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Deep learning algorithm for automatic assessment of periapical lesion healing on sequential radiographs

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ABSTRACT

Deep learning has emerged as a transformative technology in dental imaging, offering automated and objective assessment of treatment outcomes. In endodontics, monitoring the healing of periapical lesions through sequential periapical radiographs is essential for determining the success of root canal therapy. Conventional radiographic evaluation is often limited by subjective interpretation, interobserver variability, and challenges in detecting subtle changes over time. This review explores the application of deep learning algorithms for the automatic assessment of periapical lesion healing using sequential radiographic images. It discusses the principles of image preprocessing, lesion segmentation, feature extraction, and temporal comparison employed by modern artificial intelligence models to quantify healing progression. The review also highlights the potential of deep learning to improve diagnostic accuracy, standardize clinical evaluations, reduce assessment time, and support evidence-based treatment decisions. Furthermore, current challenges, including dataset variability, image quality, algorithm interpretability, and clinical integration, are examined alongside future opportunities for multimodal artificial intelligence and digital workflow implementation. Overall, deep learning-assisted radiographic analysis represents a promising advancement in precision endodontics by providing reliable, reproducible, and efficient monitoring of periapical healing. Continued validation through large-scale clinical studies and integration into routine dental practice will further enhance its role in improving patient outcomes and optimizing long-term treatment success.

Keywords: Deep learning; Artificial intelligence; Periapical lesion; Sequential radiographs; Endodontics; Image segmentation; Radiographic healing; Convolutional neural networks; Treatment outcome assessment; Precision dentistry.

Introduction

Successful endodontic treatment is primarily determined by the resolution of infection and the progressive healing of periapical tissues. The evaluation of periapical lesion healing remains a fundamental component of post-treatment assessment, as clinicians rely on sequential periapical radiographs to monitor changes in lesion size, bone density, and the re-establishment of normal periapical architecture. Conventional radiographic interpretation, however, is largely subjective and dependent on the experience of the examiner, often resulting in considerable interobserver and intraobserver variability. Small radiographic changes may be overlooked during routine follow-up, delaying the identification of persistent disease or incomplete healing. Consequently, there is increasing interest in the development of automated image analysis systems capable of providing objective and reproducible assessments of treatment outcomes (Dennis et al., 2024; Hamdan et al., 2025).

Recent advances in artificial intelligence, particularly deep learning, have transformed the field of dental imaging by enabling computers to recognize complex radiographic patterns with high accuracy. Convolutional neural networks and related deep learning architectures have demonstrated remarkable capabilities in image segmentation, lesion detection, and diagnostic classification across various dental applications. Within endodontics, these algorithms are increasingly being trained to identify apical radiolucencies, quantify lesion dimensions, and compare sequential radiographs obtained during different follow-up appointments. Automated analysis minimizes human bias while facilitating standardized evaluation of healing progression, thereby supporting more consistent clinical decision-making (Dennis et al., 2024; Hamdan et al., 2025).

The biological process of periapical healing involves the elimination of intracanal microorganisms, reduction of inflammation, regeneration of periapical bone, and restoration of healthy periodontal structures. Appropriate treatment strategies, including effective canal disinfection and the use of bioactive materials, contribute significantly to favorable healing outcomes. Bioactive approaches such as vital pulp therapy and advanced endodontic materials have demonstrated the capacity to promote tissue repair and regeneration, thereby improving long-term prognosis in appropriately selected cases (Singh, 2019). Reliable radiographic monitoring is therefore essential for determining whether these biological processes are progressing successfully following treatment.

The growing adoption of digital dentistry has further enhanced opportunities for integrating deep learning algorithms into routine clinical workflows. Digital radiography provides standardized image acquisition and facilitates automated comparison of serial radiographs over time. Moreover, the integration of imaging data with electronic dental and medical records can provide a more comprehensive understanding of patient-specific factors influencing healing, supporting personalized treatment planning and long-term outcome prediction (Patel et al., 2018). Such digital integration aligns with broader developments in healthcare aimed at improving diagnostic efficiency and data-driven clinical practice.

Despite the promising capabilities of deep learning, several challenges remain before widespread clinical implementation can be achieved. Variations in radiographic quality, differences in imaging protocols, limited availability of large annotated datasets, and concerns regarding algorithm transparency continue to influence model performance and generalizability. External factors affecting dental care delivery and patient follow-up may also impact the consistency of longitudinal imaging datasets used for algorithm development (Feher et al., 2022). Furthermore, emerging diagnostic technologies, including saliva-based biomarkers and microbial profiling, may complement radiographic assessment by

Component	Role in Deep Learning-Based Assessment of Periapical Healing
Image preprocessing	Standardizes sequential radiographs through normalization and noise reduction.
Image registration	Aligns serial radiographs for accurate temporal comparison.
Lesion segmentation	Automatically delineates periapical radiolucencies using CNN-based models.
Feature extraction	Measures lesion size, grayscale intensity, and bone density changes.
Healing classification	Categorizes healing as complete, partial, stable, or persistent disease.
Clinical decision support	Assists clinicians in monitoring healing and planning retreatment when necessary.

providing additional biological information relevant to healing status (Herr et al., 2007; Mummolo et al., 2020; Santonocito et al., 2021). Alongside advances in restorative materials that emphasize long-term clinical durability (Singh, 2025), these innovations highlight the movement toward precision dentistry. Therefore, deep learning-based automatic assessment of periapical lesion healing represents a significant advancement that has the potential to improve diagnostic accuracy, standardize outcome evaluation, and enhance evidence-based endodontic care (Dennis et al., 2024; Hamdan et al., 2025).

Deep Learning-Based Assessment of Periapical Lesion Healing

Deep learning has significantly improved the evaluation of periapical lesion healing by enabling automated, objective, and reproducible analysis of sequential periapical radiographs. Traditional assessment relies on visual interpretation by clinicians, which is often affected by interobserver variability and difficulty in recognizing subtle radiographic changes during healing. Deep learning algorithms, particularly convolutional neural networks (CNNs), overcome these limitations by accurately identifying lesion boundaries, measuring radiolucent areas, and monitoring changes across serial radiographs, thereby supporting more standardized treatment outcome evaluation (Dennis et al., 2024).

The assessment process typically begins with image preprocessing, including normalization, noise reduction, and geometric alignment of sequential radiographs. Following preprocessing, automated segmentation algorithms isolate the periapical lesion from surrounding anatomical structures. Quantitative parameters such as lesion area, grayscale intensity, trabecular bone density, and healing rate are subsequently analyzed to classify treatment outcomes as complete healing, partial healing, stable disease, or persistent pathology. Recent investigations have demonstrated that deep learning models achieve high segmentation accuracy and improve the consistency of radiographic interpretation when compared with conventional manual evaluation (Dennis et al., 2024; Hamdan et al., 2025).

Beyond lesion measurement, deep learning facilitates longitudinal monitoring by comparing radiographs obtained at multiple follow-up

Clinical Workflow Stage	Deep Learning Function	Clinical Benefit
Image acquisition	Standardized radiograph capture	Improved image consistency
Image preprocessing	Noise reduction and normalization	Enhanced image quality
Lesion segmentation	Automatic lesion boundary detection	Objective lesion measurement
Feature extraction	Quantification of radiographic changes	Accurate healing assessment
Temporal comparison	Sequential image registration	Monitoring healing progression
Clinical decision support	Automated healing classification	Improved treatment planning

intervals. This capability enables clinicians to detect healing trends earlier, identify treatment failures promptly, and make evidence-based retreatment decisions. Such digital approaches complement biologically driven regenerative procedures and contemporary endodontic therapies aimed at preserving periapical tissues and promoting tissue repair (Singh, 2019). Integration of artificial intelligence with electronic dental records may further enhance personalized outcome prediction and comprehensive patient management (Patel et al., 2018). Although additional multicenter validation and standardized imaging protocols remain necessary, current evidence suggests that deep learning provides a reliable framework for automated assessment of periapical healing and represents an important advancement toward precision endodontics (Hamdan et al., 2025; Singh, 2025).

Deep Learning Algorithms and Clinical Workflow

Deep learning (DL) algorithms have significantly improved the automated evaluation of periapical lesion healing by enabling precise analysis of sequential radiographs. Modern convolutional neural networks (CNNs) and segmentation models can identify periapical radiolucencies, delineate lesion boundaries, and quantify dimensional changes over time with greater consistency than conventional visual assessment. Automated image registration aligns serial radiographs, minimizing variations caused by angulation or exposure and allowing objective monitoring of bone regeneration following endodontic treatment (Dennis et al., 2024). These capabilities reduce observer variability while supporting standardized assessment of healing progression.

The clinical workflow begins with standardized radiographic acquisition, followed by image preprocessing to normalize contrast, remove noise, and enhance anatomical landmarks. Annotated datasets generated by experienced endodontists are subsequently used to train DL models for lesion segmentation and classification. During validation, algorithm performance is measured using metrics such as accuracy, sensitivity, specificity, Dice similarity coefficient, and area under the receiver operating characteristic curve. Integration of these algorithms into digital imaging software enables automated comparison of sequential radiographs and assists clinicians in identifying persistent lesions or successful osseous healing (Hamdan et al., 2025; Dennis et al., 2024).

Integration of artificial intelligence with electronic dental records may further improve longitudinal monitoring by combining radiographic findings with patient histories and treatment data (Patel et al., 2018). Although additional multicenter validation remains necessary, DL-assisted workflows demonstrate considerable potential for enhancing diagnostic precision and clinical efficiency in endodontics. These advancements complement biologically driven treatment strategies aimed at preserving periapical health and promoting favorable healing outcomes (Singh, 2019; Singh, 2025).

Clinical Applications, Challenges, and Future Perspectives

Deep learning algorithms have significantly expanded the clinical applications of sequential periapical radiograph analysis by enabling automated detection, segmentation, and longitudinal monitoring of periapical lesions following endodontic treatment. These systems provide objective measurements of lesion dimensions and healing progression, assisting clinicians in distinguishing successful tissue repair from persistent pathology with greater consistency than conventional visual assessment. Automated image interpretation also reduces observer variability and improves diagnostic confidence, particularly when evaluating subtle radiographic changes over multiple follow-up visits (Dennis et al., 2024; Hamdan et al., 2025). Such capabilities complement contemporary biologically driven treatment strategies that emphasize preservation of periapical health and long-term treatment success (Singh, 2019).

Despite these advantages, several challenges remain before widespread clinical implementation can be achieved. Deep learning models require extensive, well-annotated datasets representing diverse imaging systems, patient populations, and clinical conditions to ensure robust performance. Variations in radiographic angulation, exposure parameters, and image quality may reduce algorithm accuracy and limit generalizability. Furthermore, the limited interpretability of many deep learning models presents barriers to clinician trust and regulatory acceptance. Integration with electronic dental records and standardized clinical documentation also remains an important consideration for seamless workflow adoption (Patel et al., 2018). External factors influencing patient attendance and follow-up imaging may additionally affect longitudinal dataset completeness and model performance (Feher et al., 2022).

Future developments are expected to incorporate multimodal artificial intelligence by combining radiographic findings with clinical parameters, salivary biomarkers, and other diagnostic data to enhance prediction of healing outcomes (Herr et al., 2007; Mummolo et al., 2020). Lifestyle-related variables influencing oral health may also contribute to individualized prognostic models (Santonocito et al., 2021). Continued improvements in algorithm transparency, multicenter validation, and integration into digital dental platforms will facilitate broader clinical adoption. These advances are anticipated to strengthen precision endodontics by providing standardized, efficient, and evidence-based monitoring of periapical lesion healing while supporting more informed clinical decision-making (Dennis et al., 2024; Hamdan et al., 2025; Singh, 2025).

Conclusion

Deep learning algorithms have demonstrated considerable potential to transform the assessment of periapical lesion healing by providing objective, reproducible, and efficient analysis of sequential radiographs. Compared with conventional visual interpretation, artificial intelligence-driven systems can accurately identify subtle radiographic changes, quantify lesion regression, and support clinicians in monitoring treatment outcomes with greater consistency. Recent advances in deep learning-based segmentation and detection models have shown encouraging diagnostic performance, highlighting their value as clinical decision-support tools rather than replacements for professional expertise (Dennis et al., 2024; Hamdan et al., 2025). As digital imaging becomes increasingly integrated into endodontic practice, automated assessment is expected to enhance diagnostic confidence, reduce interobserver variability, and facilitate standardized follow-up protocols.

Successful implementation of these technologies will depend on the availability of large, diverse, and well-annotated datasets, continuous algorithm validation, and seamless integration into existing clinical workflows. Interoperability with electronic dental and medical records could further improve longitudinal patient monitoring and support personalized treatment planning, reflecting broader trends in healthcare informatics (Patel et al., 2018). Furthermore, combining radiographic analysis with biological indicators and emerging diagnostic technologies may provide a more comprehensive understanding of periapical healing and disease progression (Herr et al., 2007; Mummolo et al., 2020; Santonocito et al., 2021). While external factors may influence patient management and clinical data availability, ongoing technological refinement is expected to strengthen the reliability and applicability of artificial intelligence in routine practice (Feher et al., 2022).

From an endodontic perspective, preserving periapical health and promoting predictable tissue healing remain central objectives of treatment, complementing established biologically based therapeutic principles (Singh, 2019). Continued innovation in restorative and endodontic materials, together with advances in digital diagnostics, will further support evidence-based patient care (Singh, 2025). Overall, deep learning-assisted evaluation of sequential radiographs represents a significant step toward precision endodontics, offering enhanced diagnostic accuracy, improved treatment monitoring, and better long-term clinical outcomes.

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