Molar Root Canal Anatomy

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Frank Paqué

Abstract

Detailed understanding of root and root canal anatomy is the main prerequisite for successful molar endodontics. Besides typical three-rooted and two-rooted configurations for maxillary and mandibular teeth, respectively, there are specific variations such as merged roots, additional roots, and completely different shapes such as the C-shaped molars. Adding complexity, frequently small accessory canals are found that can contribute to periapical pathosis.

Guiding Reference

Stropko JJ. Canal morphology of maxillary molars: clinical observations of canal configurations. J Endod. 1999;25:446–50.

This clinical study on first and second maxillary molars treated over an 8-year period was made in an attempt to determine the percentage of second mesiobuccal (MB2) canals that could be located routinely. 1732 maxillary molars were treated and overall, the MB2 canal was found in about 73 % first molars, 51 % second molars, and 20.0 % third molars. It occurred as a separate canal in about 55 % of first molars, 45.646 % of second molars, and joined in all third molars. However, as the operator became more experienced, scheduled sufficient clinical time, routinely employed the dental operating microscope, and used specific instruments adapted for microendodontics, MB2 canals were located in about 93 % of first molars and 60 % in second molars.

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1.1 Introduction

A central goal of cleaning and shaping procedures in endodontics is to obtain a debrided root canal system that is in its entirety free of microbiota and debris. Therefore, detailed knowledge about root canal anatomy prior to any access to the root canal system is absolutely mandatory [1]. Moreover, complex root canal anatomy in molar roots should be expected in every single case. Root and root canal anatomy directly impacts practice and procedures for access cavity preparation, canal shaping and obturation, and in fact most procedures in molar endodontics (see Chaps. 5, 6, 7, 9, and 10 in this book).

It is well established that intraradicular microflora is the main cause for developing, or persisting, apical periodontitis [2]. Unfortunately, the intraradicular infection mainly consists not of planktonic bacteria but of well-organized biofilms. The bacteria in biofilms show a higher pathogenicity compared to their planktonic counterparts [3]. More than 400 different bacterial species were found in root canal systems of teeth with necrotic pulps [4]. Interactions between different species within endodontic biofilms lead to enhanced stress resistance [5]. Their location within complex molar root canal configurations makes complete eradication of endodontic biofilms virtually impossible; even reducing the microbial burden below a biologically acceptable threshold demands careful canal debridement. It is safe to say that in depth understanding of root canal anatomy is of upmost importance for successful molar endodontics.

1.2 Components of the Root Canal System and Classifications

In roots with round cross-sectional shapes, the number of root canals corresponds in most cases to the number of roots. However, an oval shaped root may have more than one canal [1]. The immense complexity of molar canal configurations is based on a wide range of root canal curvatures, different root canal sections, different accessory canals, fins, and isthmuses. Different attempts of classification contributed to a deeper understanding of root canal anatomy. There are numerous classifications for anatomical variations in root canals. Weine and coworkers [6] examined in a laboratory study the mesiobuccal roots of maxillary molars and classified these into four and later into five types as shown in Fig. 1.1.

A more detailed classification is recommended to more accurately describing the internal root canal configurations of individual molar roots. One of the most commonly used classifications is the one by Vertucci [7] with eight different canal morphologies (Fig. 1.2a).

However, if there are more than two canals within one root, this classification again is limited. Gulabivala et al. [8] further developed this classification to additional nine morphology types. Especially for describing the root canal formation of the mesial root in mandibular molars types 1, 2, and 3 of this classification is meaningful (Fig. 1.2b).

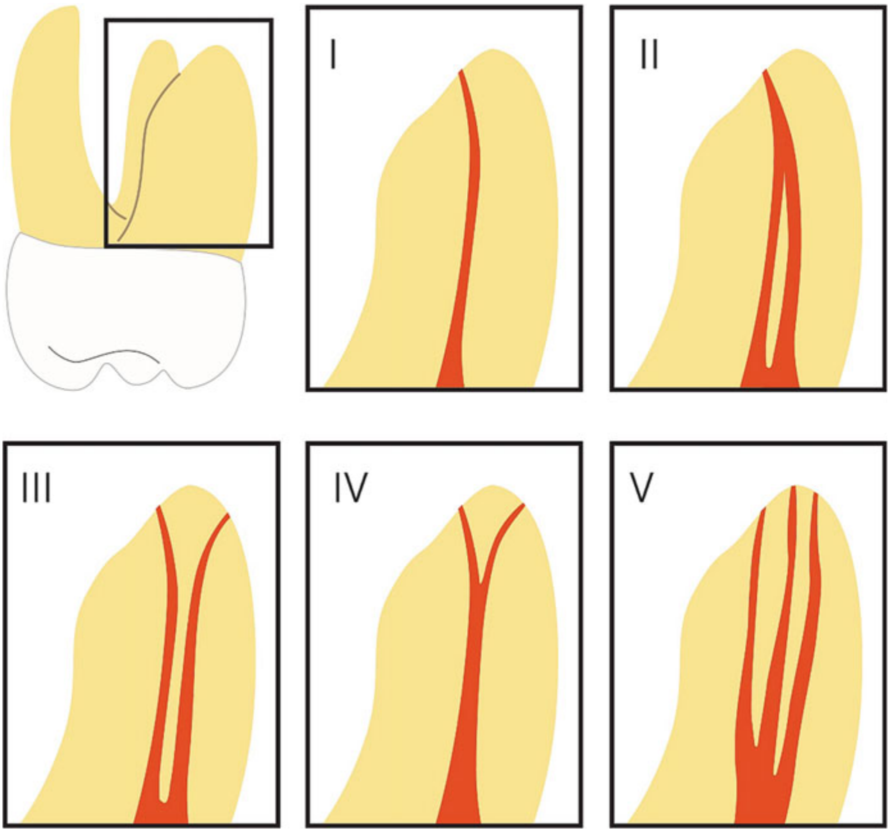


Fig. 1.1 Classification of multiple canals in one root by Weine et al. [6]. The original classification of four types was later expanded to the five configurations shown

Another research group [9] extended Vertucci's classification with additional 14 configurations examining 2800 extracted human teeth. These further developments contribute to the understanding of substantial complexity in root canal configuration.

1.3 Complexity of Root Canal Systems

As Vertucci [1] stated, a root with a tapering canal and a single foramen is the exception rather than the rule. Great complexity of root canal anatomy can be found at every level of the root canal space. It is the result of tooth development mainly after eruption of the tooth to the oral cavity and apical closing [10] due to the apposition of secondary dentin. The primary apposition of root dentin has determined the external shape of the root, and therefore the internal shape will be the very similar: if the external shape is round, the canal will also be round; if the external shape is long oval or kidney shaped, the canal will be long oval or kidney shaped too.

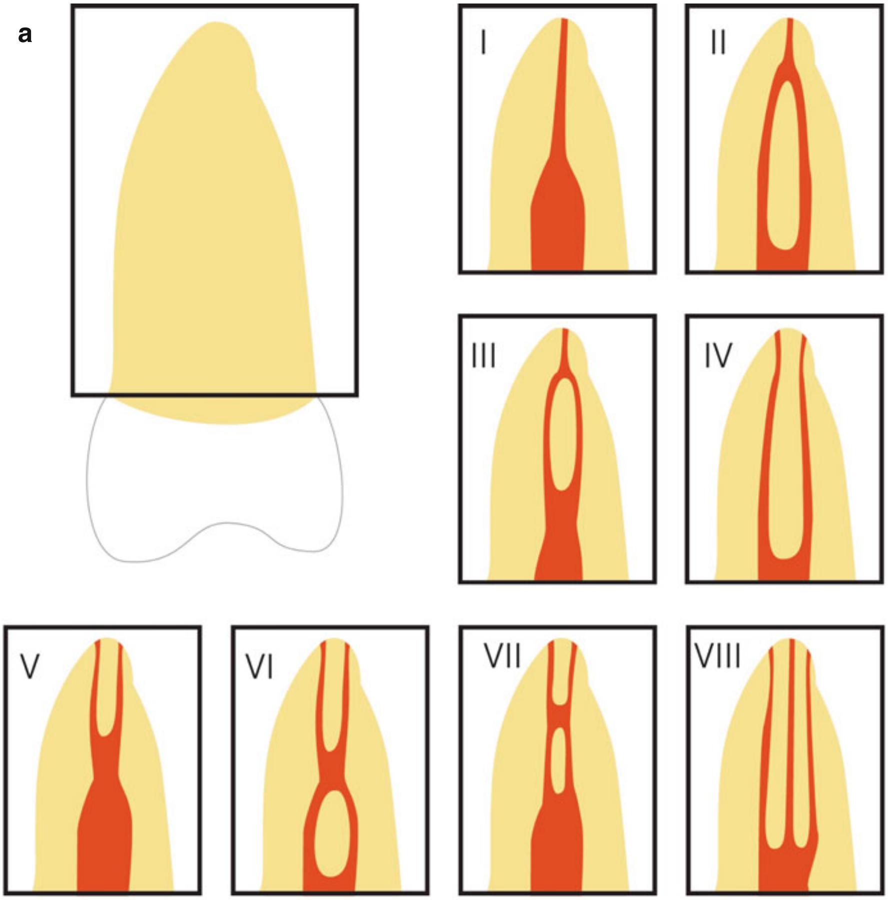


Fig. 1.2 Expanded root canal classifications by Vertucci [7] (eight types) (**a**) and by Gulabivala et al. [8] (seven types) (**b**)

Kidney-shaped roots, like in mandibular molars, mainly develop two root canals (Fig. 1.3).

For example, in mandibular first and second molars the root canal systems were completely defined at 30–40 years of age [10]. Various intercanal communications can still remain and represent one main component of complex root canal anatomy (Fig. 1.3). Others are wide ranges of root canal curvatures, different root canal cross sections, accessory canals, secondary canals, lateral canals, furcation canals, fins and multiple apical foramina, and so-called apical deltas.

More than two decades ago when rotary Nickel-Titanium instruments were introduced to the endodontic market, root canal curvatures have been stated as one of the most common endodontic complexity [11]. With the further development of these instruments and the experience gained by the practitioners, the difficulties of shaping even severely curved root canals have mainly been overcome over the past

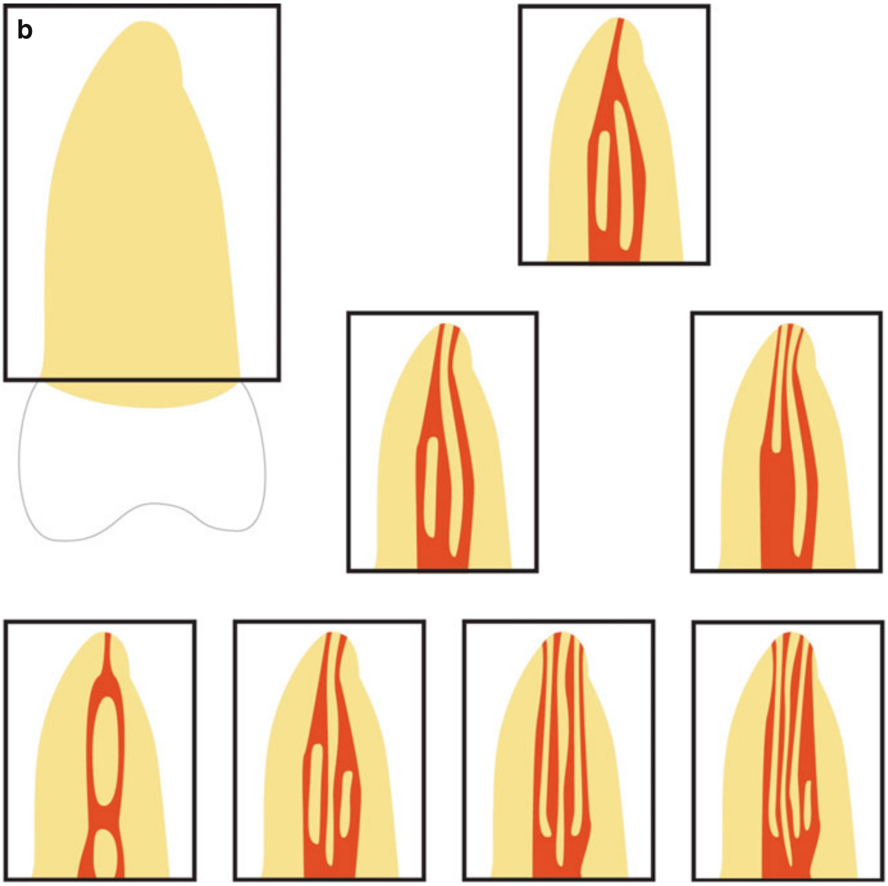


Fig. 1.2 (continued)

few years (Fig. 1.4). Taking into consideration that complex root canal systems require proper cleaning and disinfection, the main challenge remains to debride the spaces of the root canal system that cannot be reached by mechanical instrumentation. Especially in mandibular and maxillary molars, the above-mentioned components of complex root canal anatomy are a common finding. In a literature review about tooth survival after nonsurgical root canal treatments [12], the tooth type or specifically nonmolar teeth were found to significantly increase tooth survival.

1.4 The Anatomy of Maxillary Molars

A sufficient root canal treatment in maxillary molars is based on an optimal access to and preparation of all existing root canals. The goal of the treatment is to present the existing anatomy as comprehensive as possible and to widen the root canal system to

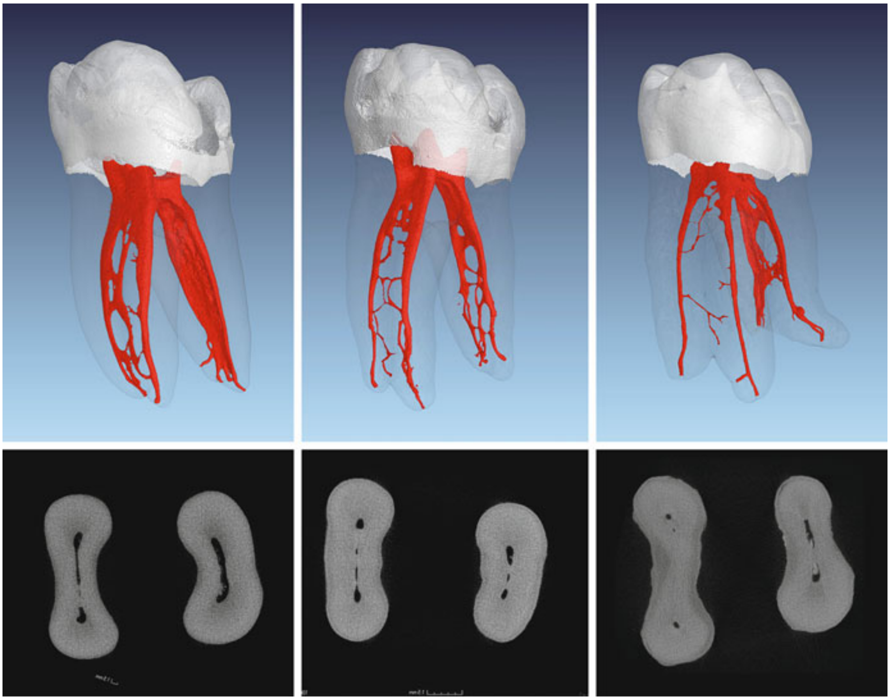


Fig. 1.3 Micro-computed tomography images of extracted teeth from patients of different ages. Three-dimensional reconstructions and corresponding cross sections from the middle third of the roots are shown. Images from *left* to *right*: extracted tooth of a young-aged, middle-aged, and older patient, respectively. Note the width of the main canals and the number and size of various ramifications and communications

enable a sufficient disinfection and filling. The anatomy of maxillary molars is very complex and the root canal treatment of this particular group of teeth represents a major challenge for dentists [1]. Carabelli documented the particular anatomy of maxillary molars as early as 1844 [13]. Numerous subsequent publications discussed the complexity of maxillary molar anatomy; most often the mesiobuccal root and the occurrence of a second mesiobuccal (MB2) canal have been in the main focus. In 1917, Walter Hess [14] presented the anatomical complexities with multitude of branches and accessory canals by illustrating in detail the number and formation of root canals. He was the first to relate age and gender of the patients to root canal complexity.

Many studies have shown the anatomy of the upper first molar and especially the presence of a MB2 canal using different techniques [15]. Failures in root canal treatment of this tooth type are often based on untreated MB2 canals [6, 16]. The clinical prevalence of the MB2 canal in maxillary first molars and in second molars is reported up to 93 % and 60 %, respectively [17].

Results from laboratory micro-computed tomography (micro-CT) studies are of special interest for molar anatomy, because this technique allows a three-dimensional presentation and analysis of the root canal system without damaging the tooth

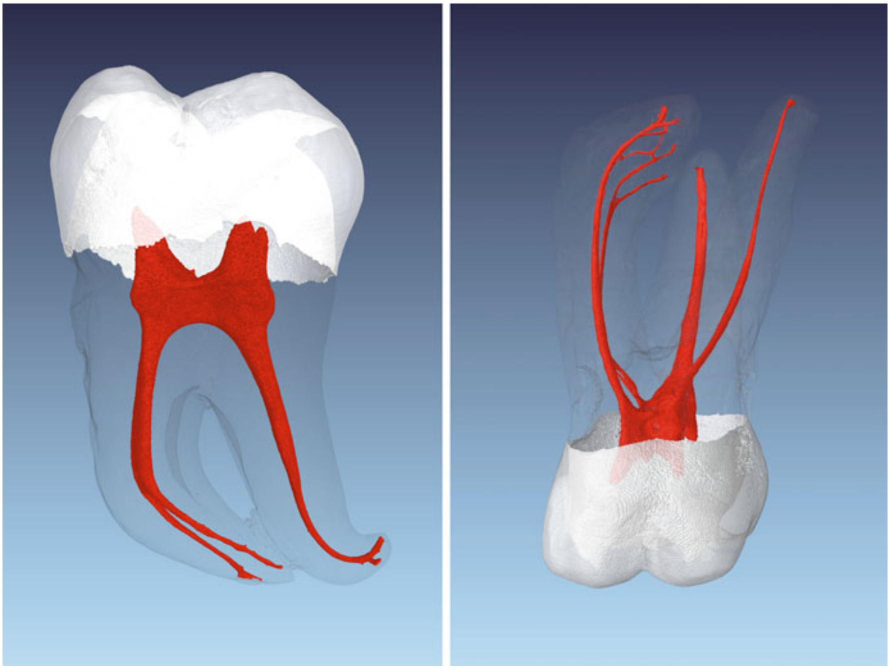


Fig. 1.4 Micro-computed tomography images of an extracted mandibular and a maxillary molar. Note the severe canal curvatures in both roots of the mandibular molar and in the MB root of the maxillary molar

structures [18]. Due to modern treatment methods like the use of dental microscopes, options for a successful therapy of difficult root canal anatomies have significantly improved [19]. The location of MB2 canals during root canal treatment of maxillary molars is much more likely by applying the dental microscope and through the use of specialized tools than without [17].

The first maxillary molar is the most voluminous of all teeth: it has four pulp horns and the pulp chamber has usually a rhomboid cross-sectional shape [1]. The second maxillary molar in principle is of similar shape (Fig. 1.5a). However, the pulp chamber is often more long oval, sometimes it is ribbon shaped (Fig. 1.5b).

A maxillary first molar has typically three separate roots and in only about 4 % of the cases just two roots are found. Two or more merged roots occur in about 5 % of all cases. The presence of four roots is extremely rare [15]. In second maxillary molars, merging of roots is much more common. Interestingly, the distobuccal (DB) root canal in second maxillary molars is often difficult to negotiate because an S-shaped DB root is a quite common finding.

Cleghorn et al. [15] evaluated laboratory studies from the years 1914 to 2004 in a literature review of the anatomy of the first maxillary molar. The occurrence of a MB2 was reported to range from 25 to 96 %. Pooled data of 21 studies gave an overall prevalence of roughly 60 %.

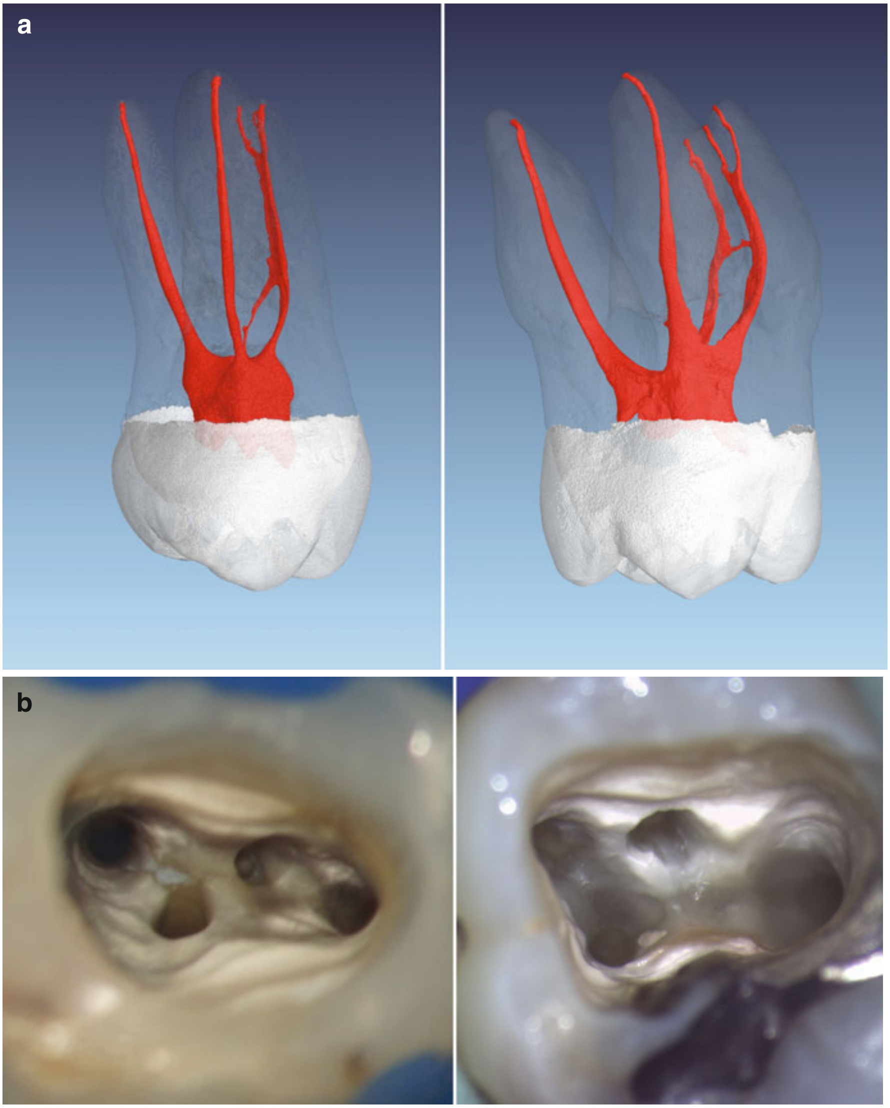


Fig. 1.5 (**a**) Micro-computed tomography images of an extracted first (*right*) and second maxillary molar (*left*). Note the in general similar shape but the overall smaller volume of the second maxillary molar. Typically, the buccal roots of the second maxillary molar seem to be fused. (**b**) Clinical images of cases after preparation of all canals in a first (*right*) and second (*left*) maxillary molar with rotary instruments. The access cavities provide an overview of all four canal orifices. Note the ribbon-shaped pulpal floor in the second maxillary molar, the entrance of MB2 is located very close to the palatal orifice, a common finding in these kinds of teeth

It should be taken into consideration that literature data from laboratory studies on the prevalence of the MB2 canals are subject to strong variations due to differences in the experimental design. Thoroughly studying the description of the methods used in these publications is an absolute requirement if someone wants to rely on the found percentages of MB2 canals. Properly designed histological and micro-CT studies could be seen as a gold standard when examining the prevalence of the MB2 canal in extracted teeth. Considering such studies, a prevalence of more than 90 % MB2 canals in the first and more than 55 % MB2 canals in the second maxillary molars should be accepted as clinical reality. Figure 1.6 shows the clinical negotiation of MB2 in a retreatment case with corresponding CBCT imaging.

This division of the mesiobuccal root canal can take place at different levels and initiate various configurations. Again, it is the result of the apposition of secondary dentin after the formation of the mesiobuccal root. After root formation, the cross section of the mesiobuccal canal resembles a kidney shape with a larger buccal and a smaller palatal part. This explains the smaller diameter of the MB2 canal after the deposition of secondary dentin [20]. Neaverth and coworkers found the prevalence of a second mesiobuccal canal in under 20-year-olds significantly lower than in an age group of 20–40-year-old patients [21].

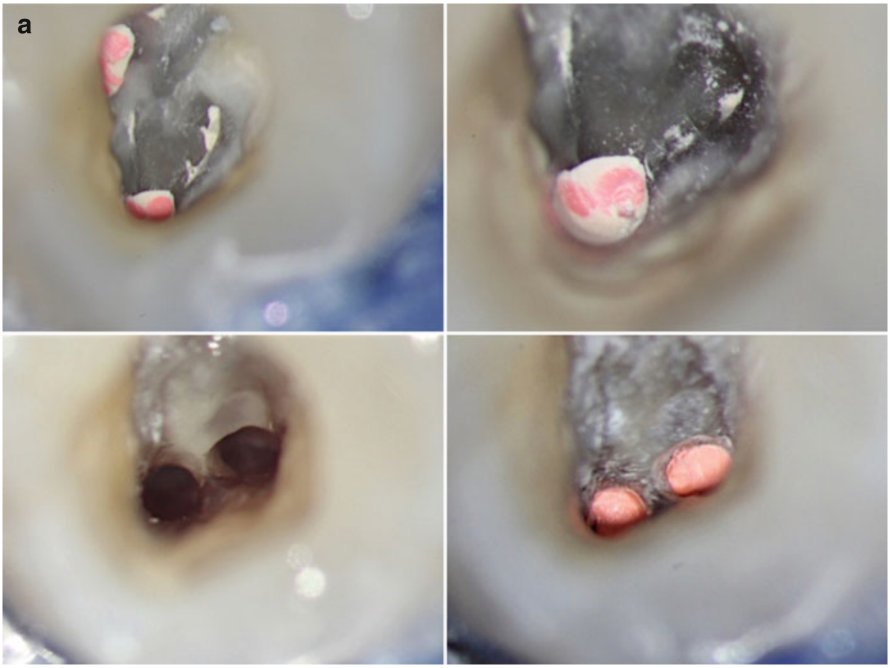


Fig. 1.6 (**a**) Clinical image during endodontic retreatment of a first maxillary molar with untreated MB2. The location identification of MB2, the access, preparation, and also filling of the canal system after retreatment of MB1 is shown. (**b**) Corresponding CBCT scan prior to retreatment of the first maxillary molar is shown in (**a**). Note the unprepared and unfilled MB2 depicted in different slices of the original dataset (*arrows*)

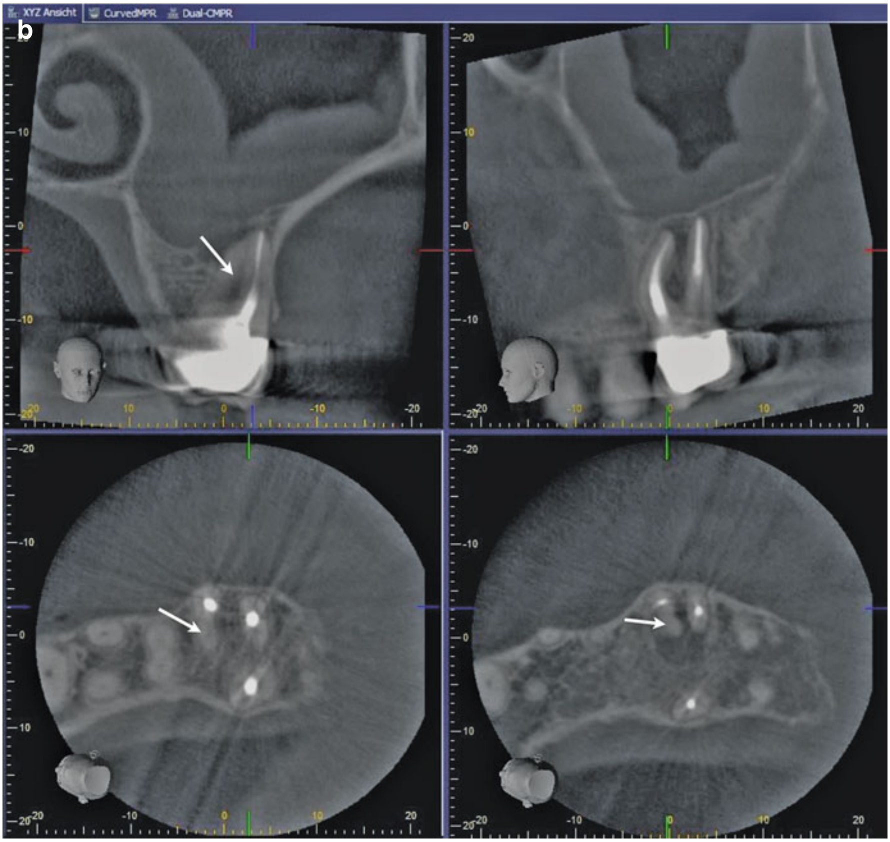


Fig. 1.6 (continued)

Due to the secondary dentin apposition, a third mesiobuccal (MB3) root canal could develop (Fig. 1.7). Most often, two of the three canals join somewhere on their travel to the apex (Fig. 1.7a). In the literature, three mesiobuccal root canals have been described to occur up to 7 % in first maxillary molars [22].

If there are two or more MB root canals, the location on the pulp chamber floor varies greatly; however, the orifice of MB2 is consistently located mesial to or directly on a line between the MB1 and the palatal orifices within about 3.5 mm palatally and 2 mm mesially from the MB1 orifices [23] (Fig. 1.5b).

Very often, the orifice of the MB2 canal is covered by a mesial shelf of dentin, which then needs to be removed to reveal access to this canal (see Chaps. 5 and 6). Below this ledge, the canal path leads toward mesiopalatal before curving back to the center and apically.

This makes the insertion or the negotiation of these canals very challenging. By removing these obstructions and carefully tracking the canal structure toward mesial and apical using ultrasonic tips or long-shank round burs ("troughing or countersinking"), a straight access to the MB2 canal is possible. It could be necessary to extend troughing 0.5–3 mm deep, which risks perforating the pulpal floor toward the furcation area [24]. During initial instrumentation and shaping of MB2 canals, there is the risk of

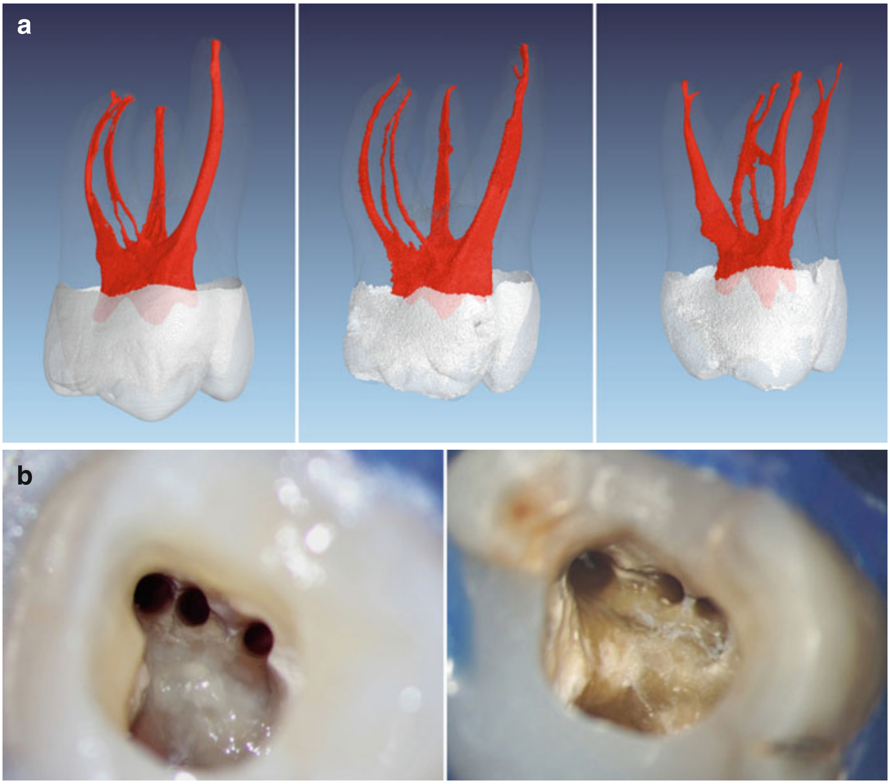


Fig. 1.7 (**a**) Micro-computed tomography images of three extracted first maxillary molars with three mesiobuccal root canals. Note that two of the extracted teeth show MB2 and MB3 joining on their travel to the apex (*left* and *middle*), while one of the extracted teeth shows a separate portal of exit (*right*). (**b**) Two clinical examples showing the mesiobuccal aspect of access cavities after preparation of three mesiobuccal root canals with rotary instruments

a strip-perforation because of the cross-sectional shape of the MB root (Fig. 1.8). A brushing movement toward the mesial aspect of the root is recommended [24].

Once we successfully manage to initially instrument the canal, a further challenge could be to reach the apical foramen in MB2 canals because of two reasons. First, these canals are often very narrow and curved. Second, the chance to encounter a Vertucci class V, VI, or VII in MB root systems is not uncommon (Fig. 1.2a). It remains a challenge for the clinician to recognize a deviation of the MB2 canal in the middle or apical third to the palatal aspect and to successfully prepare such deviations.

According to Vertucci [7], distobuccal roots of maxillary molars show one canal in 100 % of the cases. Other authors described the occurrence of a second distobuccal canal in first maxillary molars with an incidence of 1.6–9.5 %. However, in up to 98 % of these cases, the two canals merge in one apical foramen and only 2 % show two or more canals at the apex of the distobuccal root [15].

A rather rare variation of first maxillary molars is the C-shaped canal system, which is formed from merged distobuccal and palatal roots with a prevalence of 0.1 % [25, 26].

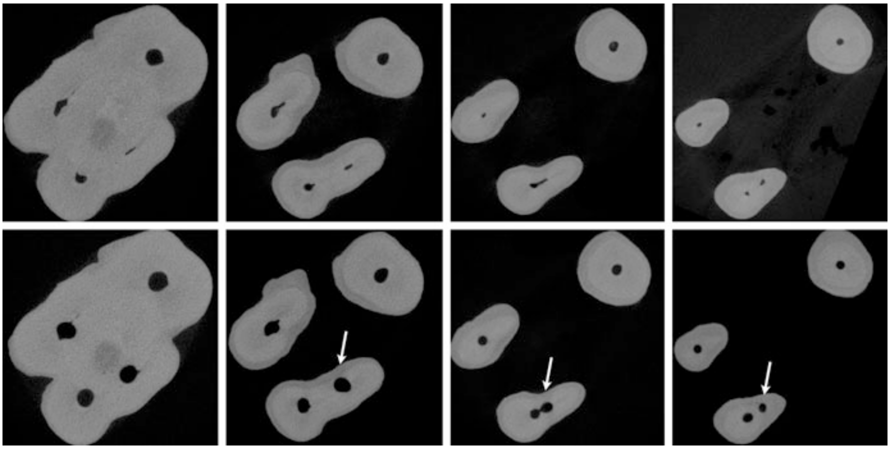


Fig. 1.8 Cross-sectional micro-computed tomography images of an extracted first maxillary molar before (*upper panel*) and after (*lower panel*) preparation with rotary instruments on four different root levels. Note the shape of the mesiobuccal root and limited radicular wall thickness before and after preparation (*arrows*)

1.5 The Anatomy of Mandibular Molars

The mandibular molars, in particular the mandibular first molar, are the most frequently endodontically treated teeth. Their treatment offers a variety of anatomical challenges. These complexities include multiple canals, isthmuses, lateral canals, and apical ramifications. Additionally, the distal dentinal wall of the mesial root is thin and known as the so-called danger zone [27, 28] (Fig. 1.9).

Harris et al. [28] scanned 22 first molars using micro-CT and showed that 1.5 mm below the furcation in the mesial root radicular wall thickness toward the furcation was smallest with values of 0.81–1.22 mm. Comparable results were obtained by others [29] showing an average dentin thickness of 1.2–1.3 mm measured also 1.5 mm beneath the furcation area.

Using the data from Harris et al. [28] regarding the pulp chamber floor, the shortest and longest distance between the orifices of the mesial canals averaged between about 1.4 and 3 mm. All scanned teeth in that study showed a single distal canal openings at the measured level 1.5 mm coronal to the furcation area, while there are two canals more apical more frequently [30]. The buccolingual dimension of the distal canal was about 2 mm. The average tangential distance from the mesial to the distal canals beneath the pulpal floor was about 4.5 mm.

1.5.1 Additional Roots in Mandibular Molars

In the Caucasian population, the majority of mandibular molars have two roots. An additional root is described as an exception. The presence of an additional distolingual root (radix entomolaris, Fig. 1.10) in mandibular first molars was observed and has been described occasionally [31].

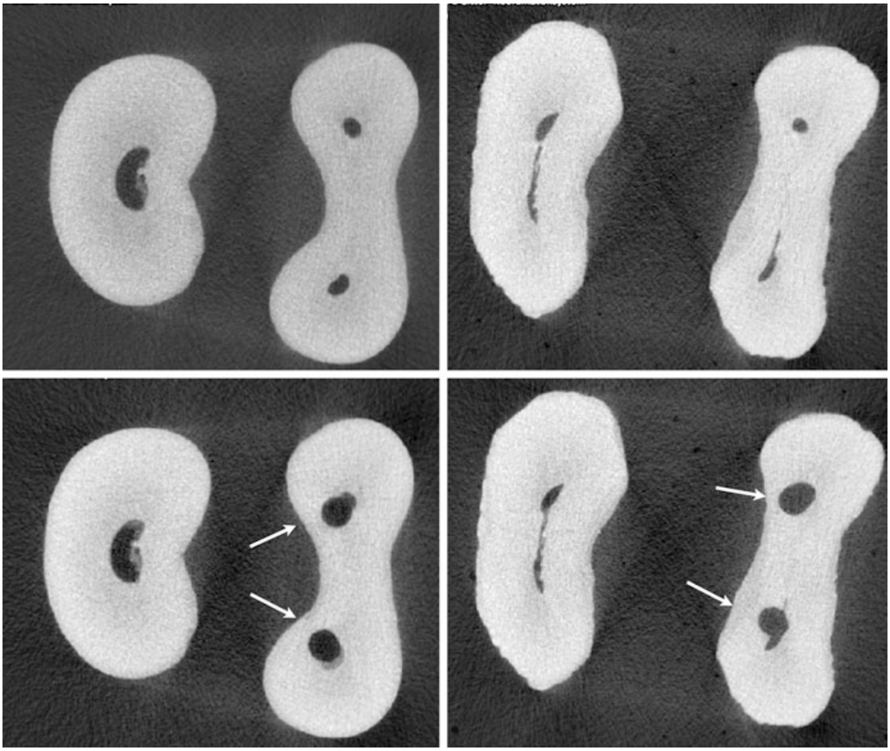
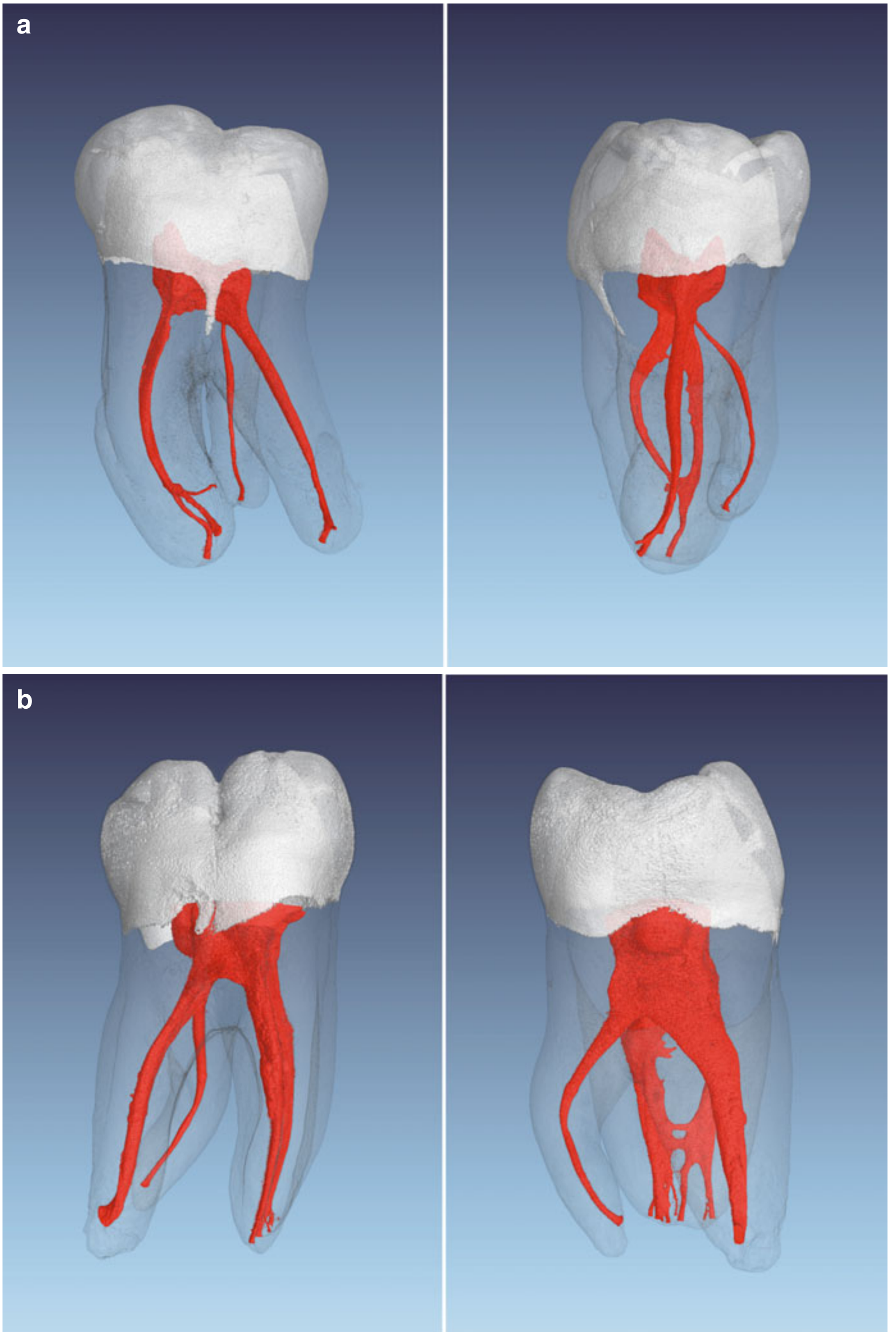


Fig. 1.9 Cross-sectional micro-computed tomography images of two extracted first mandibular molars before (*upper panel*) and after (*lower panel*) preparation with rotary instruments at a root level called the danger zone. Note the kidney shape of the mesial roots and radicular wall thickness before and after preparation (*arrows*)

An additional distolingual root was mentioned first by Carabelli in 1844 [13]. In a review, Abella et al. [32] described a frequency of 14.4 % regarding distolingual roots in mandibular first molars. There was an association to specific ethnic populations. The additional root was found more frequently in populations with Mongolian origin, like Chinese, Inuit, and Native Americans [32]. Cantatore et al. [33] determined frequencies between 5 % and more than 30 % in a population with Mongolian origin. Gu et al. [34] found an occurrence of 32 % in a Chinese population.

Gender-specific differences in the prevalence of an additional root were not recognized. The distolingual root is described either as separate or as partially merged into the other root. The distolingual root was classified according to their root curve in the buccolingual plane [32]:

- Type I: A straight root
- Type II: An initial curvature with a subsequent straight course
- Type III: An initial curvature in the coronal third of the root canal, followed by a second curvature in the middle portion, which proceeds to the apex (Fig. 1.10)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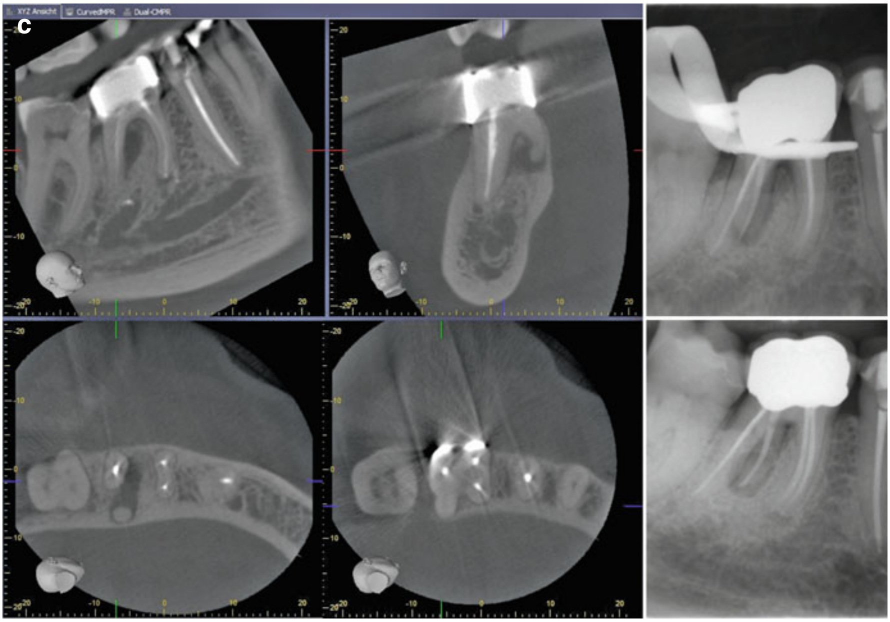

Fig. 1.10 (continued)

The radix entomolaris is usually smaller than the distobuccal root and has in general a larger angle and a smaller radius of curvature. This makes the preparation of these canals often a difficult task (Fig. 1.10c).

Three-rooted mandibular first molars exhibit usually four separate root canals and accessory canals in the mesial and DB root are found quite often [35]. The most common canal configuration was Vertucci type I for the distal root and Vertucci type IV for the mesial root [32, 35]. A recommended method for identifying a radix entomolaris was described as applying a mesio-eccentric (25°) periapical radiograph or a CBCT [32]. The conventional triangular access cavity should be modified to a trapezoidal shape in the presence of radix entomolaris to facilitate a straight access to the mostly curved root [31]. The average distance between the distolingual and the distobuccal canal opening was 2.93 mm and the average distance between the distolingual and mesiolingual canal opening was 2.86 mm [34]. The

Fig. 1.10 (**a**) Micro-computed tomography images of an extracted first mandibular molar with a radix entomolaris configuration (*left* in clinical view, *right* in approximal view). Note the root canal curvature in the approximal view. (**b**) Another example of micro-computed tomography images of an extracted first mandibular molar with a radix entomolaris (*left* in clinical view, *right* in approximal view). Note the root canal curvature in the approximal view. (**c**) Clinical retreatment case showing CBCT images of an untreated radix entomolaris with periapical pathosis. The patient was in severe pain at the first office visit. After negotiation and preparation of the untreated root, the patient was free of any symptoms

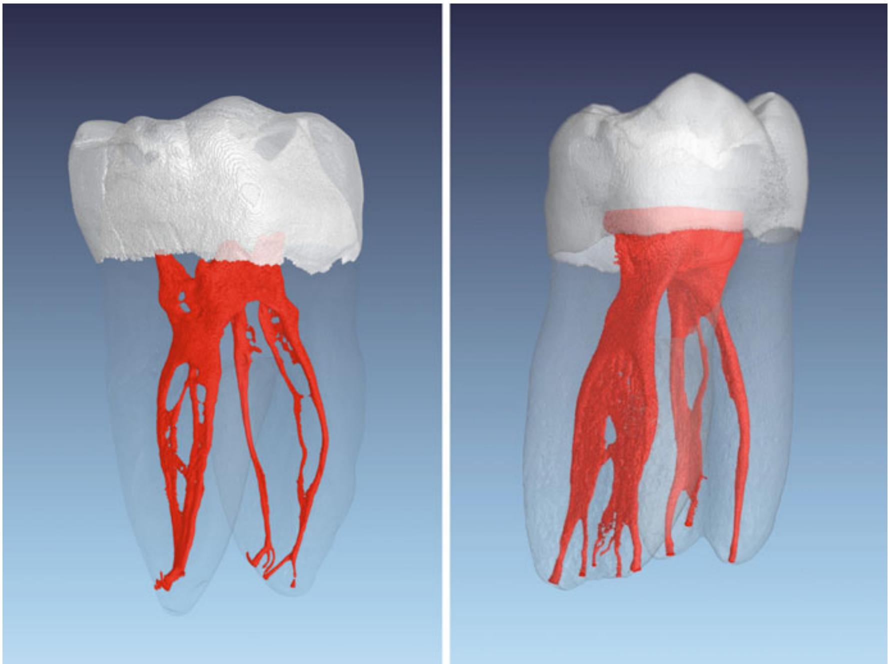

Fig. 1.11 Micro-computed tomography images of two extracted first mandibular molars with complex distal root canal anatomy. Note the various intercanal communications and the severe curvature to the distal aspect in the apical portion (*left*) and six portals of exits (*right*)

mesiobuccal, mesiolingual, and the distobuccal canal exhibited a more oval canal shape, whereas the distolingual canal revealed a relatively round canal shape [35]. The occurrence of an additional mesiobuccal root is called radix paramolaris. The frequency of a radix paramolaris is described with less than 0.5 % [33].

1.5.2 Additional Root Canals

Three canals were reported in about 61 %, four canals in 36 %, and more than five canals only in approximately 1 % [33]. In a systematic review [36] as well as reported earlier by Vertucci [7], the type IV configuration is the most frequently encountered canal configuration in the mesial root of first mandibular molars followed by type II. However, newer data generated by micro-CT showed even more complicated canal anatomy in mesial roots of mandibular first molars [28]. In about 9 % of the studied teeth, even four canals were observed in some root sections of the mesial root.

In the distal root of mandibular first molars, type I configuration dominated (63 %), followed by types II (15 %) and IV (12 %) [36]; again micro-CT studies showed a more complex image [30] (Fig. 1.11).

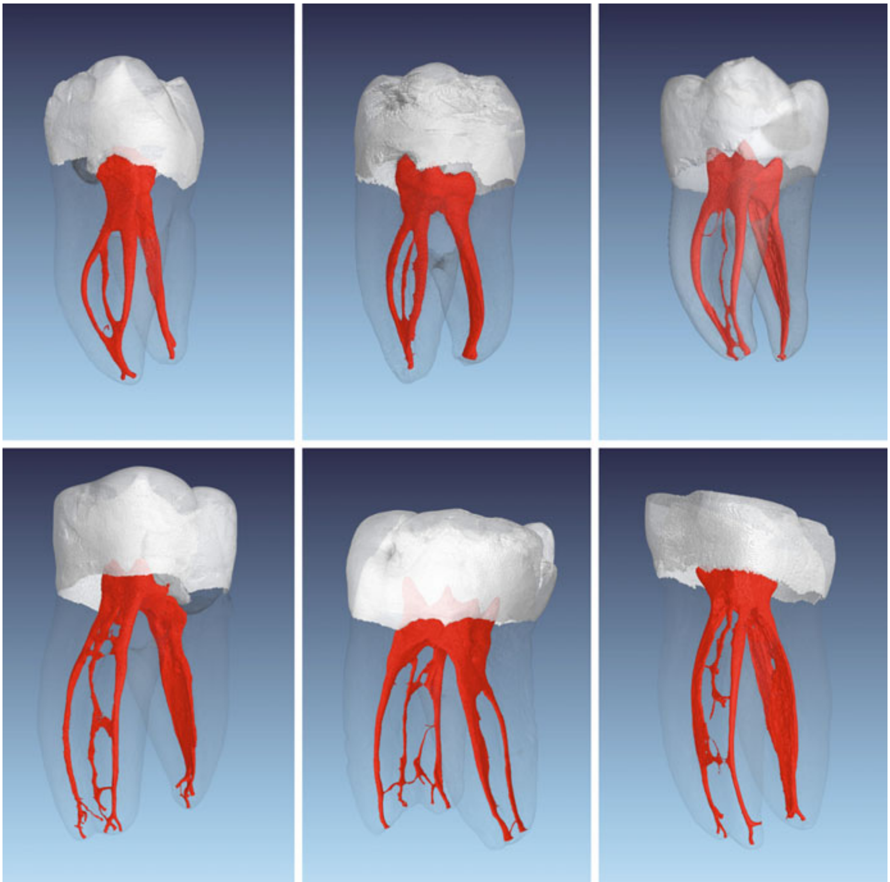

Fig. 1.12 Micro-computed tomography images of six extracted mandibular molars with middle mesial root canals. In the *upper panel*, middle mesial root canals are merging into one of the main canals. In the *lower* row, middle mesial root canals show separate portals of exit. Note the portal of exit in the middle portion of the root in the example depicted *lower right*

1.5.3 Middle Mesial Root Canals

A so-called "middle mesial" root canal in mesial roots of mandibular molars has been described as an additional canal between the mesiobuccal and the mesiolingual canal, which occurs in the development of the root [10]. Middle mesial canals were found with a frequency of 1–15 % [1]. With enhancement of clinically available detection methods (i.e., the use of the dental microscope) [37] and troughing the dentin between the two main mesial root canals up to 2 mm [38], in a recent study, a prevalence of up to 22 % was found (Fig. 1.12).

However, the age of the patients at the time of extraction during in vitro study [38] is not known; thus, the results may not be representative to the adult population

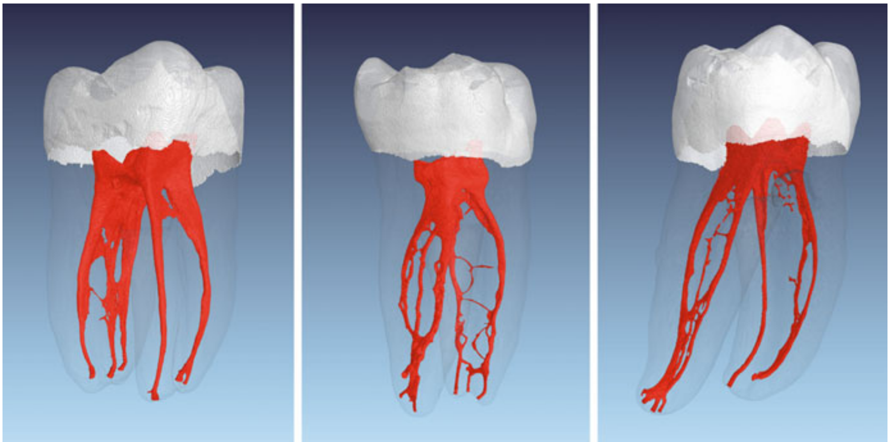

Fig. 1.13 Micro-computed tomography images of three extracted mandibular molars with middle distal root canals

of various stages of life. An age-related incidence of negotiable middle mesial root canals was indeed described by Nosrat et.al. [39]. They found about 33 % middle mesial canals in patients ≤20 years old, 24 % in patients 21–40 years old, and 4 % in patients >40 years old. The occurrence of middle mesial canals in mandibular molars is not only age-related but also related to different populations. In a micro-CT study of extracted teeth, 22 % middle mesial canals could be found in a Brazilian population, whereas only 15 % middle mesial canals were identified in a Turkish population [40].

Regarding the identification of accessory mesial canals in the mandibular first molar, there was a statistically significant difference when comparing the use of a dental microscope or CBCT with the use of a digital radiography and clinical inspection only. A good agreement between the dental microscope and the CBCT could be demonstrated. Digital radiography and clinical inspection without magnification support were not as precise as the use of the dental microscope or as the CBCT [41].

1.5.4 Middle Distal Root Canals

Three root canals in the distal root of mandibular molars might also occur (Fig. 1.13). However, the prevalence is described in a range of 0.2–3 % [42].

1.5.5 Accessory, Lateral Canals, and Apical Ramifications

Accessory and lateral canals connect the pulp space to the periodontium. An accessory canal represents a junction of the main pulp canals or the pulp chamber, which communicates with the root surface. A lateral canal is an accessory canal located in

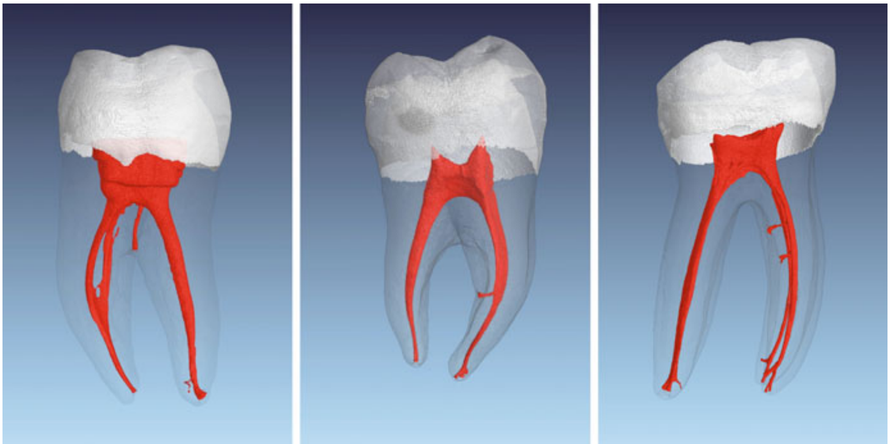

Fig. 1.14 Micro-computed tomography images of three extracted mandibular molars with accessory and lateral canals at different levels

the coronal or middle third of the root, usually branching off from the main canal (Fig. 1.14) [43]. In total, 73.5 % of accessory canals were found in the apical third, 11.4 % in the middle third, and 6.3 % in the coronal third of the root [7]. Accessory canals were also found in intraradicular regions at bi- or trifurcations of teeth with more than one root and were then called furcation canals [44].

According to Vertucci [43], accessory canals in mandibular first molars occur in three different types:

- A single furcation canal runs from the pulp chamber to the interradicular region in 13 % of all cases.
- In 23 %, a lateral canal extends from the coronal third of a root canal into the furcation. The lateral canal starts in 80 % of these cases from the distal root.
- In 10 % of all cases, teeth have both a lateral and a furcation canal.

The diameter of furcation canal openings was determined by Vertucci and Williams [44] using a scanning electron microscope. The diameter ranged from 4–720 μm, while the number of these canals ranged from 0 to more than 20 per tooth. Foramina, on both the pulp chamber floor and the furcation surface, occurred in the mandibular first molars in 32 % and the second mandibular molars in 24 %. In maxillary molars, an incidence of 36 % in first and 12 % in second molars could be found, respectively. In case of necrotic, infected pulp space, these canals could contribute to periapical pathosis in the furcation area of multirooted teeth.

Harris et al. [28] labeled openings in the apical 0.5 mm, which appeared clearly separated from the main canal, as ramifications. All other branches were designated as lateral canals. On average, almost four such openings were found in the apical 0.5 mm in the mesial root of mandibular first molars, while distal roots had 3.4 openings on average. The typical exit point of lateral canals in the mesial roots was

2.2 mm coronal from the apex, with almost 80% of lateral canals leaving the root within the apical 3 mm of the root. About 90% of lateral canals left the distal root in the apical 3 mm of the root. These data are in line with the results of a report by Kim and Kratchman [45]. This has relevance for surgical endodontics, namely, for the rule of threes: when resecting the apical 3 mm of the root, most of the lateral canals and apical ramifications are removed (see Chap. 10 in this book).

1.5.6 C-Shaped Canal Systems

A so-called C-shaped canal system is described as an anatomical variation [25]. Mostly the distal root canal is connected to one of the mesial root canals. A high prevalence of roots with C-shaped canals in mandibular second molars was found in an Asian population [43], with a range from about 14 to 50%. Cooke and Cox [46] were the first to report on C-shaped canal configurations [26]. Although most C-shaped canals occur in the second mandibular molars, C-shaped canals were also occasionally observed in first molars. Instead of various individual openings, pulp chambers of C-shaped molars showed a curved opening of a 180° circle or more into the canal system. Instead of the full arc, semicolon-type shapes are also seen.

Coronoapically, C-shaped molars showed extensive anatomical variations, which can be divided into two groups:

- A single curved C-shaped canal from the canal entrance to the apex
- Three or more distinct canals below the usual C-shaped opening

C-shaped molars with a single, wide canal are the exception. According to Vertucci [43], most commonly presented is type 2 of the C-shaped canals with individual orifices but having C-shaped connections.

A more detailed description of C-shaped roots in mandibular second molars has been published using micro-CT on extracted teeth from China [25, 26, 47, 48]. The cross-sectional canal shape was analyzed using 0.5 mm slices toward the apex and divided on each level into the following five categories: (C1) a continuous C-shaped contour without separation or division; (C2) a semicolon-shaped canal as a result of an interruption of the C-shape; (C3) two or three separate canals, which are connected by an isthmus; (C4) a single round or oval canal; and (C5) no canal lumen could be observed [25] (Fig. 1.15). The majority of the extracted molars showed the

Fig. 1.15 Schematic diagrams cross-sectional canal shapes (**a**–**f**) within a mandibular molar with typical C-shaped configurations, C1–3 according to Fan et al. [25, 26]. Note C4 with a single canal and C5 where no canal lumen is observed, usually close to the apex

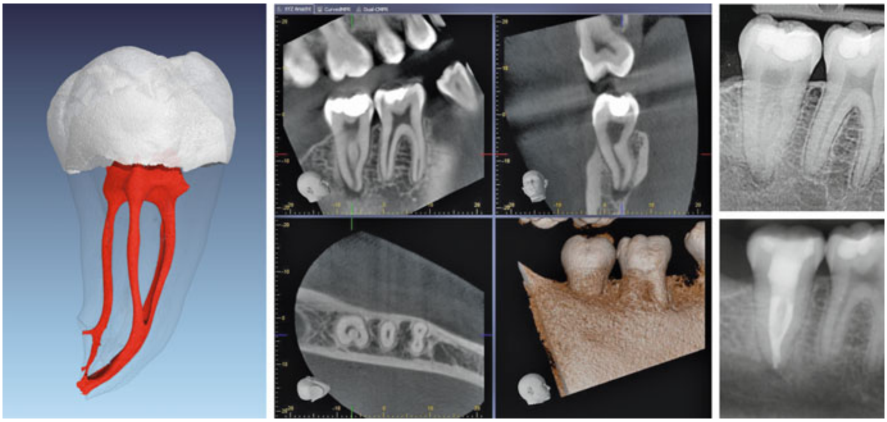

Fig. 1.16 Micro-computed tomography image of an extracted second mandibular molar with C-shaped canal configuration (*left*). CBCT (*middle*) and X-rays before and after treatment (*right*) of a similar clinical case

C1 configuration at the canal entrance. On the travel toward the apical third, the configuration C1, C2, and C3 were most commonly seen. The categories C4 and C5 were mostly observed in the apical region of the teeth.

The three-dimensional geometry of mandibular second molars was described as the following [48]: the merging type showing one major canal before exiting at the apical foramen was found in about 33 %; the symmetrical type was present in roughly 39 % and was described with separate mesial and distal canals; and a symmetry of the canals from the buccal-lingual view. In about 29 %, the asymmetrical type was found representing mesial and distal canals with a large isthmus from the distal aspect across the furcation area (Fig. 1.16).

Finally a classification of the morphology of the pulp chamber floor in C-shaped molars has been described [47]. Of the 44 teeth with C-shaped root canal systems, almost 90 % had a peninsula-like floor while about 18 % had a continuous C-shaped opening and were classified as type I. Type II was described as having a narrow dentinal band as a connection between the buccal wall and the peninsula-like floor of the pulp chamber floor, dividing the groove into one or two mesial and a distal opening. Type II was found in about 36 % of the teeth. In 32 % of the cases, a large mesiobuccal-distal and a small mesiolingual orifice was formed by a dentin fusion between the peninsula-like floor and the mesial pulp chamber wall (type III). Type IV had no C-shaped pulpal floor showing a distal and an oval or two round mesial openings and was present in 13.6 %. The authors concluded that most mandibular molars with C-shaped root canal systems also show a C-shaped pulpal floor.

1.5.7 Isthmi and Intracanal Communications

An isthmus was defined as a narrow bandlike communication between two root canals, comprising pulp tissue [49]. Mannocci et al. [50] highlighted the variability

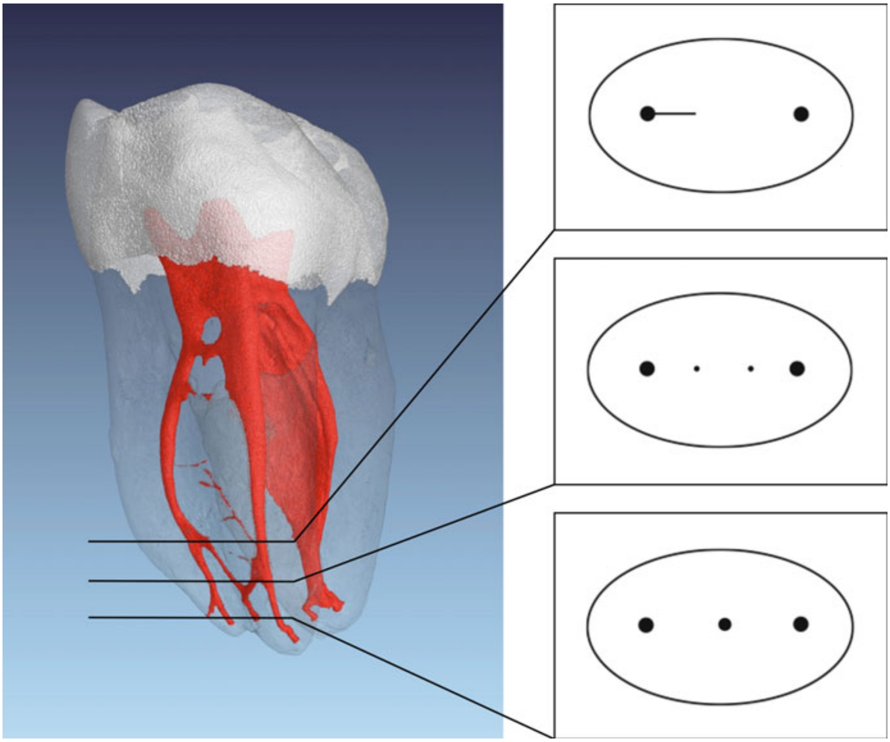

Fig. 1.17 Micro-computed tomography image of an extracted first mandibular molar with an obvious isthmus between the mesial main canals. The *right panel* illustrates different canal configurations at each section's plane; depending on the section plane during apical surgery of the mesial root, there is a chance that isthmus would have been missed completely

and frequency of isthmi in mesial roots of mandibular molars using the micro-CT technology. An isthmus in mandibular molars was found in about 17 % of teeth at 1 mm coronal to the apex and in roughly 37 % at 2 mm coronal to the apex. About half of teeth showed isthmi at 3 mm, one-third each had an isthmus at 4 mm and 5 mm from the apex, respectively. However, the data was evaluated using horizontal slides and the use of micro-CT data allows a more accurate three-dimensional analysis (Fig. 1.17). This was done by Fan et.al. [51] and gave a better three-dimensional understanding of intracanal communications in mesial roots of mandibular molars. The following classifications were made: type I: complete thin connection between two canals; type II: separate, thin, but incomplete connection between the two canals; type III: mixed, an incomplete isthmus exists above or below a complete isthmus; type IV: needlelike connection: close needlelike connection between two canals.

The authors found a prevalence of isthmi in 85 % in the coronal 5 mm from the apex of mesial roots of mandibular molars [51] and there was a significant difference of the isthmus types detected in the first and second molars. Mesial roots in first molars showed mostly type II and III isthmi, while in the mesial roots of second molars type I dominated [51].

In summary, molar anatomy is complex, with defined basic morphologies and multiple variations. Third molars are not typically root canal-treated, their anatomy may add another layer of complexity to the detailed illustration above. Therefore, in planning a molar root canal treatment, clinicians should:

- Have an understanding of possible anatomic variations of the tooth in question
- Obtain all relevant clinical impressions and images, including periapical radiographs, bitewings, cone beam CT scans
- Use magnification during the procedure
- Be ready to expect the unexpected in molar anatomy, both for the number of canals and their individual configuration

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