12

Root Canal Anatomy

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CHAPTER OUTLINE

LEARNING OBJECTIVES

After reading this chapter, the student should be able to:

1. Recognize errors that may cause difficulties or failures in root canal treatment owing to lack of knowledge of pulp anatomy.
2. List techniques that help determine the type of root canal system.
3. Draw the eight most common canal types (Vertucci's I to VIII), the shapes of roots in cross-section, and common canal configurations in these roots.
4. Understand the two most commonly used classification systems (Vertucci and Weine) for root canal system and their limitations.
5. Describe a new classification system of root canal system morphology that uses universal tooth number along with canal number and morphology of individual roots as depicted in cleared bench specimens or clinical tomography images.
6. Know about root canal research in the past and understand how present research is helping identify the complexity and variations in ethnicity of the human root canal system.
7. Describe the most common root and root canal anatomy of each tooth.
8. For each tooth type, list the average length, number of roots, and most common root curvature directions.
9. Characterize the most frequent variations in root and root canal anatomy of each tooth group.
10. Explain why standard periapical radiographs do not present the complete picture of root and root canal anatomy.
11. Draw a representative example of the most common internal and external anatomy of each tooth in the following planes: (1) sagittal section of mesiodistal and faciolingual planes and (2) cross-section through the cervical, middle, and apical thirds.
12. Suggest methods for determining whether roots and canals are curved and the severity of the curvature.
13. Explain why many root curvatures are not apparent on standard radiographs.
14. State the tenet of the relationship of pulp-root anatomy.
15. List each tooth and the root or roots that require a search for more than one canal.
16. List and recognize the significance of iatrogenic or pathologic factors that may cause alterations in root canal anatomy.
17. Define the root canal space and list and describe its major components.
18. Describe variations in the root canal system in the apical third.
19. Describe how to determine clinically the distance from the occlusal-incisal surface to the roof of the chamber.
20. Discuss the location, morphology, frequency, and importance of accessory (lateral) canals.
21. Describe relationships between the anatomic apex, radiographic apex, and actual location of the apical foramen.
22. Describe common variations in root canal anatomy resulting from developmental abnormalities and state their significance.
23. Identify the most common root and root canal morphologic variations as they relate to ethnicity.

Introduction

The ultimate goal of endodontic therapy is to seal the root canal system after all vital or necrotic tissue, microorganisms, and their byproducts are removed from the canal space. However, this objective may be difficult to attain in reality because of the complexity of the internal anatomy of teeth. Residual bacteria and debris may remain relatively unaffected in the missed canal system or even in the unprepared canal walls, isthmuses, lateral canals, apical ramifications, and recesses from oval/flattened canals which may compromise the successful treatment outcome. Thus, a thorough understanding of the number of canals, of the inner-canal morphology, and the variations in all groups of teeth is a basic requirement for successful endodontic therapy.

In the past, several studies were performed on the range of variations in human root canal anatomy, and the findings have had a noteworthy influence on clinical practice. In recent years, significant noninvasive technological advances for imaging teeth have been introduced that allow anatomic studies to be done using large populations and evaluate specific and fine anatomic features of a tooth group. The latest morphological studies on root and root canal anatomy use high-resolution three-dimensional (3D) tomographic images to illustrate and define terminologies associated with this topic.

Gaining Knowledge and Comprehension of Root and Canal Anatomy

Textbooks and courses in dental anatomy are ideal sources for teaching a dental student about normal human tooth anatomy. These study aids can present the dental student or dental practitioner with knowledge of the ideal coronal anatomy and its relation to occlusion, the anatomy of the human tooth root, and occasionally the morphology of the pulp and root canals. But the usual dental anatomy that is shown assumes the ideal (or most frequently encountered) tooth shape. Is this enough to perform endodontic treatment for our patients, when genetic variations may have produced roots and root canal systems that vary from the normal? For example, why is the maxillary first premolar inevitably depicted as having two roots (and two canals) whereas the second premolar is illustrated as a single but oval rooted tooth with one, or maybe two canals? Studies that compare the incidence of variation in root number in different populations have shown a significant variation in morphology of the human maxillary and mandibular premolars, based on ethnicity.[1] Therefore, when it comes to performing the complex operation of root canal therapy, more detailed knowledge of root number and root canal system anatomy is required. The purpose of this chapter is to acquire that knowledge at a higher level.

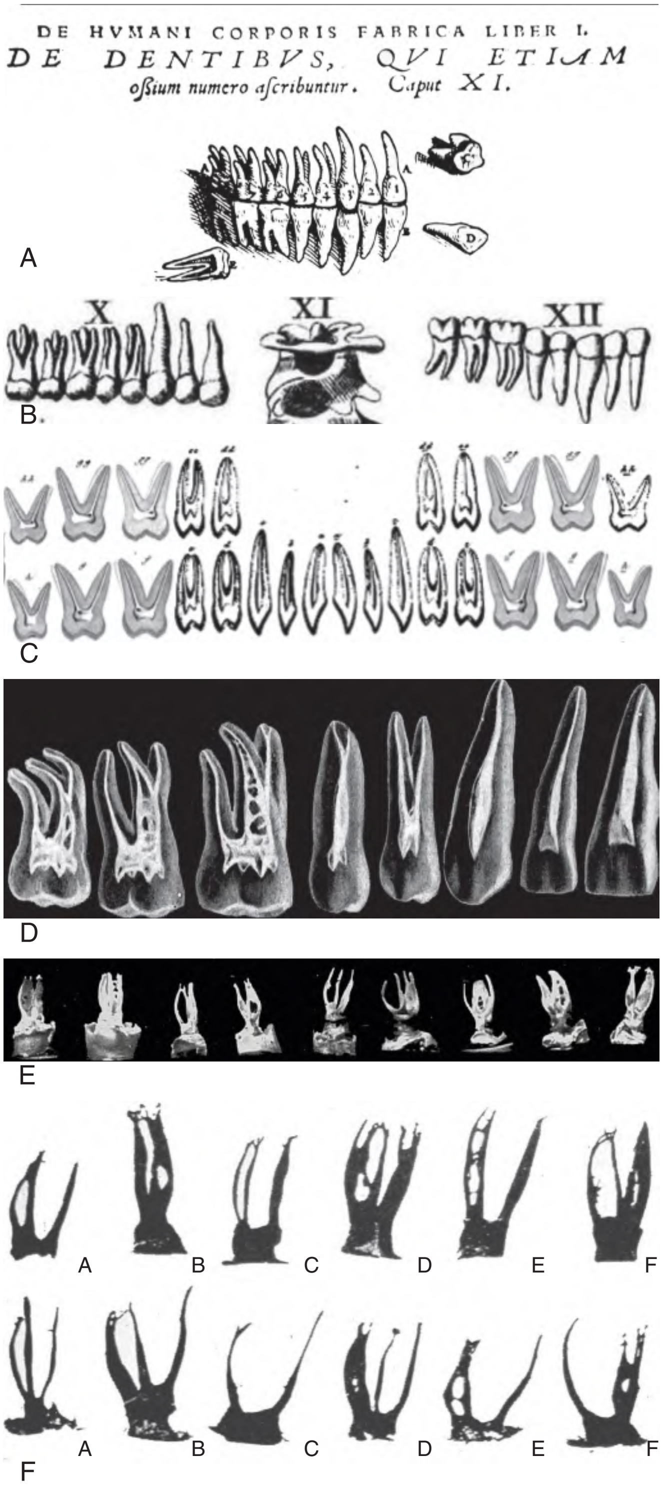
The first task for a dental student, as stated, is to learn the normal anatomy of each tooth in the arch with respect to its complex root canal system. In principle, the shape of the external root will be reflected in the internal morphology of a root canal system. This is considered a tenet of the relationship of pulp-root anatomy. Each of the individual 16 types of teeth in the permanent dentition has its own individual root canal system morphology or shape. This is considered basic dental anatomy, which must then be matched clinically to what is interpreted from the two-dimensional (2D) shadow of the radiographic image.

The second task is to acquire detailed dental anatomy knowledge of possible variations from the norm. Thus one should realize that each human tooth type has a range of variation in its morphology. The shape of the root canal system is influenced by embryonic development and is controlled by each patient's genetic background. To perform successful endodontic treatment, one must anticipate variation in chamber size and depth from the occlusal surface, the canal size, shape, length, curvature, branches, lateral canals, and apical accessory canals, to mention just a few variables. These variations may or may not be clearly seen in a standard periapical radiographic image.

Methods of Study to Learn Normal and Variations in Tooth Anatomy

In the first half of the 16th century, a set of seven books written by Andreas Vesalius (1514-1564) entitled *De Humani Corporis Fabrica* was published. This was a major advance in the history of anatomy over the long-dominant works of ancient Middle Ages writers. It is noteworthy that an important anatomic aspect of teeth that had been ignored by previous authors on which, centuries later, the endodontic specialty would be born, was highlighted for the first time in the literature. In Chapter XI, there is a drawing of a sectioned two-rooted mandibular molar showing its internal anatomy (Fig. 12.1, *A*). In 1563, Bartolomeo Eustachi (c. 1520-1574), in his treatise *il Libellus de Dentibus,* made very significant contributions toward the anatomy and physiology of the dentition, including the first descriptions of the dental pulp, the periodontal ligament, the dental follicles, the trigeminal nerve, and other oral structures, based upon extensive dissections of both human and animal specimens. In Chapter XVIII, Eustachi describes the pulp cavity and its contents, and shows accurate tables in which he specified the number of roots and the external morphologic variations of all groups of human teeth (Fig. 12.1, *B*). Eustachi's book brought the macroscopic anatomy of teeth to a high degree of perfection that remained unsurpassed until the 19th century with the posthumous work of Georg Carabelli (1787-1842), who provided the most detailed description of the number and direction of the root canals at that time (Fig. 12.1, *C*). Nevertheless, it was only at the end of 19th century that some researchers finally realized the need for in-depth research on root canal morphology. In 1903, Gustav Preiswerk (1866-1908) performed a profound and comprehensive study on this subject. In his pioneering study, Wood's metal, an alloy that melts at a low temperature, was molten and injected into the canal space. After complete decalcification of the teeth, 3D metal models of the internal anatomy were obtained for the first time (Fig. 12.1, *D*). Some years later, Guido Fischer (1877-1959) presented the challenging nature of the apical root anatomy. He obtained better results than Preiswerk by filling approximately 700 teeth with a collodion solution. This solution penetrated all the branches of the root canal system and hardened in 2 or 3 weeks, providing a full 3D replica of the root canal system (Fig. 12.1, *E*). The complexity and unpredictability of the root canal morphology led Fischer to coin the term *Kanalsystem,* which has been widely used nowadays as "root canal system." It may be said that the innovative 3D anatomic studies of Preiswerk and Fischer resulted in huge advancements, adding new and significant knowledge to the dental literature and stimulating other researchers to undertake further investigations on this topic. In those later studies, large numbers of extracted teeth were collected, placed in a category and analyzed, or counted to compare their shape and size. Root numbers for the multirooted posterior teeth could even be tabulated. Data from these in vitro studies were then printed in the tables found in the earliest textbooks in dentistry. This was the first phase of research in human root anatomy.[2]

Hess wrote a landmark publication on the morphology of root canals using some 3000 permanent teeth. Canal shapes were made visible by injecting vulcanite into canal systems and dissolving the surrounding roots. This process showed graphically how complex the canal system was for each tooth (Fig. 12.1, *F*). A similar method was used for primary teeth by Zürcher, and the results were combined and reprinted in the English literature in 1925. Many variable shapes and extra canals in single rooted



• **Fig. 12.1 Historical images of classical studies on root canal anatomy**. **A,** First drawing of a sectioned two-rooted mandibular molar showing its internal anatomy by Andreas Vesalius (1543); **B,** illustration depicting the number of roots and the external morphologic variations of all groups of human teeth by Eustachi (1563); **C,** illustration of the number and direction of the root canal in different groups of teeth by Carabelli (1842); **D,** 3D metal models of the internal anatomy of different teeth obtained by Preiswerk (1903); **E,** 3D models of the internal anatomy of teeth obtained by Fischer using collodion solution (1907); **F,** Canal shapes of mandibular molars obtained by injecting vulcanite into the canal systems by Hess (1925). (Courtesy Dr. Perrini.[241] Published with permission.)

teeth were shown to exist. For example, in the casts of mandibular incisor, mandibular premolar, and mandibular canine, the canals were complex and sometimes multiple in number. Illustrations in his publication are remarkable for their accuracy but were either overlooked or ignored as being abnormal variants at the time. Subsequent anatomic studies and an earlier published study have confirmed their observations.[2] More recent studies on canal numbers, both ex vivo and in vivo, have shown that former endodontic techniques in root canal therapy using less flexible instruments only available at the time had inadvertently missed many of these extra and complex canal systems.[3]

Clinical competence relies on the development of the widely recognized psychomotor aspect. Inextricably coupled with these psychomotor skills is the ability to self-evaluate the process of correction and the product itself compared with the desired outcome. Visual perception has been suggested as a prerequisite skill for determining the appropriate goals and strategy for a correction. Visual skill is required to observe normal 3D tooth morphology in detail, to differentiate normal tooth morphology from its variations. Further, motor skills are also required to execute clinically relevant dental procedures. In the development of psychomotor skills, the student must teach his or her hands to do that which his or her mind dictates as correct. Models that simulate teeth in which root canals can be visualized would serve as valuable teaching aids in offering direct visual information on the effects of instrumentation during endodontic procedures. The visual experiences afforded by these models must provide mental images, which can be transferred to the performance of endodontic procedures on actual teeth. Nowadays, most dental schools continue to present foundational knowledge of dental anatomy in lectures and to develop students' psychomotor skills through a combination of 2D drawing projects, radiographs, and exercises to carve teeth from oversized wax blocks. As a result, neither knowledge nor psychomotor skills are learned in the context of clinical practice, thus potentially hindering the student's ability to later recall and apply learning to actual patient care. On the other hand, practice on extracted teeth has been a universal method of teaching preclinical endodontics and gives students the opportunity of gaining expertise before moving to treating patients. However, infection control concerns, originated by the manipulation of extracted teeth, along with ethical factors are threatening such preclinical laboratory practice in some teaching institutions. These drawbacks have stimulated the development of alternative simulation methods for teaching root canal anatomy.[4]

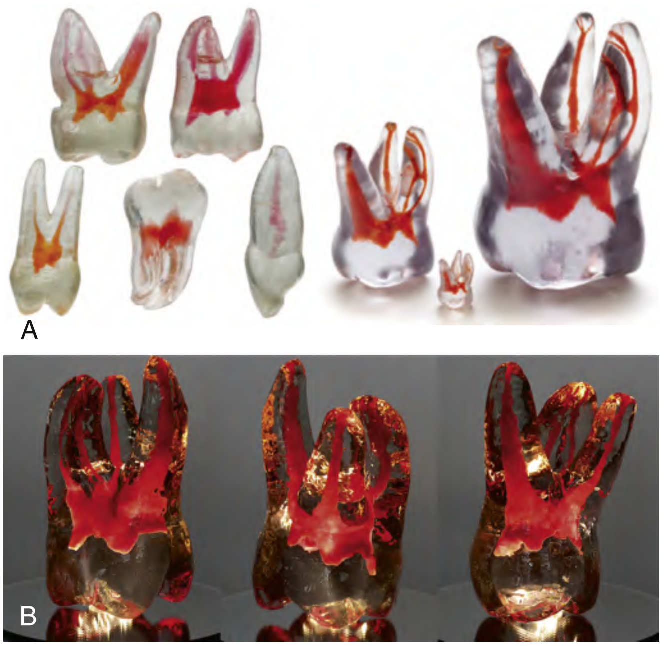
Root Canal Anatomy Since the Age of Specialization in Endodontics

One must not take away from dental practitioners who revived the popularity and viability of root canal therapy after the misinformed attitudes in the age of "Focal Infection Theory." By the mid-20th century the attitudes and instruments in endodontics had changed;[5] thus standardization of instruments and techniques led to saving many more teeth, while using a recognized and effective treatment rationale. However, it was recognized that if missed canals were leading to failure to seal the entire canal system, then new studies on the variability of root and canal anatomy had to be done. New methods of study were devised that used both radiographs and bench studies of extracted teeth. This has led to the second phase of research in dental and root anatomy, which began about the time of recognition of endodontics as a specialty branch of restorative dentistry in 1964 in the United States.

These tooth anatomy studies included methods such as conventional and laboratory radiography (with or without contrast media), resin injection, macroscopic and microscopic evaluations, tooth sectioning, root clearing techniques, and scanning electron microscopy. Kuttler in 1955[6] used a dissection microscope to show that the apical foramen in teeth varied considerably in diameter. Skidmore and Bjørndal in 1971[7] illustrated casts of mandibular first molars with multiple and complex canal systems. Another example of the practical aspect of studying root morphology was the paper by Davis et al. in 1972[8] that described the use of injected silicone into standard endodontic-prepared canals, with the resulting casts showing that some areas of the canal system had not been completely shaped. All of these canal anatomy studies and more, either in physical anthropology papers or in dental journals, built on a second wave of root and canal system knowledge.[9-11]

Undoubtedly, these techniques have shown a great potential for endodontic research. However, although most of these methods required the partial or even full destruction of the studied samples rendering irreversible changes in the specimens and many artifacts, others provided only a 2D image of a 3D structure.[12] These inherent limitations have repeatedly been discussed, encouraging the search for new methods with improved possibilities.

More recently, the third phase of studies in human root and root canal anatomy is well underway. Increased computer power of digital radiographs and advanced technology are producing studies of human teeth with conventional medical computed tomography (CT), magnetic resonance microscopy, tuned-aperture CT, optical coherence tomography, volumetric or cone beam CT (CBCT; used as a clinical enhancement of practice), and micro–computed tomography (micro-CT). CT-based training replicas produced using 3D printing technology have improved the use of artificial teeth for teaching purposes (Fig. 12.2). Replicas with different root canal complexities can be printed as oversized models in a rapid prototyping printer, allowing the students to hold them in hand to observe details of the internal anatomy in different views. Additional applications of printed models in dental education also include the possibility to (1) scale the teeth for didactic purposes, (2) build a collection of 3D tooth models showing atypical or only regionally prevalent anatomies, (3) produce a large number of teeth for destructive analysis, (4) present the teeth in the form of individual substructures that need to be assembled correctly by the students, and (5) build an extensive collection of 3D models of healthy and diseased teeth using raw data made available online by researchers and dentists from all over the world.[4]



• **Fig. 12.2** Replicas of various teeth manufactured from corresponding real-tooth micro-CT scans using three-dimensional (3D) printing technology in assorted sizes for didactic or teaching purposes. **A,** True Tooth®; **B,** RepliDens®. (**A,** images available at https://dentalengineeringlab.com/truetooth/; **B,** images available at https://www.smartodont.ch/replidens/.)

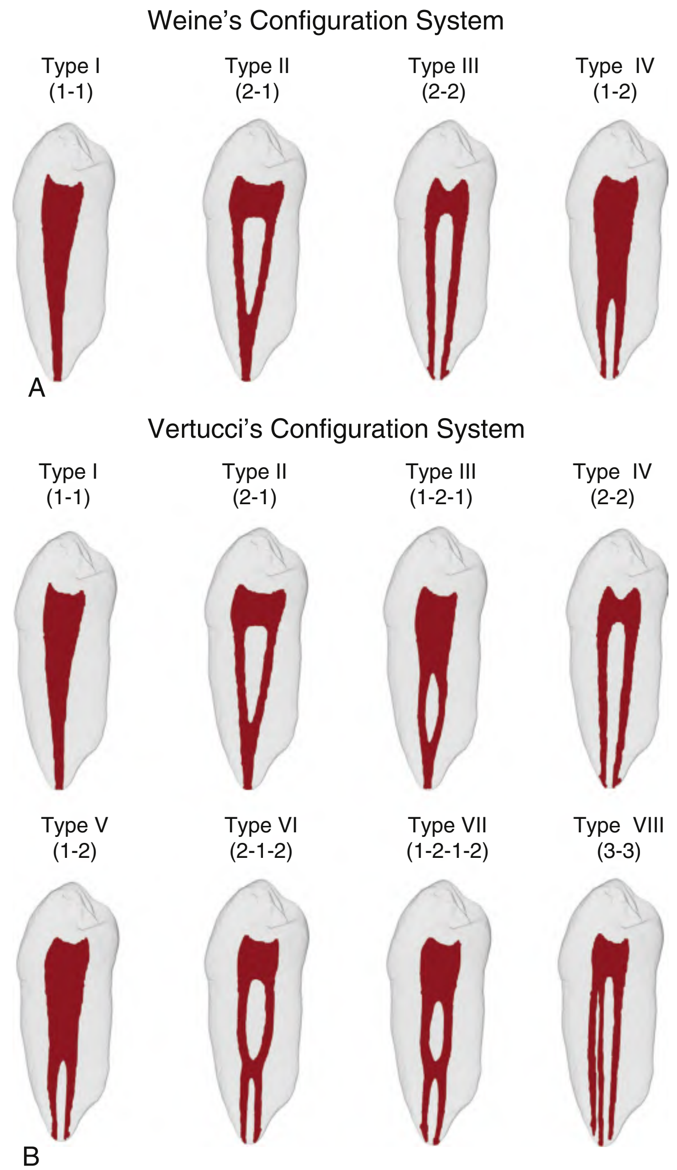
As imaging has been adopted in modern dental education, it has benefited from the concurrent development of technologies that have allowed the material to be presented electronically. One of the technologies with the greatest effect has been the Internet. The Internet has increasingly been used as an educational tool as a result of its ability to provide a large volume of educational material in a single, readily accessible location and permitting flexibility in the material format.[4] Images, text, interactive quizzes, and videos can be integrated seamlessly into a comprehensive educational resource. In this way, digital images acquired from micro-CT devices could be used to generate anatomic tooth data on a large scale and made freely accessible to the public through the Internet (www.rootcanalanatomy.blogspot.com), thus circumventing the problems of individual researchers requiring access to high-cost scanning devices.[13] Therefore one of the most important aspects of the computer age of communication is the ability to find and access research from many more dental schools and dental researchers from all over the dental academic world. Although a computer search may seem quick and easy, one must rely only on reliable research publications from journals with a credible and high impact factor. A new understanding has been forthcoming on the importance of ethnicity and human dental anatomy.[14]

The misconception of thinking about "one-root equals one-canal" in endodontic treatment has been shattered by a number of classic papers that demonstrate otherwise. In fact, a number of studies have classified and described the morphology of multiple canals in a broad diameter root. This multiple canal configuration may divide, combine, and separate as it forms in root closure toward the various morphologies of the apical foramen terminus.[15] It is prudent to assume that any root that requires treatment may contain more than one canal system per root, until proved otherwise.

Multiple Canals Within a Single Root

Weine et al. in 1969[16] were the first authors to recognize and publish how commonly two canals in one root occurred, and then to classify the two canals in the mesiobuccal root of the maxillary first molar tooth as the "type specimen" (Fig. 12.3, *A*). Piñeda and Kuttler in 1972[17] used radiographs on 7275 extracted teeth to demonstrate multiple canal systems in three dimensions not usually seen in the clinical setting. Other researchers[18-20] soon added observations that confirmed this morphology was not uncommon in many other broad labiolingual or buccolingual roots, as well as, the mesiobuccal root of maxillary molars.

Vertucci et al.[21] developed a more complex classification that is better adapted to research and applied in any other tooth that is wider in the labiolingual or buccolingual dimension (Fig. 12.3, *B*). Essentially, Weine and Vertucci's configuration systems were based on the number of root canals that begin at the pulp chamber floor,



• **Fig. 12.3 A,** Diagrammatic representations of Weine's classification for root canal morphology. Type I: A single canal from pulp chamber to the apex (1-1 configuration); Type II: Two separate canals leaving the chamber, but merging short of the apex to form a single canal (2-1 configuration); Type III: Two distinct canals from pulp chamber to the apex (2-2 configuration); Type IV: A single canal leaving the chamber and dividing into two separate canals at the apex (1-2 configuration). **B,** Diagrammatic representations of Vertucci's classification for root canal morphology. Type I: A single canal from pulp chamber to the apex (1-1 configuration); Type II: Two separate canals leaving the chamber, but merging short of the apex to form a single canal (2-1 configuration); Type III: A single canal that divides into two, and subsequently merges to exit as one (1-2-1 configuration); Type IV: Two distinct canals from pulp chamber to the apex (2-2 configuration); Type V: A single canal leaving the chamber and dividing into two separate canals at the apex (1-2 configuration); Type VI: Two separate canals leaving the pulp chamber, merging in the body of the root, and dividing again into two distinct canals short from the apex (2-1-2 configuration); Type VII: A single canal that divides, merges, and exits into two distinct canals short from the apex (1-2-1-2 configuration); Type VIII: Three distinct canals within one root from pulp chamber to the apex (3-3 configuration).

arise along the course of the canal, and open through an apical foramen. Later, Versiani and Ordinola-Zapata[22] expanded and adapted these classifications to 3D tomographic descriptions of at least 37 complex canal systems possible to be observed in a single root (Fig. 12.4). The following tables of root numbers of tooth pairings will help one understand the variation in incidence of single and multiple canal numbers based on a large sample from multiple studies. The computer-generated figures will also show graphically some of the variations in anatomy that may be found in the human dentition. Other research studies have shown that furcation canals, lateral canals, and apical ramifications have developed all too commonly.[23] Better cleansing and obturation techniques will more likely seal all portals of exit in the chamber and canal and lead to higher success rates in studies, based on evidence.

Success in root canal therapy can be achieved by first knowing the normal canal anatomy and then by being aware of the many variations that the path of the canal system can follow. One should be able to develop a 3D visualization, both in longitudinal and in cross-section while still using clinical tactile sense to guide a file toward the apical foramen or apical terminus. The following description and images will help provide that knowledge to aid one in honing that skill and expertise.

Root Canal Components and Morphology

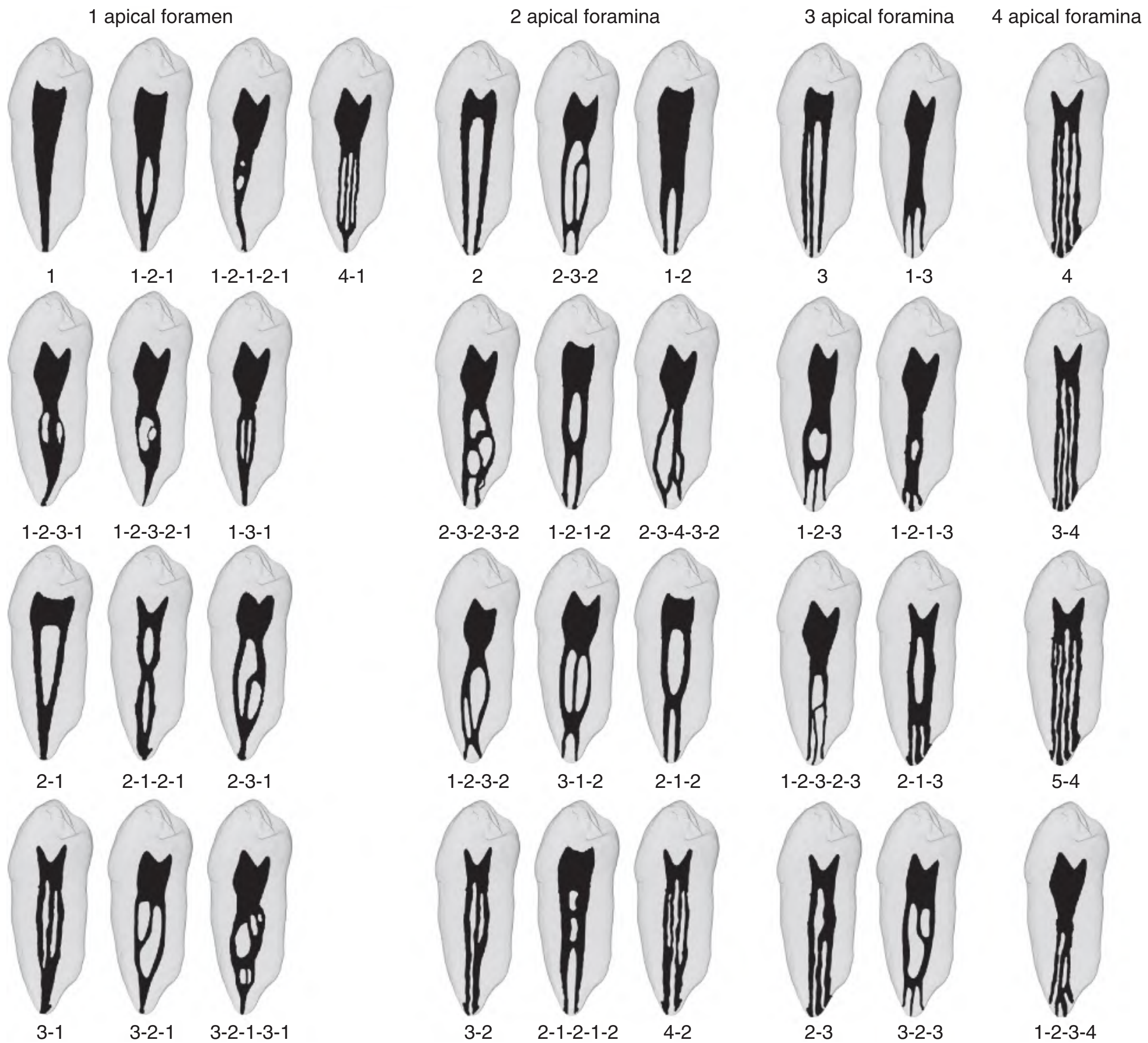
Basically, the root canal system can be divided into two parts: the pulp chamber, commonly located within the anatomic dental crown, and the root canal space, found inside the radicular portion of the tooth.[24]

Pulp Chamber

The pulp chamber is a cavity normally situated in the center of the crown and, when there are no pathologic conditions, resembles the shape of the crown surface. In anterior teeth that have a single canal in one root, the pulp chamber and root canal are continuous whereas, in posterior teeth with multiple canals and more than one root, the pulp chamber floor separates these two components. In premolars and molars, the pulp chamber usually presents a square shape with six sides: the floor, the roof, and four axial walls identified as mesial, distal, buccal, or lingual (palatal). The pulp chamber roof usually presents projections or prominences associated with cusps, mamelons, or incisal ridges, denominated pulp horns.[22] In teeth with physiologic wear or other irritation, continuous dentin formation (either physiologic or reactionary) by primary odontoblasts may lead to a decrease in the pulpal space dimensions which, in some cases, can compromise root canal treatment.[25]

Based on the anatomic study of 500 teeth, Krasner and Rankow[26] demonstrated that specific and consistent pulp chamber anatomy exists. Then, they proposed some general rules or laws (Fig. 12.5) for aiding in the determination of the pulp chamber position and the location and number of root canal entrances in each group of teeth:

- *Law of centrality:* The floor of the pulp chamber is always located in the center of the tooth at the level of the cementoenamel junction (CEJ).
- *Law of concentricity:* The walls of the pulp chamber are always concentric to the external surface of the tooth at the level of the CEJ (i.e., the external root surface anatomy reflects the internal pulp chamber anatomy).



• **Fig. 12.4** Thirty-seven most common canal configurations possible to be observed in a single root, according to Versiani and Ordinola-Zapata.[22]

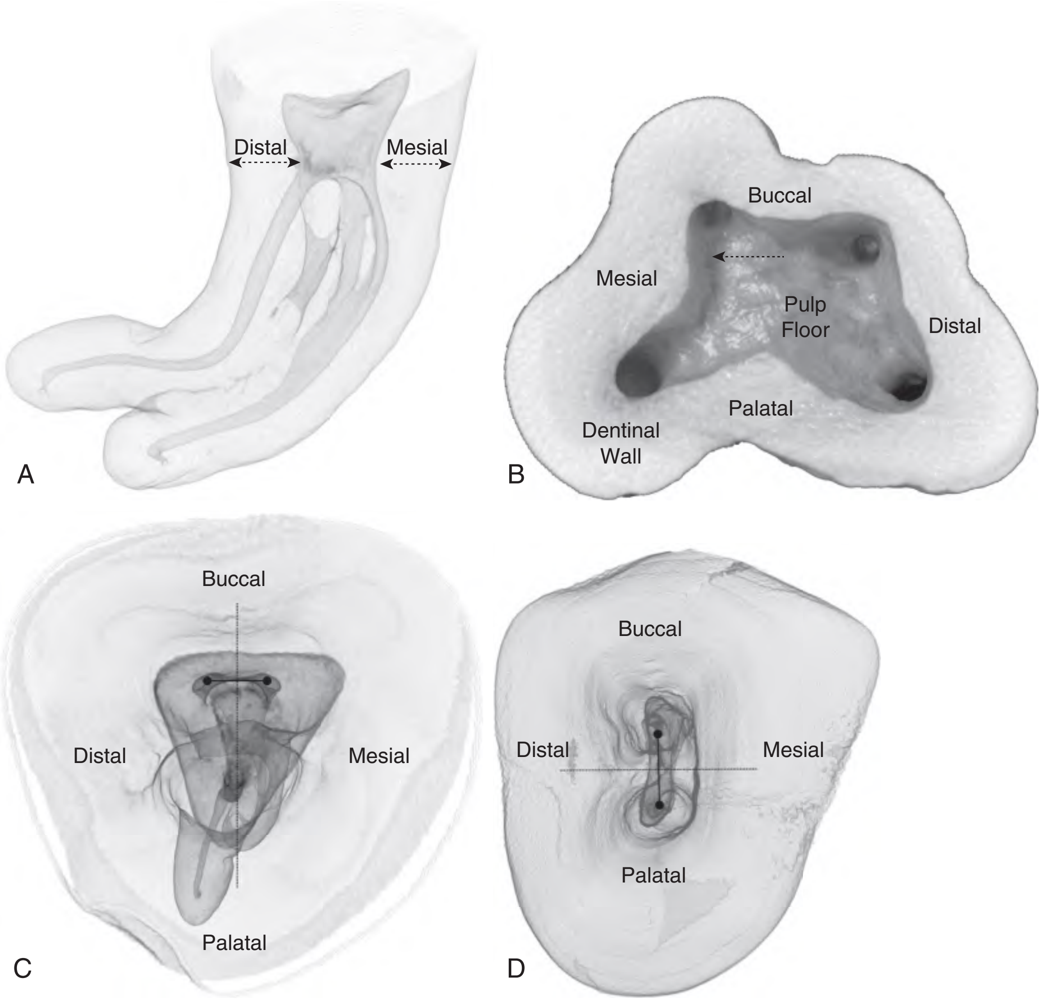
- *Law of the CEJ:* The distance from the external surface of the clinical crown to the wall of the pulp chamber is the same throughout the circumference of the tooth at the level of the CEJ. The CEJ is the most consistent, repeatable landmark for locating the position of the pulp chamber.
- *Law of symmetry 1:* Except for maxillary molars, the orifices of the canals are equidistant from a line drawn in a mesiodistal direction, through the pulp chamber floor.
- *Law of symmetry 2:* Except for the maxillary molars, the orifices of the canals lie on a line perpendicular to a line drawn in a mesiodistal direction across the center of the floor of the pulp chamber.
- *Law of color change:* The color of the pulp chamber floor is always darker than the walls.
- *Law of orifice location 1:* The orifices of the root canals are always located at the junction of the walls and the floor.
- *Law of orifice location 2:* The orifices of the root canals are located at the angles in the floor-wall junction.
- *Law of orifice location 3:* The orifices of the root canals are located at the terminus of the root developmental fusion lines.

In addition to knowing these laws, the use of better illumination and magnification sometimes associated with specific instruments, such as thin ultrasonic tips or special burs, would provide the best approach to explore the anatomic variations of the pulp chamber in order to locate all canal orifices and avoid missed canals.[24]

Root Canal

The root canal is the portion of the pulp canal space within the root of the tooth limited by the pulp chamber and the foramen that follows the external outline of the root (Fig. 12.6). The root canal can be subdivided into two components: the main canal, which is mostly cleaned by mechanical means, and lateral components composed by isthmuses, accessory canals (furcation, lateral and secondary canals), and some recesses of flattened- and oval-shaped canals.[24]

In longitudinal section, canals are usually broader faciolingually than in the mesiodistal plane. Traditionally, canal shape has been classified as round, oval, long oval, flattened, or irregular (Fig. 12.7).[27] Its geometric cross-sectional shape has been also quantitatively



• **Fig. 12.5** Three-dimensional (3D) micro–computed tomography (micro-CT) images of posterior teeth demonstrating the **(A)** laws of centrality and concentricity, at the cementoenamel junction (CEJ) in a mandibular molar tooth; **(B)** laws of color change and orifice locations 1, 2, and 3 (*arrow*: developmental fusion lines) in a four-rooted maxillary second molar tooth; and **(C–D)** laws of symmetry 1 (three-rooted maxillary molar) and 2 (two-rooted maxillary premolar).

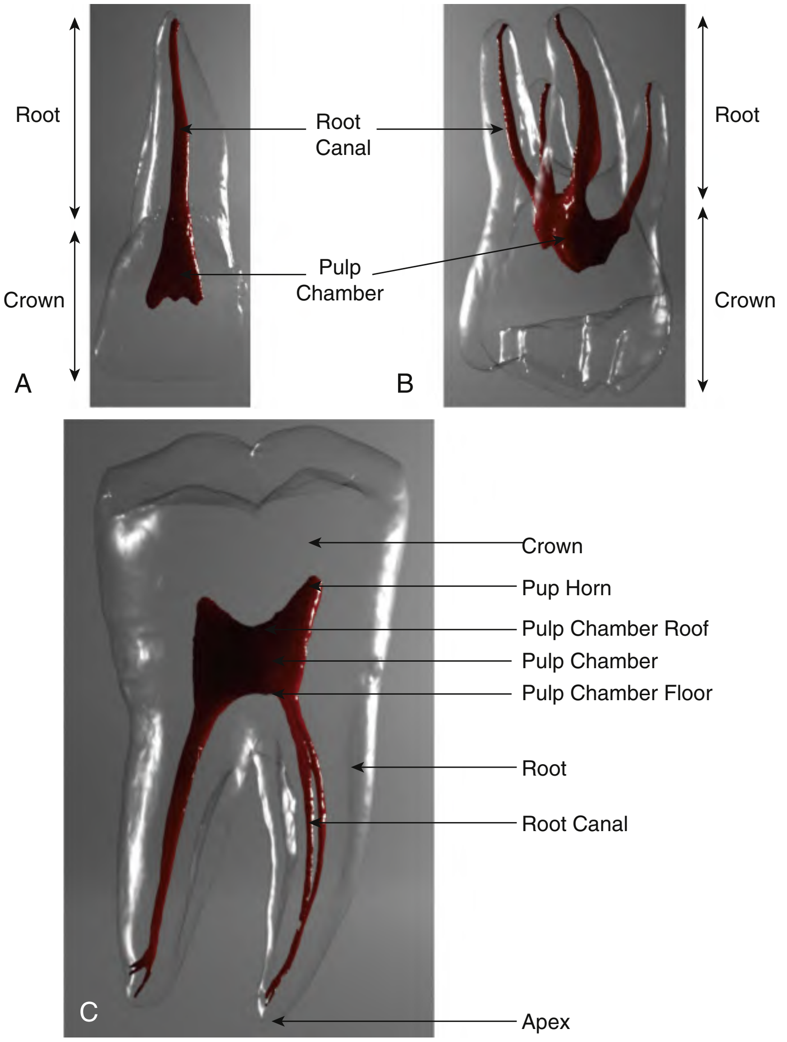
described by calculating the mean aspect ratio, defined as the ratio of the major to the minor canal diameters. The major diameter is the distance between the two most distant points of the canal in the buccolingual direction, whereas the minor diameter is the longest chord through the root canal that could be drawn in the direction orthogonal to that of the major diameter. Accordingly, an oval-shaped canal has an aspect ratio between 1 and 2, a long oval canal higher than 2 but lower than 4, and a flattened canal has a value higher than 4.[28] It is interesting to point out that, in a same tooth, canal cross-sections may show different shapes at different levels of the root; however, at the apical third, it is more round or slightly oval in shape in comparison with the middle and coronal thirds.[12,28] Thus, as previously mentioned, the anatomy of the root canal systems is often complex and can vary greatly in number and shape.

Isthmus

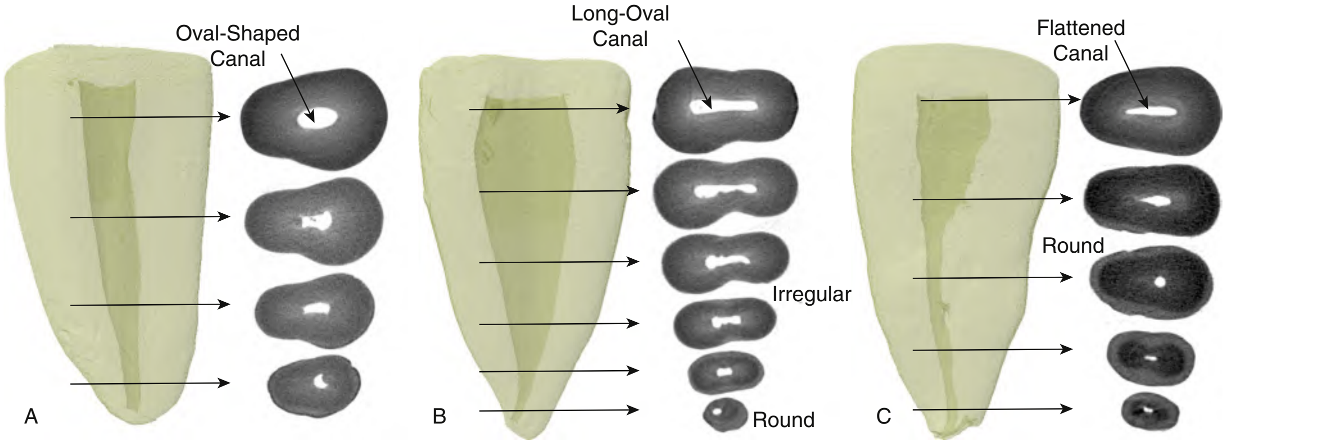
An isthmus, also called *transverse anastomosis*, is a narrow, ribbon-shaped communication between two root canals that may contain vital tissue, necrotic pulp, biofilms, or residual filling material.[29,30] Isthmuses (or isthmi) may present with different configurations (Fig. 12.8), and their prevalence is dependent on the type of teeth, the root level, and the patient's age. Hsu and Kim[31] classified the isthmuses configuration into five types:

- Type I—Two canals with no notable communication
- Type II—A hair-thin connection between the two main canals
- Type III—Differs from type II because of the presence of three canals instead of two
- Type IV—An isthmus with extended canals into the connection
- Type V—A true connection or wide corridor of tissue between two main canals.

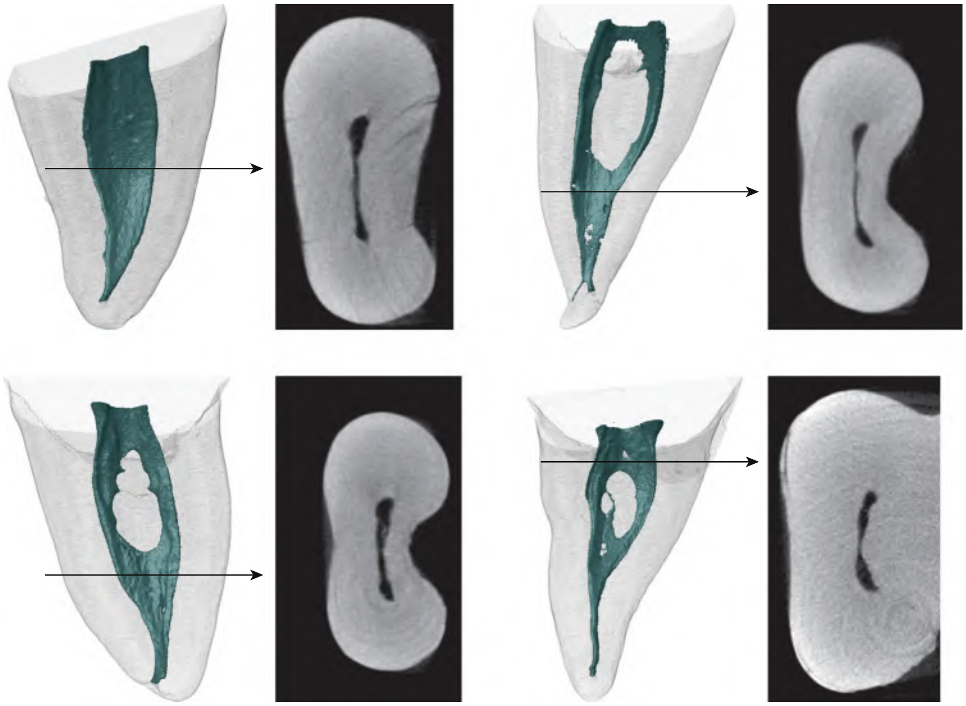
It is noteworthy that experimental studies demonstrated the impossibility of obtaining a complete mechanical debridement or chemical disinfection of isthmuses with the current technology, mostly because of the presence of hard tissue debris packed into these areas during the mechanical preparation of the main root canal.[32-36] Clinical studies have also shown that unfilled isthmuses can be commonly observed after root-end resection in cases referred for apicoectomy treatment.[37] These limitations, however, can be surpassed in nonsurgical treatment by using chemical agents that have the ability to dissolve organic tissue at fins and isthmuses level, often associated with ultrasonic activation.[33]



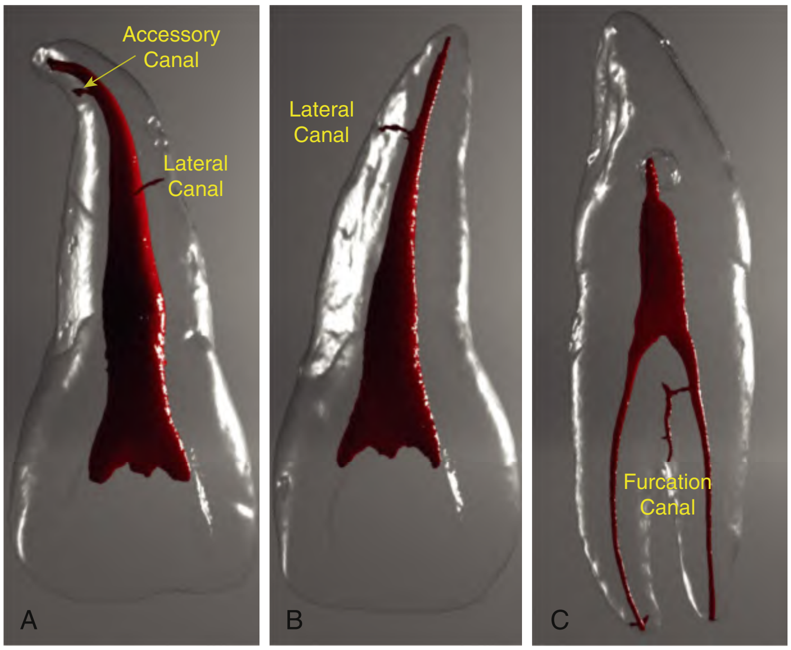
• **Fig. 12.6** Three-dimensional (3D) models of real **(A)** incisor and **(B–C)** molar teeth, obtained by micro–computed tomography (micro-CT) technology, showing the main components of the root canal system.



• **Fig. 12.7** Two-dimensional (2D) root canal cross-sections of three mandibular canines **(A–C)** showing that canals are usually broader buccolingually than in the mesiodistal plane, and may present different shapes at distinct levels of the root.



• **Fig. 12.8** Two-dimensional (2D) root canal cross-sections of four mesial roots of mandibular molars showing isthmuses with different sizes and shapes at different levels of the root.

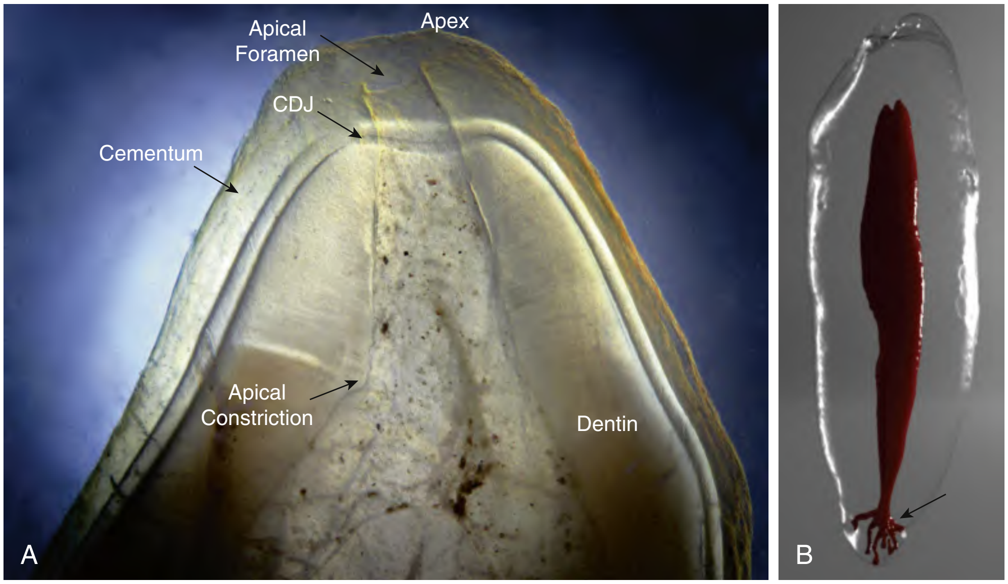


• **Fig. 12.9** Three-dimensional (3D) models of **(A–B)** two maxillary central incisors and **(C)** a two-rooted mandibular canine, obtained by micro–computed tomography (micro-CT) technology, showing the lateral components of the root canal system.

In addition, with the advent of the operatory microscope, it is possible to identify and treat most of the isthmus areas with thin ultrasonic tips, in both surgical and nonsurgical endodontic procedures, to ensure their debridement and seal.[34,35]

Accessory Canals

An accessory canal is any branch of the root canal that communicates with the periodontal ligament, whereas a lateral canal is defined as an accessory canal located at the coronal or middle third of the root (Fig. 12.9, *A* and *B*).[38] They are formed after a localized fragmentation of Hertwig's epithelial root sheath develops, leaving a small gap, or when blood vessels running from the dental sac through the dental papilla persist as collateral circulation.[39] Accessory canals represent potential pathways through which bacteria and/or their byproducts from the necrotic root canal might reach the periodontal ligament and cause disease.[39]



• **Fig. 12.10** **A,** Anatomic landmarks at the apex of a cleared single-rooted tooth (CDJ: cementodentinal junction). **B,** Three-dimensional (3D) micro–computed tomography (micro-CT) model of a mandibular canine presenting apical ramification (arrow). (**A,** Courtesy Dr. Francisco Balandrano. Published with permission.)

De Deus[23] studied the frequency, location, and direction of the accessory canals in 1140 teeth and showed that 27.4% of the sample (n = 330) had accessory canals, especially in the apical area (17%), followed by the middle (8.8%) and coronal (1.6%) thirds. Similarly, Vertucci[40] evaluated 2400 teeth and observed a lower occurrence of canal ramifications in the middle (11.4%) and coronal (6.3%) thirds compared with the apical level (73.5%). Lateral canals are not usually visible in preoperative radiographs, but their presence can be suspected when there is a localized thickening of the periodontal ligament or there is a lesion on the lateral surface of the root. Clinically, it is also relevant that lateral canals cannot be instrumented most of the time. In this way, their content can only be neutralized by means of effective irrigation with a suitable antimicrobial solution or with an additional use of intracanal medication.[24,25]

Canals connecting the pulp chamber to the periodontal ligament in the furcation region of a multirooted tooth are called furcation canals (Fig. 12.9, *C*).[38] These canals are derived from entrapment of periodontal vessels during the fusion of the parts of the diaphragm, which will become the floor of the pulp chamber. In some cases, furcation canals have been associated with primary endodontic lesions in the interradicular region of multirooted teeth. Vertucci and Williams observed the presence of furcation canals in 13% of mandibular first molars,[41] and in most of them the canal extended from the center of the pulpal floor, whereas in four and two specimens, respectively, the canals arose from the mesial and distal aspects of the floor. Later, Vertucci and Anthony[42] observed the presence of foramina on both the pulp chamber floor and the furcation surface in 36% of maxillary first molars, 12% of maxillary second molars, 32% of mandibular first molars, and 24% of mandibular second molars. Recently, micro-CT studies have also demonstrated the presence of furcation canals in two-rooted mandibular canines and three-rooted mandibular premolars.[43]

Apical Canal

The main root canal ends at the apical foramen (major foramen), which frequently opens laterally on the root surface, at a mean distance between 0.2 to 3.8 mm from the anatomic apex,[44] despite larger distances have been reported recently.[45] The anatomic apex is the tip or the end of the root as determined morphologically.[38] Depending on the type of teeth, the apical foramen can coincide with the anatomic apex in a percentage frequency ranging from 6.7% to 46% of the cases.[10,17,40,46] Its diameter has been described between 0.21 to 0.39 mm.[47] The mesial roots of mandibular molars, the maxillary premolars, and the mesiobuccal roots of maxillary molars present the highest percentage of multiple apical foramina.[47] A previous study on root apices of all groups of permanent teeth showed that the number of foramina on each root may vary from 1 to 16.[44]

The apical portion of the root canal having the narrowest diameter has been called the "apical constriction" (minor foramen).[38] From the apical constriction, the canal widens as it approaches the apical foramen. The topography of the apical constriction is not constant[12,15] and, when present, is usually located 0.5 to 1.5 mm from the center of the apical foramen.[30] The cementodentinal junction (CDJ) is the point at which the cemental surface terminates at or near the apex of a tooth and meets dentin.[38] At this histologic landmark pulp tissue ends and periodontal tissues begin (Fig. 12.10, *A*).[25]

Another relevant variation of the root canal at or near the apex is an intricate network of ramifications, also called *apical ramification of apical delta*, which is defined as a morphology in which the main canal divides into multiple accessory canals (Fig. 12.10, *B*).[38] In maxillary teeth, the percentage frequency of apical ramification ranges from 1% (central incisors) to 15.1% (second premolars), whereas in mandibular teeth its frequency varies from 5% (central incisors) to 14% (distal root of first molars).[40] In the treatment of clinical cases, the infection of this tortuous and complex anatomic configuration with several portals of exit can be related as an etiologic factor of nonsurgical failures.[39]

Canal Curvature and Size

Knowledge of the root curvature is an important factor in choosing the appropriate chemomechanical protocol for cleaning and shaping the root canal system. Before the introduction of nickel-titanium (NiTi) instruments, several iatrogenic procedures were associated with the preparation of curved canals including zips, separated instruments, ledges, and perforations.[48] Nowadays, these iatrogenic complications are no longer a problem, except for instrument separation. Therefore this is one of the factors determining the difficulty of treatment and the likelihood of iatrogenic errors and shows that preoperative recognition of canal curvature is of utmost importance.[22]

Nearly all root canals are curved in the apical third, particularly in a faciolingual direction, which is not evident on standard radiography.[30] In general, the curvature may vary from gradual curvature of the entire canal, sharp curvature of the canal near the apex, or a gradual curvature of the canal with a straight apical ending. Numerous methods have been proposed to determine root canal curvature,[49,50] but the Schneider's method has been the most widely used. Schneider[51] classified single-rooted permanent teeth according to the degree of curvature of the root, which was determined by first drawing a line parallel to the long axis of the canal, then, a second line connecting the apical foramen to the point in the first line where the canal began to leave the long axis of the tooth. The angle formed by these two lines was the angle of curvature and its degree was classified as straight (≤5 degrees), moderate (10 to 20 degrees), or severe (25 to 70 degrees).

Another method was introduced by Weine[52] that also relies on the definition of two straight lines, but it reflects the root canal curvature more accurately than Schneider's method, especially in the apical part. A third proposal, geometrically equivalent to Weine's method, was introduced by Pruett et al.,[53] but its major innovation was the concurrent measurement of the radius of curvature by the superimposition of a circular arc on the curved part of the root canal. Therefore, the Schneider angle, when used in combination with the radius and length of the curve, may provide a more precise method for describing the apical geometry of canal curvature.

Clinically, different angled views are necessary to determine the presence, direction, and severity of the root canal curvature. Schäfer et al.[54] evaluated radiographically the degree of curvature of 1163 root canals from all groups of teeth. The degree of curvature ranged from 0 to 75 degrees and from 0 to 69 degrees in clinical and proximal views, respectively. The highest degree of curvature was observed in the clinical view of the mesiobuccal canal of maxillary molars and in the mesial canals of mandibular molars. In several cases, the angles of proximal curvatures were higher than those of the clinical view. Additionally, a secondary curvature (S-shaped canal) was observed in 12.3% and 23.3% of the maxillary and mandibular teeth, respectively.

Root Canal Configuration Systems

Various classification systems have been proposed in an attempt to have a standardized root canal classification system that can be used by clinicians and researchers. The two most commonly used systems are the ones developed by Weine et al.,[16] followed by Vertucci et al. (see Fig. 12.3).[21] Weine's initial classification included three types based on a sectioning study of the mesiobuccal root of permanent maxillary first molars. The system classifies the canal configuration by two numbers. The first number is the number of canals found at the floor of the pulp chamber whereas the second number describes the canal configuration at the apex. For example, a Weine Type II canal configuration (2-1) means that two distinct canals are found at the floor of the pulp chamber and the two canals subsequently join and form a single canal at the apex. The Type IV canal configuration (1-2) was added later.[52] Vertucci's classification system was developed based on a clearing study (followed by dye injected into the canals) of 200 maxillary second premolars and eight canal types were described. Vertucci et al.[21] defined the Type VIII root canal system as three separate canals in maxillary premolars from the pulp chamber to the apex. However, the study did not specify whether the three canals were within a tooth that contained one, two, or three roots. Many studies have classified Type VIII canal configurations lumping single, double, and triple-rooted teeth together.[21,40,55,56] Some studies, though, have classified three-rooted maxillary premolars with single canals in each root as Type I canal systems in each root.[57,58] It seems logical, however, that a Type VIII canal should only be used in one broad or fused root of a tooth, and not in the separated roots and apex of the same tooth as may be shown on the radiograph.

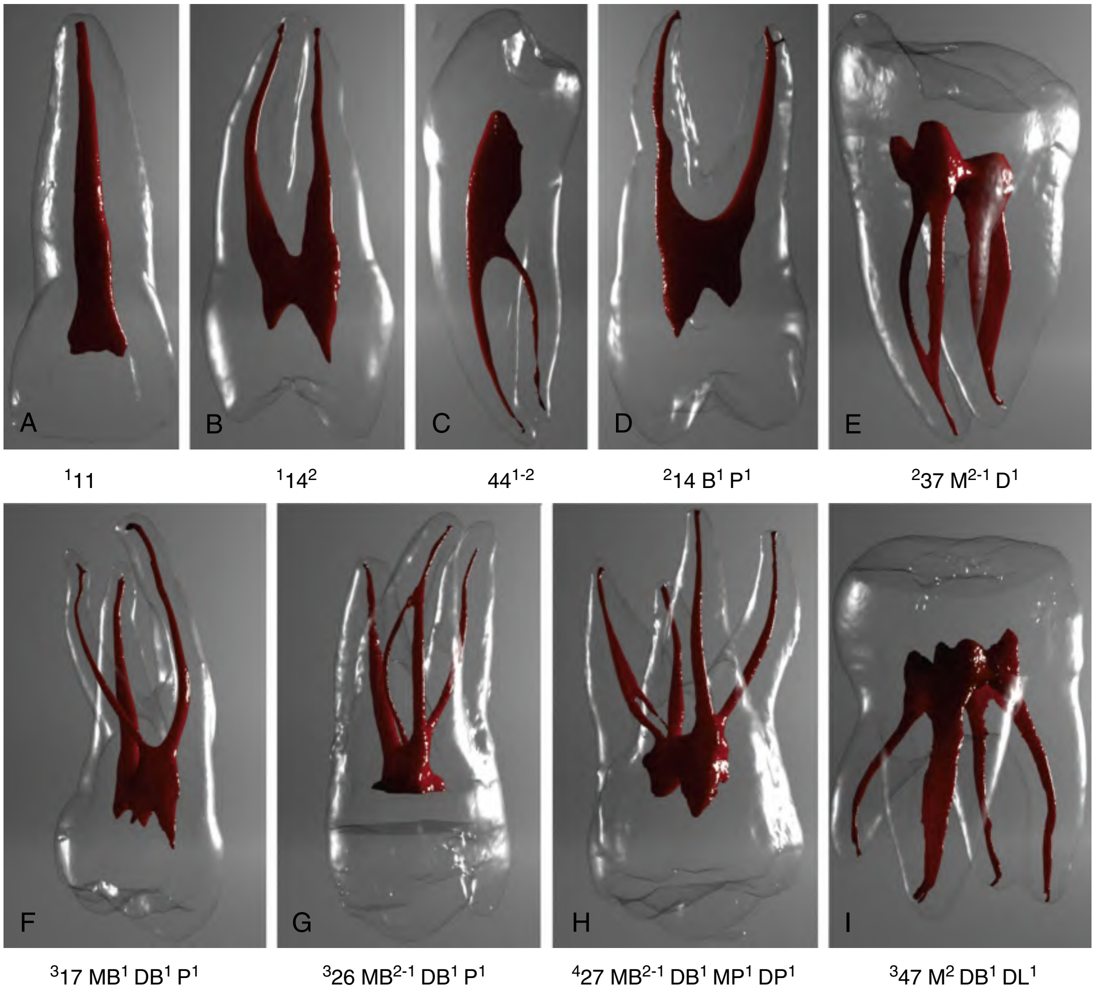
In addition, numerous other canal types have been reported by various authors that did not fit into either classification system.[59] Recently, based on the study of hundreds of permanent teeth, Versiani and Ordinola-Zapata[60] found 37 different canal types using micro-CT technology (see Fig. 12.4). Clearly, neither the Weine nor the Vertucci classification system can adequately describe these additional complex canal configurations. A simple classification system that can be used to describe all of the possible canal configurations in all teeth has yet to be developed. However, a new canal classification system proposed by Ahmed et al.[59] shows promise because the system can accommodate any type of canal configuration by using root name and canal numbers to categorize the canal configuration in each root (Fig. 12.11).

Root Canal Anomalies and Embryologic Malformations

Anomalous root and root canal morphology can be found associated with any tooth with varying degrees and frequency in the human dentition. Dental anomalies are formative defects caused by genetic disturbances during the morphogenesis of teeth.[61] Anomalies may occur during the developmental stages of the tooth that are manifested clinically later in life once the tooth is fully formed.[62-64] Failure to diagnose teeth with anomalous anatomy may lead to misdiagnosis and a treatment plan that could cause permanent irreversible damage and loss of the tooth.[30] In this way, the clinician must be aware of the existence of some anatomic anomalies to implement an appropriate treatment plan. Major anomalies that affect endodontic practice include taurodontism, dens invaginatus, dens evaginatus, extra roots (radix), and C-shaped canals.[61]

Taurodontism

Taurodontism (or a "bull-shaped" tooth) is a dental morphologic variation in which the body of the tooth is enlarged and the roots are reduced in length.[65] A taurodont tooth presents a large pulp chamber with apical displacement of the pulpal floor and furcation of the roots (Fig. 12.12, *A* and *B*).[38] The etiology of taurodontism is unclear, but it also appears in certain genetic syndromes.[66] It is thought to be caused by the failure of Hertwig's epithelial root sheath diaphragm to invaginate at the proper horizontal level, resulting in a tooth with normal dentin, short roots, elongated body, and enlarged pulp.[63,64,67] The teeth involved are almost invariably molars or rarely premolars. It can be uni- or bilateral and may affect single or multiple teeth.[68] The condition may also present rarely in the primary dentition molar teeth.[69] Taurodontism is most famously reported to occur in high



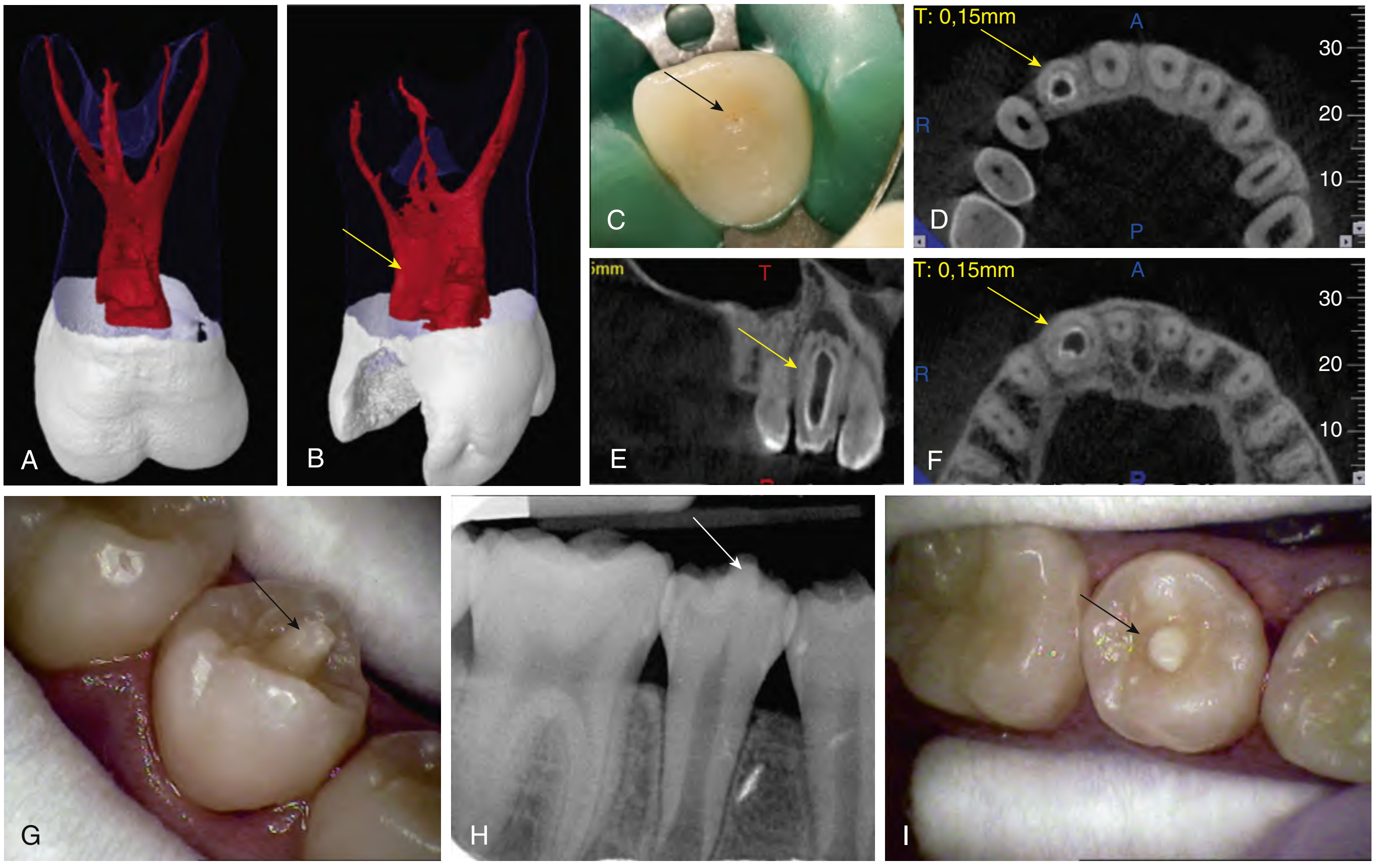
• **Fig. 12.11** Three-dimensional (3D) micro–computed tomography (micro-CT) models of **(A–C)** single-, **(D–E)** double-, and **(F–I)** multirooted teeth classified according to the new system proposal by Ahmed et al.[59] *B*, Buccal; *D*, distal; *DB*, distobuccal; *DL*, distolingual; *DP*, distopalatal; *M*, mesial; *MB*, mesiobuccal; *MP*, mesiopalatal; *P*, palatal. (Published with permission.)

incidence by Keith in 1913 as found in *Homo neanderthal* from the Krapina archaeologic find in the early 1900s.[70]

Taurodontism was classified earlier by Shaw in 1928 and has been graded according to its severity: normal (cynodont), least pronounced (hypotaurodontism), moderate (mesotaurodontism), and most severe (hypertaurodontism).[71] Clinically, the crowns of these teeth usually have normal characteristics. Therefore the diagnosis is entirely radiologic.[68] Owing to the complexity of the root canal anatomy and the proximity of the orifices to the root apex, complete filling of the root canal system in taurodontism is challenging. Because the pulp of a taurodont is usually voluminous, control of bleeding in cases of pulpitis may take some time and effort compared to teeth with normal anatomy. Additional efforts such as application of ultrasonic instrumentation combined with sodium hypochlorite (NaOCl) as an irrigant solution should be made to dissolve as much organic material as possible.[68,72,73]

Dens Invaginatus and Dens Evaginatus

Dens invaginatus (dens in dente, dilated composite odontome, dilated odontome, gestant anomaly, invaginated odontome, dilated gestant odontome, tooth inclusion, dentoid in dente) is a developmental defect resulting from invagination in the surface of the tooth crown before calcification has occurred (Fig. 12.12, *C–F*).[61] Clinically, it may appear as an accentuation of the lingual pit in anterior teeth and, in its more severe form, gives a radiographic appearance of a tooth within a tooth, hence the term *dens in dente.*[38] Its etiology is controversial and remains unclear. The affected teeth radiographically show an infolding of enamel and dentin that may extend deep into the pulp cavity and into the root and sometimes even reach the root apex.[74] The most common associated clinical finding is an early pulpal involvement, explained by the existence of a canal extending from the invagination into the pulp.[75] The invagination also allows the entry of irritants into an area that is separated from pulpal tissue by only a thin layer of enamel and dentin and presents a predisposition for the development of dental caries.[74] Therefore this condition must be recognized early and the tooth prophylactically restored.[73] The variability of its root canal system configuration is unlimited. Clinically, however, it can only be speculated upon from radiographs.[76] In this way, the most commonly referred classification was proposed by Oehlers,[77] who categorized it into three types: Type 1—the invagination is confined to the crown and does not extend beyond the CEJ; Type 2—the invagination extends past



• **Fig. 12.12 Root canal anomalies and embryologic malformations. (A–B)** Taurodont maxillary second molar presenting a large pulp chamber (yellow arrow) with apical displacement of the pulpal floor and furcation of the roots; **C–F,** Clinical and tomographic views of a maxillary lateral incisor with dens invaginatus (arrows) (Courtesy of Dr. Oscar von Stetten. Published with permission); **G–I,** Clinical and radiographic views of a mandibular second premolar with dens evaginatus (arrows). (Courtesy Dr. Daniela Bololoi. Published with permission.)

the CEJ and does not involve the periradicular tissues, but may communicate with the dental pulp; and Type 3—the invagination extends beyond the CEJ and may present a second apical foramen, with no immediate communication with the pulp. In the literature, the reported prevalence of this anomaly varies from 0.25%[78] to 10%[79] and the most affected teeth are permanent maxillary lateral incisors, despite the fact that it may occur in any tooth.[74,80] This high range frequency of dens invaginatus has been associated with the study design, sample size and composition, and diagnostic criteria.[74,75]

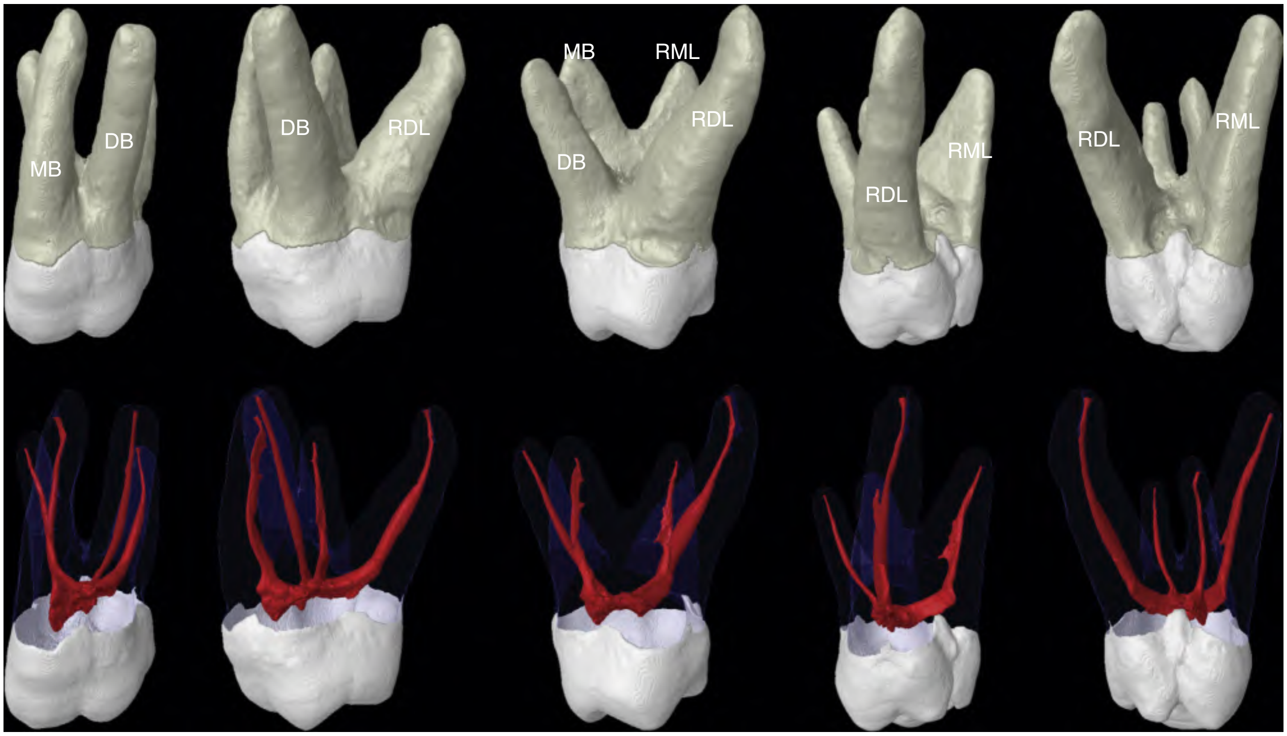
Dens evaginatus is an anomalous outgrowth of tooth structure resulting from the folding of the inner enamel epithelium into the stellate reticulum with the projection of structure exhibiting enamel, dentin, and pulp tissue (Fig. 12.12, *G–I*).[38] It arises most frequently from the occlusal surface of involved posterior teeth, mainly maxillary and mandibular premolars, and primarily from the lingual surface of associated anterior teeth (called *talon cusps* when in this location).[81,82] Its etiology remains unclear. However, it predominantly occurs in people of Asian descent with varying estimates reported at 0.5%[83] to 15%,[84] depending on the population group studied. The presence of pulp within the cusp-like tubercle has great clinical significance. Because the tubercle may extend above the occlusal surface, malocclusion or attrition with the opposing tooth may cause abnormal wear or fracture of the tubercle, and this is how pulp exposure occurs.[82] Subsequent pulpal inflammation or infection will most likely ensue, at times when the root apex closure has not occurred in the young patient. It is important for the clinician to be able to recognize and treat the entity soon after affected teeth have erupted into the oral cavity in order to avoid the development of pathologic conditions.[82]

Radix

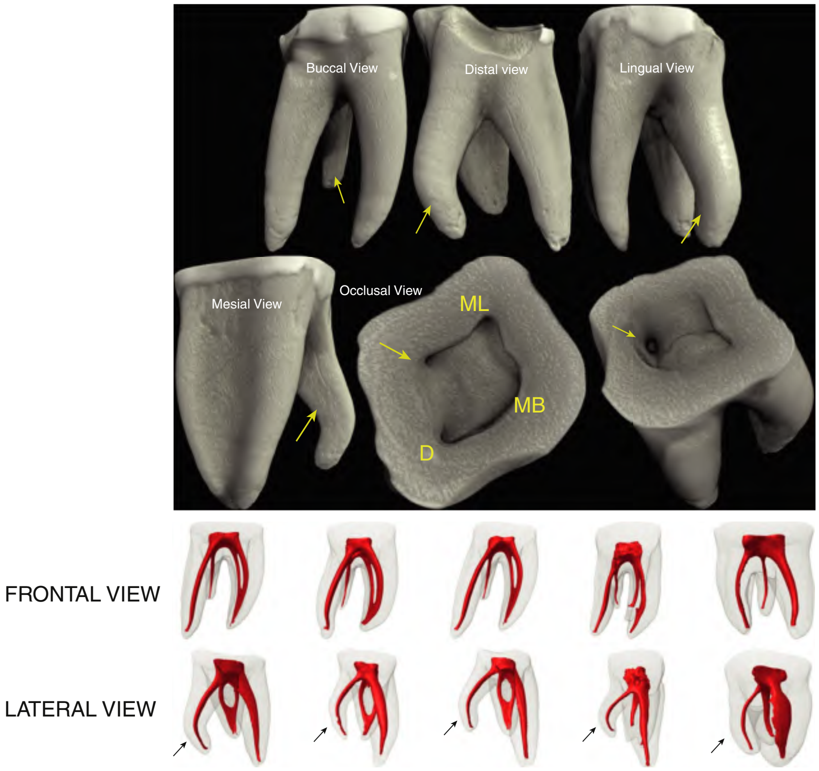
Radix is a Latin word for "root" and is referred to additional roots of teeth, mostly molars. In radix molars, each root usually contains a single root canal.[61]

In four-rooted maxillary molars, the palatal part of the root complex is made up of two macrostructures located mesially and distally, which are in principle cone-shaped and either separate or nonseparate in relation to each other.[85] If the mesial of the two palatal root structures has direct affinity to the mesiolingual part of the crown, which is more pronounced, the mesial root structure is identified as radix mesiolingualis, whereas the distal structure is identical with the palatal root component. If the distal of the two palatal root structures has direct affinity to the distopalatal part of the crown, the distal root structure is identified as radix distolingualis, whereas the mesial structure is identical with the palatal root component (Fig. 12.13).[86]

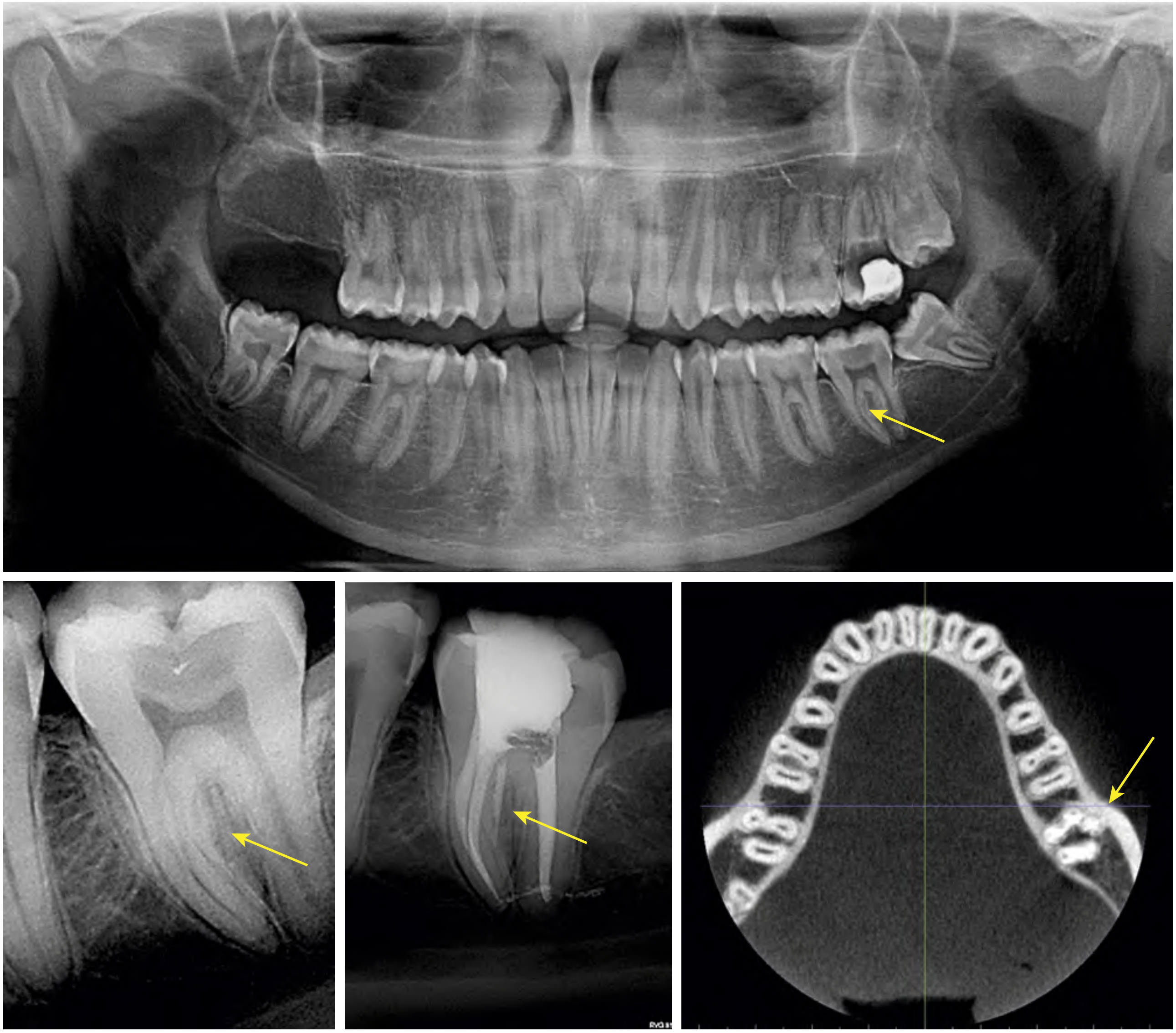
In mandibular molars, additional roots have been identified as radix entomolaris and radix paramolaris.[61,87] Radix entomolaris has been defined as a supernumerary root on a mandibular molar located distolingually (Fig. 12.14), whereas radix paramolaris is



• **Fig. 12.13** Different views of a three-dimensional (3D) micro–computed tomography (micro-CT) models of the external and internal morphologies of a four-rooted maxillary molar showing radix mesiolingualis (RML) and radix distolingualis (RDL). *DB*, Distobuccal root; *MB*, mesiobuccal root.



• **Fig. 12.14** Three-dimensional (3D) micro–computed tomography (CT) models of the external and internal morphologies of mandibular second molars showing radix entomolaris *(yellow arrows)*. In the lateral view, the curvature of the radix is depicted (black arrows).

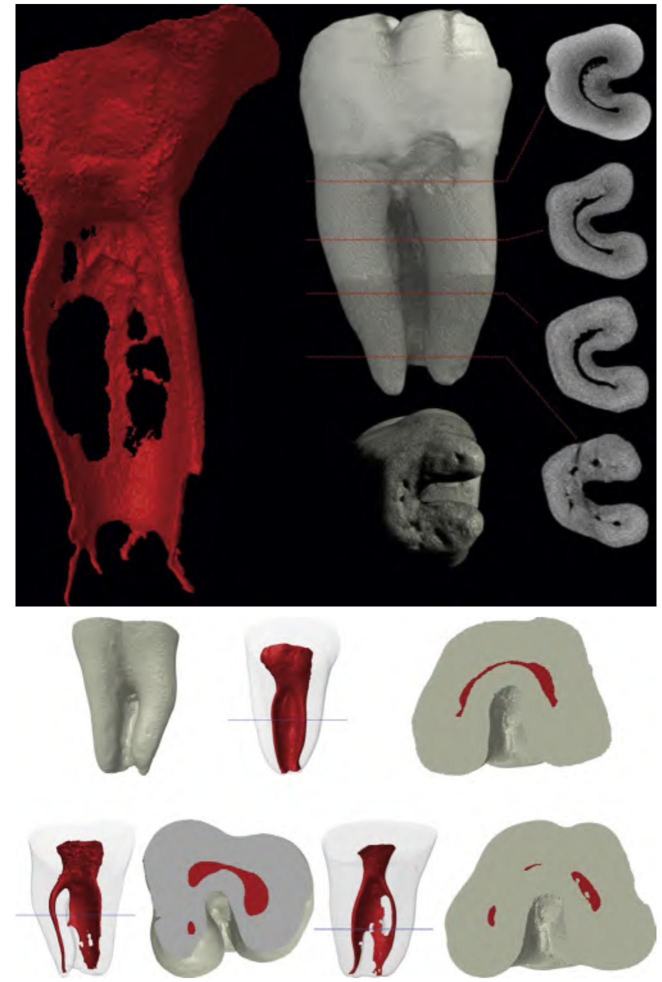


• **Fig. 12.15** Radiographic and tomographic views of a mandibular left second premolar showing a radix paramolaris *(arrows)*, before and after root canal treatment. (Courtesy Dr. Nuno Pinto. Published with permission.)

an extra root located mesiobuccally (Fig. 12.15).[38] The presence of these anatomic anomalies has been associated with certain ethnic groups such as Sino Americans, which include Chinese, Inuit, and American Indians.[88,89] Radix paramolaris is a very rare structure and its prevalence was found to be 0%, 0.5%, and 2.0% for the mandibular first, second, and third molars, respectively,[90] whereas radix entomolaris occurs with a higher frequency, ranging from 0.2%[91] to 32%[92] of the studied samples. The orifice of the radix entomolaris is located disto- to mesiolingually from the main canal or canals of the distal root, whereas the orifice of the radix paramolaris is located mesio- to distobuccally from the main mesial canals.[88] A dark line or groove from the main root canal on the pulp chamber floor leads to these orifices[89]; however, they provide a limited practical aid for its identification in clinical practice. These anatomic variations present definite challenges to therapy because of their orifice inclination and root canal curvature. In this way, preoperative periapical radiographs at different horizontal angles or a CBCT examination are required to identify this additional root, which will also result in a modified opening cavity. An accurate diagnosis of these anatomic variations is important to avoid missed canals.[87]

C-Shaped Canals

The C-shaped configuration was first reported in the endodontic literature by Cooke and Cox in 1979,[93] but this canal configuration has been well-known since the beginning of the 20th century.[94] This anatomic variation is so named for the root and root canal cross-sectional shape of the capital letter "C."[95] Its main anatomic feature is the presence of one or more isthmuses connecting individual canals, which can change the cross-sectional and 3D canal shape along the root (Fig. 12.16).[95-97] Typically, this configuration is found in teeth with fusion of the roots either on its buccal or lingual aspect, and results from the failure of Hertwig's epithelial root sheath to develop or fuse in the furcation area during the developing stage of the teeth.[63,64] Failure on the buccal side will result in a lingual groove, and the opposite cases would be possible.[63] In such teeth, the floor of the pulp chamber is frequently



• **Fig. 12.16** Three-dimensional (3D) micro–computed tomography (CT) models of the external and internal morphologies of mandibular second molars showing different C-shaped canal configurations.

situated deeply and may assume an unusual anatomic appearance.[97] Below the orifice level, the root structure of a C-shaped tooth can harbor a wide range of anatomic variations,[95] which make it a challenge with respect to disinfection.[98] This variation may occur in different types of teeth[97,99-102]; however, it is most commonly found in mandibular second molars[103,104] with a reported prevalence ranging from 2.7%[105] to 44.5%.[106] There is significant ethnic variation in the frequency of C-shaped molar teeth, which are much more common in Asian populations than in Caucasian populations.[30] In population-based studies, the reported prevalence was 10.6% in Saudi Arabians,[107] 19.14% in Lebanese,[108] 31.5% in Chinese,[104] and 44.5% in Koreans.[106] To date, two studies have addressed the efficacy of different systems in the preparation of C-shaped mandibular molar canals showing a significant percentage of canal area unaffected by the instrumentation procedure.[98,109]

In 1991 Melton et al.[96] proposed the first classification for C-shaped canal configuration in mandibular second molars based on its cross-sectional shape. They fall into three categories: Category I—a continuous C-shaped canal running from the pulp chamber to the apex; Category II—a semicolon-shaped orifice in which dentin separates a main C-shaped canal from one mesial distinct canal; Category III—two or more discrete and separate canals which could join in the apical (subdivision I), middle (subdivision II), or coronal (subdivision III) thirds.

It is important to point out that mandibular molar teeth can present with irregularities in their canal systems throughout the root and the presence of these categories may vary from the pulp chamber to the apex.[106] In this way, Fan et al.[110] modified Melton's method and recommended to classify each portion of the same tooth using five categories:

- Category I—The shape was an uninterrupted "C" with no separation or division.
- Category II—The canal shape resembled a semicolon resulting from a discontinuation of the "C" outline.
- Category III—Two or three separate canals
- Category IV—Only one round or oval canal in the cross-section (normally found near the apex)
- Category V—No canal lumen (usually seen near the apex only)

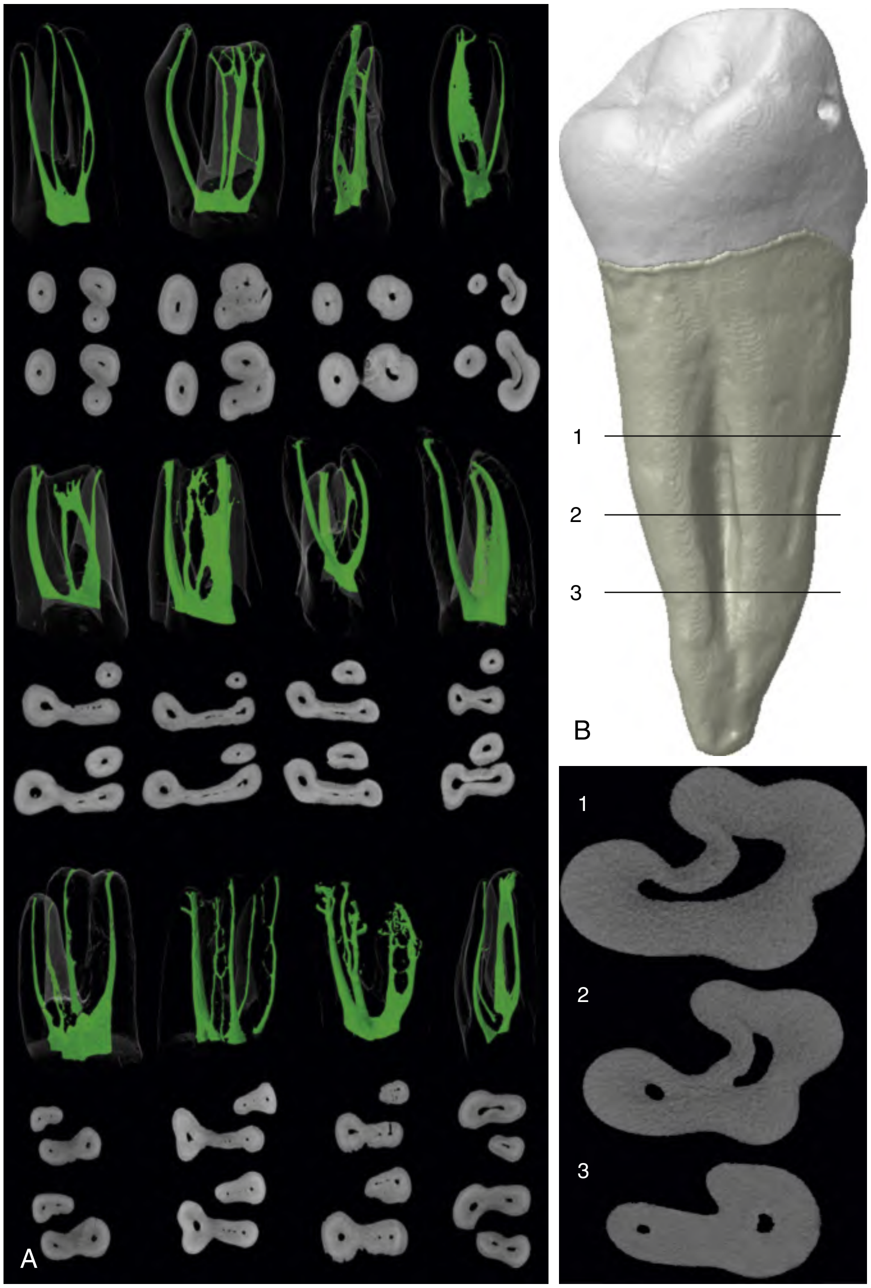
Melton's classification[96] stated that categories II and III have separated canals, but no description was provided to differentiate them. In the modified classification,[110] one of the canals in the category II would appear as an arc and would be more likely to extend into the "fused" area of the root where the dentin wall may be quite thin.

C-shaped canal anatomy has also been reported in third molars,[111] lateral incisors,[102] mandibular first premolars,[97,99,101,112,113] mandibular first molars,[114] and maxillary first[115,116] and second[117] molars. Recently the prevalence of C-shaped canal configuration in maxillary molars with root fusion was reported to be as high as 15% (Fig. 12.17, *A*).[115] Mandibular first premolars present a variety of root canal configurations that include the presence of two or three root canals[40,113] and a C-shaped configuration system (Fig. 12.17, *B*).[118] As in mandibular molars, C-shaped canal systems in the mandibular first premolars vary among different ethnic groups, with its prevalence being reported to range from 1%[119] to 18%.[120] This configuration has been highly associated with Vertucci's type V configuration[100] (i.e., a single canal that bifurcates at the middle third and with the presence of a groove or concavity on the external root surface).[97,113] Radicular grooves on mandibular first premolars usually begin 3 mm from the CEJ and present frequently on the proximal lingual area of the middle root, not always extending to the root apex.[97,120]

Preoperative diagnosis of C-shaped canals is complex, mainly because these unique anatomic features are not easily recognized on a traditional 2D periapical radiograph.[98] With the increased use of CBCT scanning, clinicians may be able to detect C-shaped canals before endodontic treatment. Nevertheless, even when recognized, the disinfection procedure still remains a challenge, mostly because of the isthmus areas. Irregular areas in a C-shaped canal that may house soft tissue remnants or infected debris may escape thorough cleaning and may be a source of bleeding and severe pain.[121] In this way, the use of a dental microscope associated with sonic or ultrasonic instrumentation techniques may make treatment outcome more predictable.[30] Because of its challenging morphology, the C-shaped canal anatomy increases the difficulty in root canal therapy and may account for the frequent occurrence of endodontic failure on this tooth.[120]

Other Anomalies

(1) **Fusion:** It is commonly defined as the union of two distinct dental sprouts that occurs in any stage of the dental organ.[38] They are joined by the dentin, whereas pulp chambers and canals may be linked or separated depending on the developmental stage when the union occurs. This process involves epithelial and mesenchymal germ layers resulting in irregular tooth



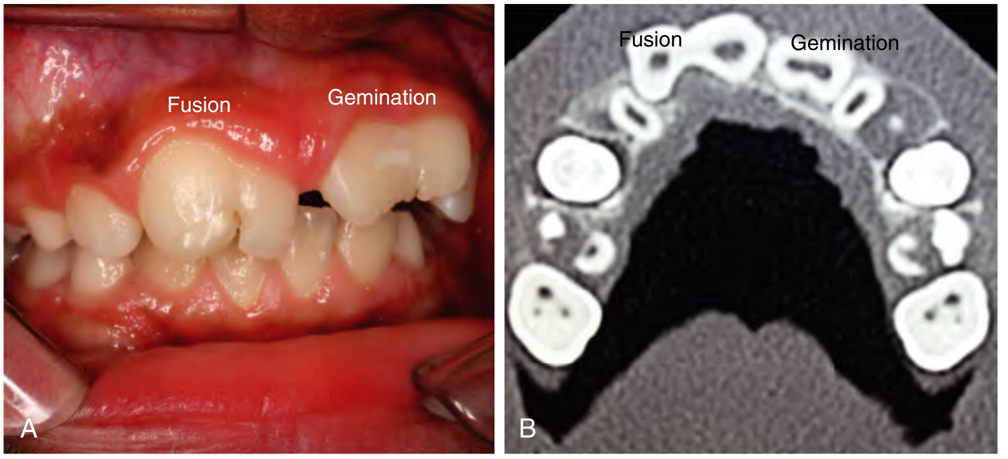
• **Fig. 12.17** **A,** Three-dimensional (3D) models and two-dimensional (2D) cross-sections of maxillary second molars with fused roots. Note the complexity of the root canal system with the presence of canal interconnections, apical ramifications and C-shaped canals; **B,** 3D model and 2D cross-sections at different levels of the root of a mandibular first premolar with radicular groove and C-shaped canal configuration.

morphology and occurs more frequently in anterior teeth (Fig. 12.18).[122]

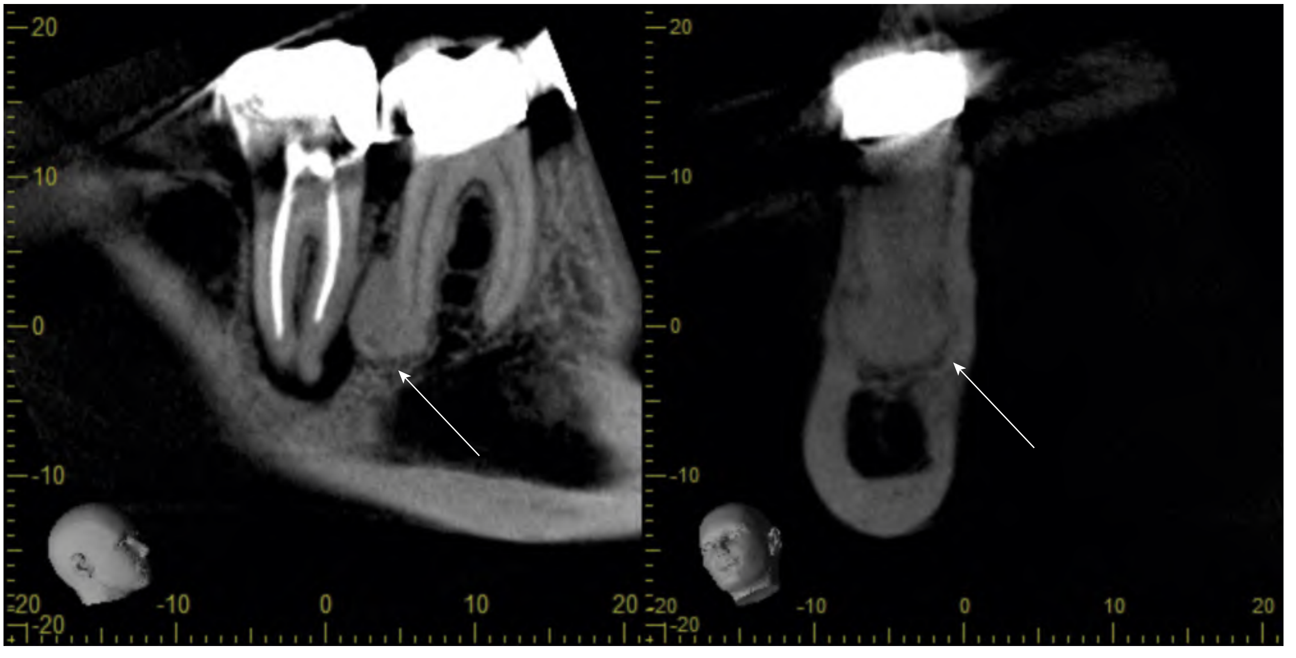
(2) **Gemination:** It is a disturbance during odontogenesis in which partial cleavage of the tooth germ occurs and results in a tooth that has a double or "twin" crown, usually not completely separated, and sharing a common root and pulp space (see Fig. 12.18).[38] The root and pulp are also irregular in morphology.

(3) **Hypercementosis:** This refers to an excessive deposition of nonneoplastic cementum over normal root cementum, which alters the root morphology macroscopic appearance.[38] Its pathogenesis is ambiguous. Most of the cases are idiopathic. Several local and systemic factors are also linked to this condition, such as Paget disease, acromegaly, or vitamin A deficiency (Fig. 12.19).[123]

(4) **Radicular Groove:** This is a developmental depression in the proximal aspect of the root surface.[124] Radicular grooves have been reported as being widespread in Africans and native Australians and are relatively rare in Western Eurasians.[125] It is relevant in clinic care because its depth may act as a reservoir for dental plaque and calculus, increasing the difficulty in the management of periodontal disease.[97,101] In mandibular premolar teeth, its presence has been associated with anatomic complexities of the root canal system, such as canal bifurcation and C-shaped configuration (Fig. 12.20).[97,99,101]



• **Fig. 12.18** **A,** Clinical and **B,** tomographic views of a patient presenting fusion and gemination at the anterior teeth. (Courtesy Dr. Antonis Chaniotis. Published with permission.)



• **Fig. 12.19** Coronal and sagittal cone beam computed tomography (CBCT) images from a distal root of a mandibular first molar presenting hypercementosis *(arrow)*. (Courtesy Dr. Oscar von Stetten. Published with permission.)

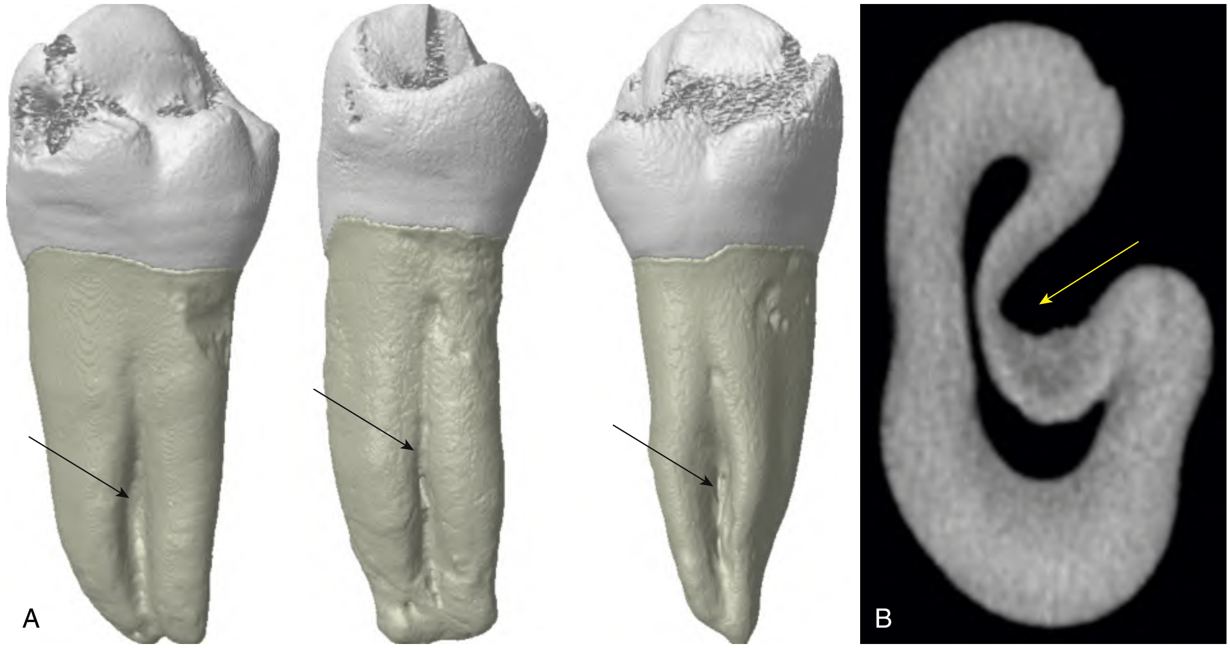
Aging

The root canal anatomy is susceptible to changes over the years because of physiologic or pathologic events. Natural physiologic aging tends to modify the root canal system morphology as a result of the deposition of secondary dentin, which starts to form once the tooth erupts and is in occlusion.[126] Consequently, young patients tend to present with large single canals and pulp chambers,[127,128] whereas older patients tend to present with more sharply defined and narrow root canals.[127] Other pathologic or iatrogenic factors can also modify the deposition of dentin including occlusal trauma, periodontal disease, carious lesions, or deep restorative procedures.[129]

In the literature, CBCT imaging technology has been also used to address in vivo root canal morphologic changes caused by aging.[3] Overall, results showed no significant difference between maxillary and mandibular anterior teeth groups regarding age, despite contradictory information can be found. While in mandibular anterior teeth most studies reported a lower prevalence of multiple canals in older patients,[130,131] in maxillary and mandibular premolars and in mandibular molars[128,132] it was observed that there was a progressive decrease of Vertucci's Type I configuration with age. The prevalence of a second canal in the mesiobuccal root of maxillary first and second molars was also evaluated and most studies reported a lower prevalence of this configuration in older patients.[129,133-135]

Root Canal Anatomy of Maxillary and Mandibular Teeth

In this section, illustrations and tables of the characteristics of the anatomy of the human root and root canals are depicted. The teeth



• **Fig. 12.20** **A,** Three-dimensional (3D) micro–computed tomography (micro-CT) models of mandibular premolars showing the external anatomy with the presence of radicular grooves *(arrows)*; **B,** Two-dimensional (2D) cross-section of the root of a mandibular premolar showing radicular groove *(arrow)* and a C-shaped canal configuration.

are paired to facilitate comparison among groups. Root and canal number averages are calculated from a weighted average of a large number of dental anatomy research articles published from a number of sources. Other data listed describe the canal characteristics such as average length of root and crown, canal curvature direction, canal shape, lateral canals, and apical anastomoses. Most important is the listing of the most common anomalies or variation from the normal that may be found in that tooth type. Those data are usually present in numerous case reports from a PubMed search.[3,136]

Of great interest, not only to dentists but also to the science of physical anthropology, are the ethnic variations that can be found in human populations.[11] It is true that genetics plays the main role in determining the shape of a crown and root. Bilateral symmetry is usually present in the antimere of the opposite quadrant but not necessarily so when it comes to variation in root number or anomalous tooth formation. A suite of dental variations in crown and root anatomy may be used to indicate ethnic identity in a population when a number of characteristics appear in a higher incidence of that population. The dental characteristics that are of interest to a physical anthropologist include deep lingual fossa (shoveling) of anterior teeth, dens invaginatus, dens evaginatus (talon cusp and occlusal tubercles of premolar teeth), bifurcated roots of mandibular canines, three roots of maxillary premolar teeth, fusion or single root of the maxillary premolar, multiple roots or multiple canals of mandibular premolar teeth, C-shaped molar teeth, taurodontism, fusion of roots, double canals in palatal or distal root of maxillary molars, four roots with double palatal root in maxillary second molar teeth, and radix entomolaris or the distolingual root of mandibular molar teeth.

Tratman in 1950[11] used extracted teeth to show a number of variations or traits in dental anatomy in Asian populations that varied from the generally accepted Western Eurasian dental anatomy of the time. Since then, many large population studies using full mouth radiographs or the panographic X-ray technique have identified root form variation.[1] A higher incidence of the distolingual root of both first and second mandibular molar teeth in Asian and North American aboriginal native populations is a good example. There have been only a few studies that show a variation in incidence that is gender linked.[137-139] More recently, a series of epidemiologic studies on root canal anatomy using CBCT 3D imaging technology have been published. The most important advantage of using CBCT is the possibility of performing in vivo studies analyzing the full dentition of a large number of patients collected from a specific population in a consecutive manner, addressing the influence of several variables such as ethnicity, aging, gender, and side (left or right) on teeth. Therefore, information regarding the number of roots and root canals and the most frequently observed canal configurations was depicted from a recent epidemiologic study using CBCT technology.[3]

The following tables and figures will help outline the common characteristics of each tooth type and list some variations or anomalies.

Incisors

Morphologic aspects of the root and root canal anatomy of maxillary and mandibular incisors are detailed in Table 12.1, Fig. 12.21, and Appendices 1 to 4 (Summary of Root Numbers and Root Canal Systems of the Permanent Teeth).

The maxillary central incisors are centered in the maxilla, one on either side of the midline, with the mesial surface of each in contact with the mesial surface of the other. The pulp cavity follows the general outline of the crown and root. In this way, the pulp chamber is very narrow in the incisal region and wider in the mesiodistal dimension than in the labiolingual dimension. The maxillary lateral incisor supplements the central incisor in function, and the crowns bear a close resemblance. However, the lateral incisor is smaller in all dimensions except root length.

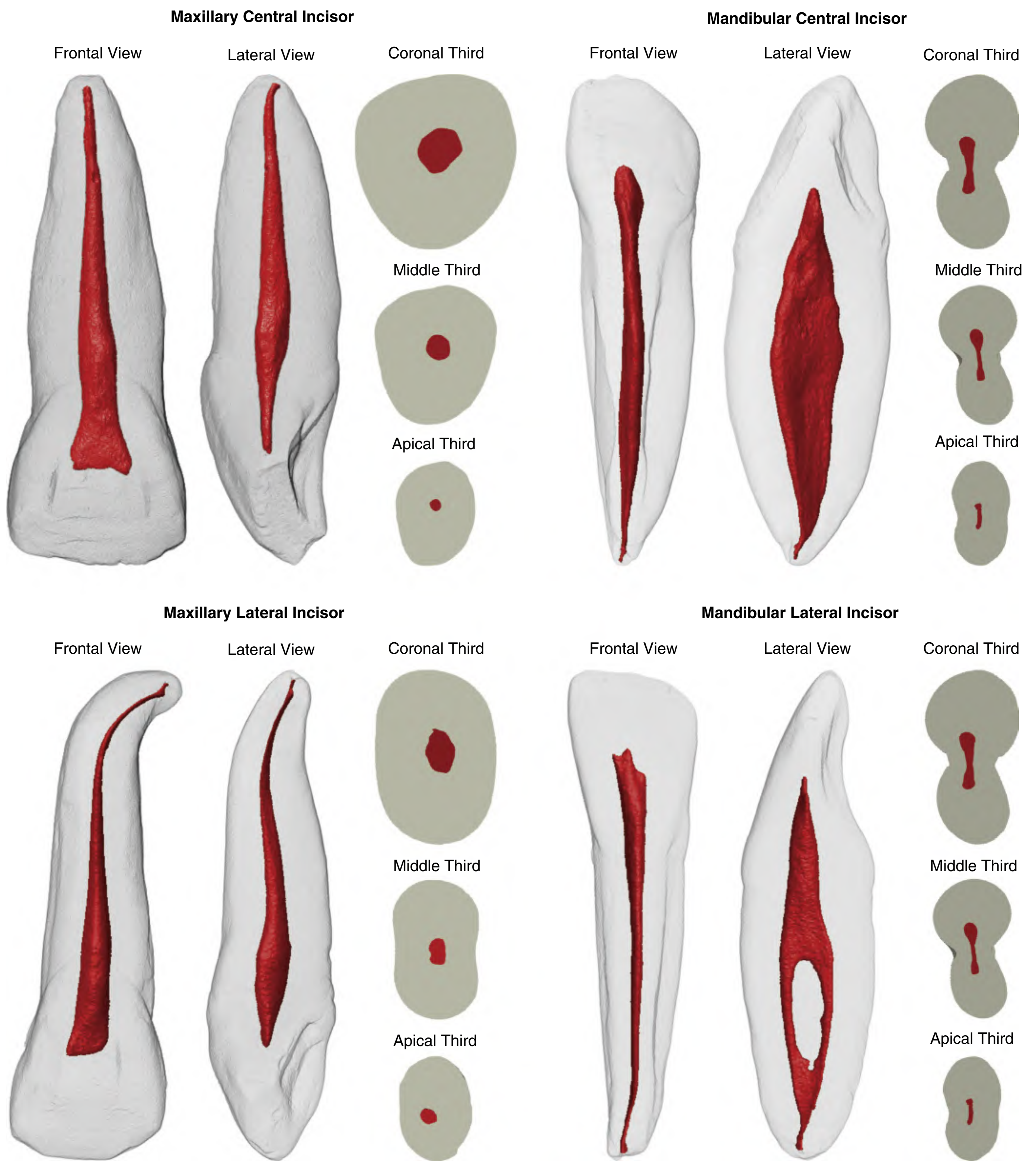
TABLE 12.1 Morphologic Aspects of the Root and Root Canal Anatomy of Maxillary and Mandibular Incisors

	Maxillary Central Incisor	Maxillary Lateral Incisor	Mandibular Incisors
Overall length	23.6 mm (16.5-32.6 mm)	22.5 mm (17.7-28.9 mm)	C: 20.8 mm (16.9-26.7 mm) L: 22.1 mm (18.5-26.6 mm)
Root length	13.0 mm (6.3-20.3 mm)	13.4 mm (9.6-19.4 mm)	C: 12.6 mm (7.7-17.9 mm) L: 13.5 mm (9.4-18.1 mm)
Number of roots	1 (99.94%) 2 (0.06%)	1 (99.94%) 2 (0.06%)	C: 1 (100%) L: 1 (99.92%) 2 (0.08%)
Number of canals	1 (99.2%) 2 (0.8%)	1 (98.5%) 2 (1.5%)	C: 1 (86.5%) 2 (14.4%) Other (0.1%) L: 1 (79.7%) 2 (20.2%) Other (0.1%)
Canal configuration	Types I (99.2%) IV (0.5%) II (0.1%) III (0.1%) V (0.1%)	Types I (98.5%) II (0.8%) V (0.4%) III (0.2%) IV (0.1%)	C: Types I (86.5%) III (8.1%) V (2.8%) II (2%) IV (1.4%) VII (0.1%) Other (0.1%) L: Types I (79.7%) III (11.9%) V (3.8%) II (2.6%) IV (1.8%) VII (0.1%) Other (0.1%)
Accessory canals	18.9%-42.6% (coronal: 1%; middle: 6%; apical: 93%)	5.5%-26% (coronal: 1%; middle: 8%; apical: 91%)	C: 0%-20% (coronal: 3%; middle: 12%; apical: 85%) L: 0.9%-18% (coronal: 2%; middle: 15%; apical: 83%)
Apical curvature	Straight (75%) Labial (9.3%) Distal (7.8%) Mesial (4.3%) Palatal (3.6%)	Distal (49.2%) Straight (29.7%) Palatal (3.9%) Labial (3.9%) Mesial (3.1%) S-shaped (1.6%) Other (8.6%)	C: Straight (66.7%) Labial (18.8%) Distal (12.5%) S-shaped (2%) L: Straight (54%) Distal (33.3%) Labial (10.7%) S-shaped (2%)
Anomalies	2 canals[141-143] 3 canals[144] 4 canals[145] 2 roots[141-143] Radicular groove[146] Fusion/gemination[147]	2 canals[148] 3 canals[149] 4 canals[150] 2 roots[151] Radicular groove[146] Fusion/gemination[152] Dens invaginatus[153] Dens evaginatus[154] C-shaped[102]	3 canals[155] Fusion/gemination[156] Dens invaginatus[157] 2 roots[158]
Ethnic variations	Deep lingual fossa (shoveling) in Asian and North American native populations	Coronal shoveling present to a lesser degree	

C, Central; *L*, lateral.

Root canal configurations are classified according to Vertucci.[40]

Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In Versiani MA, Basrani B, Sousa Neto MD, editors: *The root canal anatomy in permanent dentition*, ed 1. Switzerland, 2018, Springer International Publishing, pp 181–240.



• **Fig. 12.21** Three-dimensional (3D) micro–computed tomography (micro-CT) models and two-dimensional (2D) cross-sections depicting the internal and external anatomy of maxillary and mandibular incisors.

The pulp chamber is narrow in the incisal region and may become very wide at the cervical level of the tooth, whereas pulp horns are usually prominent.[140]

The mandibular central incisors are centered in the mandible, one on either side of the midline, with the mesial surface of each one in contact with the mesial surface of the other. The right and left mandibular lateral incisors are distal to the central incisors. The mandibular central and lateral incisors have smaller mesiodistal dimensions than any of the other teeth. The central incisor is somewhat smaller than the lateral incisor, which is the reverse of the situation in

TABLE 12.2 Morphologic Aspects of the Root and Root Canal Anatomy of Maxillary and Mandibular Canines

	Maxillary Canine	Mandibular Canine
Overall length	26.4 mm (20.0-38.4 mm)	25.9 mm (16.1-34.5 mm)
Root length	16.5 mm (10.8-28.5 mm)	15.9 mm (9.5-22.2 mm)
Number of roots	1 (100%)	1 (98.57%) 2 (1.43%)
Number of canals	1 (97%) 2 (3%)	1 (92.4%) 2 (7.3%) Other (0.3%)
Canal configuration	Types I (98.5%) III (1.2%) II (0.8%) V (0.7%) IV (0.2%) Other (0.1%)	Types I (92.4%) III (2.7%) II (1.9%) IV (1.5%) V (1.2%) Other (0.3%)
Accessory canals	3.4%-30% (coronal: 0%; middle: 10%; apical: 90%)	4.5%-30% (coronal: 4%; middle: 16%; apical: 80%)
Apical curvature	Straight (38.5%) Distal (19.5%) Labial (12.8%) Mesial (12%) Palatal (6.5%) Other (10.7%)	Straight (68.2%) Distal (19.6%) Labial (6.8%) Mesial (0.8%) S-shaped (1.5%) Other (3.1%)
Anomalies	2 canals[159] Dens invaginatus[160]	2 canals[161] 3 canals[162] 2 roots[161]
Ethnic variations		Bifurcated roots in mandibular canines are most common in some Western Eurasian populations

Root canal configurations are classified according to Vertucci.[40]

Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In Versiani MA, Basrani B, Sousa Neto MD, editors.: *The root canal anatomy in permanent dentition.* ed 1. Switzerland, 2018, Springer International Publishing, pp 181–240.

the maxilla. These teeth are similar in form and have smooth crown surfaces that show few traces of developmental lines. The mandibular central incisor is the smallest tooth in the mouth, but its labiolingual root dimension is large. This tooth usually has one canal. Two ribbon-shaped canals may be found, but not very frequently (15% and 20% of central and lateral incisors, respectively). The pulp horns are well developed in this tooth group. The mandibular lateral incisor tends to be a little larger than the mandibular central incisor in all dimensions, including the pulp chamber. The pulp canal may taper gently from the apex or narrow abruptly in the last 3 to 4 mm of the root canal.[140]

Canines

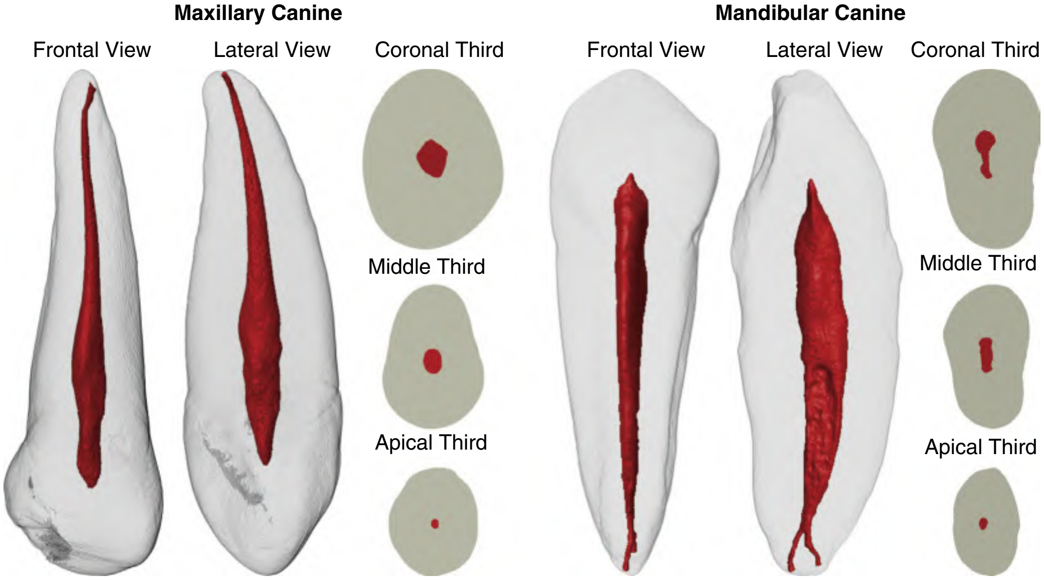
Morphologic aspects of the root and root canal anatomy of maxillary and mandibular canines are detailed in Table 12.2, Fig. 12.22, and Appendices 1 to 4 (Summary of Root Numbers and Root Canal Systems of the Permanent Teeth).

Maxillary canines are the longest teeth in the mouth. The crowns are usually as long as those of the maxillary central incisors, and the single roots are longer than those of any of the other teeth. Therefore the maxillary canine has the largest labiolingual root dimension of any tooth and because the pulp cavity corresponds closely to the outline of the tooth, the size of the pulp chamber may also be the largest in the mouth.

The mandibular canine crown is narrower mesiodistally than that of the maxillary canine, although it is just as long in most instances and, in many instances, is longer by 0.5 to 1 mm. The root may be as long as that of the maxillary canine, but usually it is somewhat shorter. The pulp cavity of the mandibular canine tends to be a little shorter than that of the maxillary canine. A not rare variation in the form of the mandibular canine is bifurcated roots, and it is also not uncommon to find two roots or at least two canals. Because the presence of two canals cannot be easily detected radiographically, their presence must be ruled out clinically as well. Some mandibular canines demonstrate an abrupt narrowing of the pulp cavity when passing from the pulp chamber to the pulp canal. Other mandibular canine teeth demonstrate an abrupt narrowing of the pulp canal in the apical region.[140]

Premolars

Morphologic aspects of the root and root canal anatomy of maxillary and mandibular premolars are detailed in Tables 12.3 and 12.4, Fig. 12.23, and Appendices 1 to 4 (Summary of Root Numbers and Root Canal Systems of the Permanent Teeth).



• **Fig. 12.22** Three-dimensional (3D) micro–computed tomography (micro-CT) models and two-dimensional (2D) cross-sections depicting the internal and external anatomy of maxillary and mandibular canines.

TABLE 12.3 **Morphologic Aspects of the Root and Root Canal Anatomy of Maxillary Premolars**

	Maxillary First Premolar	Maxillary Second Premolar
Overall length	21.5 mm (15.5-28.9 mm)	21.2 mm (15.2-28.4 mm)
Root length	13.4 mm (8.3-19.0 mm)	14.0 mm (8.0-20.6 mm)
Number of roots	2 (55.3%) 1 (43.1%) 3 (1.6%)	1 (86.2%) 2 (13.5%) 3 (0.3%)
Number of canals	2 (77.3%) 1 (20.1%) 3 (1.2%) Other (1.3%)	2 (56.7%) 1 (42.7%) 3 (0.4%) Other (0.3%)
Canal configuration	Types IV (50.1%) I (20.1%) II (17.4%) VI (4.9%) V (3%) III (1.5%) VIII (1.2%) VII (0.4%) Other (1.3%)	Types I (42.7%) II (18.7%) IV (17.6%) V (9.6%) VI (6.3%) III (4%) VII (0.5%) VIII (0.4%) Other (0.3%)
Accessory canals	17.8%-49.5% (coronal: 4.7%; middle: 10.3%; apical: 74%)	12.9%-59.5% (coronal: 4%; middle: 16.2%; apical: 78.2%)
Apical curvature	B: Palatal (36.2%) Straight (27.8%) Distal (14%) Buccal (14%) S-shaped (8%) P: Straight (44.4%) Buccal (27.8%) Distal (14%) Palatal (8.3%) S-shaped (5.5%)	Straight (37.4%) Distal (29.5%) Buccal (15.7%) S-shaped (13%) Distal (4.4%)

Continued

TABLE 12.3 Morphologic Aspects of the Root and Root Canal Anatomy of Maxillary Premolars—cont'd

	Maxillary First Premolar	Maxillary Second Premolar
Anomalies	3 canals[163] Radicular groove[164] Fusion/gemination[165] Dens evaginatus[166]	3 canals[163] Dens invaginatus[167]
Ethnic variations	Caucasian and other populations (excluding Asian and North American native populations) most commonly have 2 roots. Asian and North American native populations most commonly have a single root. Dens evaginatus on the occlusal surfaces of all premolars is more common in Asian and North American native populations	

B, Buccal root/canal; *P*, palatal root/canal.

Root canal configurations are classified according to Vertucci.[40]

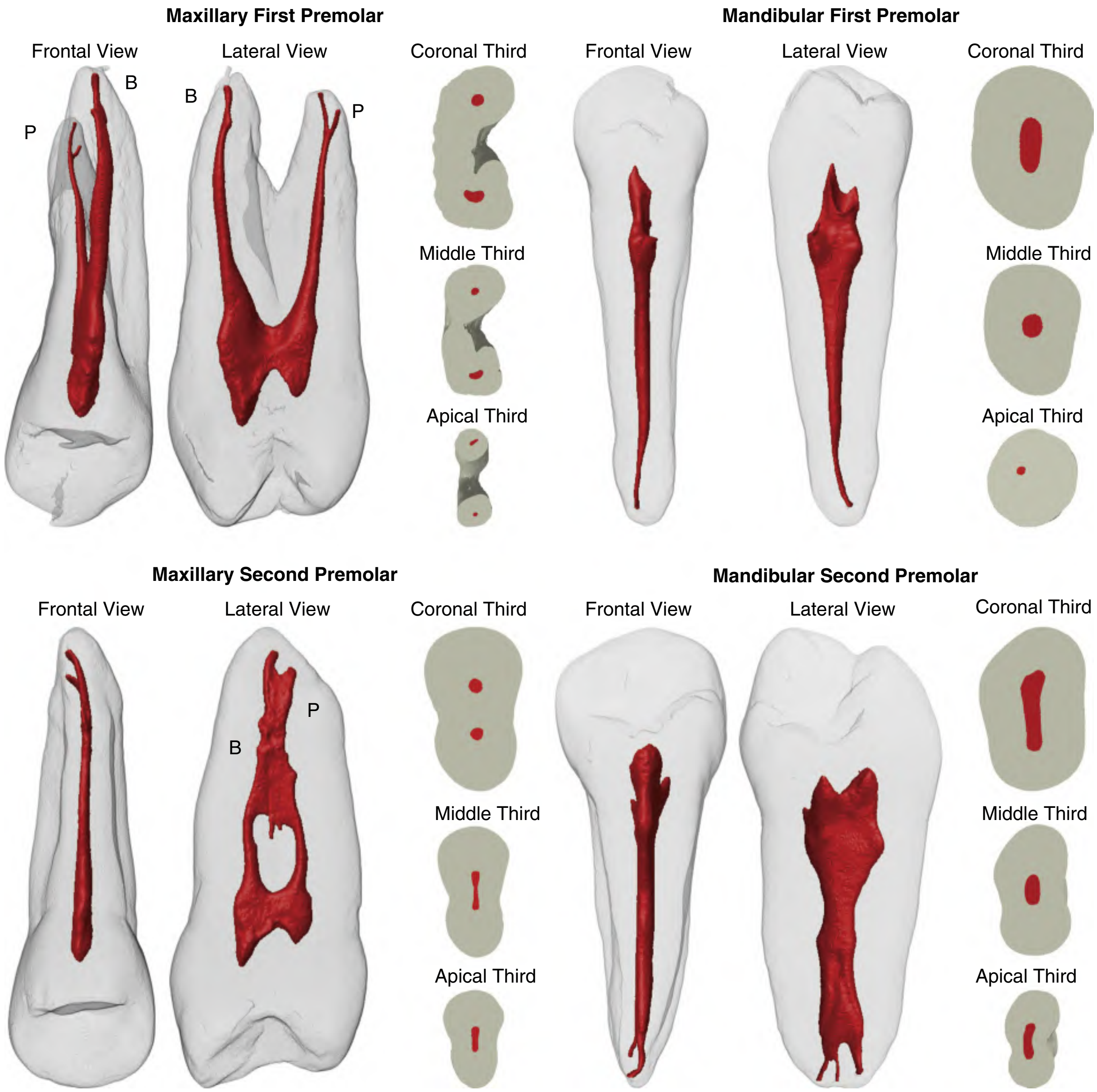
Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In: Versiani MA, Basrani B, Sousa Neto MD, editors. *The root canal anatomy in permanent dentition.* ed 1. Switzerland, 2018, Springer International Publishing, pp 181–240.

TABLE 12.4 Morphologic Aspects of the Root and Root Canal Anatomy of Mandibular Premolars

	Mandibular First Premolar	Mandibular Second Premolar
Overall length	22.4 mm (17.0-28.5 mm)	22.1 mm (16.8-28.1 mm)
Root length	14.4 mm (9.7-20.2 mm)	14.7 mm (9.2-21.2 mm)
Number of roots	1 (97.5%) 2 (2.5%)	1 (98.5%) 2 (1.5%)
Number of canals	1 (71.3%) 2 (27.9%) 3 (0.1%) Other (0.7%)	1 (84.7%) 2 (15.05%) 3 (0.05%) Other (0.2%)
Canal configuration	Types I (71.3%) V (18.7%) IV (3.5%) III (2.8%) II (2.3%) VI (0.5%) VII (0.1%) VIII (0.1%) Other (0.7%)	Types I (84.7%) V (13.44%) II (0.7%) III (0.5%) IV (0.3%) VI (0.07%) VIII (0.05) VII (0.04%) Other (0.2%)
Accessory canals	8.8%-44.3% (coronal: 4.3%; middle: 16.1%; apical: 78.9%)	4%-48.3% (coronal: 3.2%; middle: 16.4%; apical: 80.1%)
Apical curvature	Straight (47.5%) Distal (34.8%) Lingual (7.1%) Buccal (2.1%) S-shaped (6.4%) Other (2.1%)	Distal (39.8%) Straight (38.5%) Buccal (10.1%) Lingual (3.4%) S-shaped (6.8%) Other (1.4%)
Anomalies	3 canals[113] 4 canals[168] Radicular groove[112] C-shaped[97] Dens evaginatus[169] Dens invaginatus[170] Fusion/gemination[171]	3 canals[172] 4 canals[173] 5 canals[174] 2 roots[175] C-shaped[99] Dens evaginatus[176] Taurodontism[174] Fusion/gemination[177]
Ethnic variations	African American population has a significantly higher incidence of two canals and two roots compared with Caucasian[1]	

Root canal configurations are classified according to Vertucci.[40]

Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In: Versiani MA, Basrani B, Sousa Neto MD, editors. The *root canal anatomy in permanent dentition.* ed 1. Switzerland, 2018, Springer International Publishing, pp 181–240.



• Fig. 12.23 Three-dimensional (3D) micro–computed tomography (micro-CT) models and two-dimensional (2D) cross-sections depicting the internal and external anatomy of maxillary and mandibular premolars.

The premolars are so named because they are anterior to the molars in the permanent dentition. The maxillary first premolar has two cusps, a buccal and a lingual, each being sharply defined. The buccal cusp is usually about 1 mm longer than the lingual cusp and, because of that, the pulp horn usually extends further occlusally under the buccal cusp than the lingual cusp. The maxillary first premolar may have two well-developed roots, two root projections that are not fully separated, or one broad root. The majority of maxillary first premolars have two root canals, but a small percentage of teeth may have three roots and three canals that may at times be difficult to see or almost undetectable radiographically. The pulp chamber floor is below the cervical level of all the variations found in this tooth group.

The maxillary second premolar supplements the maxillary first premolar in function and closely resembles it in shape. The maxillary second premolar may have a crown that is noticeably smaller cervico-occlusally and also mesiodistally. However, it may also be larger in those dimensions. Usually the root of the second premolar is as long as, if not a millimeter or so longer than, that of the first premolar. Most maxillary second premolars have only one root and canal. Two roots are possible, although two canals within a single root may also be found. The pulp cavity may demonstrate well-developed pulp horns; others may have blunted or nonexistent pulp horns. The pulp chamber and root canal are very broad in the buccolingual aspect of teeth with single canals.[140]

The mandibular first premolar is always the smallest of the two mandibular premolars, whereas the opposite is true, in many cases, of the maxillary premolars. Most of these teeth have one canal, but two or three canals are possible. The pulp chamber is usually very large, and the pulp cavity may taper gently toward the apex or abruptly as the root canal start. The root of the first premolar usually shows a deep developmental groove that has been associated with complex anatomic features including C-shaped and extra root canals.[140]

The mandibular second premolar usually has three well-formed cusps in most cases: one large buccal cusp and two smaller lingual cusps. However, two-cusped forms of this tooth are also fairly common. It usually has one root and canal that may be curved, usually in the distal direction. The pulp horns are prominent, and the pulp chamber and root canal gently taper toward the apex. The single root of the second premolar is larger and longer than that of the first premolar. The root is seldom, if ever, bifurcated, although some specimens show a deep developmental groove buccally.[140]

Molars

Morphologic aspects of the root and root canal anatomy of maxillary and mandibular first and second molars are detailed in Tables 12.5, 12.6, Figs. 12.24 and 12.25, and Appendices 1 to 4 (Summary of Root Numbers and Root Canal Systems of the Permanent Teeth).

The maxillary molars are the largest and strongest maxillary teeth, by virtue both of their bulk and of their anchorage in the jaws. The crown of this tooth is wider buccolingually than mesiodistally. The maxillary first molar is normally the largest tooth in the maxillary arch. It has four well-developed functioning cusps and one supplemental cusp (the cusp of Carabelli) that is of little practical use. The maxillary first molar normally has three roots and four canals. The palatal root usually has the largest dimensions, followed by the mesiobuccal and distobuccal roots, respectively. The mesiobuccal root is often very wide buccolingually and normally possesses an extra accessory canal named *MB2*, which usually is the smallest of all the canals in this tooth.[140] The complexity of its root canal system may surpass all other teeth within the human dentition. More extensive use of the clinical microscope has contributed to the discovery that not only a fourth canal but other additional canals also may exist.

The maxillary second molar supplements the first molar in function. The roots of this tooth are as long as, if not somewhat longer than, those of the first molar. The tendency for root fusion is greater in the second maxillary molar than in the first maxillary molar, but the palatal root is usually separate. Most often maxillary second molars possess three roots and three canals. The mesiobuccal root of the maxillary second molar is not as complex as that formed in the maxillary first molar. The tendency for a very wide mesiobuccal canal is not present in this tooth group.[140]

The mandibular first molar is usually the largest tooth in the mandibular arch. It has five well-developed cusps, two well-developed roots, one mesial and one distal, which are very broad buccolingually. These roots are widely separated at the apices. The buccolingual cross-section of the mandibular first molar demonstrates a large pulp chamber that may extend well down into the root formation. The mesial root usually has a more complicated canal system because of the presence of two canals and their interconnections. The distal root usually has one large canal, but two canals are often present. Occasionally, a fourth canal is present that has its own separate root.

Normally, the mandibular second molar has four well-developed cusps, two buccal and two lingual, of nearly equal development. The tooth has two well-developed roots, one mesial and one distal. These roots are broad buccolingually, but they are not as broad as those of the first molar, nor are they as widely separated. The buccolingual section of the mandibular second molar demonstrates a pulp chamber and pulp canals that tend to be more variable and complex than those found in the mandibular first molar.[140]

In the literature, first and second permanent molars are the most studied teeth in relation to internal and external anatomy. On the other hand, considering that third molars have variable and unpredictable morphology and also because their extraction is frequently indicated, these teeth are rarely considered for endodontic or restorative treatment. Therefore only a limited number of studies have reported data regarding the internal and external morphology of third molars. In general, these studies show an extremely varied anatomy, with maxillary third molars having one to five roots with one to six root canals, whereas the mandibular third molars have one to four roots and one to six root canals, besides the presence of C-shaped canals. In addition, maxillary and mandibular third molars present a high incidence of fused roots, with an average of 70.1% and 40.7%, respectively, which explains their variations in number, morphology, direction, and arrangement of roots and canals (Table 12.7).

Finally, Table 12.8 shows the outcomes from epidemiologic studies using CBCT in large populations, in which both data from root and root canal anatomy were evaluated, selected, and combined, aiming to offer an overview of the percentage frequency of different number of roots and root canal configuration types in all groups of teeth.

TABLE 12.5 Morphologic Aspects of the Root and Root Canal Anatomy of Maxillary First and Second Molars

	Maxillary First Molar	Maxillary Second Molar
Overall length	20.1 mm (17.0-27.4 mm)	20.0 mm (16.0-26.2 mm)
Root length	MB:12.9 mm (8.5-18.8 mm) DB: 12.2 mm (8.9-15.5mm) P: 13.7 mm (10.6-17.5 mm)	MB: 12.9 mm (9.0-18.2 mm) DB: 12.1 mm (9.0-16.3mm) P: 13.5 mm (9.8-18.8 mm)
Number of roots	3 (97.7%) 2 (1.8%) 4 (0.3%) 1 (0.2%)	3 (73.7%) 2 (14.9%) 1 (10.7%) 4 (0.7%)

TABLE 12.5 Morphologic Aspects of the Root and Root Canal Anatomy of Maxillary First and Second Molars—cont'd

	Maxillary First Molar	Maxillary Second Molar
Number of canals	MB: 2 (60.4%) 1 (29.3%) 3 (0.1%) Other (0.4%) DB: 1 (98.6%) 2 (1.4%) P: 1 (99.26%) 2 (0.7%) Other (0.04%)	MB: 1 (66.1%) 2 (33.7%) 3 (0.05%) Other (0.2%) DB: 1 (99.6%) 2 (0.4%) P: 1 (99.67%) 2 (0.35%) 3 (0.01%) Other (0.01%)
Canal configuration	MB: Types I (39.1%) II (29.3%) IV (26%) V (2%) III (1.6%) VI (1.4%) VII (0.1%) VIII (0.1%) Other (0.4%) DB: Types I (98.6%) II (0.4%) V (0.4%) III (0.3%) IV (0.2%) VI (0.1%) P: Types I (99.26%) II (0.3%) III (0.2%) IV (0.1%) V (0.1%) Other (0.04%)	MB: Types I (39.1%) II (29.3%) IV (26%) V (2%) III (1.6%) VI (1.4%) VII (0.1%) VIII (0.1%) Other (0.4%) DB: Types I (98.6%) II (0.4%) V (0.4%) III (0.3%) IV (0.2%) VI (0.1%) P: Types I (99.26%) II (0.3%) III (0.2%) IV (0.1%) V (0.1%) Other (0.04%)
Accessory canals	MB: 51% (coronal: 10.7%; middle: 13.1%; apical: 58.2%) DB: 36% (coronal: 10.1%; middle: 12.3%; apical: 59.6%) P: 48% (coronal: 9.4%; middle: 11.3%; apical: 61.3%)	MB: 50% (coronal: 10.1%; middle: 14.1%; apical: 65.8%) DB: 29% (coronal: 9.1%; middle: 13.3%; apical: 67.6%) P: 42% (coronal: 8.7%; middle: 11.2%; apical: 70.1%)
Apical Curvature	MB: Distal (78%) Straight (21%) S-shaped (1%) DB: Straight (54%) Mesial (19%) Distal (17%) S-shaped (10%) P: Buccal (55%) Straight (40.7%) Mesial (3.2%) Distal (1.1%)	MB: Distal (54%) Straight (22%) Others (24%) DB: Straight (54%) Mesial (17%) Others (29%) P: Straight (63%) Buccal (37%)
Anomalies	1 canal[178] 5 canals[179] 6 canals[180] 7 canals[181] 8 canals[182] C-shaped[116] 4 roots[85] Taurodontism[68]	1 or 2 canals[183] 5 canals[184] Fusion/gemination[185] Taurodontism[186]
Ethnic variations		

MB, Mesiobuccal root/canal; *DB*, distobuccal root/canal; *P*, palatal root/canal.

Root canal configurations are classified according to Vertucci.[40]

Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In Versiani MA, Basrani B, Sousa Neto MD, editors. *The root canal anatomy in permanent dentition.* ed 1. Switzerland, 2018, Springer International Publishing, pp 181–240.

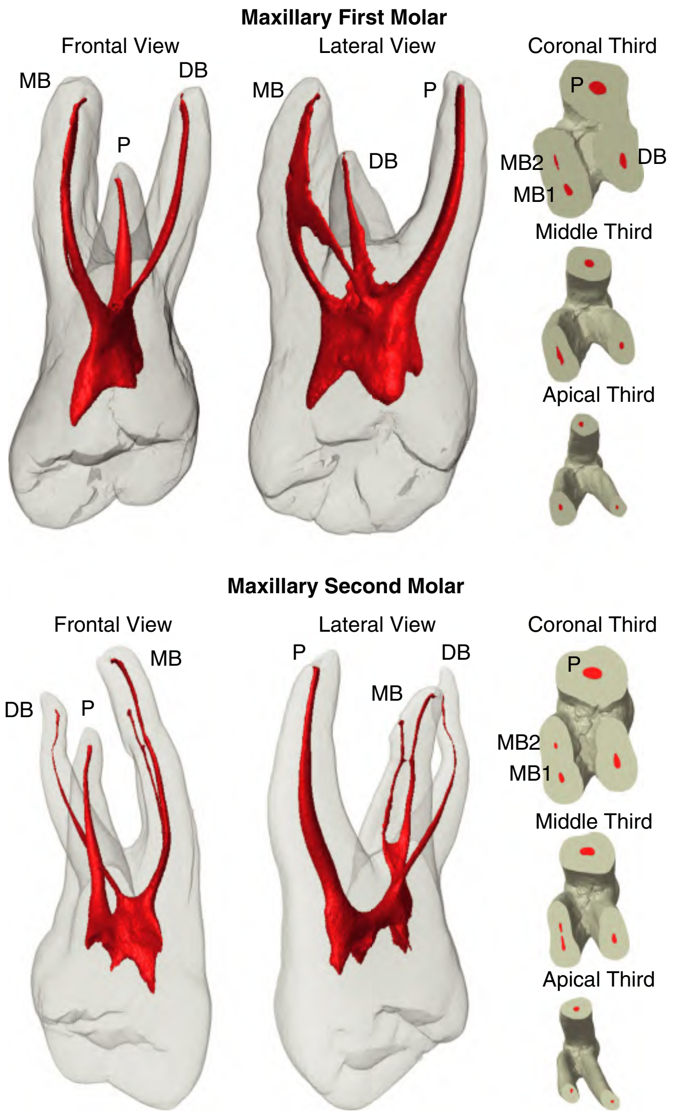
TABLE 12.6 Morphologic Aspects of the Root and Root Canal Anatomy of Mandibular First and Second Molars

	Mandibular First Molar	Mandibular Second Molar
Overall length	20.9 mm (17.0-27.7 mm)	20.6 mm (15.5-25.5 mm)
Root length	M: 14.0 mm (10.6-20.0 mm) D: 13.0 mm (8.1-17.7 mm)	M: 13.9 mm (9.3-18.3 mm) D: 13.0 mm (8.5-18.3 mm)
Number of roots	2 (86.9%) 3 (12.5%) 1 (0.55%) 4 (0.05%)	2 (78.6%) 1 (19%) 3 (2.2%) 4 (0.2%)
Number of canals	M: 1 (2.37%) 2 (96.59%) 3 (0.03%) Other (1.01%) D: 1 (70.3%) 2 (29.56%) Other (0.14%)	M: 2 (87.1%) 1 (12.5%) D: 1 (92.56%) 2 (7.44%)
Canal configuration	M: Types IV (71.3%) II (19.9%) III (2.9%) I (2.37%) V (2.1%) VI (0.3%) VII (0.09%) VIII (0.03%) Other (1.01%) D: Types I (70.3%) II (13%) IV (10.1%) III (3.6%) V (2.7%) VI (0.08%) VII (0.08%) Other (0.14%)	M: Types IV (47.8%) II (32.8%) I (12.5%) III (3.27%) V (3%) VI (0.2%) VII (0.1%) Other (0.33%) D: Types I (92.56%) II (4.4%) IV (2%) III (0.5%) V (0.5%) VI (0.04%)
Accessory canals	M: 45% (coronal: 10.4%; middle: 12.2%; apical: 54.4%) D: 30% (coronal: 8.7%; middle: 10.4%; apical: 57.9%)	M: 49% (coronal: 10.1%; middle: 13.1%; apical: 65.8%) D: 34% (coronal: 9.1%; middle: 11.6%; apical: 68.3%)
Apical curvature	M: Distal (84%) Straight (16%) D: Straight (73.5%) Distal (18%) Mesial (8.5%)	M: Distal (60.8%) Straight (27.2%) Buccal (4%) S-shaped (8%) D: Straight (57.6%) Distal (18.4%) Mesial (13.6%) Buccal (4%) S-shaped (6.4%)
Anomalies	5 canals[187] 6 canals[188] 7 canals[189] Radix[89] Taurodontism[190] Fusion/gemination[191] Isthmus[192] 3 roots[193] C-shaped[194] 3 canals in the distal root[195]	1 canal[196] 2 canals[197] 5 canals[198] Fusion/gemination[199] Isthmus[192] C-shaped[110]
Ethnic variations	Radix entomolaris is most common in Asian and North American native populations	

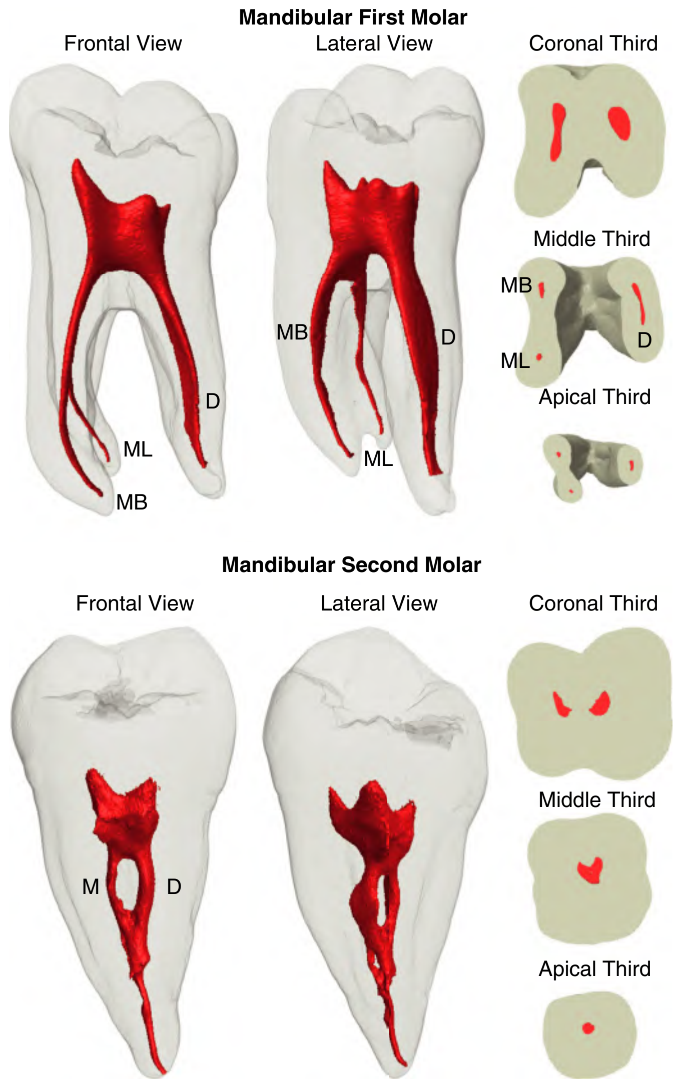
M, Mesial root/canal; D, distal root/canal.

Root canal configurations are classified according to Vertucci.[40]

Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In Versiani MA, Basrani B, Sousa Neto MD, editors: *The root canal anatomy in permanent dentition*, ed 1, Switzerland, 2018, Springer International Publishing, pp 181–240.



• **Fig. 12.24** Three-dimensional (3D) micro–computed tomography (micro-CT) models and two-dimensional (2D) cross-sections depicting the internal and external anatomy of maxillary molars.



• **Fig. 12.25** Three-dimensional (3D) micro–computed tomography (micro-CT) models and two-dimensional (2D) cross-sections depicting the internal and external anatomy of mandibular molars.

Study Questions

1. Why is there a need for a new root canal morphology classification system?
   A. The Weine's classification system is limited and cannot classify all types of canal configurations.
   B. The Type VIII canal system in the Vertucci classification is unclear.
   C. The Vertucci system does not include all types of canal configurations.
   D. All of the above are correct.
2. Which anterior tooth in the permanent dentition has the highest incidence of two roots with two bifid root apices?
   A. Maxillary central incisor
   B. Maxillary lateral incisor
   C. Maxillary canine
   D. Mandibular central incisor
   E. Mandibular lateral incisor
   F. Mandibular canine
3. Which of the following ethnic groups has the highest incidence of radix entomolaris?
   A. Western Eurasia (Western Europe, Middle East, and North Africa)
   B. Sub-Saharan Africa (West Africa, South Africa, San)
   C. Sino-America (China-Mongolia, Japan-Recent, Japan-Jomon, Northeast Siberia, South Siberia, American Arctic-Eskimo-Aleuts, Northwest North America-Indians, North and South America-Indians)
   D. Sunda-Pacific (South East Asia, Polynesia, Micronesia)
   E. Sahul-Pacific (Australia, New Guinea, Melanesia)
4. Which permanent teeth or roots of permanent teeth is there a high likelihood of finding two or more canals?
   A. Maxillary central incisor
   B. Maxillary first premolar
   C. Maxillary second premolar
   D. Mandibular first premolar
   E. Mandibular second premolar
   F. Mesiobuccal root of the maxillary first molar
   G. Palatal root of the maxillary first molar
   H. Mesial root of the mandibular first molar
   I. Distal root of the of the mandibular first molar
   J. Mesial root of the mandibular second molar
   K. Distal root of the mandibular second molar

Continued

Study Questions—cont'd

5. Which of the following ethnic groups has the highest incidence of dens evaginatus?
   A. Western Eurasia (Western Europe, Middle East, and North Africa)
   B. Sub-Saharan Africa (West Africa, South Africa, San)
   C. Sino-America (China-Mongolia, Japan-Recent, Japan-Jomon, Northeast Siberia, South Siberia, American Arctic-Eskimo-Aleuts, Northwest North America-Indians, North and South America-Indians)
   D. Sunda-Pacific (South East Asia, Polynesia, Micronesia)
   E. Sahul-Pacific (Australia, New Guinea, Melanesia)
6. Dens invaginatus is most commonly associated with which permanent anterior tooth?
   A. Maxillary central incisor
   B. Maxillary lateral incisor
   C. Maxillary canine
   D. Mandibular central or lateral incisor
   E. Mandibular canine
7. Which of the following ethnic groups has the highest incidence of bifurcated permanent mandibular canine root morphology?
   A. Western Eurasia (Western Europe, Middle East, and North Africa)
   B. Sub-Saharan Africa (West Africa, South Africa, San)
   C. Sino-America (China-Mongolia, Japan-Recent, Japan-Jomon, Northeast Siberia, South Siberia, American Arctic-Eskimo-Aleuts, Northwest North America-Indians, North and South America-Indians)
   D. Sunda-Pacific (South East Asia, Polynesia, Micronesia)
   E. Sahul-Pacific (Australia, New Guinea, Melanesia)

Influence of Root Canal Anatomy in Endodontic Procedures

Outcomes of nonsurgical and surgical endodontic procedures are highly influenced by variations in canal configuration and cross-sectional shapes and by the presence of canal irregularities and curvatures. Moreover, the high frequency of fins and communications between canals within the same root make it impossible for any mechanical or chemical technique to completely disinfect the root canal system. It is noteworthy to point out that some factors, such as physiologic aging, pathology, and occlusion, as well as the secondary deposition of dentin, can increase the mentioned variations, making shaping and cleaning the root canals a real challenge. Hence, the purpose of the treatment must be toward reducing the level of contamination as far as possible and entombing the remaining microorganisms. Clinicians ought, therefore, to be aware of complex root canal structures, cross-sectional dimensions, and iatrogenic alterations of canal anatomy. In this way, it is advisable to make a careful diagnostic interpretation based on angled radiographs or tomographic examinations, proper access preparation, and a detailed inspection of the pulp chamber floor. Ideally the search for root canal orifices should be under magnification with high intensity lighting, aiming to improve the treatment outcome.[22]

Essentially, there are three conditions that the clinician faces routinely when undertaking root canal treatment: teeth with vital and irreversibly inflamed pulps, teeth with necrotic pulps with or without primary apical periodontitis, and retreatment cases because of posttreatment apical periodontitis. In teeth with irreversible pulpitis, infection is usually restricted to the coronal parts of the canal and is easily controlled by abundant irrigation of the pulp chamber with sodium hypochlorite (NaOCl) after completion of the access cavity preparation. Then, under strict aseptic conditions, the clinician needs to clean the canal by removing the inflamed vital pulp tissue as much as possible.[216] In necrotic untreated teeth and treated teeth referred for retreatment because of posttreatment apical periodontitis an infection is established in the root canal system. In these cases, in addition to cleaning the canal from the necrotic pulp tissue or the previous filling material, the clinician also needs to combat infection. The successful treatment outcome will depend on how effective the clinician is in achieving these goals.[217]

One of the main steps of root canal treatment involved with disinfection of the root canal system is chemomechanical preparation. This procedure is of utmost importance for cleaning and disinfection, because instruments and irrigants act primarily in the main canal. Numerous studies have shown that instrumentation and irrigation are highly effective in reducing the intracanal bacterial populations.[218-220] Clinical[219,221] and in vitro studies[222,223] have clearly demonstrated that preparation using an antibacterial irrigating solution such as NaOCl significantly enhances disinfection compared with irrigation with saline or water. Most canals instrumented and irrigated with 2.5% NaOCl have the number of bacteria reduced 10^2 to 10^5 fold, which has resulted in an overall reduction of bacterial counts of 95% to 99%.[222,224] Regular exchange and the use of large volumes of irrigants should maintain the optimum antibacterial effectiveness of the NaOCl solution, compensating for the effects of concentration.[222] It has been reported that the beneficial effects of using NaOCl compared with saline are only observed after significant apical enlargement.[219,221] Several studies agree that supplementary irrigation methods using laser- or ultrasonic-activated irrigation and positive-pressure pulsed-delivery systems perform better than syringe irrigation in the removal of dentin debris or soft tissue remnants from fins and noninstrumented oval extensions,[33-35] but the relative effectiveness of each method is still unclear.[216]

Accessory canals and dentinal tubules present similar challenges for root canal irrigation but at a different length scale. Accessory canals (10 μm to 200 μm) are perceived to be smaller than the main canal but larger than dentinal tubules (0.5 μm to 3.2 μm).[25] Irrigant flow in accessory canals and dentinal tubules is driven by the flow in the main canal and appears to be limited to a depth approximately twice their diameter, whereas diffusion dominates irrigant transport beyond that point. Therefore optimum irrigant refreshment in the main canal to maintain a favorable concentration gradient, any increase in the temperature of the irrigants, and a longer application period could enhance particle transport. Nevertheless, the importance of accessory canal and dentinal tubule cleaning for the success of root canal treatment has been debated.[225]

Despite the optimal antibacterial effect obtained by chemomechanical preparation, clinical bacteriologic studies have demonstrated that 30% to 60% of the previously infected root canals still have detectable levels of bacteria after instrumentation.[218-220,226-228] The main reasons for bacteria to persist after chemomechanical procedures is that they are resistant to treatment or they are unaffected by instruments/irrigants. Although some microorganisms have been shown to be resistant to some endodontic antimicrobial agents,[229] resistance both to debridement and to NaOCl is highly unlikely to occur. Bacteria usually survive after treatment procedures not because they are more

TABLE 12.7 Summary of the Studies on Root and Root Canal Anatomy of Third Molars

				NUMBER OF ROOTS (%)				NUMBER OF ROOT CANALS (%)				
References	Population	Study Type	Sample	1	2	3	≥4	1	2	3	4	≥5
Maxillary Third Molars												
Barret[200]	USA	Sectioning	32	28.1	34.4	37.5	-	-	-	-	-	-
Piñeda & Kuttler[17]	Mexico	Radiograph	292	-	-	-	-	21.4	51.7	21.0	5.9	-
Green[18]	USA	Sectioning	100 MB	-	-	-	-	63.0	37.0	-	-	-
Hession[201]	Australia	Radiograph	12	-	-	-	-	16.7	25.0	58.3	-	-
Pécora et al.[202]	Brazil	Clearing	50	-	-	-	-	-	-	68.0	32.0	-
Guerisoli et al.[203]	Brazil	Clearing	155	12.3	1.9	81.9	3.8[a]	4.5	11.6	67.8	14.2	1.9
Stropko[204]	USA	Retrospective	25	-	-	-	-	-	20.0	60.0	20.0	-
Sidow et al.[111]	USA	Clearing	150	15.3	32	45.3	7.4	7.4 [c]	3.3	57.3	27.3	4.7[d]
Ng et al.[205]	Burma	Clearing	72	19.4	19.4	55.6	5.6	5.6	25.0	47.2	22.2	-
Alavi et al.[206]	Thailand	Clearing	151	1.3	6.6	88.1	4.0	9.9	11.3	48.3	29.1	1.3
Weng et al.[207]	China	Clearing	43	-	-	-	-	27.9	11.6	44.2	16.3	-
Sert et al.[208]	Turkey	Clearing	290	35.5	28.6	34.1	1.7	12.4	29.7	46.9	11.0	-
Cosic et al.[209]	Croatia	Sectioning	56	8.9	5.4	83.9	1.8	7.1	7.1	75.0	10.8	-
Tomaszewska et al.[210]	Poland	Micro-CT	78	38.5	-	61.5	-	23.1	15.4	46.1	15.4	-
Mandibular Third Molars												
Barret[200]	USA	Sectioning	32	15.6	71.9	12.5	-	-	-	-	-	-
Piñeda & Kuttler[17]	Mexico	Radiograph	259	-	-	-	-	-	65.8	26.4	7.8	-
Green[18]	USA	Sectioning	100 MR	-	-	-	-	74.0	26.0	-	-	-
Hession[201]	Australia	Radiograph	3	-	-	-	-	-	33.3	66.7	-	-
Zakhary et al.[211]	Egypt	Radiograph	374	11.8	82.3	5.9	-	11.8	17.6	64.7	5.9	-
Guerisoli et al.[203]	Brazil	Clearing	114	51.8	46.4	1.8	-	12.3	69.3	18.4	-	-
Sidow et al.[111]	USA	Clearing	150	16.7	76.7	5.3	1.3	7.3[e]	16.7	55.3	16.7	4.0[d]
Gulabivala et al.	Burma	Clearing	58	-	100	-	-	1.7	51.7	44.8	1.7	-
Gulabivala et al.[212]	Thailand	Clearing	173	11.6	86.7	21.2	0.6	6.4	64.1	28.3	5.2	-
Sert et al.[208]	Turkey	Clearing	370	24.9	69.5	5.4	0.3	10.8	52.7	17.3	18.6	0.5
Kuzekanani et al.[213]	Iran	Clearing	150	21.4	72.6	5.3	0.7	10.0[f]	52.0	32.7	5.3	-
Cosic et al.[209]	Croatia	Sectioning	50	56.0	44.0	-	-	4.0	6.0	90.0	-	-
Park et al.[214]	South Korea	Tomography	214	41.6[b]	56.5	1.9	-	-	-	-	-	-

MB, Mesiobuccal root; *micro-CT*, micro–computed tomography; *MR*, mesial root.

[a]0.6% of the sample had five roots; [b]3.7% of the sample had C-shaped canals;

[c]4.7% of the sample had C-shaped canals; [d]0.7% of the sample had six canals;

[e]4.0% of the sample had C-shaped canals; [f]3.3% of the sample had C-shaped canals.

Adapted from Ahmad IA, Azzeh MM, Zwiri AMA, Haija MASA, Diab MM: Root and root canal morphology of third molars in a Jordanian subpopulation, *Saudi Endod J* 6:113, 2016.[215]

TABLE 12.8 Combined Data From CBCT Studies on Root and Root Canal Morphology of Maxillary and Mandibular Permanent Teeth

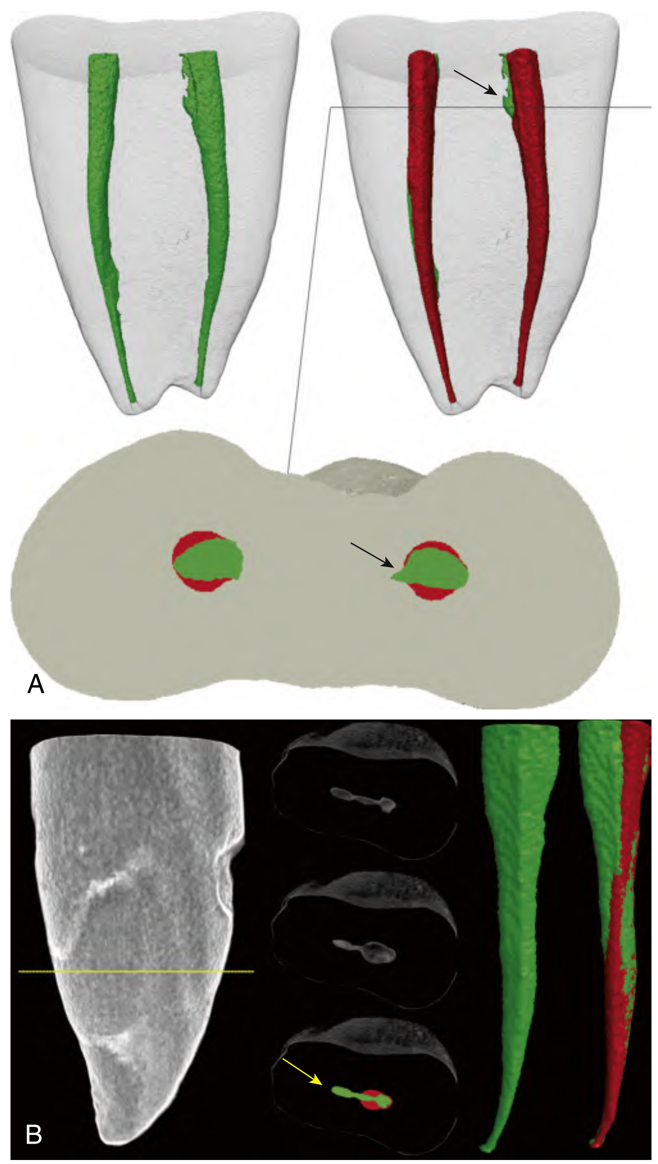
Maxillary	Number of Teeth	NUMBER OF ROOTS (%) 1	2	3	4	ROOT CANAL CONFIGURATION (%) I	II	III	IV	V	VI	VII	VIII	Other
Central incisor	3125	99.94	0.06	0	0	99.20	0.1	0.1	0.5	0.1	0	0	0	0
Lateral incisor	3068	99.94	0.06	0	0	98.50	0.8	0.2	0.1	0.4	0	0	0	0
Canine	3148	100	0	0	0	97.0	0.8	1.2	0.2	0.7	0	0	0	0.1
1st premolar	2575	43.1	55.3	1.6	0	20.10	17.4	1.5	50.1	3.0	4.9	0.4	1.2	1.3
2nd premolar	2345	86.2	13.5	0.3	0	42.70	18.7	4.0	17.6	9.6	6.3	0.5	0.4	0.3
1st molar	8934	0.2	1.8	97.7	0.3									
MB root	8934					39.10	29.3	1.6	26.0	2.0	1.4	0.1	0.1	0.4
DB root	7473					98.60	0.4	0.3	0.2	0.4	0.01	0	0	0
P root	8445					99.26	0.3	0.2	0.1	0.1	0	0	0	0.04
2nd molar	9570	10.7	14.9	73.7	0.7									
MB root	9353					66.10	15.3	2.8	13.0	1.9	0.6	0.1	0.05	0.2
DB root	9570					99.60	0.2	0.07	0.1	0.03	0	0	0	0
P root	9570					99.67	0.1	0.1	0.1	0.05	0	0	0.01	0.01
Mandibular		**1**	**2**	**3**	**4**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**Other**
Central incisor	11860	100	0	0	0	86.5	2.0	8.1	1.4	2.8	0	0.1	0	0.1
Lateral incisor	11805	99.92	0.08	0	0	79.7	2.6	11.9	1.8	3.8	0	0.1	0	0.1
Canine	10009	98.57	1.43	0	0	92.4	1.9	2.7	1.5	1.2	0	0	0	0.3
1st premolar	6043	97.5	2.5	0	0	71.3	2.3	2.8	3.5	18.7	0.5	0.1	0.1	0.7
2nd premolar	6350	98.5	1.5	0	0	84.7	0.7	0.5	0.3	13.4	0.07	0.04	0.05	0.2
1st molar	7388	0.55	86.9	12.5	0.05									
Mesial root	7388					2.37	19.9	2.9	71.3	2.1	0.3	0.09	0.03	1.01
Distal root	6712					70.3	13.0	3.6	10.1	2.7	0.08	0.08	0	0.14
2nd molar	7439	19.0	78.6	2.2	0.2									
Mesial root	6734					12.5	32.8	3.27	47.8	3.0	0.2	0.1	0	0.33
Distal root	7439					92.56	4.4	0.5	2.0	0.5	0.04	0	0	0

Root canal configurations are classified according to Vertucci.[40]

CBCT, Cone beam computed tomography; *DB*, distobuccal; *MB*, mesiobuccal; *P*, palatal.

Adapted from Versiani MA, Pereira MR, Pécora JD, Sousa Neto MD: Root canal anatomy of maxillary and mandibular teeth. In Versiani MA, Basrani B, Sousa Neto MD, editors. *The root canal anatomy in permanent dentition.* ed 1. Switzerland, 2018, Springer International Publishing, pp 181–240.

resistant but because they were not affected by instruments and irrigants. Bacteria remain unaffected because treatment was inadequately carried out (small instrumentation, too short of the apex, poor irrigation, etc.) or because bacteria were located in difficult-to-reach anatomic areas. In fact, the latter is the main reason for bacterial persistence even after diligent endodontic treatment. Canals that are flattened or oval-shaped are often not properly cleaned and disinfected by current hand or rotary NiTi instrumentation using reaming motions.[230,231] Recesses are commonly left untouched at the extremities of the canal's largest diameter (Fig. 12.26).[232,233] In addition to harboring remnants of pulp tissue or bacterial biofilms, such recesses may also be packed with dentin chips generated and pushed therein by rotating instruments.[32,33] Packed debris can interfere with the quality of obturation and, in infected root canals, can harbor bacteria to serve as a potential source of persistent infection.[234]



• **Fig. 12.26** Three-dimensional (3D) micro–computed tomography (micro-CT) models and two-dimensional (2D) cross-sections of a **(A)** mesial root of mandibular molar and **(B)** a mandibular canine showing the superimposed root canal system before *(in green)* and after *(in red)* preparation with rotary nickel-titanium (NiTi) instruments, depicting the irregularities of the root canal shape left untouched *(arrows)*.

In summary, anatomic complexities represent physical constraints that pose a serious challenge to adequate disinfection. The main root canal lumen and minor anatomic irregularities are usually incorporated into preparation and affected by NaOCl, but bacteria and organic tissue may remain in areas not reached by instruments and irrigants.[234-236] Unaffected areas include root canal walls untouched by instruments, recesses, dentinal tubules, isthmuses, lateral canals, and apical ramifications.[230,235-237] These areas are usually not affected because of the inherent physical limitations of instruments and the short retention time of irrigants within the root canal system. If bacterial biofilms remain in untouched and unaffected canal areas, the treatment outcome is put at risk.[217]

Clinical Outcome Remarks

Diagnosis and treatment planning for endodontic therapy involves the reading of clinical radiographs to determine the morphology of the root and root canals. Perhaps the most important aspect of assessing the degree of difficulty of an endodontic treatment is to know the dental anatomy of the tooth requiring treatment. A thorough cleaning and shaping of a canal system is accomplished by observing and anticipating the complexity of the internal pulpal anatomy. The Washington Study[238] and others since[239,240] have shown that not all teeth that received endodontic treatment enjoyed the same degree of success. By inference, it was the realization that all teeth in the dental arch did not have a simple, single "hollow-tube" to the apical foramen and differed in root morphology in many ways.

The dental literature is replete with examples of complex dental root anatomy, and many of the cases are a result of endodontic failure to heal because of missed, poorly filled, or unfilled canal systems. The importance of learning both the normal and variations from the normal morphology of roots and root canals in the human dentition cannot be overemphasized. The dental anatomy research of root number and root shape will help the clinician in a search for canal systems within the pulp chamber or along the canal length.

Teeth that have a broad diameter, usually in the labiolingual or buccolingual direction, have been shown to have a high incidence of double or even multiple canal numbers and apical foramen outlets. Multiple root canal classification systems have been proposed over the years, each with their own advantages and shortcomings. Standard radiographs may only give clues to the complexity of canal systems. Even 3D radiographs like the CBCT need a high resolution and a degree of skill in interpreting the image of a root canal system. The clinicians who know their ability and can anticipate a complex root canal system during instrumentation can be more thorough in cleansing and shaping the entire root canal space. The highest success rate and the lowest number of failed treatments will result as a treatment outcome when dental anatomy is taken into account.

Conclusions

Knowledge of both normal root and root canal anatomy is most critically important to perform successful endodontic treatment. The science of dental anatomy of the human dentition helps a dentist not only in restorative dentistry for coronal anatomy, but also in endodontic therapy with root and root canal anatomy research. A number of conclusions may be drawn from reading the information in this chapter about human root canal anatomy as it relates to a proposed endodontic treatment:

- The study of human anatomy of teeth started in the 16th century. Root anatomy and canal anatomy research specifically was the interest of dental anatomists for over a century, as shown by a perusal of the important early dental literature. However, its importance in performing root canal treatment has made this the province of modern endodontology.
- One can see the progression of knowledge and introduction of new techniques when the historical perspective is taken into account, with three loosely defined phases of root canal morphology research.
- The two most popular canal classification systems by Weine or Vertucci and more lately by Ahmed et al. using the Universal Tooth Number system all have their advantages and difficulties when applied to clinical or laboratory root anatomy research. Nonetheless, our understanding of the complexity of the morphology of pulp space has expanded from the earlier studies.

- The root canal components consist of the coronal pulp chamber, which is continuous with the radicular root canal space in anterior teeth. Posterior teeth may have a chamber floor when the radicular roots form in their embryonic development.
- The morphology of the pulp space is distinctive for each tooth in the arch, but each tooth also has its own unique morphology of root shape and canal number as controlled by many genetic factors.
- By analyzing the detailed description and tables of root number and canal number for each tooth in the dental arch, one can see the relative likelihood of finding more than one canal per root in a clinical situation.
- Radix entomolaris, or the extra distal root on the lingual aspect of mandibular molar teeth, is most common in Asian and North American native indigenous populations, and the incidence may be as high as 20% in some populations.
- A comparison of root number, canal number, root size, and many other variable features of the human dentition in the printed tables shows that the more posterior tooth is slightly smaller and less distinctive in its dental characteristics.
- The incidence of dental characteristics that vary from the normal may occur in greater numbers in certain ethnic populations and include things like root number in maxillary and mandibular premolar teeth, bifurcation and double canals in mandibular canines, dens evaginatus in premolar teeth, C-shaped, and taurodont anomalies, to name a few. All of these variations from the average must be recognized as possible complications before endodontic treatment is initiated.
- Root canal anatomy influences treatment procedures in a number of ways and may result in a high degree of difficulty, which would be a reason to refer treatment to a specialist for endodontic treatment.
- One of the most common reasons for a failed root canal treatment is to not anticipate or locate the double or multiple canal system in roots that have a wide labiolingual or buccolingual diameter.
- Illustrations of root and canal anatomy will aid a student to visualize the shape and dimensions of teeth in the dental arch.

Study Questions

8. When a tooth requires endodontic therapy, which of the following statements is correct with respect to root canal morphology?
   A. There is usually one straight canal within any given root.
   B. The canal is usually positioned more to the facial.
   C. Assume that each root may contain more than one canal system.
   D. Canals tend to become larger with age.
9. The resurgence of studies of human root and canal anatomy may be attributed to:
   A. Newer laboratory and clinical radiographic techniques such as CBCT
   B. Additional populations to be studied in dental schools outside of North America and Europe
   C. A growing interest in endodontics and realization that knowledge of variations in dental root anatomy is the key to successful treatment
   D. The resurrection of practitioners wanting to prove the “theory of focal infection” and the inability to seal root canals 100%
10. Krasner and Rankow proposed a series of laws to aid in determining the position of the pulp chamber and the location and number of canal entrances. The “law of centrality” means that the pulp chamber is centered in the tooth:
   A. At the midpoint of the crown
   B. At the level of the cementoenamel junction
   C. 1 mm occlusal to the furcation
   D. But it is highly variable in its vertical position
11. Krasner and Rankow proposed a series of laws to aid in determining the position of the pulp chamber and the location and number of canal entrances. The “law of color change” means that:
   A. The walls are darker than the floor of the pulp chamber.
   B. The walls are lighter than the floor of the pulp chamber.
   C. Both the walls and floor become lighter in color with secondary dentin with age.
12. Which of the following are routinely used for the identification of all canal orifices during molar root canal therapy during routine access opening procedure?
   A. Good illumination
   B. Magnification
   C. CBCT imaging
   D. Specialized instruments
13. Which of the following components of the root canal system are primarily cleansed by chemomechanical means?
   A. Accessory canals.
   B. Lateral canals.
   C. Main canal.
   D. Furcation canals.
14. In cross-section, root canal shapes are classified as:
   A. Oval
   B. Round
   C. Long oval
   D. Flattened
   E. Irregular
   F. Regular
15. Which of the following are consistent with a transverse anastomosis as found in some ovoid-shaped roots, which contain two or more canal systems?
   A. It is also called an isthmus.
   B. It is a narrow, ribbon-shaped communication between two root canals.
   C. It always contains vital tissue.
   D. It can contain necrotic debris.
   E. It may contain biofilm.
16. In the study by Schäfer and colleagues that measured the degree of curvature of more than 1000 root canals from all groups of teeth by using radiographs, the highest degree of curvature was found in the:
   A. Mesiobuccal canal of maxillary molars
   B. Distobuccal canal of maxillary molars
   C. Mesial canals of mandibular molars
   D. Distal canals of mandibular molars
17. Which of the following developmental anomaly condition is characterized by an enlarged pulp chamber and root trunk and a shortening of the roots?
   A. Dens invaginatus
   B. Dens evaginatus
   C. Taurodontism
   D. Radix entomolaris
   E. C-shaped canal system
18. Which of the following root canal anatomy factors are known to affect the outcome of surgical and nonsurgical endodontics?
   A. Canal irregularities
   B. Canal curvature
   C. The presence of fins
   D. The deposition of secondary and tertiary dentin with age

ANSWERS

Answer Box 12

1. Correct Answer: D. Both the Weine and Vertucci classification systems have limitations because neither can classify all canal system configurations. The Vertucci classification system has sometimes been used inconsistently. One example is how a three-rooted maxillary first premolar with a single canal in each root is classified. Some authors classify this as Type VIII, whereas others classify the canal system in each root (mesiobuccal, distobuccal, and palatal) as Type I canal systems.
2. Correct answer: F. The mandibular canine is the most common anterior tooth to have a bifurcated root. The root bifurcates into a labial and lingual root and can have an incidence of 3% to 5%, especially in some Western Eurasian populations.
3. Correct answer: C. Radix entomolaris is an extra root found in a lingual position of the permanent mandibular molar. Therefore a mandibular molar would have three roots (mesial, distolingual, and distobuccal) instead of the typical two roots (mesial and distal). This is most common in Asian and North American aboriginal populations in the permanent mandibular first molar. The incidence can be 20% or more in these populations.
4. Correct answers: B, F, H and J. Each of these teeth or roots of teeth generally have a significantly high incidence of two canals.
5. Correct answer: C. Dens evaginatus presents as a tubercle on the occlusal surface of any of the premolars and has the highest incidence in Asian and North American aboriginal populations.
6. Correct answer: B. This infolding of enamel can be mild to severe. Oehlers classified dens invaginatus as Types 1, 2, and 3 with the most severe form being Type 3. The permanent maxillary lateral incisor is the tooth that is most commonly affected with this developmental anomaly.
7. Correct answer: A. Although the incidence of bifurcated permanent mandibular canines is relatively low, it is highest in the Western Eurasian ethnic group (approximately 5% to 6%) in both ancient and modern populations.
8. Correct answer: C. It is critically important to always assume that a root has more than one canal until proven otherwise. Failure to find, cleanse, instrument, and obturate the entire root canal system in any given tooth will likely result in treatment failure. Although some roots and some teeth may be more likely to be elongated in cross-section and not round, there are a few rare anomalies of double canal formation that may not appear on a standard radiograph.
9. Correct answer: D. Only statement "D" is incorrect. The practitioners who are trying to discredit the safety and successfulness of current endodontic treatment use the century-old and faulty research methods and papers. The third phase of human root anatomy research uses modern imaging systems and have expanded to include worldwide dental schools and touch on all ethnicities.
10. Correct answer: B. Understanding the series of laws outlined by Krasner and Rankow is critical to endodontic treatment success and conversely, avoiding iatrogenic errors that could lead to adverse treatment outcome.
11. Correct answer: B. Understanding the series of laws outlined by Krasner and Rankow is critical to endodontic treatment success and conversely, avoiding iatrogenic errors that could lead to adverse treatment outcome.
12. Correct answers: A, B and D. Although CBCT can be a valuable adjunct in endodontics, it should be used selectively where indicated. The standard of practice and ALARA concept (**A**s **L**ow **A**s **R**easonably **A**chievable) do not dictate special imaging techniques in routine operations.
13. Correct answer: C. Accessibility, location, and orientation of the main canal in a tooth receiving endodontic therapy are the primary reasons for the importance of mechanical means in canal cleansing.
14. Correct answer: A, B, C, D and E. The internal shape of the root canal system mirrors the external shape of the root, which is variable in its morphology throughout the dentition.
15. Correct answers: A, B, D and E. The four answers describe a root canal system transverse anastomosis. This difficult to reach region of a root canal system is contaminated both in necrotic therapy and in retreatment endodontics and thus difficult to seal effectively.
16. Correct answers: A and C. The greater the canal curvature, the more complex the endodontic treatment of that canal becomes. Also, age leads to narrower canal systems, which compounds the complexity.
17. Correct answer: C. This accurately describes taurodontism. Teeth most commonly involved are the molars and possibly premolars. As a result of the large volume of pulp contained in the large pulp chamber, excess bleeding may be challenging to manage on performing an access opening when the pulp is highly inflamed.
18. Correct answer: A, B, C and D. All of the factors listed previously contribute to increasing the complexity of root canal treatment and the clinical outcome.

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