

A Comprehensive Review of Root Canal Morphology Assessed by Radiographic Techniques: Evolution from Vertucci Classification to Contemporary Classification Systems

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ABSTRACT

Understanding root canal morphology is essential for successful endodontic diagnosis and treatment. Variations in canal anatomy are considered one of the major causes of endodontic failure due to missed canals and inadequate debridement. Over the years, several techniques have been used to study root canal systems, ranging from tooth clearing methods to advanced radiographic imaging modalities. Among these, radiographic techniques have become highly valuable because they allow non-invasive assessment of root canal anatomy both clinically and in research settings. Conventional intraoral radiography, digital radiography, cone beam computed tomography (CBCT), and micro-computed tomography (micro-CT) have significantly contributed to the understanding of root canal complexity. Various classification systems have also been proposed to describe canal configurations. The Vertucci classification system remains the most widely accepted and commonly used method in endodontic literature. However, increasing knowledge regarding complex root canal anatomy has led to the development of more comprehensive systems such as those proposed by Sert and Bayirli and Ahmed et al. The present review aims to summarize the literature on radiographic techniques used for evaluating root canal morphology and to discuss the evolution of root canal classification systems from traditional to contemporary concepts.

Keywords: CBCT, Endodontics, Micro-CT, Radiographic techniques, Root canal anatomy, Root canal classification, Root canal configuration, Root canal morphology, Vertucci classification.

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Introduction

Successful endodontic treatment depends on complete cleaning, shaping, and obturation of the entire root canal system. A thorough understanding of root canal morphology is therefore essential for achieving long-term treatment success. Variations in root canal anatomy are common and may differ according to ethnicity, age, gender, and tooth type. Failure to identify additional canals and anatomical complexities is considered one of the primary reasons for endodontic failure [1].

The root canal system is highly complex and consists of fins, lateral canals, accessory canals, isthmuses, apical deltas, and multiple canal configurations. Clinicians often encounter challenges in identifying these variations during treatment. Therefore, accurate diagnostic methods are necessary to study root canal anatomy and improve treatment outcomes [2].

Historically, root canal morphology was studied using destructive methods such as sectioning and tooth clearing techniques. Although these methods provided valuable anatomical details,

they could not be used clinically. The development of radiographic imaging revolutionized the assessment of root canal systems by enabling non-invasive visualization of internal tooth anatomy [3]. Conventional radiographs initially served as the primary diagnostic tool, followed by digital radiography and advanced three-dimensional imaging modalities such as cone beam computed tomography (CBCT) [4].

Several classification systems have been introduced to describe root canal configurations. The classification proposed by Vertucci in 1984 became the most widely accepted due to its simplicity and clinical relevance [1]. However, increasing use of CBCT and micro-CT revealed more complex anatomical variations that could not be adequately described by traditional classifications [5, 6, 7]. Consequently, newer systems such as the Ahmed et al. coding classification were developed to provide a more comprehensive description of root canal anatomy [8].

The aim of this review is to summarize literature related to radiographic evaluation of root canal morphology and to provide an overview of historical and contemporary root canal classification systems, including Vertucci and recently proposed coding systems.

Historical Background of Root Canal Morphology Studies

The study of root canal anatomy has evolved considerably over the past century. Early investigations were mainly based on tooth sectioning and staining techniques. Hess and Zurcher were among the first researchers to describe the complexity of root canal systems using dye penetration and sectioning methods. Their studies demonstrated that root canals frequently exhibited accessory branches, apical ramifications, and irregular pathways [9].

Later, Okumura and Weine contributed significantly to the understanding of root canal anatomy by introducing early classification systems [6, 10]. Tooth clearing methods became highly popular because they allowed visualization of the internal canal system after decalcification and dye injection. These techniques provided detailed anatomical information and served as the foundation for future morphological studies [11]. Despite their accuracy, invasive laboratory methods had limitations because they could not be applied clinically. With the introduction of radiographic imaging, clinicians gained the ability

to study canal morphology in vivo. Conventional intraoral radiography became the standard diagnostic method for evaluating canal anatomy during endodontic treatment [3].

Advancements in digital imaging and CBCT further improved the accuracy of anatomical assessment. Modern imaging techniques now allow three-dimensional visualization of root canal systems and have significantly enhanced the understanding of anatomical variations in different populations [12,13].

Radiographic Techniques Used in Root Canal Morphology Studies

1. Conventional Intraoral Periapical Radiography

Conventional intraoral periapical radiography has long been used in endodontics for diagnosing periapical pathology and evaluating root canal morphology. It remains one of the most commonly used diagnostic tools because of its accessibility, low cost, and ease of use.

Multiple angulated radiographs can provide additional information regarding canal configuration and root anatomy. The buccal object rule and Clark's technique are commonly used to identify additional canals and roots. However, conventional radiographs produce two-dimensional images of three-dimensional structures, resulting in superimposition and distortion [13].

One of the major limitations of conventional radiography is its inability to accurately visualize canals in the buccolingual dimension. This limitation often leads to missed canals, especially in teeth with complex anatomy such as mandibular molars and maxillary premolars [12].

2. Digital Radiography (RVG)

Digital radiography or radiovisiography (RVG) represents a major advancement over conventional film-based radiography. RVG provides immediate image acquisition, lower radiation exposure, and improved image quality. Digital images can be enlarged, enhanced, and manipulated to improve visualization of root canal anatomy. The ability to adjust contrast and brightness assists clinicians in identifying additional canals and complex canal systems.

RVG also facilitates better storage and transfer of patient data. Despite these advantages, digital radiography still produces two-dimensional images and shares similar limitations related to anatomical superimposition [2, 14].

3. Cone Beam Computed Tomography (CBCT)

It has transformed endodontic diagnosis by enabling three-dimensional evaluation of root canal systems. It provides axial, coronal, and sagittal views, allowing clinicians to accurately identify canal configurations, accessory canals, root curvatures, and anatomical variations. It has become highly valuable in the diagnosis of complex cases, retreatment procedures, and evaluation of teeth with unusual anatomy. Numerous studies have demonstrated that CBCT is more accurate than conventional radiography for detecting additional canals. CBCT has also facilitated population-based studies on root canal morphology using Vertucci and contemporary classification systems. Researchers have extensively used CBCT to investigate anatomical variations among different ethnic groups. However, CBCT has certain limitations, including higher radiation dose compared to conventional radiography, higher cost, and potential image artifacts. Therefore, its use should be justified according to clinical requirements [12].

4. Micro-Computed Tomography (Micro-CT)

Micro-computed tomography is considered the gold standard for anatomical evaluation of root canal systems in research settings. It provides extremely high-resolution three-dimensional images and allows detailed assessment of canal morphology, isthmuses, accessory canals, and apical anatomy. Micro-CT is primarily used for in vitro studies because of its high radiation dose and limited clinical applicability. Nevertheless, it has greatly contributed to the understanding of root canal complexity and has revealed anatomical variations not previously recognized.

Studies using micro-CT have shown that root canal systems are far more complex than previously believed. The technique has also highlighted the limitations of traditional classification systems [15].

Radiographic Classifications Used in Root Canal Morphology Studies:

1. Vertucci Classification System

M. M. Vertucci proposed the classification system in 1984, which remains one of the most influential and widely used classification methods in Endodontics. He studied root canal morphology using tooth clearing techniques and described eight different canal configurations.

This classification gained worldwide acceptance because of its simplicity and clinical applicability.

It has been extensively used in studies involving conventional radiography, CBCT, and micro-CT [Table 1]. This classification system remains useful for describing common canal configurations. However, the increasing use of advanced imaging techniques has revealed many anatomical variations that cannot be adequately categorized within these eight types.

One limitation of this system is its inability to describe accessory canals, multiple roots with varying canal patterns, and highly complex anatomical configurations. Nevertheless, it continues to serve as the foundational classification system in endodontics [1].

Table 1: Types of Vertucci Classification (Courtesy: Vertucci, et al., (1984))

Type	Configuration	Description
Type I	1-1	Single canal from pulp chamber to apex
Type II	2-1	Two canals leaving chamber and merging into one
Type III	1-2-1	One canal divide and rejoins
Type IV	2-2	Two separate canals from chamber to apex
Type V	1-2	One canal divide into two separate canals
Type VI	2-1-2	Two canals merge and divide again
Type VII	1-2-1-2	Complex dividing and rejoining pathway
Type VIII	3-3	Three separate canals

2. Other Traditional Classification Systems

Weine Classification

Frank S. Weine proposed one of the earliest root canal classification systems in 1969. The Weine classification was primarily based on the configuration of canals within a single root and became an important foundation for later classification systems. Although relatively simple, it played a major role in improving the understanding of root canal anatomy in Endodontics.

This classification consists of four major canal configurations [Table 2]. The Weine classification system was simple and clinically applicable; however, it could not adequately describe the complex canal variations observed in multi-rooted teeth. As anatomical studies progressed, more comprehensive classification systems became necessary [6].

Table 2: Weine classification (Courtesy: Weine, et al., (1961))

Type	Configuration	Description
Type I	1-1	A single canal extends from the pulp chamber to the apex
Type II	2-1	Two separate canals leave the pulp chamber and merge into one canal before exiting at the apex
Type III	2-2	Two separate canals extend independently from the pulp chamber to the apex
Type IV	1-2	One canal leaves the pulp chamber and divides into two separate canals near the apex

Gulabivala Classification

Kishor Gulabivala and colleagues introduced a more detailed classification system while studying root canal morphology in mandibular molars. Their studies, published in 2001, highlighted the complexity of root canal systems and demonstrated anatomical variations beyond the configurations described by M. M. Vertucci.

This classification expanded the description of canal pathways by using numerical representations to describe canal division and merging patterns throughout the root length. Examples of Gulabivala configurations are depicted in [Table 3]. This classification system provided a broader understanding of canal anatomy and demonstrated that root canal morphology is more variable than previously believed. It became particularly important in studies involving mandibular molars and Asian populations. Despite its detailed nature, the system was considered relatively complex for routine clinical application. Nevertheless, it contributed significantly to the evolution of modern root canal classification concepts [2].

Table 3: Gulabivala configuration (Courtesy: Gulabivala, et al., (2001))

Configuration	Description
1-1	Single canal from chamber to apex
2-1	Two canals merging into one
1-2-1	One canal dividing and rejoining
2-2	Two separate canals throughout
1-2	One canal dividing into two
3-1	Three canals merging into one
2-3	Two canals dividing into three
3-2	Three canals merging into two

Sert and Bayirli Classification

SertBayirli proposed a modified root canal classification system in 2004 to overcome the limitations of the M. M. Vertucci classification. Their study demonstrated that many canal configurations observed in different populations could not be adequately categorized using the

existing eight Vertucci types. They expanded the Vertucci system by introducing additional canal configurations, thereby increasing the total number of classified canal types. Their classification included complex patterns involving multiple divisions, rejoinings, and additional canals frequently observed in mandibular premolars and molars.

Some additional Sert and Bayirli canal configurations are depicted in [Table 4]. This classification highlighted the complexity of root canal anatomy and emphasized the need for more comprehensive systems in anatomical studies. Although highly detailed, it became difficult to apply clinically because of the large number of configurations and complex coding patterns.

Nevertheless, this classification represented an important step in the evolution of root canal morphology research and contributed significantly to the development of modern classification concepts [7].

Table 4: Sert and Bayirli canal configurations (Courtesy: Sert and Bayirli, et al., (2004))

Type	Configuration
Type IX	1-3
Type X	1-2-1-2-1
Type XI	4-2
Type XII	2-3-1
Type XIII	1-3-1
Type XIV	4-4
Type XV	2-1-2-1
Type XVI	2-3-2
Type XVII	1-3-2
Type XVIII	3-1-2
Type XIX	2-1-2-1-2
Type XX	4-1

3. Contemporary and New Classification Systems

Ahmed et al. Classification System

Ahmed et al. proposed a classification system that represented a major advancement in the description of root canal anatomy. Unlike previous systems, this classification used a coding method capable of describing tooth number, number of roots, and canal configuration

simultaneously. It provides a highly detailed and standardized approach for describing complex root canal anatomy. The coding system can represent variations that are difficult or impossible to classify using M. M. Vertucci's system.

For example, the code may describe the number of roots and canal pathways in a precise and universal manner. This system is particularly useful in CBCT-based studies where highly detailed anatomical information is available. One of the major advantages of this classification is its flexibility and ability to accommodate newly discovered anatomical patterns. It also improves communication among clinicians and researchers. However, the system has a steeper learning curve compared to traditional classifications. Clinicians unfamiliar with the coding format may initially find it difficult to interpret [Table 5] [8].

Table 5: Ahmed classification (Courtesy: Ahmed, et al., (2017))

Code Format	Interpretation	Description
¹ TN ¹	One root – one canal	Single canal from orifice to apex
¹ TN ²	One root – two separate canals	Two independent canals within one root
¹ TN ¹⁻²	One canal dividing into two	Canal bifurcates before apex
¹ TN ²⁻¹	Two canals merging into one	Two canals join before exiting apex
¹ TN ¹⁻²⁻¹	One canal divide and rejoins	Canal separates and merges again
¹ TN ²⁻¹⁻²	Two canals merge and divide again	Complex canal configuration
² TN ²	Two roots with two canals	Common in premolars/molars
² M ² D ¹	Mesial root has two canals; distal root has one canal	Typical mandibular molar anatomy
² M ²⁻¹ D ¹	Two mesial canals merge into one; distal root has one canal	Modified mesial root anatomy

³ MB ¹ DB ¹ P ¹	Three roots with one canal in each root	Common maxillary molar configuration
² B ¹ P ¹	Buccal and palatal roots each with one canal	Common maxillary premolar anatomy
¹ TN ³	One root containing three canals	Three separate canals in single root
² M ³ D ²	Mesial root with three canals and distal root with two canals	Complex mandibular molar anatomy

C-Shaped Canal Classifications

C-shaped canals are commonly observed in mandibular second molars and present significant clinical challenges. Various classification systems have been proposed to describe C-shaped canal morphology based on cross-sectional appearance and canal continuity.

Advanced imaging techniques such as CBCT and micro-CT have improved the understanding of C-shaped canal anatomy and its variations [Table6] [16, 17].

Table 6: C-Shaped Canal Classification (Courtesy:Melton’s Classification Modified by Fan, et al.)

Classification	Morphology	Description
C1	Continuous C-shape	An uninterrupted “C”-shaped canal from one end to another
C2	Semicolon shape	Dentin separates the main C outline into a semicolon appearance
C3a	Two separate canals	Two distinct canals present
C3b	Three separate canals	Three distinct canals present
C4	Single round or oval canal	Only one round or oval canal present

C5	No visible canal lumen	Canal not visible near apex due to calcification or narrowing
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Isthmus and Accessory Canal Classifications

Recent studies have also focused on isthmus morphology, accessory canals, and apical deltas. These anatomical structures are clinically important because they may harbor residual bacteria and contribute to treatment failure. Three-dimensional imaging has enabled detailed classification of these structures and improved the understanding of their prevalence. Yi Hsu and Syngcuk Kim classified root canal isthmuses based on the communication between canals in cross-sectional anatomy (Table.7) [18].

Table 7: Yi Hsu and Syngcuk Kim classification (Courtesy: Yi Hsu and Syngcuk Kim, et al., (1997))

Type	Isthmus Configuration	Description
Type I	Two or three separate canals	No communication between canals
Type II	Incomplete connection	Thin connection exists between two canals
Type III	Complete connection	Continuous corridor between canals
Type IV	Extension into isthmus area	Canals extend into isthmus region without complete corridor
Type V	Complex isthmus	Broad communication with irregular canal anatomy

Artificial Intelligence (AI) and Digital Analysis

The integration of AI, machine learning (ML), deep learning (DL) into radiographic analysis represents a new direction in endodontic research. AI-based software can assist in automatic detection of root canal morphology and identification of anatomical variations. Future technologies may further improve diagnostic accuracy and facilitate personalized treatment planning [Table 8] [19-21].

Table 8: AI and Digital Analysis

Technology	Application in Endodontics	Advantages	Limitations
Artificial Intelligence (AI)	Automatic detection of root canals and anatomical variations	Improves diagnostic accuracy	Requires large datasets
Machine Learning (ML)	Pattern recognition in radiographic images	Faster analysis	Dependent on image quality
Deep Learning	Identification of complex canal morphology using CBCT	High sensitivity and specificity	Expensive computational systems
Convolutional Neural Networks (CNNs)	Detection of missed canals and periapical lesions	Reduces operator variability	Requires training and validation
Digital Radiographic Analysis	Enhancement and interpretation of RVG images	Better visualization	Two-dimensional limitations remain
CBCT-based Digital Reconstruction	Three-dimensional evaluation of root canal systems	Accurate anatomical assessment	Radiation exposure and cost

Micro-CT Digital Mapping	High-resolution analysis of canal anatomy	Gold standard for research	Limited clinical use
3D Reconstruction Software	Virtual visualization of root canal pathways	Improved treatment planning	Software expertise required
Automated Segmentation Software	Separation and mapping of canals in CBCT images	Saves time in analysis	Technique sensitive
AI-assisted Diagnosis	Prediction of anatomical complexity and treatment difficulty	Better clinical decision-making	Still under development

Table 9: Advantages of AI in Endodontics

Advantages	Explanation
Early Detection	Helps identify additional canals and anatomical variations
Improved Accuracy	Reduces chances of missed canals
Faster Analysis	Saves diagnostic time
Standardization	Minimizes operator-dependent interpretation
Enhanced Research	Assists in large-scale morphological studies
Better Treatment Planning	Supports precise endodontic procedures

Table 10: Limitations of AI in Endodontics

Limitations	Explanation
Need for Large Datasets	AI models require extensive

	training images
Cost	Advanced software and hardware are expensive
Technical Expertise	Requires knowledge of digital systems
Dependence on Imaging Quality	Poor radiographs affect accuracy
Ethical Concerns	Data privacy and reliability issues
Limited Clinical Integration	Still evolving in routine dental practice

Table 11: Future Scope of AI in Root Canal Morphology

Future Application	Expected Benefit
Automated CBCT Interpretation	Faster and more accurate diagnosis
AI-guided Access Preparation	Improved canal location

Traditional classification systems played a significant role in improving the understanding of root canal anatomy. However, the emergence of CBCT and micro-CT revealed numerous anatomical variations that could not be adequately represented using earlier systems.

Contemporary classification systems provide more detailed and accurate descriptions of root canal morphology. These systems are particularly important for research involving advanced imaging techniques.

Clinical Significance of Root Canal Morphology:

Knowledge of root canal morphology is essential for successful endodontic treatment. Failure to recognize additional canals and anatomical complexities may lead to incomplete debridement, persistent infection, and treatment failure [17].

Mandibular molars frequently exhibit additional canals such as middle mesial canals and multiple distal canals. Similarly, maxillary molars often

Predictive Anatomy Models	Identification of probable canal configurations
Real-time Digital Navigation	Enhanced endodontic precision
Personalized Endodontics	Patient-specific treatment planning
Integration with Robotics	Advanced minimally invasive procedures

Table 12: Comparison Between Traditional and Contemporary Classification Systems

Classification System	Year	Advantages	Limitations
Weine	1969	Simple and easy to use	Limited canal patterns
Vertucci	1984	Widely accepted and clinically useful	Cannot describe all complex anatomies
Gulabivala	2001	Detailed canal description	More complex
Sert and Bayirli	2004	Expanded configurations	Difficult clinical application
Ahmed et al.	2017	Comprehensive and universal coding system	Learning curve

present with a second mesiobuccal canal. Accurate identification of these variations significantly improves treatment outcomes [16]. Radiographic techniques play a vital role during access cavity preparation and canal negotiation. Multiple angulated radiographs and CBCT imaging help clinicians detect extra canals and avoid procedural errors [12, 13]

Understanding root canal morphology also assists in retreatment procedures, surgical endodontics, and management of complex anatomical cases. Therefore, clinicians should possess thorough knowledge of canal classification systems and radiographic interpretation [22].

Future Directions in Root Canal Morphology Research

Future research in root canal morphology is expected to focus increasingly on advanced imaging technologies and digital analysis methods. AI and DL algorithms may assist clinicians in automatic identification of root canal configurations and anatomical variations

[19]. Three-dimensional imaging techniques are likely to become more accessible and integrated into routine clinical practice. CBCT software with enhanced resolution and reduced radiation dose may further improve diagnostic capabilities [12]. Population-based studies involving different ethnic groups are also important because root canal morphology varies significantly among populations. Such studies may contribute to the development of region-specific anatomical databases [2, 22-26]. Additionally, three-dimensional printing and virtual canal mapping technologies may provide new opportunities for education, treatment planning, and simulation-based training [12, 15].

Conclusion

Root canal morphology is highly complex and variable, making its accurate assessment essential for successful endodontic treatment. Radiographic techniques have played a major role in improving the understanding of root canal anatomy, progressing from conventional two-dimensional imaging to advanced three-dimensional modalities such as CBCT and micro-CT.

The Vertucci classification system remains one of the most widely accepted methods for describing canal configurations and continues to serve as the foundation for morphological studies. However, advancements in imaging technology have revealed increasingly complex anatomical variations that cannot always be adequately represented using traditional classification systems.

Contemporary classification systems provide a more comprehensive approach for describing root canal anatomy and are particularly useful in studies utilizing CBCT and micro-CT.

A thorough understanding of root canal morphology, combined with appropriate use of radiographic imaging and classification systems, is essential for improving diagnostic accuracy, treatment planning, and clinical outcomes in endodontics.

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