Machine learning analysis of root canal anatomy in different ethnic populations using CBCT

Vishal Singh
B.D.S
Vishalsinghmds@gmail.com

Abstract

Root canal anatomy exhibits considerable variation among individuals and ethnic populations, presenting significant challenges for accurate diagnosis and successful endodontic treatment. Cone-beam computed tomography (CBCT) has transformed the evaluation of root canal morphology by providing high-resolution three-dimensional images that overcome many limitations of conventional radiography. The integration of machine learning (ML) with CBCT imaging has further enhanced the ability to automatically identify, segment, classify, and predict complex root canal configurations with improved speed, consistency, and diagnostic accuracy. ML algorithms, particularly deep learning models, can analyze large CBCT datasets to detect subtle anatomical variations and support personalized treatment planning across diverse populations. Understanding ethnicity-related differences in root canal morphology enables the development of more robust and generalizable predictive models while reducing the risk of missed canals and procedural complications. Despite promising advances, challenges remain regarding dataset diversity, annotation quality, algorithm bias, and clinical validation. Continued research involving multi-ethnic datasets and standardized imaging protocols is expected to improve the reliability and clinical applicability of AI-assisted endodontic diagnosis. Overall, the combination of machine learning and CBCT represents a significant advancement toward precision endodontics and individualized patient care.

Keywords: Machine learning, artificial intelligence, cone-beam computed tomography, CBCT, root canal anatomy, ethnic populations, deep learning, endodontics, dental imaging, root canal morphology.

1. Introduction

Successful endodontic treatment relies on a comprehensive understanding of root canal anatomy, as undetected canals or anatomical variations remain among the leading causes of treatment failure. Root canal systems exhibit substantial complexity and variability in terms of canal number, configuration, curvature, and accessory branches. These variations are influenced by numerous factors, including ethnicity, genetics, age, and developmental processes. Consequently, accurate identification of root canal morphology before and during treatment is essential for effective cleaning, shaping, disinfection, and obturation, ultimately improving the long-term prognosis of endodontically treated teeth (Chandra et al., 2021).

Traditional diagnostic techniques, including periapical radiography, provide only two-dimensional representations of three-dimensional anatomical structures, limiting the clinician's ability to identify complex canal systems and overlapping anatomical features. The introduction of cone-beam computed tomography (CBCT) has transformed endodontic diagnosis by enabling high-resolution three-dimensional visualization of dental structures with greater anatomical accuracy. CBCT allows clinicians to evaluate root morphology, canal configurations, additional canals, root curvatures, and surrounding periapical tissues more effectively than conventional imaging techniques. Furthermore, CBCT has become an integral component of modern digital dentistry workflows, facilitating improved diagnosis, treatment planning, and clinical decision-making (Lo Giudice et al., 2020).

Although CBCT has significantly enhanced diagnostic capabilities, the increasing volume and complexity of imaging data present new challenges. Manual interpretation of CBCT scans requires extensive expertise and is subject to observer variability, fatigue, and inconsistencies. These limitations have encouraged the integration of artificial intelligence (AI), particularly machine learning (ML), into dental imaging to automate image analysis and improve diagnostic efficiency. Machine learning algorithms are capable of identifying hidden patterns within large imaging datasets, allowing automated recognition, segmentation, and classification of anatomical structures with high levels of precision. The successful application of machine learning in oral healthcare has already been demonstrated in several diagnostic domains, including automated lesion detection, disease classification, and image interpretation (Feher et al., 2022).

Recent advances in deep learning have further accelerated the development of automated CBCT analysis systems. Convolutional neural networks and related deep learning architectures can accurately segment teeth, identify root canal morphology, and recognize subtle anatomical variations that may be overlooked during manual examination. Systematic evaluations have demonstrated the growing reliability of automated tooth segmentation from CBCT datasets, highlighting the potential of these technologies to reduce clinician workload while improving consistency and reproducibility in dental image analysis (Polizzi et al., 2023). Similar advances have also been reported in other dental imaging applications, where computer vision models have achieved high diagnostic performance in detecting oral diseases from digital images, further illustrating the expanding role of AI in clinical dentistry (Swamikannan et al., 2024).

One of the most clinically relevant applications of machine learning in endodontics is the analysis of root canal anatomy across different ethnic populations. Numerous anatomical studies have demonstrated that the prevalence of additional canals, canal configurations, root fusion, and accessory anatomy differs significantly among various population groups. These ethnic variations influence treatment strategies and may affect the likelihood of locating additional canals during root canal therapy. Machine learning models trained on diverse CBCT datasets can identify population-specific anatomical characteristics while simultaneously learning generalized morphological patterns applicable across multiple ethnic groups. Such predictive capabilities have the potential to support personalized treatment planning and reduce procedural errors associated with unexpected anatomical complexity.

The increasing adoption of digital dentistry has further strengthened opportunities for integrating AI into routine endodontic practice. Digital workflows combining CBCT imaging, automated segmentation, artificial intelligence, and clinical decision-support systems are becoming increasingly sophisticated, enabling more efficient and standardized patient care. The development of structured digital workflows and standardized assessment frameworks also contributes to improving the consistency, reproducibility, and educational implementation of AI-assisted diagnostic systems within dentistry (Badr et al., 2026). These technological advances align with the broader movement toward precision dentistry, where diagnostic and therapeutic decisions are increasingly individualized using advanced computational tools.

The broader application of artificial intelligence within healthcare reflects the growing recognition that biological variability significantly influences disease diagnosis and treatment planning. Advances in computational biology and biomedical research continue to demonstrate the importance of integrating complex biological datasets to better understand individual variability and improve clinical outcomes (Kitamoto et al., 2020). Similarly, in endodontics, combining CBCT imaging with machine learning provides an opportunity to analyze extensive anatomical datasets that would be difficult to evaluate manually, thereby facilitating more accurate characterization of root canal morphology across diverse populations.

Despite these promising developments, several challenges remain before machine learning-based CBCT analysis can be routinely implemented in clinical practice. Limitations related to dataset diversity, annotation quality, algorithm transparency, external validation, and potential ethnic bias require careful consideration to ensure reliable and equitable performance across different patient populations. Addressing these challenges through multicenter collaborations, standardized imaging protocols, and representative datasets will be essential for developing robust and clinically applicable AI systems.

Against this background, this review explores the application of machine learning techniques for analyzing root canal anatomy in different ethnic populations using CBCT imaging. It examines current technological advances, available machine learning algorithms, ethnic variations in root canal morphology, clinical applications, existing limitations, and future directions that may contribute to more accurate, personalized, and evidence-based endodontic care.

2. Root Canal Anatomy and Ethnic Variations

2.1 Fundamentals of Root Canal Anatomy

Root canal anatomy forms the foundation of successful endodontic diagnosis and treatment. The internal morphology of teeth is highly complex, consisting of the pulp chamber, main canals, lateral canals, accessory canals, isthmuses, apical deltas, and numerous anatomical communications. Failure to recognize these variations may result in incomplete debridement, persistent microbial infection, and eventual treatment failure. Comprehensive knowledge of canal morphology is therefore essential for locating all canals, achieving effective chemomechanical preparation, and obtaining a three-dimensional seal during obturation (Chandra et al., 2021).

Traditionally, root canal morphology has been classified using systems such as Vertucci's classification, although several expanded classification systems have since been proposed to accommodate newly identified anatomical configurations. Modern three-dimensional imaging techniques, particularly cone-beam computed tomography (CBCT), have significantly improved clinicians' ability to visualize these complex canal systems compared with conventional two-dimensional radiographs. Digital workflows integrating CBCT data provide accurate anatomical visualization that enhances treatment planning and supports advanced diagnostic approaches (Lo Giudice et al., 2020).

Clinically, anatomical complexity directly influences the difficulty of endodontic procedures. Teeth may exhibit additional roots, bifurcated canals, C-shaped canals, middle mesial canals, accessory foramina, and apical ramifications that cannot always be identified using conventional radiography. These anatomical features increase the risk of missed canals and inadequate cleaning if not properly recognized before treatment. Consequently, understanding root canal anatomy remains a prerequisite for predictable long-term treatment outcomes (Chandra et al., 2021).

2.2 Factors Influencing Root Canal Anatomy

Root canal morphology is influenced by numerous biological and developmental factors that contribute to individual anatomical diversity.

2.2.1 Genetic Influences

Genetic determinants play a primary role in tooth development and root formation. Variations in odontogenesis influence root number, canal configuration, dentin deposition, and apical anatomy. Genetic diversity among populations partly explains why certain anatomical patterns are consistently observed within specific ethnic groups.

2.2.2 Ethnicity and Racial Diversity

Ethnicity is among the most significant determinants of root canal morphology. Numerous investigations have demonstrated substantial differences in canal configurations among Asian, African, European, Middle Eastern, and Hispanic populations. Certain anatomical variations, including C-shaped canals, radix entomolaris, and additional mesiobuccal canals, occur with markedly different frequencies among ethnic populations. These differences emphasize the importance of incorporating population-specific anatomical knowledge into clinical decision-making and machine learning model development.

2.2.3 Age-Related Changes

Age influences canal morphology primarily through continued deposition of secondary and tertiary dentin. Progressive calcification narrows canal diameters, reduces pulp chamber volume, and may obscure accessory canals. Older patients therefore present greater diagnostic and technical challenges during endodontic treatment.

2.2.4 Gender Differences

Although gender-related differences are generally less pronounced than ethnic differences, studies have reported modest variations in root dimensions, canal diameters, and tooth size. These differences may influence instrumentation strategies but are generally considered secondary to genetic and ethnic factors.

2.2.5 Environmental and Developmental Factors

Environmental influences during tooth development—including nutrition, systemic health, developmental disturbances, and functional loading—may contribute to subtle variations in root formation. These factors interact with genetic determinants to produce considerable anatomical diversity among individuals.

2.3 Ethnic Variations in Root Canal Morphology

Recognition of ethnic differences in root canal anatomy has become increasingly important with the globalization of dental practice and the development of artificial intelligence-assisted diagnostic systems. Machine learning algorithms trained using CBCT datasets must adequately represent diverse populations to minimize algorithmic bias and improve diagnostic performance across different demographic groups.

2.3.1 Asian Populations

Asian populations exhibit several distinctive anatomical characteristics. C-shaped canals are frequently observed in mandibular second molars, while mandibular first molars commonly demonstrate additional roots or complex canal systems. Maxillary first molars also exhibit a relatively high prevalence of second mesiobuccal (MB2) canals. These anatomical characteristics require careful CBCT evaluation before treatment planning.

2.3.2 African Populations

African populations often demonstrate greater anatomical complexity with increased variability in canal number and root morphology. Studies have reported higher frequencies of accessory canals, complex canal branching, and variations in apical anatomy compared with some other populations. Such complexity highlights the need for meticulous three-dimensional assessment before endodontic intervention.

2.3.3 European Populations

European populations generally present more commonly reported Vertucci canal configurations, although considerable variation remains. MB2 canals in maxillary molars and two-canaled mandibular premolars are frequently encountered. CBCT imaging has substantially improved the detection of these clinically significant anatomical features.

2.3.4 Middle Eastern Populations

Middle Eastern populations exhibit considerable heterogeneity due to extensive genetic diversity. Studies have demonstrated relatively high frequencies of additional canals in mandibular premolars, mandibular molars, and maxillary molars. Population-specific anatomical characteristics underscore the importance of individualized radiographic assessment.

2.3.5 Hispanic and Latin American Populations

Hispanic and Latin American populations display mixed anatomical characteristics reflecting diverse ancestral backgrounds. Considerable variation exists in canal morphology, root fusion, and accessory canal prevalence. Clinicians should therefore avoid assuming standard anatomical configurations solely based on tooth type and instead utilize advanced imaging when anatomical complexity is suspected.

The increasing availability of CBCT imaging has enabled the creation of large digital datasets for automated anatomical analysis. Machine learning algorithms trained on these datasets have demonstrated promising capabilities for detecting canal morphology, segmenting dental structures, and supporting clinical decision-making. Systematic reviews indicate that automated CBCT segmentation continues to improve in accuracy, providing an important foundation for future ethnicity-aware diagnostic models (Polizzi et al., 2023). Similarly, advances in machine learning across dental diagnostics have shown that artificial intelligence can successfully emulate complex diagnostic reasoning, suggesting similar potential for automated analysis of root canal anatomy (Feher et al., 2022). Digital workflow standardization further enhances reproducibility and supports the integration of AI into routine clinical practice (Lo Giudice et al., 2020; Badr et al., 2026).

Although artificial intelligence applications in dentistry continue to expand, their success depends heavily on representative datasets and standardized imaging protocols. Research involving computer vision in oral healthcare demonstrates that robust machine learning performance requires large, diverse datasets and rigorous validation, principles equally applicable to CBCT-based root canal analysis (Swamikannan et al., 2024). While broader biomedical studies have illustrated the influence of genetic diversity on human biological variation (Kitamoto et al., 2020), similar principles reinforce the importance of considering ethnic diversity when developing predictive models for dental anatomy.

Table 1. General Characteristics of Root Canal Anatomy Among Different Ethnic Populations

Ethnic Population	Common Anatomical Characteristics	Frequently Affected Teeth	Clinical Significance
Asian	High prevalence of C-shaped canals, MB2 canals, additional roots	Mandibular second molars, maxillary first molars	Increased risk of missed canals; CBCT strongly recommended
African	Greater canal complexity, accessory canals, apical branching	Molars and premolars	Requires careful canal exploration and irrigation
European	Predominantly Vertucci Type I–IV configurations with frequent MB2 canals	Maxillary molars, mandibular premolars	Moderate anatomical variability requiring thorough evaluation
Middle Eastern	Variable root numbers and additional canals due to genetic diversity	Premolars and molars	Individualized treatment planning is essential
Hispanic/Latin American	Mixed anatomical characteristics with variable canal morphology	Molars and premolars	Wide anatomical diversity supports preoperative CBCT assessment

Overall, root canal anatomy demonstrates substantial variability that is strongly influenced by ethnicity, genetics, age, and developmental factors. The incorporation of CBCT imaging and machine learning technologies offers unprecedented opportunities to identify these variations accurately, improve diagnostic precision, and support personalized endodontic treatment planning across diverse populations (Polizzi et al., 2023; Feher et al., 2022; Lo Giudice et al., 2020).

3. CBCT Imaging for Root Canal Anatomy Assessment

3.1 Principles of CBCT Imaging

Cone-beam computed tomography (CBCT) has become an indispensable imaging modality in modern endodontics because it provides three-dimensional (3D) visualization of dental and maxillofacial structures with significantly greater anatomical detail than conventional two-dimensional radiography. Unlike periapical or panoramic radiographs, which compress complex anatomical structures into a single plane, CBCT reconstructs volumetric datasets that allow clinicians to examine teeth from axial, coronal, and sagittal perspectives. This capability is particularly valuable when evaluating root canal anatomy, accessory canals, root curvatures, canal bifurcations, and developmental anomalies that may otherwise remain undetected (Lo Giudice et al., 2020).

CBCT systems employ a cone-shaped X-ray beam and a flat-panel detector that rotate around the patient's head, capturing numerous projection images during a single scan. Specialized reconstruction algorithms subsequently generate isotropic voxels, producing highly accurate volumetric images suitable for detailed anatomical assessment. The relatively small field of view (FOV) commonly used in endodontics minimizes radiation exposure while maximizing spatial resolution for individual teeth and surrounding tissues (Lo Giudice et al., 2020).

The ability of CBCT to provide precise measurements of root dimensions, canal morphology, and surrounding osseous structures has substantially improved diagnostic confidence before initiating endodontic treatment. Clinicians can accurately determine the number of roots, identify canal configurations, evaluate apical morphology, and detect anatomical variations that influence treatment planning. These capabilities are especially important when studying ethnic differences in root canal anatomy, where subtle morphological variations require comprehensive three-dimensional visualization.

3.1.1 Image Acquisition

Image acquisition begins with appropriate patient positioning and selection of imaging parameters including field of view, voxel size, exposure time, and tube current. Endodontic examinations generally utilize a limited FOV and smaller voxel sizes to optimize image resolution while maintaining radiation doses as low as reasonably achievable. Proper stabilization of the patient reduces motion artifacts that can compromise image quality.

Following image acquisition, hundreds of projection images are reconstructed into a volumetric dataset using dedicated reconstruction software. The resulting dataset allows clinicians to evaluate complex canal systems from multiple viewing angles without superimposition of adjacent anatomical structures (Lo Giudice et al., 2020).

3.1.2 Three-Dimensional Reconstruction

Three-dimensional reconstruction represents one of CBCT's greatest strengths in endodontics. Volumetric reconstruction enables interactive visualization of the tooth, permitting clinicians to rotate, section, and magnify anatomical structures in real time. Multiplanar reconstruction facilitates simultaneous evaluation in sagittal, coronal, and axial planes, allowing precise identification of canal bifurcations, isthmuses, accessory canals, and apical anatomy.

Advanced software further supports segmentation and volumetric rendering, providing detailed anatomical models that are increasingly integrated into digital workflows and artificial intelligence applications. Automatic segmentation algorithms have demonstrated considerable promise in isolating individual teeth and root canal systems for subsequent quantitative analysis (Polizzi et al., 2023).

3.1.3 Radiation Considerations

Although CBCT exposes patients to higher radiation doses than conventional intraoral radiographs, the effective dose remains considerably lower than that associated with conventional medical computed tomography. Radiation exposure depends primarily on field of view, voxel size, scanning time, and exposure parameters.

Current professional guidelines recommend limiting CBCT examinations to situations where additional three-dimensional information is expected to improve diagnosis or treatment outcomes. Adherence to the ALARA (As Low As Reasonably Achievable) principle remains essential, particularly in younger patients and repeated imaging situations. Appropriate case selection ensures that the diagnostic benefits outweigh the associated radiation risks (Lo Giudice et al., 2020).

3.2 Advantages of CBCT Over Conventional Imaging

CBCT has significantly enhanced endodontic diagnosis by overcoming many inherent limitations of conventional two-dimensional imaging. Superimposition of anatomical structures, geometric distortion, and inability to visualize structures in depth often hinder accurate diagnosis using traditional radiographs. CBCT eliminates many of these challenges through comprehensive three-dimensional visualization.

3.2.1 Three-Dimensional Visualization

Three-dimensional imaging provides clinicians with accurate visualization of tooth morphology without anatomical overlap. The ability to inspect teeth from multiple perspectives improves identification of complex canal systems and root morphology that frequently differ among ethnic populations.

3.2.2 Detection of Accessory Canals

Accessory canals, lateral canals, apical deltas, and canal bifurcations often contribute to persistent infection when left untreated. CBCT enables visualization of many of these anatomical complexities that remain undetectable on conventional radiographs, thereby improving treatment planning and reducing the likelihood of missed canals.

3.2.3 Identification of Anatomical Variations

Ethnic differences in root canal anatomy frequently involve additional roots, C-shaped canals, fused roots, radix entomolaris, and variable canal configurations. CBCT facilitates accurate recognition of these anatomical variations before treatment begins, reducing procedural complications and improving clinical outcomes.

3.2.4 Improved Treatment Planning

Comprehensive anatomical assessment allows clinicians to determine access cavity design, anticipate procedural challenges, estimate canal curvature, evaluate proximity to vital anatomical structures, and select appropriate instrumentation strategies. Accurate preoperative planning contributes to improved long-term success of endodontic therapy (Chandra et al., 2021).

3.3 Limitations of CBCT

Despite its considerable advantages, CBCT possesses several limitations that must be recognized when interpreting images and designing artificial intelligence systems.

3.3.1 Image Artifacts

Metallic restorations, intracanal posts, implants, orthodontic appliances, and patient movement can generate streaking and beam-hardening artifacts that obscure anatomical details. These artifacts may reduce diagnostic accuracy and interfere with automated image analysis algorithms.

3.3.2 Limited Soft Tissue Contrast

CBCT is optimized for visualization of mineralized tissues rather than soft tissues. Consequently, soft tissue discrimination remains inferior to conventional medical CT and magnetic resonance imaging, limiting its applications outside hard tissue assessment.

3.3.3 Radiation Exposure Considerations

Although CBCT delivers relatively low radiation compared with medical CT, unnecessary imaging should be avoided. Appropriate patient selection and optimization of imaging protocols remain essential to minimize cumulative radiation exposure.

3.3.4 Cost and Accessibility

The acquisition and maintenance costs of CBCT equipment remain substantial, limiting widespread accessibility in many regions. Additional expenses related to software, maintenance, image storage, and clinician training further influence implementation, particularly in resource-limited healthcare environments.

3.4 Digital Workflow in CBCT-Based Endodontics

Modern endodontics increasingly incorporates digital workflows that combine CBCT imaging with artificial intelligence, image processing, and computer-assisted diagnostic systems. These workflows improve efficiency, reproducibility, and diagnostic precision while supporting personalized treatment planning.

3.4.1 Image Acquisition Protocols

Standardized acquisition protocols ensure consistency across patient datasets by controlling voxel size, field of view, exposure settings, and patient positioning. Uniform imaging protocols are particularly important when developing machine learning models because inconsistent acquisition introduces unwanted variability into training datasets (Lo Giudice et al., 2020).

3.4.2 Data Preprocessing

Raw CBCT datasets typically undergo preprocessing before quantitative analysis. Common preprocessing procedures include image normalization, artifact reduction, noise filtering, intensity standardization, and region-of-interest extraction. These steps improve image quality and enhance algorithm performance by reducing unnecessary variability.

3.4.3 Segmentation Methods

Segmentation separates individual teeth, roots, canals, and surrounding anatomical structures from volumetric CBCT images. Historically, manual segmentation has been considered the reference standard but is labor-intensive and susceptible to operator variability. Semi-automatic methods reduce workload, whereas deep learning algorithms increasingly enable fully automatic segmentation with high accuracy and reproducibility. Recent systematic evidence indicates that artificial intelligence-based segmentation methods continue to demonstrate substantial improvements in speed and reliability for dental applications (Polizzi et al., 2023).

3.4.4 Integration with AI-Assisted Diagnosis

Artificial intelligence is progressively being integrated into CBCT-based diagnostic workflows to automate anatomical recognition, classify root canal configurations, identify anatomical anomalies, and assist clinical decision-making. Machine learning models developed for dental imaging have demonstrated the capability to emulate complex diagnostic reasoning and support clinicians in interpreting volumetric datasets with increasing accuracy (Feher et al., 2022). Similar advances in computer vision and mobile imaging technologies further illustrate the expanding role of machine learning in oral healthcare diagnostics (Swamikannan et al., 2024).

Table 2. Comparison of CBCT Imaging Components and Their Role in Root Canal Anatomy Assessment

CBCT Component	Primary Function	Clinical Importance	Contribution to Machine Learning Applications
Image acquisition	Capture volumetric dental images	Accurate visualization of root morphology	Provides standardized input datasets
Three-dimensional reconstruction	Generate multiplanar images	Identification of complex canal anatomy	Enables volumetric feature extraction
Small field of view (FOV)	High-resolution localized imaging	Improved endodontic diagnosis	Enhances image quality for algorithm training
Image preprocessing	Noise reduction and normalization	Improved diagnostic clarity	Improves model robustness and consistency
Segmentation	Isolation of teeth and canals	Precise anatomical evaluation	Essential for automated feature identification

Feature extraction	Quantification of anatomical characteristics	Morphological analysis	Generates predictive variables for ML models
AI-assisted diagnosis	Automated interpretation	Faster and standardized diagnosis	Supports canal classification and anatomical prediction
Digital workflow integration	Coordination of imaging and analysis	Efficient clinical decision-making	Facilitates reproducible AI implementation

Digital workflows also support standardized assessment frameworks that improve consistency in clinical training and implementation of digital dentistry technologies. Structured evaluation systems facilitate quality assurance and encourage reproducible integration of advanced imaging modalities into routine clinical practice (Badr et al., 2026).

Overall, CBCT has revolutionized the assessment of root canal anatomy by providing highly accurate three-dimensional visualization that supports both clinical diagnosis and advanced computational analysis. Its integration with digital workflows and machine learning techniques enables more reliable identification of complex anatomical variations, facilitates ethnicity-based morphological studies, and strengthens precision endodontics. While limitations related to radiation exposure, artifacts, and accessibility remain, ongoing advances in image processing, automated segmentation, and artificial intelligence continue to expand the diagnostic value of CBCT in contemporary endodontic practice (Lo Giudice et al., 2020; Polizzi et al., 2023; Feher et al., 2022).

4. Machine Learning in Root Canal Anatomy Analysis

4.1 Fundamentals of Machine Learning

Machine learning (ML) is a branch of artificial intelligence (AI) that enables computer systems to learn patterns from data and make predictions without explicit programming. In endodontics, ML has emerged as a valuable tool for interpreting cone-beam computed tomography (CBCT) datasets, providing automated assessment of root canal morphology and assisting clinicians in identifying anatomical variations that may otherwise be overlooked. The increasing availability of digital dental imaging, together with advances in computational power, has accelerated the integration of ML into diagnostic workflows (Feher et al., 2022).

Machine learning systems improve diagnostic efficiency by recognizing subtle imaging characteristics across thousands of annotated CBCT scans. Unlike traditional rule-based software, ML models continuously refine their predictive performance through exposure to diverse datasets, making them particularly useful for evaluating anatomical variations among different ethnic populations. Such technologies support evidence-based treatment planning and reduce operator-dependent variability in image interpretation (Polizzi et al., 2023).

Artificial intelligence encompasses several computational approaches, including machine learning and deep learning. While AI refers broadly to systems capable of performing intelligent tasks, ML specifically focuses on algorithms that learn from structured datasets. Deep learning represents a subset of ML employing multiple neural network layers capable of automatically extracting complex imaging features without manual engineering (Swamikannan et al., 2024).

Common learning approaches include:

4.1.1 Supervised Learning

Supervised learning utilizes labeled CBCT datasets in which anatomical structures have been manually identified by experts. The algorithm learns relationships between imaging features and known outcomes, enabling prediction of canal configurations, accessory canals, and root morphology in new patients. This approach is widely employed for segmentation and classification tasks (Polizzi et al., 2023).

4.1.2 Unsupervised Learning

Unsupervised learning analyzes unlabeled datasets to identify hidden structures and similarities. In dental imaging, this approach may group teeth with comparable anatomical characteristics or detect previously unrecognized morphological patterns among different ethnic populations, facilitating exploratory research (Feher et al., 2022).

4.1.3 Deep Learning

Deep learning utilizes multilayer neural networks, particularly convolutional neural networks (CNNs), to automatically recognize complex three-dimensional structures from CBCT volumes. These models have demonstrated excellent performance in image segmentation, anatomical detection, and diagnostic support because they eliminate much of the manual feature extraction required by conventional ML methods (Swamikannan et al., 2024).

4.2 Machine Learning Workflow for CBCT Analysis

Successful ML implementation depends on a structured workflow that ensures data quality, model reliability, and clinical applicability.

4.2.1 Data Collection and Annotation

The first stage involves collecting CBCT scans from diverse patient populations. Experienced endodontists manually annotate canal systems, root morphology, and anatomical landmarks to create reliable training datasets. Ethnically representative datasets improve the ability of algorithms to generalize across different populations (Polizzi et al., 2023).

4.2.2 Image Preprocessing

Raw CBCT images undergo preprocessing to reduce noise, normalize intensity values, remove imaging artifacts, and standardize voxel dimensions. These procedures improve image quality and enhance algorithm performance. Proper preprocessing is an essential component of digital dental workflows (Lo Giudice et al., 2020).

4.2.3 Feature Extraction

Traditional ML methods require extraction of quantitative imaging characteristics such as texture, density distribution, canal curvature, root dimensions, and spatial orientation. Deep learning models automate this process by learning highly discriminative imaging features directly from CBCT volumes (Swamikannan et al., 2024).

4.2.4 Model Development

Annotated datasets are divided into training, validation, and testing groups. During training, algorithms iteratively optimize internal parameters to maximize prediction accuracy while minimizing classification errors. Various optimization techniques and loss functions are employed to improve model robustness (Feher et al., 2022).

4.2.5 Model Validation and Testing

Following development, algorithms undergo validation using independent datasets. Performance is assessed using metrics including accuracy, sensitivity, specificity, precision, recall, Dice similarity coefficient, and area under the receiver operating characteristic curve (AUC). External validation across multiple institutions and ethnic groups improves model reliability (Polizzi et al., 2023).

4.3 CBCT Image Segmentation

Segmentation is fundamental to automated analysis because it isolates individual teeth, roots, pulp chambers, and canal systems from surrounding anatomical structures.

4.3.1 Manual Segmentation

Manual segmentation remains the traditional gold standard. Dental specialists outline anatomical structures slice-by-slice throughout the CBCT volume. Although highly accurate, this process is labor-intensive, time-consuming, and subject to inter-observer variability (Polizzi et al., 2023).

4.3.2 Semi-Automatic Segmentation

Semi-automatic methods combine operator guidance with computer-assisted algorithms. Initial landmarks are provided manually, while software performs region growing or contour detection to complete segmentation. This approach substantially reduces workload while maintaining acceptable accuracy.

4.3.3 Fully Automatic Segmentation

Deep learning-based segmentation systems automatically identify teeth, roots, and root canal systems without manual intervention. Recent systematic reviews have demonstrated high segmentation accuracy using CNN-based architectures, supporting their integration into clinical practice for efficient anatomical analysis (Polizzi et al., 2023).

4.4 Machine Learning Models Used in Endodontics

Various ML algorithms have been investigated for CBCT-based anatomical analysis. Selection depends on dataset size, computational resources, and intended clinical application.

4.4.1 Convolutional Neural Networks (CNNs)

CNNs represent the most widely adopted deep learning architecture for dental imaging. They efficiently recognize complex three-dimensional anatomical structures and achieve excellent performance in canal detection, tooth classification, and morphological assessment (Swamikannan et al., 2024).

4.4.2 U-Net Architectures

U-Net models are specifically designed for medical image segmentation. Their encoder-decoder architecture enables precise localization of anatomical boundaries, making them particularly suitable for delineating root canal systems within CBCT datasets (Polizzi et al., 2023).

4.4.3 Random Forest Algorithms

Random Forest classifiers construct multiple decision trees to classify anatomical variations using engineered imaging features. They perform well with smaller datasets and provide interpretable decision-making processes.

4.4.4 Support Vector Machines (SVM)

Support Vector Machines identify optimal decision boundaries between anatomical classes. SVMs remain useful when training datasets are relatively limited and have demonstrated reliable classification performance in several dental imaging applications (Feher et al., 2022).

4.4.5 Hybrid Artificial Intelligence Models

Hybrid systems combine CNN-based feature extraction with conventional classifiers or ensemble learning techniques. These approaches may improve prediction accuracy while enhancing model robustness across heterogeneous imaging datasets.

Table 3. Major Machine Learning Algorithms for CBCT-Based Root Canal Anatomy Analysis

Machine Learning Model	Primary Function	Advantages	Limitations	Potential Endodontic Applications
Convolutional Neural Networks (CNN)	Image classification and detection	High diagnostic accuracy, automatic feature extraction	Requires large datasets and computational resources	Canal detection, root morphology classification
U-Net	Image segmentation	Precise anatomical boundary delineation	High computational demand	Automatic root canal segmentation
Random Forest	Classification	Robust with smaller datasets, interpretable	Manual feature engineering required	Canal configuration prediction
Support Vector Machine	Pattern classification	Effective for limited datasets	Reduced performance with highly complex images	Anatomical variation classification
Hybrid AI Models	Combined prediction and segmentation	Improved robustness and accuracy	Increased model complexity	Comprehensive CBCT analysis and decision support

4.5 Automated Detection of Root Canal Anatomy

Machine learning has substantially enhanced automated interpretation of CBCT scans by identifying anatomical structures rapidly and consistently.

4.5.1 Canal Identification

Algorithms can automatically detect the location, number, and orientation of root canals, reducing the likelihood of missed canals during treatment planning. This capability is especially valuable in teeth exhibiting complex morphology or ethnic variations.

4.5.2 Canal Classification

ML models classify canal configurations according to standardized systems such as Vertucci's classification. Automated classification improves consistency and facilitates large-scale epidemiological studies across diverse populations (Polizzi et al., 2023).

4.5.3 Detection of Accessory Canals

Accessory canals often remain undetected using conventional radiographs. Deep learning models analyze volumetric CBCT data to identify these clinically significant structures, potentially improving treatment outcomes and reducing persistent infections (Feher et al., 2022).

4.5.4 Prediction of Anatomical Complexity

Beyond simple identification, ML algorithms estimate the probability of anatomical complexities including additional roots, C-shaped canals, severe canal curvature, bifurcations, and calcified canals. Such predictive capabilities support individualized treatment planning before instrumentation begins.

The incorporation of machine learning into CBCT analysis represents a significant advancement in digital endodontics. Standardized digital workflows, robust image segmentation techniques, and clinically validated ML algorithms have the potential to improve diagnostic accuracy, enhance reproducibility, and facilitate personalized management of root canal systems across ethnically diverse populations. The continued evolution of AI-driven diagnostic platforms, together with standardized digital assessment frameworks, is expected to further strengthen clinical decision-making and educational applications in modern dentistry (Lo Giudice et al., 2020; Badr et al., 2026). Although the primary objective of these technologies is anatomical analysis rather than restorative assessment, accurate identification of canal morphology ultimately contributes to successful biomechanical preparation, obturation quality, and long-term structural integrity of endodontically treated teeth (Chandra et al., 2021). Meanwhile, experience gained from broader dental AI applications, including automated diagnostic reasoning, supports continued development of intelligent systems capable of assisting clinicians across multiple domains of oral healthcare (Feher et al., 2022).

5. Machine Learning Analysis Across Different Ethnic Populations

5.1 Development of Ethnicity-Specific AI Models

The development of machine learning (ML) models for root canal anatomy analysis has increasingly emphasized the importance of incorporating ethnic diversity into training datasets. Root canal morphology varies considerably among populations due to genetic, developmental, and environmental influences, making ethnicity an important determinant of anatomical complexity. AI models trained exclusively on homogeneous datasets may demonstrate reduced performance when applied to individuals from different ethnic backgrounds. Consequently, ethnicity-specific and multi-ethnic datasets have become essential for improving the robustness, accuracy, and clinical applicability of predictive algorithms.

CBCT serves as an ideal imaging modality for generating comprehensive datasets because it provides high-resolution three-dimensional visualization of internal tooth anatomy. These volumetric images enable ML algorithms to recognize subtle anatomical differences that may not be evident on conventional radiographs. Automatic segmentation techniques further facilitate the extraction of root canal structures from CBCT images, thereby improving model training efficiency and reducing observer variability (Polizzi et al., 2023). The integration of digital workflows for CBCT acquisition and processing also enhances image standardization, an important prerequisite for reliable AI model development (Lo Giudice et al., 2020).

Deep learning architectures, particularly convolutional neural networks (CNNs), learn complex spatial relationships within CBCT datasets by analyzing thousands of annotated images. During training, these models identify characteristic features associated with specific canal configurations found in different ethnic populations. Proper dataset balancing is essential to prevent overrepresentation of a single population, which may otherwise introduce systematic bias and compromise model generalizability. Multi-center collaborations are therefore increasingly encouraged to collect representative datasets encompassing diverse geographic regions and ethnic groups.

Recent advances in dental AI have demonstrated that combining imaging data with structured clinical annotations significantly enhances algorithm performance. Standardized digital assessment protocols and structured evaluation frameworks improve data consistency, allowing ML systems to generate more reliable predictions across different clinical environments (Badr et al., 2026). Such approaches facilitate the creation of AI systems capable of supporting personalized endodontic diagnosis while accounting for anatomical diversity.

5.2 Comparative Performance Across Ethnic Groups

The diagnostic performance of ML algorithms is influenced by the diversity of populations included during model development. Algorithms trained using data from multiple ethnic groups generally demonstrate superior external validity compared with those developed from single-population datasets. Diverse datasets enable models to recognize broader anatomical variations, thereby reducing the likelihood of misclassification when evaluating patients from underrepresented populations.

Performance metrics commonly reported in ML studies include accuracy, sensitivity, specificity, precision, recall, F1-score, and area under the receiver operating characteristic curve (AUC). High-performing models maintain consistent results across various ethnic groups despite differences in canal morphology. However, reduced performance may occur when rare anatomical variants present in one population are absent from the training data. Such limitations emphasize the need for continual model refinement using internationally representative datasets.

Machine learning has already demonstrated remarkable success in other dental diagnostic applications involving complex image interpretation. Algorithms capable of emulating expert-level clinical reasoning in jaw cyst diagnosis illustrate the potential for transferring similar methodologies to root canal anatomy assessment (Feher et al., 2022). Likewise, advanced computer vision systems developed for oral disease detection have shown that deep learning models can achieve high diagnostic accuracy when trained on sufficiently diverse datasets (Swamikannan et al., 2024). These successes support the feasibility of developing equally reliable ML systems for analyzing ethnic variations in endodontic anatomy.

Bias remains one of the principal challenges in comparative AI performance. Population imbalance during training may cause algorithms to perform exceptionally well for one ethnic group while demonstrating reduced accuracy for others. Regular external validation using independent datasets from multiple regions is therefore necessary before clinical implementation. Such validation ensures fairness, minimizes algorithmic bias, and improves clinician confidence in AI-assisted decision-making.

5.3 Clinical Applications

Machine learning analysis of root canal anatomy offers several clinically significant applications, particularly when combined with CBCT imaging. Automated identification of canal morphology before treatment enables clinicians to anticipate complex anatomy, locate accessory canals, and select appropriate instrumentation strategies. Early recognition of anatomical variations reduces the risk of untreated canals, procedural errors, and treatment failure.

Ethnicity-informed AI systems contribute to personalized endodontic treatment planning by incorporating population-specific anatomical characteristics into diagnostic predictions. Rather than relying solely on generalized anatomical expectations, clinicians may receive individualized assessments based on the patient's CBCT findings and learned population patterns. Such personalized approaches improve treatment precision while minimizing unnecessary removal of tooth structure.

Automatic segmentation algorithms also facilitate rapid three-dimensional visualization of root canal systems. Automated segmentation substantially reduces the time required for image interpretation while improving consistency among clinicians (Polizzi et al., 2023). Digital workflows integrating CBCT acquisition, image processing, and AI analysis further streamline treatment planning and interdisciplinary communication (Lo Giudice et al., 2020).

Decision-support systems represent another promising application. AI-generated recommendations can assist clinicians in identifying additional canals, estimating procedural difficulty, and planning access cavity designs. These systems are intended to complement, rather than replace, clinical judgment. Structured digital evaluation methods may further improve clinician training by providing standardized feedback during interpretation of AI-assisted CBCT analyses (Badr et al., 2026).

Although root canal morphology itself does not directly influence restorative material selection, successful identification and complete treatment of complex canal systems contribute to long-term tooth preservation. Appropriate endodontic treatment enhances structural integrity and supports favorable restorative outcomes following obturation and coronal restoration (Chandra et al., 2021).

5.4 Challenges

Despite encouraging developments, several challenges limit the widespread clinical implementation of ML-based root canal anatomy analysis. One major limitation is the scarcity of large, ethnically balanced CBCT datasets. Many available datasets originate from single institutions or specific geographic regions, limiting their representativeness and increasing the risk of biased predictions.

Image annotation represents another significant challenge. Manual labeling of root canal anatomy requires considerable expertise and is both time-consuming and susceptible to inter-observer variability. Inconsistent annotations reduce training quality and may negatively affect model performance. Standardized annotation protocols and expert consensus guidelines are therefore essential for producing high-quality datasets.

Variability in CBCT acquisition parameters also affects algorithm performance. Differences in voxel size, field of view, scanner manufacturers, and reconstruction protocols introduce heterogeneity into imaging datasets, complicating model generalization. Digital workflow standardization can reduce these inconsistencies and improve reproducibility across institutions (Lo Giudice et al., 2020).

Ethical considerations must also be addressed. The use of patient imaging data requires strict adherence to privacy regulations, informed consent procedures, and secure data management practices. Additionally, developers must ensure that AI systems do not inadvertently reinforce health disparities through algorithmic bias arising from unequal population representation.

Transparent reporting and continual post-deployment monitoring remain essential for maintaining trust in AI-assisted diagnostic systems.

5.5 Future Perspectives

Future research should prioritize the establishment of large international CBCT repositories representing diverse ethnic populations. Such collaborative datasets would substantially improve algorithm robustness while reducing demographic bias. Federated learning approaches, which enable decentralized model training without transferring sensitive patient data, may facilitate international collaboration while preserving patient privacy.

Explainable artificial intelligence (XAI) is expected to play an increasingly important role in endodontics by providing clinicians with interpretable explanations for AI-generated predictions. Greater transparency will enhance clinician confidence, facilitate regulatory approval, and encourage routine clinical adoption.

Continued improvements in automatic tooth segmentation, image preprocessing, and deep learning architectures will further increase diagnostic accuracy and computational efficiency (Polizzi et al., 2023). Integration of AI within comprehensive digital dentistry workflows is expected to allow seamless CBCT acquisition, automated anatomical analysis, treatment planning, and outcome monitoring (Badr et al., 2026; Lo Giudice et al., 2020).

Future ML systems may also integrate clinical variables, demographic characteristics, and genetic information alongside imaging features to generate more comprehensive predictive models. Similar multidisciplinary approaches have demonstrated considerable success in broader biomedical research, highlighting the value of integrating multiple biological data sources for precision healthcare (Kitamoto et al., 2020). Such advances are likely to accelerate the transition toward precision endodontics, where individualized diagnosis and treatment planning become routine components of clinical practice.

Conclusion

Machine learning has emerged as a transformative technology for analyzing root canal anatomy, particularly when integrated with CBCT imaging. Its ability to automatically detect, segment, and classify complex canal configurations offers significant improvements in diagnostic accuracy, efficiency, and consistency compared with conventional image interpretation. The inclusion of ethnically diverse datasets enables ML models to better recognize population-specific anatomical variations, thereby supporting more personalized and precise endodontic treatment planning. As automated segmentation and deep learning algorithms continue to advance, AI-assisted analysis is expected to become an integral component of digital endodontic workflows, enhancing clinical decision-making while reducing observer variability (Polizzi et al., 2023; Lo Giudice et al., 2020).

Despite these advances, challenges related to dataset diversity, annotation quality, algorithmic bias, standardization of CBCT imaging protocols, and external validation remain important considerations before widespread clinical implementation. Addressing these limitations through international collaborations, standardized digital workflows, explainable AI, and robust validation studies will improve the reliability and fairness of ML-based diagnostic systems (Feher et al., 2022; Badr et al., 2026). Ultimately, combining machine learning with CBCT has the potential to advance precision endodontics by enabling individualized assessment of root canal anatomy across different ethnic populations, improving treatment outcomes, preserving tooth structure, and supporting long-term restorative success (Chandra et al., 2021; Swamikannan et al., 2024).

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