining the anatomy of the root canal during instrumentation (Mohammad-Rahimi et al., 2023). If the curvature of the canal is kept natural during instrumentation, necrotic tissue and microbial contaminants inside the canal are removed satisfactorily during cleaning and shaping procedures, and on the other hand, structural damage to the tooth is curbed (Chavan, 2023). In case we lose the orientation and fail to follow the canal's natural course, procedural errors arise in forms such as ledges, zipping, or perforations that would adversely affect the seal of the obturation and thereby becoming a candidate for failure (Warin et al., 2023). Another advantage of respect to canal anatomy is a conservation of dentin thickness, which protects the tooth from fracturing against functional stress (Fukuda et al., 2023). Respect to natural morphology thus provides a viable compromise to allow for adequate disinfection while conserving maximum tooth structure, resulting in a more predictable treatment outcome that benefits patients and holds greater potential for long-term tooth survival (Hausdörfer et al., 2023).

WHAT CANAL TRANSPORTATION IS AND ITS CLINICAL IMPLICATIONS

Canal transportation is an objectionable deviation of the root canal departure from its original anatomical path during instrumentation (Sarwar & Jabin, 2023). The mechanical preparation proceeds more on one side of the canal than on the other, especially when the canals are curved or narrow (Pérez de Frutos et al., 2023). Such a change in canal morphology would be against the uniformity and taper of the prepared canal and would eventually interfere with the ability to get a proper seal during obturation. Canal transportation creates various procedural issues clinically-ledges, perforations, and apical zipping, which seriously threaten persistent infection and treatment failure (Wang et al., 2023). Excessive dentin removal shall furtherly weaken the tooth structure that gives rise to vertical fractures (Mohammad-Rahimi et al., 2023). The existence of canal displacements, whether sometimes require retreatment otherwise may even require tooth extraction, makes the entire terrain of instrumentation techniques and instruments that do not greatly undermine the original anatomy of the canal (Chavan, 2023).

SIGNIFICANCE OF ARTIFICIAL INTELLIGENCE FOR MODERN ENDODONTICS

AI dawns as a transformation tool in modern endodontics with abilities that would yield more precision, a better degree of efficiency, and finally the preservation of power in outcome prognostication and treatment planning (Mohammad-Rahimi et al., 2023). Among other things, AI uses several machine learning (ML) and deep learning (DL) algorithms to scrutinize differential sets of imaging data pertaining to radiographs, CBCT, and micro-CT scans with a high degree of accuracy and reproducibility (Hausdörfer et al., 2023). Clinically, an AI system can be utilized for the detection of periapical lesions; mapping out root canal morphology; forecasting outcome processes; and identifying distortions such as canal transportation (Sarwar & Jabin, 2023). These can be measured with results that offer both objectivity and reproducibility, thereby reducing bias stemming from operator variability while enhancing the possibility of standardization in endodontics (Pérez de Frutos et al., 2023). It is possible that AI shall also be integrated with endodontic instruments and imaging systems to offer real-time feedback during canal preparation, thereby warning and guiding the clinicians to minimize aberrations and risks (Wang et al., 2023). In essence, the transformation of AI is now the landmark of endodontics-to-Modern Dentistry-from diagnosis through procedural safety and quality of care (Mohammad-Rahimi et al., 2023).

SHORTCOMINGS OF CONVENTIONAL ASSESSMENT TECHNIQUES (RADIOGRAPHS, MICRO-CT)

Due to their inability to provide that crucial contrast in the endodontic evaluation of canal anatomy and instrumentation outcomes, periapical radiographs, especially so, may destroy corrections in terms of accuracy and clinical utilities (Chavan, 2023). Superimposition of anatomical structures prevents these two-dimensional radiographs from showing sufficient evidence to detect slight deviations like canal transportation or minor ledges in curved or complex canals (Warin et al., 2023). These assessments are heavily operator-dependent, subject to subjective interpretations, and most of the time, not able to address the three-dimensional subtleties of root canal systems (Fukuda et al., 2023). Micro-CT, on the other hand, is excellent for high-resolution three-dimensional imaging and quantitative analysis; however, the use of it in routine clinical cases has been hampered due to reasons of cost, long duration of scans, and incidence of accidental radiations (Hausdörfer et al., 2023). These also include gaining expertise in image acquisition and interpretation, resulting in an inability of reproducibility (Sarwar & Jabin, 2023). Such reduction in the capability of these assessment methods paints a far-reaching picture calling for an emerging automated technique like AI promising an objective, repeatable, and efficient evaluation of canal morphology and instrumentation outcomes (Pérez de Frutos et al., 2023).

OVERVIEW OF DIFFERENT ROOT CANAL INSTRUMENTATION TECHNIQUES

Root-canal instrumentation is a key step in endodontic treatment that involves cleaning and shaping the canals with emphasis on maintaining the canal's natural anatomy into certain finalities (Wang et al., 2023). It basically dissimulates canal inappropriate pulp tissues, microorganisms, debris, and biofilms while shaping the canal for irrigation and obturation (Mohammad-Rahimi et al., 2023). Instrumentation methods can be broadly categorized as manual, rotary, or reciprocating (Chavan, 2023). Manual instrumentation, such as the use of stainless-steel hand files, relies mostly on the operator's feel and control in negotiating and shaping the canal; hence, it requires considerable skill on the part of the operator (Hausdörfer et al., 2023). Rotary instrumentation employs rotary motors for Ni-Ti files application and provides great flexibility, efficiency, and consistency, especially in curved canals (Sarwar & Jabin, 2023).

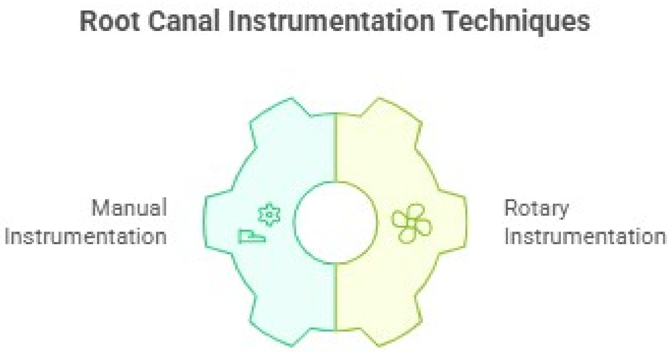

Figure 1

CAUSES AND RISK FACTORS OF CANAL TRANSPORTATION

Canal transportation occurs when the prepared root canal strays away from its true anatomical path (Mohammad-Rahimi et al., 2023). There are procedural and anatomical factors behind its causation. The first and main anatomical factor on canal deviation is that deviation tends to occur in all curved canals during instrumentation, which may be explained by the tendency of instruments to straighten within a curved or S-type canal and so remove dentin more from the outer wall of the curve, leading to canal deviation (Chavan, 2023). Such deviation is further increased with the rigidity and design of endodontic instruments, mainly stainless-steel files, while flexible nickel-titanium (NiTi) files would lessen but never completely nullify the risk (Warin et al., 2023). Operator-dependent factors include excessive apical pressure, inappropriate angulation of instrumentation, and lack of experience (Fukuda et al., 2023). Other factors contributing to risk would include diameter and length of the canal, with narrow or long canals exerting higher temptation toward transportation and frequent use of instruments predisposing these to fatigue and bending (Hausdörfer et al., 2023). Poor lubrication and irrigation add more friction and resistance in canal deviation (Sarwar & Jabin, 2023). Awareness of the causes and risk factors would always choose espousal toward the correct instrumentation technique to minimize procedural errors, retain intact anatomy of the original tooth, and in turn maximize treatment outcomes (Pérez de Frutos et al., 2023).

CONVENTIONAL METHODS FOR MEASURING CANAL DEVIATIONS

Measurement of canal deviation, including transportation, has been classically analyzed by imaging and measurement methods that could reflect the changes taking place in canal morphology after instrumentation (Wang et al., 2023). Two-dimensional radiographs remain commonly taken in contemporary clinics because they are most accessible and cheapest (Mohammad-Rahimi et al., 2023). These techniques can illustrate the general canal track and occasionally gross deviations, but overlapping and lacking depth limit their accuracy, making their use for detecting subtle canal transportation questionable (Chavan, 2023). Micro-CT is exceptional in its very high resolution and gives three-dimensional images and is considered the reference procedure for detailed analysis of root canal anatomy (Warin et al., 2023). Given the objective measurement of canal curvature, volume changes, and dentin removal, micro-CT can accurately quantify transportation (Fukuda et al., 2023). However, because of its exorbitant price, long scanning time, and radiation exposure, this technique is rarely put to clinical use and is mainly restricted to in vitro investigations (Hausdörfer et al., 2023). The major differences in measurements are finalized by digitally analyzing the pre- and post-instrumentation photographs with software programs designed to calculate the deviation and transportation of canals (Sarwar & Jabin, 2023). These protocols improve the objectivity and reproducibility of measurements but are still dependent on image quality and manual landmarking, which can introduce another source of variability (Pérez de Frutos et al., 2023). In a nutshell, traditional methods provide some info but have limitations, mainly subjectivity and time-consumption, and rarely can transpose accurate measurements into immediate clinical aids that will give mediocrity to AI-assisted assessment (Wang et al., 2023).

LIMITATIONS OF MANUAL AND OPERATOR-DEPENDENT ASSESSMENT

The great limitation of manual evaluation of root canal instrumentation and operator dependency, including tactile sensations when using hand files or graphical interpretation of radiographs, lies within the standardization of treatment and thus the degree of accuracy (Mohammad-Rahimi et al., 2023). The evaluation is dependent entirely on the experience, skill, and subjective judgment of the person doing the assessing, thereby introducing a variance between different operators, and sometimes even repeated evaluation done by the same evaluator presents variability (Chavan, 2023). Any slight deviation in the canal morphology, like minor transportation or micro-perforations, may escape detection because of limited tactile sensitivity or simply the two-dimensional limitations of imaging (Warin et al., 2023). Manual evaluation can be time-consuming and might suffer from fatigue, distraction, and cognitive biases, which cast doubt onto its reliability and dependability (Fukuda et al., 2023). Absence of objective and reproducible standards renders these manual procedures impossible to standardize or reliably compare results across cases (Hausdörfer et al., 2023). In view of the presence of all these limitations, it becomes vital to have automated and AI-assisted evaluation methods that will grant consistent, accurate, measurable analyses of canal anatomy and instrumented quality (Sarwar & Jabin, 2023).

INTRODUCTION TO AI, ML, AND DL

AI simulates human intelligence into machines that can learn, reason, solve problems, and make decisions (Pérez de Frutos et al., 2023). The field of Machine Learning (ML) is an AI subfield where systems learn patterns from data and gain knowledge and improve their performance in time, without being explicitly programmed to do so (Wang et al., 2023). ML algorithms work on huge datasets of information to identify relationships, make predictions, or classify information based upon what they detect, thereby hugely facilitating complex-pattern recognition in medical and dental applications (Mohammad-Rahimi et al., 2023). Deep Learning (DL) is a more advanced subfield of ML using multilayered artificial neural networks to model highly complex patterns and hierarchical representations within the data (Chavan, 2023). DL is good for high-dimension data, such as images, and can perform automated feature extraction, segmentation, and classification with little human intervention (Warin et al., 2023). In endodontics, DL algorithms—especially CNN—are utilized for analyzing radiographs, CBCT, and micro-CT scans to detect root canal morphology, procedural errors, or canal transportation with very high accuracy (Fukuda et al., 2023). AI, ML, and DL, therefore, provide a mean to build automated, objective, and reproducible tools that assist clinical decision-making to reduce human error and increase the quality of dental care (Hausdörfer et al., 2023).

AI CHALLENGES IN DENTISTRY AND ENDODONTICS

AI has entered the arena of dentistry for enhancing diagnosis, treatment, and procedural accuracy (Sarwar & Jabin, 2023). The algorithms generally identify dental caries, periodontal bone loss, and oral lesions on X-rays more rapidly and accurately compared to traditional methods (Pérez de Frutos et al., 2023). Automating image segmentation and analysis in order to perform treatment planning in orthodontics, prothodontics, and implantology is yet another AI advantage (Wang et al., 2023).

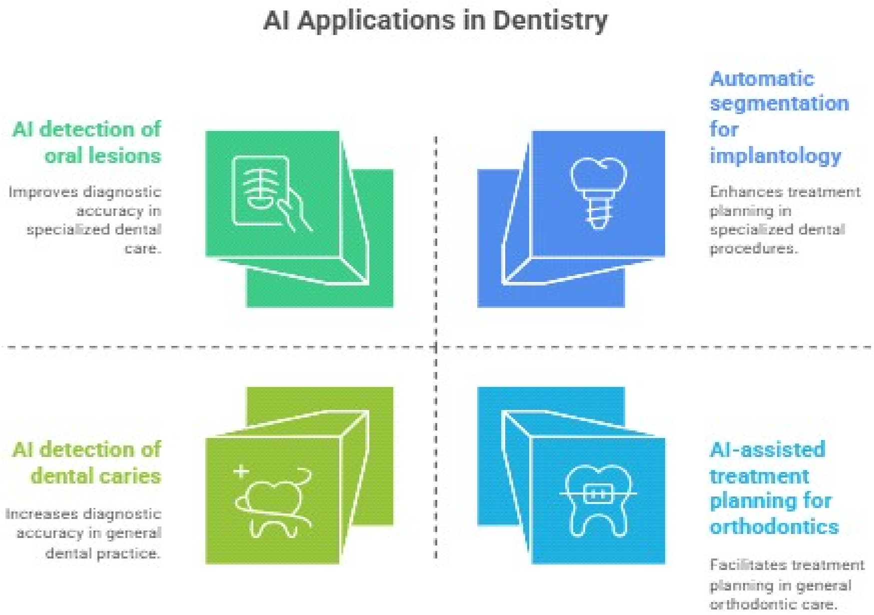

Figure 2

INTRODUCTION TO AI, MACHINE LEARNING, AND DEEP LEARNING

Artificial intelligence is defined as a branch of computer science which tries to impart to machines the ability to execute certain tasks such as problem-solving, pattern recognition, and decision-making, which generally require the intervention of human intelligence. Within AI, the term machine learning defines systems that acquire knowledge from data, discover various patterns, and make predictions or classifications concerning unseen data without being explicitly programmed for every particular task. In fact, an ML algorithm with more running time and exposure to additional examples eventually improves its own performance, thus holding much potential when it comes to exploring complex sets. DL, one subset of ML, uses artificial neural networks with numerous layers to define the very complex association within large and highly dimensional datasets. It has powerful application in the analysis of images and signals since it extracts features automatically without the need for human intervention. In dental practice, more in endodontics, DL-based systems such as convolutional neural networks (CNNs) have been increasingly applied for analysis of radiographs, CBCT, and micro-CT images. These models are capable of detecting root canal morphology, signaling procedural errors, and quantifying canal transportation with very high accuracy. In short, AI, ML, and DL provide a technical back-end that allows for evaluation of dental procedures and dental imaging in a more objective, reproducible, and efficient way, thereby enhancing clinical decision-making and patient treatment.

DISCUSSION

Being able to maintain the anatomy of a root canal during instrumentation is probably the most important factor for a successful endodontic therapy. Canal transportation, being the deviation of the canal from its natural path, dates back in compromising disinfection and quality of obturation and in the long-term viability of tooth. Assessing canal transportation through traditional methods, measuring from two-dimensional radiographs, micro-computed tomography (micro-CT), to software measurements, be appreciated by their respective working principles, but also suffer somewhat from subjectivity, operator dependency, and practical limitations. Radiographs, although easy to obtain, lack 3D correctness; hence, subtle deviations sometimes cannot be pictured. Micro-CT, despite being accurate, is more an in vitro-based measurement due to cost constraint, radiation exposure, and time limit, while its manual evaluation continues to be contentious due to operator-dependent variabilities. This scarcity could be answered with objective, reproducible, and efficient methods of assessment. Artificial intelligence (AI), specifically through machine learning (ML) and deep learning techniques, has gained prominence as a possible fix for such problems. AI algorithms, such as CNNs, identify canal morphology and quantify deviations with high precision by analyzing high-dimensional imaging datasets from CBCT, micro-CT, and digital radiographs. Because it limits subjective interpretation, a standardized protocol provided by AI for canal transportation evaluation enhances reproducibility and reduces variability between operators or even with the same operator under different conditions. AI application in endodontics promoting the detection of procedural errors and prognosis of treatment were reported in several studies in recent years. In the context of canal transportation, AI can measure the amount and direction of deviation with high accuracy, providing quantifiable evidence to facilitate clinical decision-making. This is particularly important in complicated cases with curved or narrow canals that are prone to underestimating the degree of deviation with conventional methods. Additionally, it has also been proposed that AI could be integrated into real-time guidance systems that provide dynamic feedback to clinicians during instrumentation, assisting them in maintaining natural canal pathways and reducing potential iatrogenic errors. The clinical implications of AI-assisted canal transportation assessment are tremendous. They can improve detection and quantification of deviations, which can help further the planning of treatments and the choice of instrumentation, therefore assisting in successful treatment outcomes of endodontic therapy. In preserving tooth tissue and reducing procedural complications, the AI-driven evaluation strives toward a conservative and accurate approach to endodontic practice. There are still walls between the two sides. The greater the number of training images and their quality, the better the AI learns to assess the canal transportation; hence, changes in acquisition protocols or in morphology may affect the performance of AI models. Operational integration of AI will require easy-to-use software awaiting validation in appropriate clinical scenarios. There is also the ethical dimension, related to data privacy and involving professionals in the use of such tools, which must be taken into consideration for the development of AI in a safe and responsible way.

CONCLUSION

Where AI has also shown promise is in the assessment of canal transportation following the root canal instrumentation procedure, much of which typical evaluation methods have failed to put. ML and DL methods allow AI to give an objective arthroscopic reference to deviations, accuracies to a degree incomparable in other methods, and reproducibility not confounded by operators' subjectivity. AI not only helps in accurate assessment of canal transportation with real-time evaluation of canal instrumentation but can also provide guidance to endodontists for maintaining the natural canal anatomy with minimal errors during instrumentation. From the standpoint of AI application, from the evolution of AI systems in endodontics toward the enhancement of procedural accuracy and optimization of treatment outcomes for long-term tooth survival is a worthwhile experience despite challenges faced related to data quality, validation of the model, and clinical integration.

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