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Research Article

AI-assisted real-time detection of canal morphology during endodontic treatment using an operating microscope

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ABSTRACT

The integration of artificial intelligence (AI) with operating microscopes represents a significant advancement in modern endodontics by enhancing the real-time detection of complex root canal morphology during treatment. Accurate identification of root canal anatomy is essential for successful endodontic therapy, as undetected canals and anatomical variations remain major causes of treatment failure. Conventional diagnostic approaches, including periapical radiography, cone-beam computed tomography, and magnification through operating microscopes, have substantially improved clinical outcomes but continue to rely heavily on the clinician's expertise and interpretation. AI-assisted image analysis introduces automated recognition of canal structures through advanced machine learning and deep learning algorithms capable of processing microscopic images in real time. These technologies can improve the detection of accessory canals, calcified canals, canal bifurcations, and other anatomical complexities while providing immediate clinical guidance during instrumentation. The integration of AI with digital imaging workflows has the potential to increase diagnostic accuracy, reduce procedural errors, improve treatment efficiency, and support minimally invasive endodontic procedures. Despite challenges related to algorithm validation, data standardization, equipment integration, and regulatory considerations, ongoing technological advancements continue to expand the clinical applicability of AI-assisted systems. The incorporation of intelligent image analysis into operating microscopy is expected to transform endodontic practice by improving precision, consistency, and long-term treatment outcomes.

Introduction

Successful endodontic treatment depends largely on the accurate identification, cleaning, shaping, and obturation of the entire root canal system. Variations in root canal morphology, including accessory canals, isthmuses, lateral canals, and complex apical configurations, present significant clinical challenges that may compromise treatment outcomes if left undetected. Missed canals remain one of the leading causes of persistent periapical disease and endodontic treatment failure, highlighting the importance of precise visualization and anatomical assessment during every stage of root canal therapy. Although advances in magnification and illumination have substantially improved clinicians' ability to locate canal orifices, the interpretation of complex anatomical structures continues to depend heavily on operator experience and clinical judgment.

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The introduction of the dental operating microscope has revolutionized modern endodontics by providing enhanced magnification, superior illumination, and improved visualization of intricate pulp chamber anatomy. The operating microscope enables clinicians to identify calcified canals, additional canal orifices, developmental grooves, and microfractures with greater precision than unaided vision. Nevertheless, even with microscopic magnification, the accurate recognition of subtle anatomical variations remains challenging, particularly in teeth exhibiting severe calcification, developmental anomalies, or previous restorative interventions. Consequently, there is increasing interest in integrating intelligent computational systems capable of assisting clinicians during real-time clinical procedures.

Artificial intelligence (AI) has emerged as one of the most transformative technologies in contemporary healthcare and dentistry. Through machine learning, deep learning, and computer vision algorithms, AI systems can analyze large volumes of imaging and clinical data, identify complex patterns, and support diagnostic and therapeutic decision-making with increasing levels of accuracy. Recent developments have demonstrated the successful application of AI across multiple dental specialties, including the detection of dental caries, interpretation of radiographic images, prediction of disease progression, and automated analysis of electronic dental records (Gonzalez et al., 2024; Patel et al., 2023). These advancements have established AI as a valuable adjunct for improving diagnostic precision while reducing variability associated with human interpretation.

Within endodontics, AI-assisted image analysis has gained considerable attention for its potential to enhance the identification of root canal anatomy and improve treatment planning. Modern deep learning algorithms are capable of recognizing subtle anatomical landmarks, segmenting dental structures, and detecting variations that may not be readily apparent during conventional clinical examination. When integrated with operating microscopes, these algorithms can process high-resolution microscopic images in real time, providing clinicians with immediate visual guidance regarding canal location, morphology, and potential anatomical complexities. Such integration has the potential to improve procedural accuracy, facilitate minimally invasive access cavity preparation, reduce the likelihood of missed canals, and ultimately enhance treatment success (Feher et al., 2024).

The rapid evolution of AI in dentistry has been supported by advances in imaging technologies, computational power, and the availability of large annotated datasets. Emerging AI models increasingly combine multimodal data sources—including radiographs, cone-beam computed tomography (CBCT), intraoral scans, microscopic imaging, and electronic health records—to generate more comprehensive diagnostic insights and clinical recommendations (Feher et al., 2024; Patel et al., 2023). These developments reflect a broader transition toward evidence-based, data-driven clinical decision-making, in which intelligent systems complement rather than replace the expertise of dental professionals. Similar evidence-based approaches have contributed to improved clinical outcomes in other areas of dentistry, emphasizing the importance of integrating scientific evidence with technological innovation in patient care (Hämmerle et al., 2012; Isola et al., 2023).

Beyond diagnostic enhancement, AI-assisted systems offer opportunities to improve workflow efficiency, standardize clinical procedures, and support educational training by providing consistent guidance during complex endodontic interventions. Automated identification of canal morphology may shorten treatment time, reduce procedural complications, and enhance clinician confidence, particularly among less experienced practitioners. Furthermore, AI-driven decision support systems may contribute to improved patient communication by enabling visualization of anatomical findings and facilitating informed treatment planning. These capabilities align with the broader trend toward digital dentistry, where intelligent technologies increasingly support precision, predictability, and personalized patient care. The successful application of AI in restorative dentistry further illustrates the growing role of advanced technologies in optimizing clinical performance and treatment outcomes across dental disciplines (Singh, 2025).

The growing emphasis on preventive and precision dentistry also underscores the importance of accurate diagnosis and individualized treatment planning. AI technologies have demonstrated significant potential for improving diagnostic consistency across various oral health conditions, while advances in understanding the biological and microbial determinants of oral diseases continue to inform comprehensive patient management strategies (Mummolo et al., 2020; Isola et al., 2023). The convergence of intelligent image analysis, high-resolution operating microscopy, and digital clinical workflows represents a promising advancement capable of overcoming many longstanding challenges associated with the management of complex root canal systems.

This review explores the principles, technologies, clinical applications, advantages, limitations, and future prospects of AI-assisted real-time detection of canal morphology using operating microscopes in endodontic treatment. Particular emphasis is placed on the integration of artificial intelligence with microscopic visualization, the algorithms supporting real-time image interpretation, current clinical evidence, implementation challenges, and the potential of intelligent imaging systems to improve diagnostic accuracy, procedural efficiency, and long-term endodontic treatment outcomes.

Fundamentals of Canal Morphology and AI-Based Detection

Anatomy and Variations of Root Canal Systems

A comprehensive understanding of root canal morphology is fundamental to successful endodontic treatment. The root canal system is highly complex, exhibiting considerable variations in the number, shape, curvature, and interconnections of canals among different teeth and individuals. Although traditional anatomical classifications have provided a framework for clinical practice, advances in microscopic visualization and three-dimensional imaging have demonstrated that canal systems frequently possess accessory canals, lateral canals, fins, isthmuses, apical deltas, and complex bifurcations that may be overlooked during routine treatment. Failure to identify and adequately instrument these anatomical variations is a leading cause of persistent infection and endodontic treatment failure.

The morphology of root canals is influenced by developmental, genetic, and age-related factors. Calcification associated with aging may obscure canal orifices, whereas previous restorative procedures, trauma, and pathological changes can further complicate canal identification. These variations necessitate meticulous clinical examination and advanced visualization techniques to ensure complete debridement and obturation of the root canal system. Evidence-based clinical decision-making remains essential when managing anatomical complexities, emphasizing the importance of integrating emerging technologies with established biological principles (Hämmerle et al., 2012).

The increasing application of digital technologies has enhanced clinicians' ability to recognize morphological variations before and during treatment. AI-assisted image analysis provides an additional level of support by identifying subtle anatomical patterns that may not be readily apparent through conventional visual assessment. Such technologies are designed to complement rather than replace clinical expertise, promoting greater consistency and diagnostic confidence (Feher et al., 2024).

Conventional Methods for Canal Identification

Successful localization of root canals depends on careful interpretation of clinical and radiographic findings. Conventional diagnostic techniques include tactile exploration using endodontic explorers, periapical radiography, cone-beam computed tomography (CBCT), dye staining, ultrasonic troughing, and magnification provided by dental loupes or operating microscopes.

Periapical radiographs remain one of the most commonly employed diagnostic tools because of their accessibility and relatively low radiation exposure. However, two-dimensional radiographic images frequently suffer from anatomical superimposition, distortion, and limited visualization of complex canal systems. CBCT has substantially improved preoperative assessment by providing three-dimensional visualization of root anatomy and surrounding structures, although radiation dose, cost, and accessibility continue to limit its routine application in every clinical scenario.

The introduction of operating microscopes revolutionized endodontic practice by offering superior magnification and coaxial illumination. Enhanced visualization enables clinicians to detect additional canal orifices, identify developmental grooves, and distinguish calcified canals with greater precision. Nevertheless, even under magnification, canal identification remains dependent on operator experience and subjective interpretation.

Recent advances in artificial intelligence have demonstrated that computer-assisted image analysis can augment traditional diagnostic methods by recognizing anatomical landmarks and identifying image features associated with hidden canal systems. Similar AI-driven diagnostic approaches have already shown excellent performance in detecting dental pathologies from radiographic images, suggesting comparable potential for endodontic applications (Gonzalez et al., 2024). Furthermore, automated analysis of longitudinal dental datasets illustrates the capability of AI algorithms to recognize subtle structural changes that may otherwise escape conventional clinical assessment (Patel et al., 2023).

Artificial Intelligence in Endodontic Imaging

Artificial intelligence has emerged as one of the most transformative innovations in digital dentistry, offering advanced computational methods capable of analyzing complex imaging datasets with remarkable speed and consistency. AI systems utilize machine learning, deep learning, and computer vision algorithms to extract clinically relevant information from microscopic images, radiographs, CBCT scans, and other digital imaging modalities (Feher et al., 2024).

Machine learning algorithms identify statistical relationships between image characteristics and known anatomical structures through iterative training processes. Deep learning models, particularly convolutional neural networks (CNNs), automatically learn hierarchical image features without requiring manual feature engineering. These models excel in recognizing subtle differences in grayscale intensity, texture, and structural boundaries that characterize various canal morphologies.

Image segmentation algorithms further enhance AI performance by delineating canal boundaries from surrounding dentin and pulp chamber structures. Once segmented, object detection algorithms classify anatomical features and provide clinicians with real-time visual guidance during treatment. Continuous refinement through larger datasets improves algorithm robustness and adaptability across diverse patient populations.

Table 1: Comparison of Conventional Canal Detection Methods and AI-Assisted Detection Techniques

Diagnostic Method	*Principle*	*Advantages*	*Limitations*	*Clinical Role*
Clinical tactile exploration	Manual identification of canal orifices using endodontic instruments	Simple, inexpensive, immediate feedback	Operator dependent; limited sensitivity in calcified canals	Initial canal localization
Periapical radiography	Two-dimensional radiographic imaging	Widely available, low radiation dose, economical	Image distortion, anatomical overlap, limited three-dimensional visualization	Routine preoperative and intraoperative assessment
Cone-beam computed tomography (CBCT)	Three-dimensional volumetric imaging	Excellent visualization of complex anatomy and additional canals	Higher radiation exposure, increased cost, limited routine use	Preoperative evaluation of challenging cases
Operating microscope	Magnification with coaxial illumination	Improved visualization, enhanced precision, identification of hidden canals	Requires experience and specialized equipment	Gold standard for microscopic endodontics
AI-assisted image analysis	Machine learning and deep learning algorithms analyze digital images in real time	Automated detection, improved diagnostic consistency, real-time decision support, reduced operator variability	Requires validated datasets, computational infrastructure, regulatory approval, and integration with imaging systems	Adjunctive tool for real-time canal morphology detection and clinical decision support

The successful implementation of AI depends heavily on the availability of high-quality annotated datasets, standardized imaging protocols, and rigorous external validation. The evolution of multimodal AI systems integrating radiographs, CBCT data, microscopic images, and electronic dental records represents an important advancement toward comprehensive clinical decision support (Feher et al., 2024; Patel et al., 2023).

Beyond image recognition, AI contributes to predictive analytics by estimating the likelihood of additional canals, identifying potential procedural complications, and assisting clinicians in selecting appropriate treatment strategies. Similar AI methodologies have already demonstrated significant diagnostic value in restorative dentistry, pediatric radiology, and periodontal disease monitoring, highlighting their broad applicability across dental specialties (Gonzalez et al., 2024; Singh, 2025).

Although AI primarily focuses on image interpretation, successful endodontic outcomes remain closely linked to overall oral health and biological considerations. The interaction between oral microbial ecology, systemic health, and tissue healing continues to influence treatment prognosis, emphasizing the need for comprehensive patient evaluation alongside technological innovation (Mummolo et al., 2020; Isola et al., 2023).

AI Integration with Operating Microscopes for Real-Time Canal Morphology Detection

The combination of artificial intelligence (AI) with operating microscopes has introduced a new dimension to endodontic treatment by enabling enhanced visualization and real-time interpretation of root canal morphology. Although the operating microscope has become an indispensable tool in contemporary endodontics, its effectiveness remains dependent on the clinician's experience in identifying subtle anatomical landmarks and canal variations. AI-assisted systems complement microscopic magnification by analyzing live images, recognizing morphological patterns, and providing immediate decision support during treatment. This integration represents a transition from passive magnification to intelligent visualization, where machine learning algorithms assist clinicians in identifying complex canal systems with greater consistency and accuracy (Feher et al., 2024).

Architecture of AI-Assisted Operating Microscope Systems

AI-assisted operating microscope systems combine advanced optical imaging with computational intelligence to facilitate the detection of root canal anatomy during clinical procedures. The workflow begins with high-resolution image acquisition through the operating microscope. Modern digital microscopes capture continuous video streams or high-definition still images that serve as the primary input for AI algorithms. These images undergo preprocessing to improve contrast, eliminate optical noise, normalize illumination, and enhance anatomical details, thereby optimizing image quality for subsequent analysis (Feher et al., 2024).

Following preprocessing, feature extraction algorithms identify morphological characteristics such as canal entrances, dentinal grooves, pulp chamber floors, calcification patterns, and color differences within the tooth structure. Deep learning models trained on extensive annotated datasets analyze these features to distinguish canal orifices from surrounding dentin and restorative materials. Object detection and segmentation algorithms subsequently outline canal boundaries while simultaneously estimating their spatial orientation within the pulp chamber. The processed information is then superimposed onto the microscope display, allowing clinicians to visualize probable canal locations during treatment without interrupting clinical workflow (Patel et al., 2023).

The integration of cloud-based computing and embedded graphical processing units has further improved the speed of image analysis, making real-time interpretation increasingly feasible. Rather than replacing clinical expertise, AI functions as an intelligent assistant by continuously evaluating microscopic images and highlighting regions that warrant closer inspection. Such systems reduce reliance on subjective visual interpretation while supporting evidence-based clinical decision-making (Feher et al., 2024).

AI Algorithms Used in Canal Morphology Detection

Several AI methodologies contribute to the identification of root canal morphology during endodontic procedures. Among these, convolutional neural networks (CNNs) remain the most widely employed due to their exceptional ability to recognize complex image patterns. CNNs automatically learn hierarchical features from microscopic images, enabling accurate identification of canal orifices, accessory canals, isthmuses, and calcified pathways without requiring manual feature engineering (Gonzalez et al., 2024).

Semantic segmentation models, including encoder-decoder neural network architectures, further improve anatomical visualization by assigning every image pixel to specific anatomical structures. These models facilitate precise delineation of canal boundaries, enhancing navigation during instrumentation while minimizing unnecessary dentin removal. Object detection algorithms simultaneously identify multiple anatomical landmarks within a single microscopic field, allowing clinicians to distinguish canal openings from developmental grooves, restorative materials, or pulp stones.

Image enhancement techniques employing AI also contribute substantially to microscopic visualization. These algorithms improve brightness uniformity, sharpen structural boundaries, suppress optical artifacts, and compensate for variable illumination conditions encountered during treatment. Improved image quality enhances algorithmic performance while facilitating clinician interpretation of complex anatomical structures (Feher et al., 2024).

Predictive analytical models represent another important application of AI in endodontics. By integrating demographic variables, tooth morphology, radiographic findings, and microscopic observations, predictive algorithms estimate the probability of additional canals or anatomical variations. Similar predictive approaches have demonstrated effectiveness in analyzing longitudinal dental datasets and identifying disease progression, supporting their broader application in endodontic diagnostics (Patel et al., 2023).

Clinical Workflow

Implementation of AI-assisted operating microscopy follows a structured clinical workflow designed to integrate seamlessly into conventional endodontic procedures. After patient preparation and isolation with rubber dam placement, access cavity preparation is performed according to established endodontic principles. The operating microscope provides magnified visualization of the pulp chamber, while integrated digital imaging continuously captures the operative field.

The acquired images are transmitted to AI software for instantaneous analysis. During preprocessing, the software enhances image quality by correcting illumination inconsistencies, reducing noise, and emphasizing structural features. Machine learning algorithms subsequently identify probable canal locations based on anatomical characteristics learned from extensive training datasets.

The detected canal orifices are displayed as visual overlays, color-coded markers, or contour outlines within the microscope interface. These real-time recommendations guide clinicians toward additional canals that may otherwise remain undetected, particularly in teeth with calcifications, developmental anomalies, or previous restorative procedures. The clinician retains full control over treatment decisions while using AI-generated information as supplementary guidance.

Following canal identification, clinicians verify anatomical findings using endodontic explorers, ultrasonic tips, working length determination, and appropriate radiographic confirmation. Continuous AI monitoring throughout canal negotiation and instrumentation provides additional assistance by recognizing changes in morphology as treatment progresses. This collaborative interaction between clinician and AI improves procedural efficiency without compromising operator autonomy (Feher et al., 2024; Gonzalez et al., 2024).

Clinical Advantages

The integration of AI with operating microscopes offers numerous clinical advantages that extend beyond enhanced visualization alone. One of the most significant benefits is improved identification of accessory canals and unusual anatomical configurations that frequently contribute to endodontic treatment failure when

Table 2: Major AI Algorithms Used for Real-Time Canal Morphology Detection and Their Clinical Applications

AI Algorithm/Technique	*Primary Function*	*Application in Operating Microscope*	*Clinical Advantages*	*Limitations*
Convolutional Neural Networks (CNNs)	Automated image recognition	Identification of canal orifices and accessory canals	High detection accuracy and rapid image analysis	Requires extensive annotated training datasets
Semantic Image Segmentation	Pixel-level anatomical classification	Delineation of canal boundaries and pulp chamber anatomy	Precise localization of complex canal systems	Performance depends on image quality
Object Detection Algorithms	Detection of multiple anatomical landmarks	Simultaneous identification of canal entrances and calcified regions	Supports efficient navigation during treatment	May generate occasional false-positive detections
Image Enhancement Algorithms	Contrast optimization and noise reduction	Improves visualization under varying illumination	Enhanced microscopic image clarity and diagnostic confidence	Limited effectiveness with severely degraded images
Predictive Machine Learning Models	Estimation of anatomical variations	Predicts probability of additional canals based on clinical data	Supports treatment planning and risk assessment	Dependent on representative clinical datasets
Hybrid AI Decision-Support Systems	Integration of multiple AI models	Continuous real-time guidance during canal exploration	Combines high diagnostic accuracy with clinical workflow integration	Requires advanced computational resources and software validation

overlooked. AI-assisted recognition of subtle anatomical cues reduces the likelihood of missed canals, thereby increasing the completeness of root canal debridement and obturation (Gonzalez et al., 2024).

AI also enhances procedural precision by assisting clinicians during access refinement and canal localization. Real-time guidance reduces excessive dentin removal, preserving tooth structure while minimizing the risk of iatrogenic complications such as perforations or unnecessary enlargement of access cavities. This aligns with contemporary minimally invasive endodontic principles that emphasize structural preservation alongside effective disinfection.

Another important advantage involves reducing operator dependency. Clinical performance in canal detection often varies according to practitioner experience and familiarity with complex anatomical variations. AI provides standardized analytical support, helping less experienced clinicians achieve greater diagnostic consistency while also assisting experienced specialists in managing unusually challenging cases. Similar improvements in diagnostic standardization have been demonstrated across multiple dental AI applications involving radiographic interpretation and longitudinal patient assessment (Patel et al., 2023; Feher et al., 2024).

Efficiency during treatment also improves through automated image interpretation. Instead of repeatedly adjusting microscope positioning or performing extensive manual exploration, clinicians receive immediate feedback regarding likely canal locations, shortening chairside time and reducing operator fatigue. Faster canal identification may improve patient comfort while optimizing clinical workflow.

The broader integration of AI into dentistry further supports comprehensive patient management by combining imaging data, electronic health records, and predictive analytics to improve treatment planning. As AI applications continue to mature across restorative dentistry, periodontology, orthodontics, and diagnostic imaging, their incorporation into endodontic operating microscopes represents a logical progression toward intelligent, digitally integrated clinical practice (Feher et al., 2024; Patel et al., 2023). Furthermore, evidence-based treatment planning remains fundamental to successful clinical outcomes, emphasizing that AI should complement rather than replace professional clinical judgment (Hämmerle et al., 2012; Isola et al., 2023). Although AI technologies primarily focus on imaging and anatomical detection, comprehensive patient care continues to require consideration of restorative factors, oral microbial status, and overall oral health, all of which contribute to long-term treatment success (Singh, 2025; Mummolo et al., 2020).

Clinical Applications, Challenges, and Future Perspectives

Current Clinical Applications

Artificial intelligence (AI)-assisted operating microscope

Table 3: Current Challenges, Proposed Solutions, and Future Opportunities in AI-Assisted Canal Morphology Detection

Challenge	*Clinical Impact*	*Proposed Solutions*	*Future Opportunities*
Limited annotated datasets	Reduced diagnostic accuracy across diverse populations	Development of large multicenter image databases and standardized annotation protocols	More robust and generalizable AI models (Feher et al., 2024)
Limited external clinical validation	Uncertain reliability in routine practice	Multicenter prospective clinical studies and independent validation	Greater clinician confidence and regulatory acceptance (Patel et al., 2023)
Equipment compatibility	Difficult integration with existing operating microscopes and imaging systems	Standardized software interfaces and interoperable digital platforms	Fully integrated digital endodontic workflows
High implementation cost	Limited adoption in smaller practices	Cost reduction through technological advancement and broader commercialization	Increased accessibility across diverse healthcare settings
Ethical and legal concerns	Questions regarding accountability, patient privacy, and data security	Regulatory guidelines, transparent algorithms, cybersecurity measures, and clinician oversight	Safe and responsible implementation of AI-supported clinical decision-making (Feher et al., 2024)
Dependence on clinician acceptance	Variable utilization of AI recommendations	Comprehensive education, clinical training, and user-friendly interfaces	Greater integration into routine endodontic education and practice
Limited multimodal data integration	Fragmented diagnostic information	Integration of operating microscopy, CBCT, electronic health records, and AI analytics	Personalized, precision-based endodontic treatment planning (Patel et al., 2023; Feher et al., 2024)

systems have expanded the capabilities of contemporary endodontics by providing real-time support for the identification and interpretation of root canal morphology. By combining high-magnification optical visualization with advanced image analysis algorithms, these systems assist clinicians in recognizing anatomical landmarks that may otherwise be overlooked during conventional treatment. Such integration enhances procedural precision while reducing dependence solely on operator experience (Feher et al., 2024).

One of the most significant clinical applications is the detection of additional canals in teeth exhibiting complex internal anatomy. Missed canals remain a major contributor to persistent apical pathology and endodontic treatment failure. AI algorithms trained on extensive dental imaging datasets can continuously analyze microscopic images and identify subtle morphological features suggestive of accessory canals or unusual canal trajectories. Similar AI-based image interpretation strategies have already demonstrated high diagnostic performance in other areas of dentistry, including the automated detection of proximal caries, highlighting the adaptability of deep learning models across dental specialties (Gonzalez et al., 2024).

Calcified canals present another major clinical challenge, particularly in older patients and teeth affected by trauma or extensive restorative procedures. Progressive calcification often obscures canal orifices, making their localization difficult even under high magnification. AI-assisted operating microscopes can enhance image contrast, detect faint anatomical landmarks, and provide visual guidance that facilitates conservative dentin removal while minimizing unnecessary structural loss. These capabilities contribute to safer access cavity preparation and preservation of healthy tooth structure. Recognition of complex canal configurations, including bifurcations, trifurcations, C-shaped canals, isthmuses, and apical deltas, represents another valuable application. Continuous image segmentation allows AI systems to highlight probable canal pathways during instrumentation, enabling clinicians to modify treatment strategies as new anatomical information becomes available. This dynamic guidance improves the likelihood of complete cleaning, shaping, and obturation of the root canal system (Feher et al., 2024).

AI-assisted microscopy also demonstrates considerable value during nonsurgical endodontic retreatment. Previously treated teeth often present altered anatomy due to calcification, restorative materials, fractured instruments, perforations, or missed canals. Real-time image analysis can assist clinicians in distinguishing original canal pathways from procedural defects, facilitating safer retreatment while reducing procedural complications.

Educational applications are increasingly recognized as another important area of implementation. AI-guided visualization enables dental students and postgraduate residents to receive immediate feedback regarding canal identification and access cavity preparation.

Automated annotations and decision-support systems provide objective learning opportunities that supplement conventional clinical instruction and may accelerate competency development. Similar AI-driven educational approaches have been proposed across multiple dental disciplines as digital technologies continue to evolve (Patel et al., 2023; Feher et al., 2024).

Advantages Over Conventional Endodontic Procedures

The integration of AI with operating microscopes provides several advantages compared with traditional methods of canal detection. Conventional endodontic diagnosis depends heavily on clinician expertise, visual acuity, tactile sensation, and interpretation of radiographic findings. Although operating microscopes substantially improve visualization, diagnostic accuracy remains influenced by operator experience. AI introduces an additional layer of computational analysis capable of recognizing subtle anatomical patterns beyond normal human perception (Feher et al., 2024).

Improved diagnostic accuracy is among the most significant benefits. AI algorithms analyze thousands of image features simultaneously, allowing rapid identification of canal orifices, accessory canals, developmental grooves, and anatomical landmarks. This capability reduces the likelihood of untreated canals, thereby improving treatment predictability and long-term success.

AI-assisted systems also reduce procedural errors during access preparation. By identifying the most probable canal locations before extensive dentin removal, clinicians can perform more conservative access cavities while minimizing the risk of perforations, gouging, excessive dentin removal, or unnecessary weakening of tooth structure. Conservative treatment principles remain essential for preserving long-term structural integrity of endodontically treated teeth (Singh, 2025).

Workflow efficiency is another important advantage. Continuous real-time image processing decreases the time required for canal exploration, enabling clinicians to locate complex anatomy more rapidly. Reduced chairside time benefits both practitioners and patients by improving procedural efficiency without compromising diagnostic quality.

AI also contributes to greater procedural consistency among clinicians with varying levels of experience. Less experienced operators may benefit from computerized guidance that reinforces anatomical recognition and supports clinical decision-making. Such standardization has the potential to reduce variability in treatment outcomes across different clinical settings (Patel et al., 2023).

From a patient-centered perspective, improved canal detection may contribute to better treatment outcomes by reducing postoperative complications associated with missed anatomy. More complete debridement and obturation decrease microbial persistence within the root canal system, supporting favorable healing responses consistent with evidence-based principles of oral tissue repair (Hämmerle et al., 2012). Furthermore, successful elimination of intracanal infection supports broader oral health goals by reducing chronic microbial reservoirs that may influence surrounding periodontal tissues and systemic health (Isola et al., 2023; Mummolo et al., 2020).

Challenges and Limitations

Despite its considerable promise, AI-assisted real-time canal morphology detection continues to face several technical, clinical, and regulatory challenges that must be addressed before widespread implementation becomes routine.

One major limitation is the availability of high-quality datasets required for algorithm training. AI systems depend upon large numbers of accurately annotated microscopic images representing diverse tooth types, anatomical variations, clinical conditions, and imaging environments. Limited dataset diversity may reduce algorithm generalizability and introduce diagnostic bias when applied to different patient populations (Feher et al., 2024).

Algorithm validation remains another important concern. Many AI models demonstrate excellent performance under controlled experimental conditions but require further multicenter clinical validation before routine adoption. Prospective studies involving diverse clinical environments are necessary to confirm diagnostic reliability, reproducibility, and safety across various treatment scenarios (Patel et al., 2023).

Integration with existing dental equipment presents additional challenges. Current operating microscopes differ considerably in optical characteristics, image resolution, software architecture, and digital compatibility. Successful implementation requires standardized communication protocols that allow seamless interaction between AI software, imaging hardware, electronic patient records, and digital treatment planning systems.

Economic considerations may also influence adoption. The acquisition of AI-compatible operating microscopes, high-performance computing hardware, software licensing, and ongoing system maintenance may represent substantial financial investments for many dental practices. Cost-effectiveness analyses are therefore essential to determine long-term clinical and economic benefits.

Ethical and legal considerations remain equally important. AI should function as a clinical decision-support tool rather than replacing professional judgment. Questions surrounding liability, algorithm transparency, patient privacy, cybersecurity, informed consent, and regulatory approval require careful consideration as AI technologies continue to mature. Appropriate governance frameworks will be essential to ensure safe, equitable, and responsible implementation within clinical practice (Feher et al., 2024).

Future Directions

Future developments are expected to further expand the role of AI-assisted operating microscopes in intelligent endodontic care. Continuous improvements in deep learning algorithms, computational power, and digital imaging technologies will likely increase diagnostic precision while reducing processing times.

Integration with cone-beam computed tomography (CBCT) represents one promising direction. AI systems capable of combining preoperative CBCT datasets with intraoperative microscopic imaging could generate three-dimensional navigation maps that guide clinicians toward hidden canals while continuously updating anatomical information throughout treatment.

Augmented reality (AR) technologies may further enhance clinical visualization by projecting AI-generated anatomical overlays directly into the operating microscope's visual field. Such systems could provide intuitive guidance without requiring clinicians to divert attention from the treatment site, thereby improving workflow efficiency and procedural accuracy.

Cloud-based AI platforms are also expected to facilitate continuous algorithm improvement through secure analysis of anonymized clinical datasets collected from multiple institutions. Larger datasets would enhance algorithm robustness while allowing rapid incorporation of newly identified anatomical variations and treatment patterns (Patel et al., 2023).

Future AI platforms may also support personalized endodontic treatment planning by integrating microscopic images with CBCT findings, patient demographics, clinical history, previous restorative procedures, and electronic health records. Similar multidimensional AI frameworks have already been proposed across other dental disciplines and represent an important step toward precision dentistry (Feher et al., 2024).

Long-term development may eventually lead to semi-autonomous robotic assistance during selected stages of endodontic treatment. Although fully autonomous procedures remain unlikely in the immediate future, AI-guided navigation systems could provide increasingly sophisticated real-time recommendations that enhance clinician performance while maintaining human oversight.

As AI technologies continue to mature, their successful integration into endodontic practice will depend upon collaborative efforts among clinicians, engineers, computer scientists, regulatory agencies, and professional organizations. Such multidisciplinary cooperation will ensure that technological innovation remains aligned with evidence-based clinical practice, patient safety, and ethical standards.

Conclusion

Artificial intelligence-assisted real-time detection of canal morphology using an operating microscope represents a promising advancement in contemporary endodontic practice. By combining high-resolution magnification with intelligent image analysis, AI has the potential to improve the identification of complex root canal anatomy, accessory canals, calcified canals, and anatomical variations that may otherwise remain undetected during treatment. These capabilities contribute to greater diagnostic precision, facilitate more predictable canal negotiation, and support minimally invasive treatment strategies, thereby enhancing the overall quality of endodontic care.

The rapid evolution of machine learning, deep learning, and computer vision technologies has further expanded the potential applications of AI in dentistry, enabling more efficient interpretation of clinical images and improved decision support systems (Feher et al., 2024; Gonzalez et al., 2024).

The integration of AI into endodontic workflows also aligns with the broader digital transformation occurring across dentistry, where automated algorithms are increasingly being used to analyze clinical records, monitor disease progression, and assist clinicians in making evidence-based decisions (Patel et al., 2023). Although operating microscopes have significantly enhanced visualization during root canal therapy, AI-assisted image processing provides an additional level of precision by offering real-time recognition of anatomical landmarks and reducing operator-dependent variability. Such technological synergy has the potential to improve treatment efficiency, minimize procedural errors, and increase the likelihood of long-term treatment success.

Despite these encouraging developments, several challenges remain before widespread clinical implementation can be fully realized. The availability of large, diverse, and well-annotated datasets is essential for developing robust and generalizable AI models. Furthermore, issues related to algorithm validation, interoperability with existing imaging systems, regulatory approval, data privacy, and clinician acceptance require continued attention. Standardized clinical protocols and multicenter validation studies will be necessary to ensure the safety, reliability, and reproducibility of AI-assisted diagnostic systems across diverse patient populations and clinical settings (Feher et al., 2024; Patel et al., 2023).

The successful incorporation of AI into endodontic practice should also remain grounded in evidence-based clinical principles. While technological innovations provide valuable diagnostic support, they are intended to complement rather than replace clinician expertise, sound biological understanding, and comprehensive patient assessment. The importance of evidence-based treatment planning and preservation of oral tissues continues to underpin successful dental care across all specialties

(Hämmerle et al., 2012; Isola et al., 2023). Similarly, maintaining optimal oral health through effective disease prevention and microbial control remains fundamental to achieving favorable long-term outcomes following endodontic therapy (Mummolo et al., 2020).

As digital dentistry continues to evolve, AI-assisted operating microscopy is expected to become an increasingly valuable component of precision endodontics. Future developments involving multimodal imaging, augmented reality, cloud-based learning systems, and continuous algorithm refinement may further improve real-time clinical decision-making and treatment predictability. Together with ongoing advances in restorative materials and comprehensive patient-centered care, these innovations are likely to contribute to more accurate diagnoses, improved procedural efficiency, and enhanced clinical outcomes in modern dental practice (Singh, 2025; Feher et al., 2024). Ultimately, AI-assisted real-time canal morphology detection represents a significant step toward more intelligent, precise, and evidence-based endodontic treatment, with considerable potential to improve both clinician performance and patient care.

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