

MACHINE LEARNING MODELS FOR ROOT CANAL LENGTH DETERMINATION

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ABSTRACT

The exact determination of working length in root canal treatment forms a critical aspect of endodontic treatment, as lapses in working length estimation can leave the root canals inadequately cleaned, shaped, and obturated. Traditional methods of working length determination have been used and still remain in use. These methods by their inherent nature are limited by anatomical variations, and operator dependency and, in the case of radiographs, are prone to imaging inaccuracy. AI and ML techniques have, recently, brought data-driven models to ensure a greater degree of precision in measuring root canal lengths. The models employ CNNs, deep learning algorithms, and image processing techniques to analyze periapical radiographs and CBCT scans to offer measurements that are automated and reproducible. This review elucidates the ML-based techniques currently employed in endodontics with a focus on their application in determining root canal length, how they compare with traditional methods in terms of performance, and the possibility of integrating these into clinical workflows. It also highlights the trends emerging in the field, the challenges pertaining to model generalization, and future directions concerning AI-assisted endodontic diagnosis and treatment planning.

KEYWORDS: *Machine Learning; Root Canal Length; Endodontics; Artificial Intelligence; Cone-Beam Computed Tomography; Deep Learning; Apex Locators; Dental Imaging.*

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INTRODUCTION

The precise determination of the length of root canal is crucial in achieving a predictable result in endodontics. An accurate working length at which an instrument is to be maintained for cleaning and obturating purposes will ensure the complete debridement of the root canal system, hence reducing the chances of periapical pathology and treatment failure. Over the years, clinicians have used techniques such as peri-apical radiographs, tactile sensation, and electronic apex locators to determine the actual length of a canal. Although such methods have been recognized for their utility, their accuracy may be affected by anatomical variations, superimposed structures, distorted images, and operator experience. Machine learning, a branch of artificial intelligence, has turned to be an instigating force in improving dental diagnostics. By utilizing huge amounts of data and computational models, it enabled automated feature extraction and prediction, thereby minimising subjectivity in diagnostic decisions. In endodontics, machine learning-based image analyses provide improved accuracy in canal morphology identification, apical constriction detection, and canal length prediction. Models such as convolutional neural networks and ensemble models were shown to offer promising results in analyses of 2D radiographs and 3D CBCT datasets, allowing accurate and reproducible measurements. This paper assesses machine-learning models for the determination of root-canal length in terms of their principles, advantages, and limitations. The integration of these

technologies into clinical practice will be discussed, with a particular focus on the ability of these approaches to act as an adjunct to traditional methods. The paper further considers future avenues for investigation, including optimization of algorithms, standardization of datasets, and the role of artificial intelligence in complimentary personalized treatment planning.

DEFINITION AND FUNDAMENTALS OF MACHINE LEARNING

Technologies developed for the distinction between ML and artificial intelligence. Machine learning (ML) is one of the methods of building algorithms that enable a computer to detect patterns and predict or decide on its own, without having been programmed explicitly for it. Fundamentally, the ML models are made to increase their performance as they are exposed to more data, by using some form of statistical methods to find patterns and relationships too complex to describe via conventional programming (Jordan & Mitchell, 2022). In fact, under the hood, ML consists of three major learning paradigms: supervised learning, unsupervised learning, and reinforcement learning. Under supervised learning, the model trains using labeled data, making it suitable for prediction tasks, such as classifying dental radiographs or predicting root canal lengths. Unsupervised learning processes unlabeled data, solving clustering and pattern identification in complex medical data. Reinforcement learning, on the other hand, uses trial-and-error methods to optimize decision-making, applying it to dynamic treatment planning (Zhang et al., 2022). The establishment of an ML model revolves majorly around getting feature extraction from training, validating, and testing. Deep learning, which is ML based on artificial neural networks, has become highly popular due to its performance in handling large datasets and automatic feature extraction; such an approach is suitable for the analysis of dental imaging such as cone-beam computed tomography (CBCT) scans. The use of ML in healthcare, including in the domain of endodontics, can enhance diagnostic ability, reduce human error, and optimize clinical workflows (Li et al., 2022).

LIMITATIONS OF TRADITIONAL APPROACHES

Traditional methods like tactile sensation, radiographics, and apex locators have traditionally paved the way for endodontic treatment. All these, however, have certain limitations that might come in the way of precision and clinical safety considerations. Radiographs are known to depict a mere two-dimensional image of an extremely complicated root canal anatomy, and in that sense, they can be said to be sources of distortion, error in magnification, and at times even misidentification of anatomical variations-such as the accessory canals and curvatures (Ahmed et al., 2022). This disadvantage of lacking a view in depth becomes a calamity when one has to take exact measurements of canals, especially in multi-rooted teeth or in particular cases of complicated root canal morphology. EALs do overcome the limitations of radiographs to some extent but nevertheless carry further drawbacks, too. Interference caused due to the presence of moisture, metal restoration, and open apices along the course of the measurement can affect the accuracy of EALs, thus yielding an inconsistent measurement in certain clinical conditions (Singh & Sharma, 2022). Though they are helpful tools, nothing is very straightforward, and both require multiple steps and also expert hands, which consume precious chair time and may even permit operator-dependent errors. Another limitation that shadows all these methods is their inability to handle huge volumes of diagnostic information. The reliance on subjective interpretation is quite evident in traditional methods, which differs from individual clinicians to clinicians, thus decreasing chances for reproducibility and diagnostic consistency (Kumar et al., 2022). As endodontics is going toward a more data-driven era, these limitations are indeed the impetus for developing newer-age technologies such as machine learning so that root canal length determination can be done terminologically in an objective, accurate, and quick manner.

GROWING NEED FOR ADVANCED DIAGNOSTIC SUPPORT

Endodontic diagnosis and treatment planning relies much on determining precisely the root canal length, on observing complex anatomy, and on spotting periapical pathology. Traditional methods of diagnosis have usually involved such tools as periapical radiographs and the sense of touch of the clinician, but these tools have their limitations mainly because of their two-dimensional visualization, distortion, or operator dependency (Ahmed et al., 2022). Such cases often do not present easy measurement opportunities, especially in teeth with multiple roots, extreme curvatures, or unusual canal morphology. With advancements in dentistry, CBCT has improved diagnostic accuracy through the visualization of the anatomy in three dimensions. The presence of a huge amount of data generated by CBCT or other imaging modalities poses increased issues in data interpretation and further increases clinician workload (Patel et al., 2022). With the evolution of dental imaging, it becomes imperative to develop computational tools that handle big data, reduce diagnostic errors, and provide useful clinical information. ML fills this gap in the best way possible. In endodontics, ML algorithms mainly aid in pattern recognition, automated feature-extraction, and predictive analytics by elucidating complex anatomical details and standardizing canal length measurement (Li et al., 2022). Thus, by implementing ML into an endodontic setting, clinicians can improve diagnostic precision and decrease variability, leading to better patient care.

EVOLUTION OF METHODS: TACTILE SENSATION, RADIOGRAPHS, AND APEX LOCATORS

The determination of the root canal length has surely changed and developed through the years, influenced by changes in dental technology and diagnostic science. In the beginning, the clinician relied almost completely on tactile sensation, a process that depended on the experience and perception of the practitioner while moving instruments through the canal until resistance was felt at the apical constriction. Resisting inside the canal gave resistance to the instrument at this point. This included an element of subjectivity, as two practitioners may have disagreed over the subjective perception of the apical stop, did not lend itself to standardization, and hence was prone to error, particularly in cases of curved or calcified canals (Ahmed et al., 2022). After the introduction of the radiographic method, the practice of endodontics made significant strides forward. Periapical radiographs thus came to be seen as reliable instruments for assessing canal length in a relatively objective and standardized manner. But the primary limitation lies in the fact that one has to deal with two-dimensional images, thus there occur distortions and sometimes magnification of the image, and also the radiographs cannot make a complete visualization of the complex anatomical structures (Kumar et al., 2022). These limitations often resulted in inaccurate working length estimation, thereby predisposing both over- and under-instrumentation. The creation of the Electronic Apex Locator (EAL) came as a landmark in the evolution of endodontic diagnostics. Taking advantage of the physical phenomenon of electrical resistance or impedance between two electrodes, EALs can determine, with greater certainty, canal length according to the position of the apical foramen. Because of this, reliance on radiography was reduced, and accurate measurements became possible even in complicated anatomies. The only drawbacks to EALs are instances when canal conditions like moisture, open apices, and metallic restorations tend to alter the readings (Singh & Sharma, 2022). The evolution lateral towards endodontic apex locators and radiography indicate the efforts smoothed down to achieve full accuracy and reliability. However, traditional methods also still carry inherent limitations. This calls for much more advanced diagnostic technologies, such as machine learning and artificial intelligence, which promise much better accuracy and reproducibility when it comes to endodontic treatment planning.

Table 1: Comparison of Traditional vs. Advanced Diagnostic Support in Endodontics

Criteria	Traditional Methods (Radiographs, Apex Locators)	Advanced Diagnostic Support (CBCT + Machine Learning)
Dimensionality	2D visualization, prone to distortion	3D visualization with volumetric data processing
Accuracy in Complex Anatomy	Limited in multi-rooted teeth and curved canals	High precision through automated pattern recognition
Operator Dependency	High; results vary with clinician experience	Reduced dependency; standardized outputs
Data Interpretation	Manual, time-consuming	Automated, data-driven, faster analysis
Reproducibility	Variable	Consistently high with ML algorithms
Integration into Workflow	Limited	Seamless integration with digital systems
Potential for Continuous Learning	No capability	ML models continuously improve with new datasets

EVOLUTION OF METHODS: TACTILE SENSATION, RADIOGRAPHS, AND APEX LOCATORS

The elements of evolution in the determination of root canal length over the years obviously denote advancement in dental technology and diagnostic science. In the period before the era of radiographs, practitioners relied mostly on tactile sensation—an approach based on the clinician's experience and perception as he was negotiating the instruments through the canal until a sensation of resistance was felt from the apical constriction. This method was, however, subjective and inconsistent and highly susceptible to error, especially in cases of curved or calcified canals (Ahmed et al., 2022). With the introduction of radiographic techniques, methods of endodontics were further improved. Periapical radiographs were used as a primary means of making an approximate measurement of canal length and thereby offer a more objective and standardized approach to working length determination. On the other hand, radiographs being two-dimensional had their own limitations, which include image distortion, image magnification, and inability to properly visualize the various complex anatomical structures (Kumar et al., 2022). Though these are limiting factors resulting mostly in improper working length determination, they also predispose to over-or under-instrumentation. Endodontic diagnoses made a huge leap forward with the development of electronic apex locators (EALs). EALs determine the location of the apical foramen using electrical resistance or impedance and measure the canal length with much reach. A relatively more controlled set of methodologies with the development of electrical machinery gave them freedom from dependency on radiographs. This type, in fact, became helpful in cases of anatomical complexities. Though, the working of apex locators is affected by conditions inside the canal, as moisture, an open apex, or presence of metallic restorations may impair the readings (Singh & Sharma, 2022). The movement from the method of tactile to radiographic and apex locators marks a pathway to better accuracy and reliability. Still, the limitations of these traditional techniques call for ever-evolving sophisticated diagnostic technologies such as machine learning and artificial intelligence, which would be much more precise and reproducible in endodontic treatment planning.

USE OF MACHINE LEARNING IN RADIOGRAPHIC INTERPRETATION

ML started off as a really revolutionary tool in dental radiographic interpretation, promising higher accuracy, reproducibility, and efficiency than the conventional diagnostic approaches. Traditional methods of diagnostic interpretation rely much on the expertise of the clinician and are subject to human error, inter-observer variability, and fatigue effects. Majorly, ML algorithms (especially with CNN architecture) work in the large volume of image data by

automatically detecting general and focused anatomical variations invisible to the human eye (Chen et al., 2022). Possibly, the most famous application of ML is the automated detection of lesions in dental imaging. ML models are said to rival experienced clinicians' diagnostic judgement when it comes to detecting periapical lesions, dental caries, and periodontal bone loss (Lee et al., 2022). By learning from thousands of annotated radiographic images, these systems identify key features to make subsequent predictions with increased accuracy. Another advancement involves challenges in landmark identification and measurements automation. ML systems allow determination of anatomical landmarks such as apical foramen, canal curvature, and bone density, all used as parameters for treatment planning and for reducing some of the time spent on manual measurements by clinicians (Patel et al., 2022). ML also informs clinical decisions via predictive modeling. Algorithms evaluate treatment outcomes, recognize high-risk patients, and provide evidence-based recommendations. Such ability not only makes diagnostics faster but also improves workflow efficiency in busy dental offices (Zhou et al., 2022). Integration of ML into dental radiology is still encumbered despite its clear possibilities. These include its need for large and diverse data sets to help the generalization of the model, a concern over its interpretability, and the view that ML raises issues of ethics regarding patient privacy and algorithmic bias. On the other hand, ML truly represents a major step towards standardized dental diagnostics guided by data.

DATASETS USED FOR TRAINING AND VALIDATION

The whole system of machine learning models in the endodontics and dental radiology settings is dependent on really big and good datasets so that they can really perform a reliable diagnosis. Usually, the dataset consists of periapical radiographs, panoramic images, and CBCT scans being annotated by expert clinicians to have an accurate labeling of anatomical structures and findings in pathology (Liu et al., 2022). The availability of sedimented datasets is essential as these visual representations are what ML algorithms learn from to recognize and classify patterns and eventually make a prediction. To increase the generalizability of a model, it is common for datasets to contain images from a combination of devices, patient demographics, and imaging protocols. For example, Dental Image Library and Radiopaedia, serve as public repositories containing diverse imaging data that enable the training of robust models (Kim et al., 2022). In addition, some works produce synthetic datasets via augmentation techniques such as image rotation, scaling, and contrast adjustment to enhance the diversity of the training data to better prevent overfitting (Zhang et al., 2022). A validation dataset is an independent subset that is set apart from the training data to evaluate the performance of a model. It safeguards the ML algorithms from memorizing training images; instead, it attests to the ML algorithm's diagnostic accuracy with previously unseen cases. In practice, there is often application of a cross-validation procedure, wherein a dataset is divided into several subsets and then iteratively trained and tested (Huang et al., 2022). Nonetheless, the problem of dataset quality still is a forefront concern in dental ML research. A series of datasets is relatively small compared to those in general medical imaging, and there exists a need for annotation protocols to be standardized so that consistency among experts is assured. Hence, collaboration in dental institutions and imaging centers will foster the construction of large, standardized, and publicly available datasets that will basically increase ML accuracy and reliability in root canal length determination and other diagnostic functions.

COMPARISON WITH RADIOGRAPHY AND APEX LOCATORS

For many years, endodontic practice has traditionally considered periapical radiography and electronic apex locators (EALs) as methods to determine root canal length. Periapical radiographs are used in many countries because of their easy accessibility and cost-effectiveness, but they provide a mere two-dimensional image of a three-dimensional structure. Such

limitations often contribute to errors occurring due to distortion, angulations of the image, or overlapping anatomical structures rendering it almost impossible to precisely gauge the position of the apical constriction. The use of electronic apex locators does bring further accuracy and have become a valuable adjunct to endodontic treatment. The disadvantage comes with their working principles being affected by irrigants and the presence of metallic restorations, or pathological cases such as root resorption and apices open, causing inaccuracies in their readings. ML-based techniques with CBCT have been heralded as a breakthrough because they provide three-dimensional visualization and automated measurement, limiting operator involvement. These systems analyze large amounts of information with very advanced algorithms that enable accurate and repeatable identification of anatomical landmarks. Therefore, this evolution represents a major stride in overcoming the drawbacks of conventional techniques and gives clinicians more consistent and reliable tools for root canal length determination.

DISCUSSION

Accurate determination of root canal length is an important step for any endodontic practice as it provides effective cleaning, shaping, and obturation, along with the avoidance of procedural errors such as over- or under-instrumentation. Despite being put to use for more than 100 years, traditional methods of determining apex length using tactile sensation, periapical radiographs, or electronic apex locators somehow have constraints owing to the experience of the operator, anatomical variations, and external conditions like radiographic distortions or calcification in canals. These constraints have precipitated the search for a superior diagnostic technique. From the ML model point of view, it is clearly a disruptive technology for determining root canal length, utilizing large and well-annotated datasets to train an algorithm, which can in a fully automated manner detect the apical landmarks with high precision. Unlike traditional systems, ML-based systems can reduce subjectivity, reduce chair time, and provide highly reproducible results even when confronted with very complex anatomical cases. Combining ML techniques with cone-beam computed tomography (CBCT) will increase accuracy further, allowing three-dimensional visualization of root canal anatomy. This is particularly beneficial in cases involving curved canals, accessory canals, and resorption defects. Recent studies also demonstrate that ML can supersede traditional methods in both consistency and adaptability, while the models also have the benefits of improvement over time as more data is fed into the system, making it an ever-evolving diagnostic tool. Though promising, a number of other practical challenges, such as availability of a sufficiently large high-quality dataset, training of the medical personnel, and costs of advanced imaging/AI implementation, have to be addressed before these methods can be used widely. This progression toward AI-based solutions in dentistry and medicine of course reflects the larger trend of digital solutions serving as adjuncts to clinical expertise. The long-term aim, then, is in fact not to provide another stand-alone diagnostic technique but to develop a fusion data-driven system, which will assist with decisions in clinics, enhance treatment outcomes, and decrease the likelihood of complications.

CONCLUSION

Over the decades, the determination of root canal instrumentation length has gone through changes, going from perception of resistance and conventional radiographic measures to electronic methods of root design measurement. Despite the continued usefulness of these techniques in clinical practice, they have certain limitations due mostly to subjectivities, operator dependence, and anatomical variations. Machine learning methods could be good at improving diagnostic accuracy, reducing human error, and aiding clinical decision-making by learning from large datasets of radiographs and CBCT images. However, issues such as the variation in datasets, opacity in algorithmic design, and the expanding need for

strong clinical validation still remain. In the future, with technological advancements, the incorporation of machine learning methods within the environment of endodontics could change the planning behind root canal therapy, thus providing clinicians with a more exact, consistent, and standardized approach for working length determination.

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