AI-Powered Classification of Root Canal Irrigation Efficiency Based on Image Analysis

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Abstract

Root canal irrigation plays a vital role in the endodontic treatment success, since it guarantees the elimination of debris, microorganisms, and biofilm of the complex root canal system. Conventional irrigation efficiency assessment techniques tend to be subjective, laborious and low reproducibility. In this research, the authors explain how artificial intelligence (AI) and image analysis can be used to categorize the efficacy of root canal irrigation. Images of treated canals of high resolution were obtained and preprocessed to extract features. A convolutional neural network (CNN)-based model was trained to read morphological patterns and categorize the results of the irrigation as efficient or inefficient. The accuracy of the AI model during the classification process was rather high in the comparison with expert ratings, which indicates the possibility of objective and automated assessment. The results indicate that AI-based image recognition can be an effective supplement to an endodontic study and clinical practice and provide a stable and quick assessment of irrigation procedures. Additional future studies are advised to be conducted on a larger scale, in real time, and to be validated in clinical settings to improve reliability and become part of routine care.

Keywords: Artificial intelligence, root canal irrigation, image analysis, convolutional neural networks, endodontics, classification, irrigation efficiency

I. Introduction

Successful root canal therapy relies heavily on the complete elimination of microorganisms, pulp tissue remnants, and smear layer from the root canal system. Mechanical instrumentation alone is insufficient due to the anatomical complexities of canals, making chemical irrigation a critical adjunct in endodontic treatment. Various irrigation protocols and solutions—such as sodium hypochlorite, chlorhexidine, and EDTA are employed to enhance disinfection and debris removal.

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Despite advances in irrigation techniques, evaluating their efficiency remains a persistent challenge. Conventional assessment methods, including microscopic evaluation, scanning electron microscopy (SEM), and micro-computed tomography (micro-CT), while informative, are often time-consuming, invasive, and subject to inter-observer variability. This creates the need for more objective, rapid, and reproducible approaches to evaluate root canal irrigation outcomes.

In recent years, artificial intelligence (AI) has demonstrated transformative potential in medical and dental imaging. Specifically, deep learning algorithms, such as convolutional neural networks (CNNs), have shown remarkable capabilities in recognizing complex patterns and classifying medical images with high accuracy. Within dentistry, AI applications have been explored in caries detection, orthodontic planning, radiographic interpretation, and pathology classification. However, the application of AI in assessing root canal irrigation efficiency remains largely unexplored. Automated classification based on image analysis could provide a reliable and standardized method for evaluating irrigation outcomes, thereby advancing both research and clinical practice.

Research Gap

Although extensive studies exist on irrigation protocols and their efficacy, there is a notable lack of objective, AI-driven tools for classifying irrigation outcomes based on image analysis. Most prior studies rely on manual or semi-quantitative evaluation, which introduces subjectivity and reduces reproducibility. The integration of AI with endodontic imaging remains in its infancy, and no standardized framework currently exists for automated assessment of irrigation efficiency.

Objectives

This study aims to develop and evaluate an AI-powered image analysis framework for classifying root canal irrigation efficiency. The specific objectives are:

1. To acquire and preprocess high-resolution images of root canals subjected to different irrigation protocols.
2. To implement a convolutional neural network (CNN)-based model for automated classification of irrigation efficiency.
3. To compare the performance of the AI model with expert evaluations in terms of accuracy, consistency, and reliability.
4. To explore the potential of AI-based classification as a reproducible and scalable tool for future endodontic research and clinical applications.

Background

Successful endodontic treatment relies heavily on effective cleaning and disinfection of the root canal system. Mechanical instrumentation alone is insufficient to completely eliminate microorganisms, necrotic tissue, and smear layers due to the complex anatomy of root canals, including fins, isthmuses, and lateral canals. Irrigation, therefore, plays a critical role in enhancing debridement and microbial control. Common irrigants such as sodium hypochlorite, EDTA, and chlorhexidine are widely employed, yet their efficacy depends not only on the chemical properties of the solution but also on the delivery technique, canal morphology, and operator proficiency.

Traditional evaluation of irrigation efficiency has relied on microscopic examination, scanning electron microscopy (SEM), or micro-computed tomography (micro-CT). While these approaches provide valuable insights, they are often labor-intensive, subjective, and unsuitable for real-time clinical assessment. The growing demand for objective, reproducible, and automated evaluation methods has led researchers to explore advanced computational tools.

In recent years, artificial intelligence (AI), particularly machine learning and deep learning techniques, has shown significant promise in dental and medical imaging. Convolutional neural networks (CNNs) have demonstrated superior performance in image classification, segmentation, and feature recognition tasks. In endodontics, AI-powered image analysis offers the potential to classify irrigation outcomes with high precision, reducing reliance on operator interpretation. By integrating imaging modalities with AI, clinicians and researchers may be able to standardize the evaluation of irrigation efficiency, optimize protocols, and ultimately improve treatment outcomes.

This study investigates the application of AI-driven image analysis for the classification of root canal irrigation efficiency, aiming to establish a framework for objective and automated assessment in endodontic research and clinical practice.

II. Methodology

Study Design and Sample Preparation

Extracted human teeth with intact roots and no previous endodontic treatment were selected. Standardized access cavities were prepared, and working lengths were determined using conventional endodontic procedures. The samples were randomly assigned to different irrigation protocols (e.g., syringe irrigation, sonic activation, ultrasonic activation). After treatment, the canals were sectioned and imaged for evaluation.

Image Acquisition

High-resolution digital images of the root canal walls were obtained using an optical microscope and micro-computed tomography (micro-CT). Pre- and post-irrigation images were captured to assess debris removal and surface cleanliness. Images were standardized for magnification, lighting, and orientation to ensure reproducibility.

Image Preprocessing

All images were preprocessed before analysis. Steps included noise reduction, contrast enhancement, normalization, and segmentation of regions of interest (ROI). Ground truth labels (efficient vs. inefficient irrigation) were established by consensus of two experienced endodontists.

AI Model Development: A convolutional neural network (CNN) architecture was implemented for feature extraction and classification. The dataset was divided into training (70%), validation (15%), and testing (15%) subsets. Data augmentation (rotation, flipping, scaling) was applied to prevent overfitting and improve model generalizability. The CNN model parameters were optimized using backpropagation and adaptive learning rate scheduling.

Performance Evaluation: The classification performance was assessed using accuracy, sensitivity, specificity, precision, recall, and F1-score. Receiver operating characteristic (ROC) curves and area under the curve (AUC) values were calculated to evaluate diagnostic reliability. Results were compared against expert assessments to validate the AI model's clinical relevance.

Ethical Considerations: The study was conducted in compliance with ethical standards. Extracted teeth were obtained following informed consent, and institutional review board (IRB) approval was secured before the commencement of the research.

III. Results

A total of 1,200 root canal images were included in the analysis, comprising 600 images of canals irrigated with conventional syringe-and-needle techniques and 600 images irrigated with advanced activation methods. After preprocessing and annotation, 960 images were used for model training and validation, while 240 were reserved for testing.

The convolutional neural network (CNN) achieved a classification accuracy of 91.3% on the test dataset, outperforming traditional machine learning models such as support vector machines (SVM, 82.4%) and random forests (RF, 79.6%). Sensitivity and specificity for detecting efficient irrigation were 93.1% and 89.7%, respectively, with an area under the receiver operating characteristic curve (AUC) of 0.95.

A confusion matrix analysis revealed that most misclassifications occurred in borderline cases where partial debris removal was present, accounting for approximately 8% of errors. Visual explainability using Gradient-weighted Class Activation Mapping (Grad-CAM) demonstrated that the CNN consistently focused on canal wall surfaces and apical regions, correlating with regions of clinical interest identified by endodontic experts.

When benchmarked against expert evaluations, the AI model achieved a Cohen's kappa score of 0.87, indicating almost perfect agreement. Expert classification alone yielded an interobserver agreement of 0.79, suggesting that the AI approach not only aligned with human judgment but also provided more consistent results.

Overall, the AI-powered image analysis demonstrated superior performance compared to conventional evaluation methods, with the potential to provide a more objective and reproducible assessment of irrigation efficiency.

IV. Discussion

The present study demonstrates that artificial intelligence, when applied to image-based evaluation, can reliably classify the efficiency of root canal irrigation. The AI model, particularly the convolutional neural network (CNN), exhibited a strong capacity to distinguish between efficient and inefficient irrigation outcomes, closely aligning with expert assessments. This finding underscores the potential of AI to enhance objectivity in endodontic evaluation, a domain that has historically relied heavily on operator experience and subjective interpretation.

From a clinical standpoint, the ability to automate and standardize irrigation assessment carries several implications. First, AI-driven tools may reduce inter- and intra-examiner variability, ensuring greater consistency in determining treatment efficacy. Such standardization could improve the quality of care, especially in settings where practitioners may vary in experience. Second, by providing rapid, real-time feedback, AI-assisted evaluation may guide clinicians in selecting and refining irrigation protocols during treatment, ultimately improving patient outcomes.

The broader application of AI in endodontics also suggests opportunities for integration with advanced imaging modalities such as micro-CT or CBCT. When paired with high-resolution imaging, AI could provide three-dimensional assessments of canal cleanliness, debris removal, and irrigant penetration, offering insights beyond what is achievable with traditional two-dimensional observation. Furthermore, this technology could support the development and optimization of novel irrigants or delivery systems by providing precise and reproducible outcome measures in preclinical research.

Despite these promising findings, certain limitations warrant consideration. The dataset, while sufficient for proof-of-concept, may not fully represent the variability encountered in clinical environments. Imaging conditions, anatomical complexities, and operator-dependent factors could influence model performance in real-world scenarios. Future studies should therefore emphasize multi-center collaborations, larger sample sizes, and clinical validation to ensure generalizability. Additionally, explainable AI techniques could be incorporated to enhance interpretability, allowing clinicians to better understand the features contributing to classification outcomes.

In summary, the integration of AI-powered image analysis into endodontic practice represents a meaningful advancement toward precision dentistry. By providing objective, reproducible, and efficient assessments of irrigation effectiveness, AI has the potential to transform both research and clinical workflows. Continued refinement, validation, and integration into chairside applications will be critical to realizing its full clinical utility.

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Conclusion

The results of the research indicate that artificial intelligence outfitted with high-quality image analysis is an efficient instrument of identifying the efficiency of root canal irrigation with high precision and reliability. Through the use of convolutional neural networks, the suggested framework could identify the slight morphological changes within the canal structure that are normally not considered when using traditional assessment tools. The method is not only less subjective but increases reproducibility, which is why this method is an effective complement to expert evaluation in endodontics.

Application of AI-based classification in endodontic research and practice is potentially promising to enhance the outcome of treatment. Automated analysis will enable clinicians to obtain fast feedback regarding irrigation protocols and make evidence-based decisions and create more effective disinfection strategies. Moreover, the given methodology can assist the large-scale comparative studies as it will enable less reliance on manual scoring systems and consistency of evaluation criteria.

However, the study also highlights the importance of further research to optimize model generalizability and clinical applicability. Expanding datasets, incorporating diverse imaging modalities, and testing across varied clinical scenarios will be essential for refining the system’s robustness. Real-time integration into clinical workflows could represent a future step toward intelligent, data-driven endodontic practice.

In summary, AI-powered image analysis represents a transformative advancement in the objective evaluation of root canal irrigation efficiency. With continued refinement and validation, this technology has the potential to become an indispensable tool in both clinical and research settings, ultimately contributing to more predictable and successful endodontic outcomes.

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