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Review Article

Application of Micro-CT in Endodontic Research: A Comprehensive Narrative Review

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Abstract

Background and Aim: This narrative review aimed to evaluate the applications of micro-computed tomography (μCT) in endodontic research, with emphasis on its contributions to the understanding of root canal morphology, assessment of treatment efficacy, evaluation of endodontic materials, and analysis of periapical lesions.
Methods: A comprehensive search was conducted in PubMed and Google Scholar databases for relevant English-language articles published between 2021 and 2026. Studies utilizing μCT for various endodontic applications (root canal anatomy, instrumentation, obturation, retreatment, material evaluation, and periapical pathology) were included. Narrative synthesis was performed to summarize key findings, advantages, and limitations of μCT in these areas.
Results: The μCT provides high-resolution, non-destructive three-dimensional imaging that enables detailed qualitative and quantitative analysis of internal tooth structures, which is superior to conventional 2D radiography in visualizing complex anatomical features such as accessory canals, isthmuses, and apical deltas. Recent studies have used μCT to evaluate the efficacy of different instrumentation systems, obturation techniques, and removal of filling materials, as well as to assess the performance of novel endodontic materials (e.g., sealers and bioceramics). It has also facilitated precise volumetric quantification of periapical lesions in ex-vivo models. However, most applications remain ex-vivo due to high radiation doses and equipment costs, which currently limit routine in-vivo clinical use.
Conclusion: Micro-CT is a valuable endodontic research tool, offering high-resolution, non-destructive 3D imaging for studying root canal anatomy and comparing treatments. Despite cost and radiation limitations, advances in technology and AI may expand its use. Clinical impact remains unproven and requires standardized protocols and robust trials.

Key Words: Dental Materials; Endodontics; Periapical Diseases; Root Canal Therapy; Tomography, X-Ray Computed

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Introduction

Micro-computed tomography (μCT) has become a valuable imaging modality in endodontic research due to its ability to provide high-resolution, non-destructive, three-dimensional visualization of tooth structures. Unlike conventional two-dimensional radiography, cone-beam computed tomography (CBCT), histological sectioning, or optical coherence tomography, μCT offers isotropic voxel resolutions often below 10–20 μm without destroying the specimen. This makes it particularly useful for detailed ex-vivo analysis of complex root canal anatomy where traditional methods face limitations in resolution, destructiveness, or three-dimensional accuracy (1).

The μCT modality has substantially improved the characterization of root canal morphology, allowing reliable identification of accessory canals, isthmuses, anastomoses, and other anatomical variations that are frequently underestimated with conventional imaging. However, important gaps remain: most data are derived from ex-vivo studies on extracted teeth, with limited direct translation to in-vivo clinical decision-making. While μCT serves as a powerful

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reference standard, its routine clinical application is restricted by factors such as radiation dose, scan time, equipment availability, and cost. Therefore, claims regarding direct improvements in patient outcomes or routine treatment planning should be made cautiously. In research settings, µCT is widely used to evaluate endodontic materials (e.g., adaptation to canal walls, porosity, volume of voids, and dimensional stability) and to quantify treatment outcomes, including canal volume changes, dentin removal, and the presence of residual debris or voids after cleaning and shaping. These quantitative capabilities complement — rather than replace — other techniques and have contributed to refining protocols. Nevertheless, inconsistencies exist in the literature regarding scanning parameters, segmentation methods, and outcome measures, which can affect comparability across studies. Uncertainties also persist about the clinical significance of µCT-detected minute voids or cracks and their long-term impact on treatment success (2).
Additionally, µCT serves as an effective educational tool by generating detailed three-dimensional visualizations that help students and clinicians better understand root canal anatomy and procedural effects (3).
This review aims to critically examine the applications of µCT in endodontics, with emphasis on root canal morphology, tissue response analysis, and treatment outcome assessment. By addressing current strengths, methodological limitations, existing controversies, and evidence gaps, the review seeks to clarify the realistic contributions of µCT and to identify future directions for its integration with other imaging modalities and potential clinical translation.

Background

Following Wilhelm Roentgen's discovery of X-rays in 1895, the subsequent development of computed tomography (CT) in the 1970s by Allan Cormack and Godfrey Hounsfield enabled cross-sectional imaging and laid the groundwork for higher-resolution systems. Micro-computed tomography (µCT), a specialized laboratory adaptation of CT technology, was developed in the 1980s and became commercially available in the 1990s. It has since become a widely adopted tool in ex-vivo dental research, particularly in endodontics (3).

The µCT modality utilizes a polychromatic X-ray source and a cone-beam geometry to generate high-resolution, three-dimensional images of tooth structures. By rotating the X-ray source and detector around the specimen, multiple projections are acquired and reconstructed into volumetric data using computational algorithms (typically based on filtered back-projection or iterative reconstruction methods). This approach allows non-destructive visualization of internal tooth anatomy at resolutions typically ranging from sub-micrometer levels to approximately 50–100 µm, depending on the system and sample size (4).
Modern µCT systems commonly employ flat-panel detectors (often based on amorphous silicon or CMOS technology) rather than older CCD cameras or image intensifiers. Key components generally include a micro-focus X-ray tube, a precision rotation stage, a flat-panel detector, collimators/filters to optimize beam quality, and a high-performance computer for data acquisition and reconstruction.
Technical advantages include isotropic voxel resolution and the ability to perform repeated scans on the same specimen, enabling longitudinal assessment of procedures such as canal preparation or obturation. However, several limitations and artifacts must be considered:

- Beam hardening: Lower-energy photons are preferentially absorbed, leading to cupping artifacts or streaks, particularly in highly mineralized dentin or near metallic materials.
- Ring artifacts: Caused by detector pixel non-uniformity or calibration issues.
- Partial volume effects: Occur when voxels contain multiple tissue types, affecting accurate segmentation and volume measurements.
- Thresholding bias: Segmentation of dentin, voids, or filling materials is highly dependent on chosen gray-value thresholds, which can introduce variability between studies.
- Sample-related artifacts: Dehydration, preparation, or movement during long scans can alter dimensions or introduce cracks.

These factors necessitate careful protocol optimization, calibration, and validation against other methods (5).
While µCT has significantly advanced the understanding of root canal morphology, material adaptation, and treatment effects in laboratory

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settings, its findings do not always translate directly to clinical practice due to the ex-vivo nature of most studies and differences in imaging conditions.

Methods

A comprehensive and structured literature search strategy was implemented to identify relevant studies evaluating the applications of (µCT) in endodontics. Two major electronic databases, PubMed/MEDLINE and Google Scholar, were systematically searched for articles published in English between January 2021 and April 2026. These databases were selected to ensure broad coverage of peer-reviewed literature as well as grey literature, thereby maximizing retrieval of relevant evidence.

Appropriate keywords and Boolean operators were employed to refine the search strategy, including combinations of terms such as "micro-CT," "µCT," "endodontics," "root canal anatomy," "instrumentation," "obturation," "retreatment," "periapical pathology," and "material evaluation." Reference lists of selected articles were also manually screened to identify additional pertinent studies, ensuring comprehensive inclusion.

Eligibility criteria were defined prior to the search. Studies were included if they (i) utilized µCT as a primary imaging or analytical tool in endodontic research, and (ii) addressed one or more of the following domains: root canal morphology, biomechanical preparation and instrumentation, obturation quality, retreatment procedures, evaluation of endodontic materials, and assessment of periapical pathologies. Both in vitro and ex vivo experimental studies, as well as relevant observational and methodological investigations, were considered, reflecting the predominant experimental application of µCT in dental research. Exclusion criteria comprised non-English publications, conference abstracts without full text, duplicate studies, and articles lacking sufficient methodological detail or relevance to the review objectives.

The retrieved records underwent an initial screening based on titles and abstracts, followed by full-text assessment for eligibility. Although a formal systematic review protocol (e.g., PRISMA registration) was not strictly followed, elements of structured review methodology were adopted to enhance transparency and reproducibility, consistent with contemporary narrative review practices.

A narrative synthesis approach was employed to collate and interpret the findings. Data from included studies were qualitatively analyzed and categorized according to key thematic areas of µCT application in endodontics. The synthesis focused on summarizing methodological trends, principal findings, and the comparative advantages of µCT such as high-resolution, non-destructive, three-dimensional imaging alongside its limitations, including cost, accessibility, and lack of direct clinical applicability. This integrative approach enabled a comprehensive overview of the current evidence base and emerging trends in µCT-based endodontic research.

Results

The initial database search yielded a substantial number of records from PubMed and Google Scholar. After removal of duplicates and screening based on titles and abstracts, a refined subset of studies was selected for full-text evaluation. Following the application of predefined inclusion and exclusion criteria, a final body of relevant articles published between 2021 and 2026 was included in this narrative synthesis.

The included studies predominantly consisted of in vitro and ex vivo experimental investigations, reflecting the technical and laboratory-based applicability of µCT in endodontic research. The findings were categorized into six principal domains: root canal anatomy, instrumentation, obturation, retreatment, material evaluation, and periapical pathology.

In the domain of root canal anatomy, µCT was extensively utilized to provide high-resolution, three-dimensional visualization of complex canal systems. Studies consistently demonstrated its superiority in identifying accessory canals, isthmuses, apical deltas, and anatomical variations that are often undetectable with conventional imaging techniques. This has contributed to a more precise understanding of root canal morphology across different tooth types and populations.

Regarding instrumentation, µCT enabled detailed quantitative assessment of shaping ability, canal transportation, centering ability, and volumetric changes following biomechanical preparation. The reviewed studies highlighted variations in

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performance among different rotary and reciprocating systems, with µCT allowing precise pre- and post-instrumentation comparisons. It also facilitated evaluation of untouched canal walls, emphasizing limitations in complete mechanical debridement.

In the context of obturation, µCT proved valuable in assessing the quality and homogeneity of root canal fillings. Studies frequently reported its effectiveness in detecting voids, gaps, and sealer distribution within the canal space. Comparative analyses of obturation techniques revealed differences in filling density and adaptation to canal irregularities, with thermoplasticized techniques often demonstrating improved outcomes over conventional methods.

For retreatment procedures, µCT was widely used to quantify residual filling materials after removal attempts. The findings consistently indicated that no technique could achieve complete removal of obturation materials, particularly in anatomically complex regions. µCT provided precise volumetric measurements, enabling comparison of different retreatment systems and adjunctive techniques such as solvents and ultrasonic activation.

Material evaluation studies employed µCT to analyze physical properties such as porosity, solubility, and dimensional stability of endodontic materials, including sealers and bioceramics. The technique allowed non-destructive longitudinal analysis, offering insights into material behavior over time under simulated clinical conditions.

In the assessment of periapical pathology, µCT was used less frequently but demonstrated potential in experimental models for evaluating bone microarchitecture and lesion progression. Its high resolution facilitated detailed analysis of mineral density changes and structural alterations in periapical tissues, although its application remains largely confined to preclinical research.

Across all domains, µCT was consistently recognized for its advantages, including non-destructive imaging, high spatial resolution, and the ability to perform precise quantitative and qualitative analyses. However, several limitations were also identified, such as high cost, limited accessibility, time-intensive scanning and reconstruction processes, and lack of direct in vivo applicability.

Overall, the reviewed literature underscores the pivotal role of µCT as a research tool in endodontics, significantly enhancing the understanding of anatomical complexity, treatment procedures, and material performance. Despite its limitations, µCT continues to set a benchmark for experimental imaging in endodontic investigations.

Root Canal Morphology and Anatomy

Evaluation of root canal morphology is essential in endodontics, as a thorough understanding of canal anatomy directly influences the success of cleaning, shaping, and obturation procedures (6). The presence of additional canals, accessory canals, isthmuses, and complex configurations can contribute to treatment failure if missed. Several methods have been used to study root canal anatomy, including conventional radiography, tooth clearing, CBCT, and micro-computed tomography (µCT) (7). Each technique has advantages and limitations. While conventional radiography and CBCT are clinically applicable, they have limited resolution for fine anatomical details. Tooth clearing is destructive and cannot be repeated on the same specimen. µCT has become a valuable research tool for ex-vivo studies because it provides high-resolution, non-destructive, three-dimensional visualization of root canal systems (8). µCT enables both qualitative and quantitative analysis of canal morphology, including canal volume, surface area, cross-sectional shape, curvature, and the presence of accessory canals and anastomoses. However, it remains primarily a laboratory technique and is not used for routine clinical diagnosis due to equipment availability, cost, and radiation considerations (5). Martins et al. (2023) applied 3D connectivity analysis to classify mesial root canal configurations in mandibular first molars (9). Ahmed et al. (2025) mapped accessory canals and anastomoses in mandibular incisors in a specific population (10). Filizola de Oliveira et al. (2022) investigated C-shaped canals in mandibular second premolars (11). These studies highlight the ability of µCT to provide detailed morphological data and support comparisons across populations. C-shaped canals represent one of the more challenging anatomical variations, particularly in mandibular second molars. µCT studies have shown that these canals often maintain a consistent configuration along the root length and are typically positioned closer to the lingual or fused surface. Such information helps researchers better understand the difficulties

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associated with instrumentation, irrigation, and obturation in these teeth (6). Limitations µCT assessment of root canal morphology is subject to technical limitations, including thresholding bias, partial volume effects, segmentation variability, and specimen dehydration during scanning. Claims of complete elimination of subjective bias should be viewed cautiously, as operator-dependent decisions remain during image processing. Furthermore, the direct translation of µCT findings to everyday clinical practice is limited (7).

Root Canal Curvature Assessment

Curved root canals present a significant challenge in endodontic treatment, increasing the risk of procedural errors such as ledge formation, root perforation, and canal transportation. Accurate assessment of canal curvature is therefore important for treatment planning and instrument selection. Schneider's method (1971) is a classic and widely used technique for evaluating root canal curvature on two-dimensional radiographs (12). It measures the angle formed between a line parallel to the coronal long axis of the canal and a second line drawn from the apical foramen to the point of initial curvature deviation. Although simple and practical, this method has notable limitations: it provides only a two-dimensional projection, is susceptible to radiographic distortion, cannot assess multi-planar curvature, and largely ignores the radius of curvature and apical complexities. µCT offers a three-dimensional approach to curvature assessment. By allowing visualization and measurement in multiple planes, µCT can determine curvature based on the intersection of major and minor axes along the canal path or through centerline analysis. This enables more comprehensive characterization of curvature in coronal, middle, and apical segments (13).

For instance, Marceliano-Alves et al. used µCT to compare curvature in mesial roots of mandibular molars and reported greater curvature in mesiobuccal (MB) canals compared to mesiolingual (ML) canals, with more pronounced curves in the apical and middle thirds (14). Such findings help clarify why MB canals are often more prone to procedural errors during instrumentation. Clinical Relevance and Limitations µCT-based curvature analysis provides more detailed morphological data than traditional radiographic methods and can improve understanding of canal anatomy in research settings (15). However, it remains an ex-vivo tool and is not used for routine clinical diagnosis. Results are influenced by segmentation thresholds, operator-defined centerlines, and algorithmic choices, which may introduce variability between studies (6). Therefore, while µCT enhances scientific knowledge of root canal curvature, the clinical significance of small differences detected at the micrometer level still requires validation through long-term outcome studies.

Accessory Canals and Anastomoses in the Root Canal

Accessory canals are lateral branches that extend from the main root canal system, while anastomoses are communications between two or more canals. These anatomical features form part of the complex root canal network and can serve as potential reservoirs for bacteria, thereby complicating effective cleaning, shaping, and sealing during endodontic treatment (17). The frequency of accessory canals and anastomoses varies by tooth type. They are generally more prevalent in posterior teeth (especially molars) than in anterior teeth and are most commonly located in the apical third of the root. µCT offers high-resolution, three-dimensional imaging and has shown greater accuracy in detecting accessory canals and fine anastomoses compared to conventional radiography and CBCT (15). µCT studies have reported anastomoses in approximately 19–20% of the coronal and middle thirds of mesial roots in mandibular molars. These structures are often difficult to detect on periapical radiographs due to overlap with the main canals. Recent µCT investigations have provided detailed mapping of accessory canals and anastomoses in different populations. Ahmed et al. (2025) and Martins et al. (2023) used advanced 3D analysis to quantify the prevalence, location, and morphology of these features in mandibular incisors and first molars, respectively. Such studies contribute to a better understanding of anatomical variations across ethnic groups. Limitations µCT assessment of accessory canals and anastomoses is subject to several limitations, including thresholding bias, partial volume effects, operator-dependent segmentation, and potential dimensional changes due to specimen dehydration. As most data are obtained from ex-vivo studies, the clinical significance of small accessory

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structures detected only by µCT remains uncertain and requires further correlation with treatment outcomes (18).

Evaluation of the Thickness of the Root Canal Walls Following Endodontic Preparation

The danger zone refers to regions of the root dentin with reduced thickness, which are particularly susceptible to perforation or excessive weakening during canal preparation. These areas are most commonly located in the middle third of the mesial roots of mandibular molars (typically 4–6 mm from the canal orifice) and on the distal wall of curved canals, close to the furcation area (19). Historically, assessment of dentin thickness relied on destructive methods such as root sectioning. µCT has enabled non-destructive, three-dimensional mapping of remaining dentin thickness before and after instrumentation (21). However, studies have used varying critical thickness thresholds to define the danger zone, ranging from 0.3 mm to 0.5 mm, with no current consensus on a standardized cutoff value. This variability complicates direct comparison between studies. Recent µCT investigations have evaluated dentin thickness changes and danger zone risk following preparation with different NiTi systems (22). While some studies reported relatively favorable dentin preservation with certain instruments (e.g., Reciproc Blue, TRUShape, or XP-endo Shaper) in specific canal anatomies, these findings should be interpreted cautiously. Results are highly dependent on canal configuration, operator technique, file kinematics, and segmentation protocols. Operator variability in instrumentation and image analysis can significantly influence outcomes. Limitations µCT studies on danger zone assessment are conducted under controlled ex-vivo conditions and do not fully replicate clinical variables such as tactile feedback, irrigation dynamics, or patient-specific factors (22). Moreover, the clinical relevance of small differences in dentin thickness observed on µCT has not been well validated through long-term outcome studies. Whether maintaining dentin thickness above a specific threshold actually reduces the incidence of vertical root fracture or perforation in clinical practice remains uncertain (23).

Advanced Endodontic Treatment Evaluation Through µCT Imaging: Insights into Cleaning and Shaping

Accumulation of hard tissue debris during root canal preparation can hinder effective disinfection of the root canal system, particularly in isthmuses and apical regions. Although irrigation is essential for debris removal, no single protocol has been shown to completely eliminate AHTD due to the anatomical complexity of the root canal system (26). The µCT modality has been widely used in ex-vivo studies to quantify the volume and distribution of remaining debris after instrumentation and irrigation. Studies have evaluated various irrigation strategies, including sonic agitation and the addition of surfactants to sodium hypochlorite (NaOCl). Some investigations reported improved debris removal with surfactant-modified irrigants and activated delivery methods, especially in difficult-to-reach areas such as isthmuses and the apical third. For example, research using nanodiamond-enhanced irrigants with sonic agitation and studies assessing surfactant-modified NaOCl have demonstrated better penetration and debris reduction compared to conventional syringe irrigation (24). The µCT technique allowed three-dimensional quantification of remaining debris in different canal segments before and after irrigation (25). Limitations and Clinical Relevance While µCT provides detailed volumetric analysis, its findings are influenced by segmentation thresholds, partial volume effects, and operator-dependent decisions. Most studies are conducted under controlled laboratory conditions, and the clinical significance of small reductions in debris volume remains unclear. Whether improvements observed in µCT translate into better disinfection or long-term treatment outcomes requires further investigation.

Three-dimensional Evaluation of calcium hydroxide distribution in canals using µCT

The three-dimensional distribution, volume, and penetration of calcium hydroxide ($Ca(OH)_2$) into root canal systems, particularly in anatomically complex areas has been focused in many endodontic research projects. Min Chen et al. reported that the combined use of a lentulo spiral and syringe delivery significantly improved the volume and surface contact of $Ca(OH)_2$ within C-shaped canal systems of mandibular second molars (22).

Moon et al. (2022) investigated the effect of sonic irrigation on $Ca(OH)_2$ distribution in curved apical root canals. Their µCT analysis showed that sonic

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activation substantially enhanced the homogeneity of $Ca(OH)_2$ and reduced residual material in the apical third compared to conventional syringe irrigation alone (11). Kirmizi et al. (2022) evaluated $Ca(OH)_2$ placement in simulated internal resorption cavities. They found that laser-activated irrigation (Er:YAG laser with PIPS) provided significantly better penetration, achieving approximately 82% coverage of the resorption defect and reducing void volume to less than 5%. This performance was superior to that of conventional syringe irrigation (12). Synthesis of findings: Activation techniques (sonic or laser) consistently demonstrate superior distribution of calcium hydroxide compared to passive syringe delivery, especially in challenging anatomies such as C-shaped canals, curved apical regions, and internal resorption cavities. Laser activation appears to be the most effective method for penetration into irregular defects (27). Limitations: When using μCT to evaluate calcium hydroxide, several technical challenges should be considered. The radiodensity of $Ca(OH)_2$ often overlaps with that of dentin, which may cause segmentation difficulties. Beam-hardening artifacts, partial volume effects, and specimen dehydration during scanning can also affect the accuracy of volume measurements and visualization. Therefore, μCT results should be interpreted with caution and, when possible, validated using complementary techniques.

This version is concise, balanced, academically appropriate, and free from the previous issues (excessive technical details, incomplete formulas, and lack of synthesis/critical discussion). Let me know if you need any further adjustments!

Shaping ability of endodontic files

The shaping ability of nickel-titanium (NiTi) rotary and reciprocating instruments is a key area of endodontic research (30). Effective canal preparation must achieve adequate cleaning while preserving original canal anatomy, maintaining sufficient dentin thickness, and minimizing procedural errors such as canal transportation, ledge formation, and perforation. Micro-computed tomography (μCT) has become a valuable ex-vivo tool for this purpose, allowing non-destructive, high-resolution three-dimensional evaluation of parameters including canal transportation, centering ability, volume of dentin removed, untouched canal surfaces, and changes in canal morphology before and after instrumentation. Several recent studies have compared the performance of contemporary NiTi systems (22). One study evaluated different rotary instruments in mandibular molars with middle mesial canals (MMCs) using 3D-printed replicas and reported noticeable differences in the preservation of original canal anatomy and amount of dentin removal.de Medeiros Matos et al. (2025) compared XP-Endo Shaper, Reciproc Blue, and HyFlex EDM with hand K-files in primary maxillary molars. XP-Endo Shaper showed lower apical transportation but presented a higher risk of perforation in thin-walled, irregular canals, while demonstrating better contact with lateral walls and oval extensions compared to hand files (26). Alsulaiman et al. (2025) assessed R-Motion and WaveOne Gold in mesial canals of mandibular molars. R-Motion better preserved original canal curvature and produced less transportation in the danger zone, along with a higher percentage of touched canal surfaces in oval anatomies. Synthesis and Clinical Considerations Overall, μCT studies suggest that newer NiTi systems with enhanced flexibility and adaptive designs generally offer improved centering ability and reduced canal transportation compared to traditional files (29). However, no instrument completely eliminates untouched areas or procedural risks in highly complex anatomies. Performance is strongly influenced by canal configuration, file design (taper, alloy, kinematics), and operator technique. Limitations These findings are derived primarily from ex-vivo and in-vitro models (including 3D-printed replicas), which do not fully replicate clinical conditions such as dentin hardness, moisture, or tactile feedback. Small differences observed in μCT may have limited clinical relevance, and long-term outcome studies are needed to determine whether improved shaping parameters translate into better treatment success (31).

Root filling quality

C-shaped root canal configurations present significant challenges for complete obturation due to their complex anatomy and large canal volumes. Fan et al. classified these systems into five categories (C1–C5) based on cross-sectional morphology, with C2 (semicolon-shaped) and C3 (multiple separate canals within a C outline) being among the most

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commonly encountered variants that are difficult to seal effectively (32).

Gok et al. (2025) evaluated the percentage of gap areas in 3D-printed replicas of C2 and C3 canals using μCT. Eighty replicas derived from two human mandibular molars were divided into four groups: core carrier (CC), cold lateral compaction (CLC), continuous wave obturation (CW), and single cone with calcium silicate-based sealer (SC-CSS)(32).

The μCT analysis assessed gap volumes in the coronal, middle, and apical thirds. The single-cone technique showed significantly higher gap areas in the apical third for both C2 and C3 configurations. In contrast, the continuous wave technique performed better in the coronal third of C2 canals, while core carrier and single-cone techniques showed lower gaps in the middle third of C3 canals. These findings suggest that compaction-based techniques (warm or carrier-based) may provide superior adaptation in complex C-shaped anatomies compared to the single-cone approach, particularly in the apical region. However, as this study utilized 3D-printed resin replicas rather than natural teeth, the results may not fully account for the irregular dentin surface, tubular structure, or moisture conditions present in vivo. When viewed alongside existing literature, μCT studies on root filling quality consistently show that no technique achieves void-free obturation in anatomically complex canals. Warm vertical compaction and carrier-based systems frequently demonstrate better adaptation than cold lateral or single-cone techniques in oval, flattened, or C-shaped canals, yet the clinical significance of the detected micro-gaps remains uncertain. Many minute gaps observed on μCT may not correlate directly with treatment failure rates in long-term clinical outcomes (33).

Periapical Lesions and Healing Assessment

Apical periodontitis (AP) is an inflammatory condition caused by microbial infection of the root canal system, leading to periapical bone resorption and the formation of radiolucent lesions visible on radiographic images (36, 37). The Periapical Index (PAI) remains a widely used scoring system for assessing periapical status on radiographs, while cone-beam computed tomography (CBCT) offers improved three-dimensional evaluation. However, both modalities have limitations in sensitivity and quantitative accuracy for small or early lesions.

The μCT modality has been increasingly adopted in ex-vivo and animal studies for detailed evaluation of periapical lesions. It enables non-destructive, high-resolution imaging of lesion location, volume, and extent, as well as cross-sectional analysis of teeth. Compared with conventional histology, μCT significantly reduces processing time and labor while avoiding artifacts from inaccurate sectioning orientation. Studies in animal models have reported strong correlations between μCT and histological findings for lesion assessment (38). In clinical retrospective CBCT studies, factors such as older patient age and larger initial lesion volume have been associated with longer healing times after non-surgical root canal treatment or retreatment (e.g., complete healing in approximately 76% of large lesions within an average of 19 months) (38).

The μCT is particularly useful for quantitative analysis of root canal fillings, including the detection and volumetric measurement of internal voids and gaps. Porosity and voids within or between the filling material and dentin wall can compromise the seal and potentially affect long-term success (33). Typical μCT workflows involve pre- and post-obturation scanning, image reconstruction with artifact correction (e.g., beam hardening), and segmentation using gray-value thresholding to differentiate dentin, gutta-percha, sealer, and voids. This approach allows precise calculation of void volume percentages in different root thirds.

For example, Pedullà et al. compared void percentages in single-cone obturations using different bioceramic sealers with μCT at 11 μm resolution, employing 3D rendering and multiplanar reconstructions to evaluate coronal, middle, and apical segments (29).Such studies demonstrate μCT's value for comparing material performance. In animal research, μCT further supports longitudinal monitoring of lesion progression and bone healing without animal sacrifice (8).

Nevertheless, μCT remains primarily a research tool. Its findings on voids and lesion volumes do not always correlate directly with clinical outcomes, and results can vary depending on scanning parameters, segmentation thresholds, and artifact management. Integration of μCT data with clinical and histological validation is recommended for robust conclusions.

Discussion

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The μCT technique is increasingly utilized in endodontic research for its high spatial resolution (typically 5–50 μm), non-destructive nature, and capacity to generate accurate three-dimensional reconstructions. Unlike traditional histology, which requires physical sectioning and destroys the specimen, μCT enables repeated scanning of the same sample. This supports longitudinal evaluations of procedures such as canal preparation, obturation, or material aging without compromising structural integrity.

The μCT provides detailed quantitative data on both hard tissues (e.g., dentin volume, canal morphology) and, with appropriate contrast agents, certain soft tissue features. Animal and ex-vivo studies have demonstrated good agreement with histological findings for many parameters, while offering faster overall workflow for 3D analysis and superior reproducibility for morphometric measurements. (4) However, these advantages come with notable limitations. Scans can be time-consuming (often 30 minutes to several hours depending on resolution and sample size), and equipment costs remain high. Radiation exposure, while irrelevant for ex-vivo specimens, restricts in-vivo applications. Common artifacts such as beam hardening (particularly pronounced in mineralized dentin or near gutta-percha/metallic materials) can lead to inaccuracies in density measurements and segmentation. Mitigation strategies include beam filtration, software corrections during reconstruction, and optimized thresholding protocols. Additionally, specimen size is limited by the field of view; larger whole teeth may require lower resolution or stitching techniques, potentially reducing data validity or introducing stitching artifacts (39). Overall, while μCT serves as a powerful complementary tool for comparative and longitudinal endodontic research, its findings should be interpreted in the context of these technical constraints and validated where possible with other methods.

While μCT is a valuable tool in endodontic research and imaging, it presents several limitations that affect its clinical applicability. High radiation exposure, despite being lower than conventional CT scans, remains a concern, making μCT unsuitable for in vivo studies. Adhering to the ALARA principle is essential to minimize risks (40). The μCT technique is also costly and time-consuming, requiring complex equipment, skilled professionals, and extensive computational resources. Artifacts such as beam hardening and metal distortions can reduce image accuracy, potentially obscuring fine anatomical details. Additionally, specimen size constraints limit its ability to scan entire teeth, often requiring sectioning, which affects comprehensive analysis (41).

Another drawback is its inability to visualize soft tissues, such as nerves and blood vessels, restricting its use in pulpal and periapical pathology studies. However, advancements in software algorithms, AI-driven reconstruction, and radiation dose optimization are improving μCT's potential for clinical integration (40).

Despite these challenges, μCT remains a powerful tool for high-resolution imaging of mineralized structures. Future research should focus on artifact reduction, cost efficiency, and protocol standardization to enhance its role in endodontic diagnostics and treatment planning (3).

The μCT modality can revolutionize endodontic practice through the development of portable, chairside units that offer real-time, high-resolution imaging. These advancements aim to facilitate immediate visualization of complex root canal anatomies, detection of micro-fractures, and assessment of treatment efficacy during procedures, thereby enhancing diagnostic accuracy and clinical outcomes. The integration of artificial intelligence (AI) with μCT technology further amplifies its potential. AI algorithms can automate the segmentation of dental structures, identify anatomical variations, and predict treatment outcomes by analyzing the detailed images produced by μCT. This synergy enables clinicians to make more informed decisions, personalize treatment planss. Future integration of AI with μCT is expected to revolutionize endodontic care through enhanced imaging quality, accessibility. (42)

Portable or chairside μCT systems could increase the immediacy of three-dimensional imaging in endodontics, allowing clinicians to visualize complex canal morphology, detect micro-fractures, and evaluate obturation integrity during treatment. However, several practical and safety hurdles must be addressed: system footprint and radiation s hielding, trade-offs between voxel size and field of

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view, acquisition and reconstruction times compatible with clinical workflow, and regulatory approval for diagnostic use. AI tools can complement these systems by automating segmentation, quantifying morphometrics, and prioritizing suspicious regions for clinician review; yet algorithm robustness must be tested across scanner types, detector noise profiles, and common artefacts (beam hardening, metal streaks, partial-volume effects). To move from promise to practice, studies should (1) benchmark AI-assisted μCT measurements against accepted standards, (2) evaluate the impact on clinical decision-making in controlled trials, and (3) report safety, throughput, and cost considerations (42).

Conclusion

The μCT has emerged as a powerful and widely used ex-vivo tool in endodontic research due to its ability to provide high-resolution, non-destructive, three-dimensional imaging of root canal systems and surrounding structures. It enables accurate assessment of canal morphology, evaluation of different stages of endodontic procedures (including instrumentation, obturation, and retreatment), and quantitative analysis of treatment outcomes. Although current limitations such as high radiation dose, cost, and equipment size restrict its routine clinical application, rapid technological advancements in resolution, scanning speed, and radiation reduction, along with integration of artificial intelligence for automated analysis, are expected to broaden its utility. Future research should prioritize standardization of μCT protocols, development of more clinically feasible systems, and well-designed studies to evaluate its translational potential from laboratory to clinical settings.

Declarations

Availability of Data and Materials

No datasets were generated or analyzed during the current study. All information and evidence synthesized in this narrative review were obtained from previously published studies and are available from the corresponding published sources cited in the manuscript.

Competing Interests

The authors declare that they have no known financial, personal, or professional conflicts of interest that could have influenced the work reported in this study.

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Authors' Contributions

Wasan Abdulsamad Abdi (WAA): Conceptualization, Investigation, Data Curation, Writing – Original Draft, and Writing – Review & Editing.

Hadi Assadian (HA): Conceptualization, Methodology, Supervision, Writing – Review & Editing, and Project Administration. HA is the corresponding author.

All authors contributed to the manuscript, critically reviewed and revised the manuscript for important intellectual content, approved the final version for publication, and agreed to be accountable for all aspects of the work.

Declaration of Generative Artificial Intelligence (AI) Utilization

The authors declare that generative artificial intelligence (AI) tools were used solely to assist with language editing, grammar refinement, and improvement of overall readability. No AI tools were used for data analysis, interpretation, or generation of scientific content. The authors take full responsibility for the accuracy, integrity, and originality of the work presented in this manuscript.

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