Endodontic Topics 2005, 10, 3–29

ENDODONTIC TOPICS 2005
1601-1538

Root canal morphology and its relationship to endodontic procedures

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The hard tissue repository of the human dental pulp takes on numerous configurations and shapes. A thorough knowledge of tooth morphology, careful interpretation of angled radiographs, proper access preparation and a detailed exploration of the interior of the tooth are essential prerequisites for a successful treatment outcome. Magnification and illumination are aids that must be utilized to achieve this goal. This article describes and illustrates tooth morphology and discusses its relationship to endodontic procedures. A thorough understanding of the complexity of the root canal system is essential for understanding the principles and problems of shaping and cleaning, for determining the apical limits and dimensions of canal preparations, and for performing successful microsurgical procedures.

It is important to visualize and to have knowledge of internal anatomy relationships before undertaking endodontic therapy. Careful evaluation of two or more periapical radiographs is mandatory. These angled radiographs provide much needed information about root canal morphology. Martinez-Lozano et al. (1) examined the effect of x-ray tube inclination on accurately determining the root canal system present in premolar teeth. They found that by varying the horizontal angle 20° and 40° the number of root canals observed in maxillary first and second and mandibular first premolars coincided with the actual number of canals present. In the case of mandibular second premolars only the 40° horizontal angle identified the correct morphology. The critical importance of carefully evaluating each radiograph taken prior to and during endodontic therapy was stressed by Friedman et al. (2). In a case report of five canals in a mandibular first molar, these authors emphasized that it was the radiographic appearance which facilitated recognition of the complex canal morphology. They cautioned 'that any attempt to develop techniques that require fewer radiographs runs the risk of missing information which may be significant for the success of therapy'. Radiographs, however, may not always determine the correct morphology particularly when only a buccolingual view is taken. Nattress et al. (3) radiographed 790 extracted mandibular incisors and premolars in order to assess the incidence of canal bifurcation in a root. Using the 'fast break' guideline (Fig. 1) that disappearance or narrowing of a canal infers that it divides resulted in failure to diagnose one-third of these divisions from a single radiographic view. The evaluation of the root canal system is most accurate when the dentist uses the information from multiple radiographic views together with a thorough clinical exploration of the interior and exterior of the tooth.

The main objective of root canal therapy is thorough shaping and cleaning of all pulp spaces and its complete obturation with an inert filling material. The presence of an untreated canal may be a reason for failure. A canal may be left untreated because the dentist fails to recognize its presence. It is extremely important that clinicians use all the armamentaria at their disposal to locate and treat the entire root canal system. It is humbling to be aware of the complexity of the spaces we are expected to access, shape, clean and fill. We can take comfort in knowing that even under the most

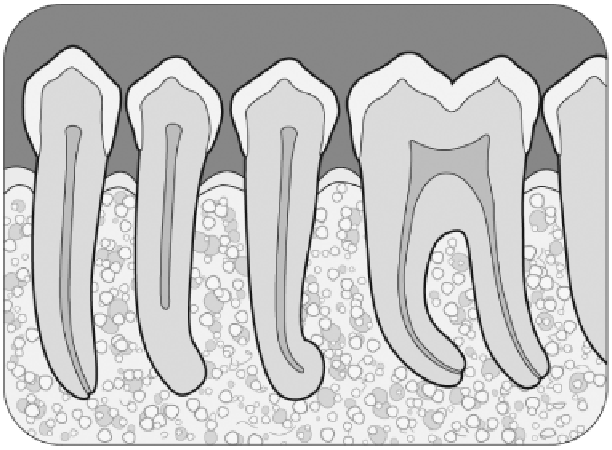

Fig. 1. Schematic representation of a premolar periapical radiograph which reveals clues about root canal morphology. An abrupt disappearance of the large canal in the mandibular first premolar usually signifies a canal bifurcation.

Fig. 2. The adaptation of the dental operating microscope has provided exceptional advances in locating and negotiating canal anatomy.

difficult circumstances our current methods of root canal therapy result in an exceptionally high rate of success.

Diagnostic measures such as multiple pre-operative radiographs, examination of the pulp chamber floor with a sharp explorer, troughing of grooves with ultrasonic tips, staining the chamber floor with 1% methylene blue dye, performing the sodium hypochlorite 'champagne bubble' test and visualizing canal bleeding points are important aids in locating root canal orifices. Stropko (4) recommends the use of 17% aqueous EDTA, 95% ethanol and the Stropko irrigator, fitted with a 27 G notched endodontic irrigating needle to clean and dry the pulp chamber floor prior to visually inspecting the canal system.

An important aid for locating root canals is the dental-operating microscope (DOM) which was introduced into endodontics to provide enhanced lighting and visibility (Fig. 2). It brings minute details into clear view. It enhances the dentists ability to selectively remove dentine with great precision thereby minimizing procedural errors. Several studies have shown that it significantly increases the dentists ability to locate and negotiate canals. Studying the mesiobuccal root of maxillary molars, Baldassari-Cruz et al. (5) demonstrated an increase in the number of second mesiobuccal canals (MB-2) located from 51% with the naked eye to 82% with the DOM. Coelho de Carvalho and Zuolo (6) concluded that the DOM made canal location easier by magnifying and illuminating the grooves in the pulpal floor and differentiating the color differences between the dentine of the floor and walls. The DOM enabled them to find 8% more canals in mandibular molars.

Gorduysus et al. (7) determined that the DOM did not significantly improve their ability to locate canals but rather facilitated their ability to negotiate them. Schwarze et al. (8) identified 41.3% of MB-2 canals using magnifying loops and 93.7% of MB-2 canals with the DOM. Buhrley et al. (9) on the other hand, determined that dental loops and the DOM were equally effective in locating MB-2 canals of maxillary molars. When no magnification was used this canal was located in only 18.2% of the teeth.

Kulild and Peters (10) utilizing the DOM located two canals in the mesiobuccal root of maxillary molars 95.2% of the time. Stropko (4) determined that a higher incidence of MB-2 canals were located 'as he became more experienced, schedule sufficient time for treatment, routinely used the DOM and employed specific instruments adopted for microendodontics'. Working in this environment he clinically located MB-2 canals in 93% of maxillary first molars and 60% of second molars. All of these studies demonstrate that mangification and illumination are essential armamenteria for performing endodontic therapy.

Components of the root canal system

The entire space in the dentine of the tooth where the pulp is housed is called the pulp cavity (Fig. 3). Its

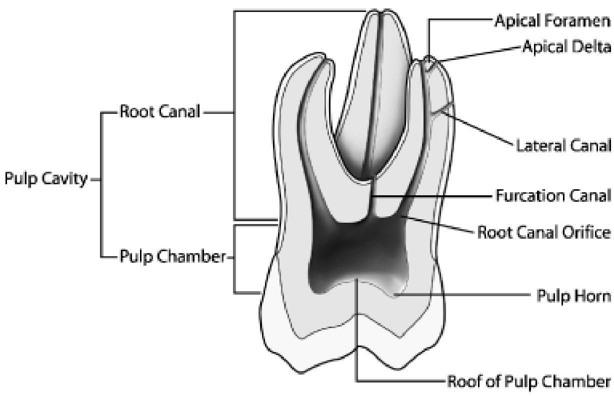

Fig. 3. Major anatomic components of the root canal system.

outline corresponds to the external contour of the tooth (11). However, factors such as physiologic aging, pathology and occlusion shape its size by the production of secondary and tertiary dentine and cementum. The pulp cavity is divided into two portions: the pulp chamber which is located in the anatomic crown of the tooth and the pulp or root canal(s) which are found in the anatomic root. Other features include pulp horns, lateral, accessory and furcation canals, canal orifices, intercanal connections, apical deltas and apical foramina. A root canal begins as a funnel-shaped canal orifices generally present at or slightly apical to the cervical line and ends at the apical foremen which opens onto the root surface between 0 and 3 mm from the center of the root apex (12–17). Nearly all root canals are curved particularly in a facial-lingual direction (18). These curvatures may pose problems during shaping and cleaning procedures because they are not evident on a standard facial radiograph. Angled views are necessary to determine their presence, direction and severity. A curvature may be a gradual curve of the entire canal or a sharp curvature near the apex. Double 's-shaped' canal curvatures can also occur. In most cases, the number of root canals corresponds with the number of roots but an oval-shaped root may have more than one canal.

Accessory and lateral canals extend from the pulp to the periodontium. An accessory canal is any branch of the main pulp canal or chamber that communicates with the external surface of the root. A lateral canal is an accessory canal located in the coronal or middle third of the root, usually extending horizontally from the main root canal (19). They occur 73.5% of the time in the apical third, 11.4% of the time in the middle third and 6.3% of the time in the cervical third of the root (13). They are formed by the entrapment of periodontal vessels in Hertwig's epithelial root sheath during calcification (20). They serve as avenues for the passage of irritants primarily from the pulp to the periodontium.

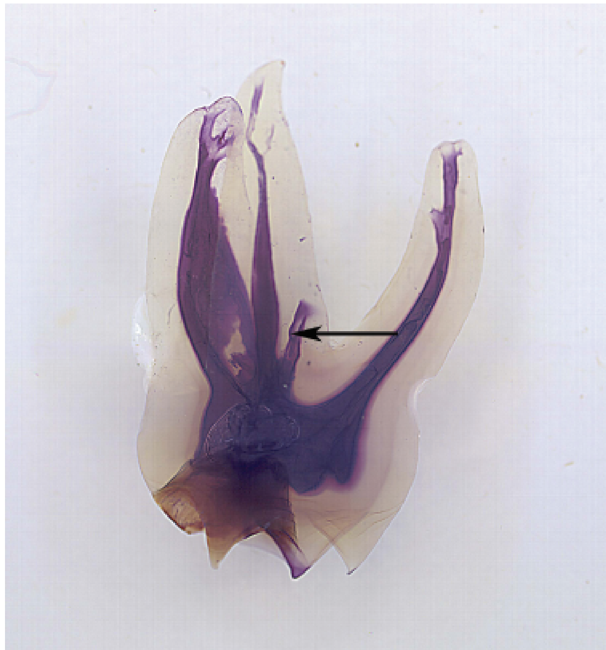

Fig. 4. Maxillary first molar illustrating a furcation canal (arrow).

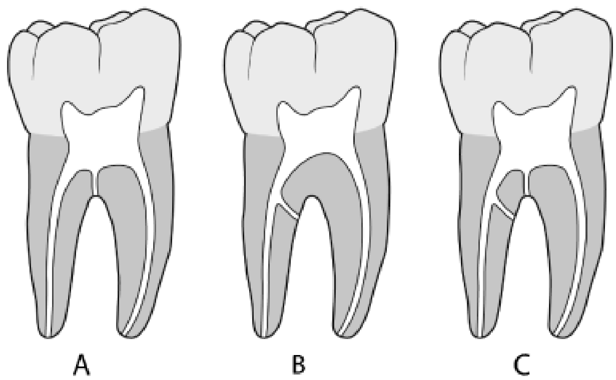

Fig. 5. Accessory canals occur in three distinct patterns in mandibular first molars. (A) In 13%, a single furcation canal extends from the pulp chamber to the intraradicular region. (B) In 23%, a lateral canal extends from the coronal third of a major root canal to the furcation region; 80% extend from the distal root canal. (C) Ten percentage of the teeth exhibit both lateral and furcation canals.

Accessory canals may also occur in the bifurcation or trifurcation of multirooted teeth (13). Vertucci (21) called these furcation canals (Fig. 4). They form as a

Table 1. Morphology of the maxillary permanent teeth*

Tooth	Root	No. of teeth	Canals with lateral canals	Position of lateral canals				Transverse anastomosis between canals	Position of transverse anatomosis			Position of apical foramen		Apical deltas
				Cervical	Middle	Apical	Furcation		Cervical	Middle	Apical	Central	Lateral	
Central	–	100	24	1	6	93	–	–	–	–	–	12	88	1
Lateral	–	100	26	1	8	91	–	–	–	–	–	22	78	3
Canine	–	100	30	0	10	90	–	–	–	–	–	14	86	3
First premolar	–	400	49.5	4.7	10.3	74	11	34.2	16.4	58	25.6	12	88	3.2
Second premolar	–	200	59.5	4	16.2	78.2	1.6	30.8	18.8	50	31.2	22.2	77.8	15.1
First molar	MB	100	51	10.7	13.1	58.2	↑	52	10	75	15	24	76	8
	DB	100	36	10.1	12.3	59.6	18	0	0	0	0	19	81	2
	P	100	48	9.4	11.3	61.3	↓	0	0	0	0	18	82	4
Second molar	MB	100	50	10.1	14.1	65.8	↑	21	8	72	20	12	88	3
	DB	100	29	9.1	13.3	67.6	10	0	0	0	0	17	83	2
	P	100	42	8.7	11.2	70.1	↓	0	0	0	0	19	81	4

Note: Figures represent percentage of the total.
*Results published previously in: Vertucci FJ. Root canal anatomy of the human permanent teeth. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1984: 58:589–599.

result of the entrapment of periodontal vessels during the fusion of the diaphragm which becomes the floor of the pulp chamber (20). In mandibular molars they occur in three distinct paterns (Fig. 5). The incidence of furcation canals for each tooth can be found in Tables 1 and 2.

Vertucci and Anthony (22) utilizing the scanning electron microscope found that the diameter of furcation openings in mandibular molars varied from 4 to 720 μm. Their numbers ranged from 0 to more than 20 per specimen. Foramina on both the pulp chamber floor and the furcation surface were found in 36% of maxillary first molars 12% of maxillary second molars, 32% of mandibular first molars, and 24% of mandibular second molars (Fig. 6A and B). Mandibular teeth have a higher incidence (56%) of foramina involving both the pulp chamber floor and furcation surface than do maxillary teeth (48%). No relationship was found between the incidence of accessory foramina and the occurrence of calcification of the pulp chamber or the distance from the chamber floor to the furcation. Radiographic evidence failed to demonstrate the presence of furcation and lateral canals in the coronal portion of these roots. Haznedaroglu et al. (23) determined the incidence of patent furcation canals in 200 permanent molars in a Turkish population. Using a stereomicroscope this group examined the pulp chamber floor which was stained with 0.5% basic fuschian dye. Patent furcal canals were detected in 24% of maxillary and mandibular first molars, 20% of mandibular second molars and 16% of maxillary second molars. These canals may be the cause of primary endodontic lesions in the furcation of multirooted teeth.

Root canal anatomy

Together with diagnosis and treatment planning, knowledge of the canal morphology and its frequent variations is a basic requirement for endodontic success. Stressing the significance of canal anatomy, Peters et al. (24) reported that variations in canal geometry before shaping and cleaning procedures had more influence on the changes that occur during preparation than the instrumentation techniques themselves.

From the early work of Hess and Zurcher (25) to the most recent studies demonstrating anatomic complexities of the root canal system, it has long been established that a root with a tapering canal and a single foremen is the exception rather than the rule. Investigators have shown multiple foramina, additional canals, fins, deltas, intercanal connections, loops, 'C-shaped' canals and accessory canals. Consequently the practitioner must treat each tooth assuming that complex anatomy occurs often enough to be considered normal.

The dentist must be familiar with the various pathways that root canals take to the apex. The pulp canal system is complex and canals may branch, divide and rejoin. Weine (26) categorized the root canal systems in any root into four basic types. Vertucci et al. (27) utilizing cleared teeth which had their pulp cavities stained with hematoxalin dye (Fig. 7), found a much more complex canal system and identified eight pulp space configurations (Fig. 8).

The percentages of human permanent teeth with these canal configurations are presented in Tables 3 and 4. The anatomic variations present in these teeth are listed in Tables 1 and 2. The only tooth to demonstrate all eight configurations was the maxillary second premolar.

Caliskan et al. (28) evaluated 1400 permanent teeth in a Turkish population and obtained morphology results similar to those reported by Vertucci. However, these authors found more than one canal in 22% of maxillary laterals, 55% of the mesiobuccal roots of maxillary second molars and 30% in the distobuccal root of mandibular second molars. They attributed the differences to the variations of populations in both studies. Kartal and Yanikoglu (29) studied 100 mandibular anterior teeth and found two new root canal types which had not been previously identified. The first new configuration consists of two separate canals which extend from the pulp chamber to mid-root where the lingual canal divides into two; all three canals then join in the apical third and exit as one canal. In their second configuration, one canal leaves the pulp chamber, divides into two in the middle third of the root, rejoins to form one canal which again splits and exits as three separate canals with separate foramina. Gulabivala et al. (30) examined mandibular molars in a Burmese population and found seven additional canal configurations (Fig. 9). These include three canals joining into one or two canals; two canals separating into three canals; two canals joining, redividing into two and terminating as one canal; four canals joining into two; four canals extending from orifices to apex and five canals joining into four at the apex. Sert and

Table 2. Morphology of the mandibular permanent teeth*

Tooth	Root	No. of teeth	Canals with lateral canals	Position of lateral canals				Transverse anastomosis between canals	Position of transverse anastomosis			Position of apical foramen		Apical deltas
				Cervical	Middle	Apical	Furcation		Cervical	Middle	Apical	Central	Lateral	
Central	–	100	20	3	12	85	–	–	–	–	–	25	75	5
Lateral	–	100	18	2	15	83	–	–	–	–	–	20	80	6
Canine	–	100	30	4	16	80	–	–	–	–	–	30	70	8
First premolar	–	400	44.3	4.3	16.1	78.9	0.7	32.1	20.6	52.9	26.5	15	85	5.7
Second premolar	–	400	48.3	3.2	16.4	80.1	0.3	30	0	66.7	33.3	16.1	83.9	3.4
First molar	Mesial	100	45	10.4	12.2	54.4	↑	63	12	75	13	22	78	10
							23							
	Distal	100	30	8.7	10.4	57.9	↓	55	10	72	18	20	80	14
Second molar	Mesial	100	49	10.1	13.1	65.8	↑	31	10	77	13	19	81	6
							11							
	Distal	100	34	9.1	11.6	68.3	↓	16	11	74	15	21	79	7

Note: Figures represent percentage of the total.
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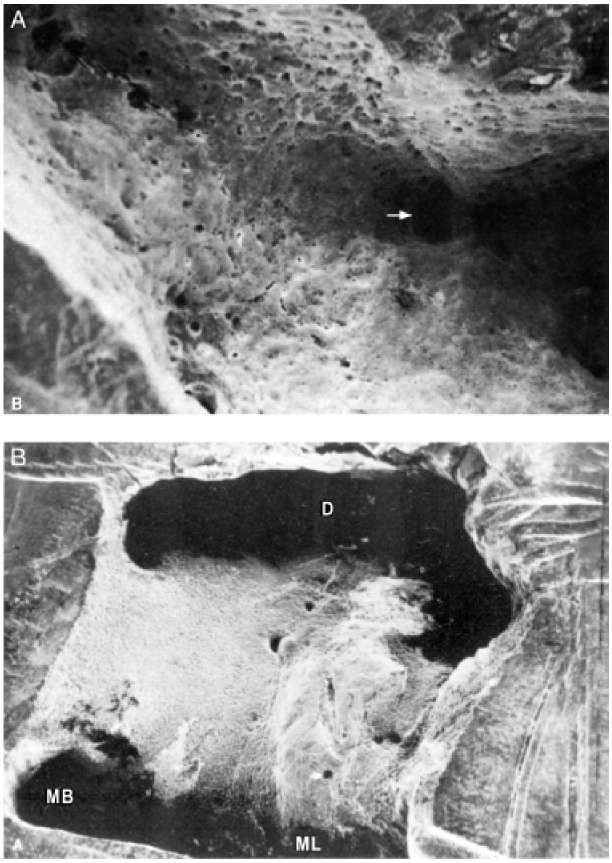

Fig. 6. (A) Electron photomicrograph of furcation surface of mandibular second molar. Multiple accessory foramina on furcation surface (original magnification, × 30). (B) Electron photomicrograph of the pulp chamber floor of a mandibular second molar. Multiple accessory foramina range from 20 to 140 μm. Distal canal (D), mesial canals (M) are identified for orientation (original magnification, × 30).

Bayirli (31) evaluated root canal configurations in 2800 teeth by gender in a Turkish population. Ninety-nine percent of their specimens were identical to the specimens in the Vertucci classification. The remaining 1% (36 teeth) represent 14 additional canal morphologies which occurred twice as often in mandibular teeth. These authors concluded that gender plays a role in determining canal morphology and that both gender and ethnic origin should be considered during the pre-operative evaluation stage of root canal therapy.

In addition to *in vitro* studies, a large number of case reports have been published over the past two decades which describe a variety of complex canal configurations. Some of these reports are listed in Tables 5–8. One report (81) was critical about studies reporting 'freak' cases that he felt were rare. However, there seems to be an increase in the reporting of complex anatomy both *in vitro* and *in vivo*. It is important that these reports be published because it draws attention to their existence so that similar anatomy may be recognized and treated.

Specific types of canal morphology appear to occur in different racial groups. Trope et al. (82) found that black patients have a higher number of mandibular premolars with extra canals than white patients. Black patients had more than one canal in 32.8% of first premolars and 7.8% of second premolars. Multiple canals in white patients occur in 13.7% of first premolars and 2.8% of second premolars. Walker (83–85) determined that Asians have different percentages of canal configurations than those reported in studies dominated by Caucasians and Africans. Wasti et al. (86) concluded that south Asian Pakistanis have root canal systems that are different than Caucasians. Manning (87) found that Asians have a higher frequency of single rooted and C-shaped mandibular second molars. Weine et al. (88) on the other hand concluded that the occurrence of two canals in the mesio-buccal root of maxillary first molars in Japanese patients was similar to the morphology described for other ethnic populations. The clinician is confronted daily with a highly complex and variable root canal system. All available armamentaria must be utilized to achieve a successful outcome.

Prior to beginning treatment, the dentist cannot precisely determine the actual number of root canals present. Pulp chamber floor and wall anatomy provides a guide to determining what morphology is actually present. Krasner and Rankow (89) in a study of 500 pulp chambers, determined that the cemento-enamel junction was the most important anatomic landmark for determining the location of pulp chambers and root canal orifices. They demonstrated that specific and consistent pulp chamber floor and wall anatomy exists and proposed laws for assisting clinicians identify canal morphology. The relationships expressed in these laws are particularly helpful in locating calcified canal orifices.

These laws are:

1. '*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.'
2. '*Law of symmetry 2*: Except for 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.'

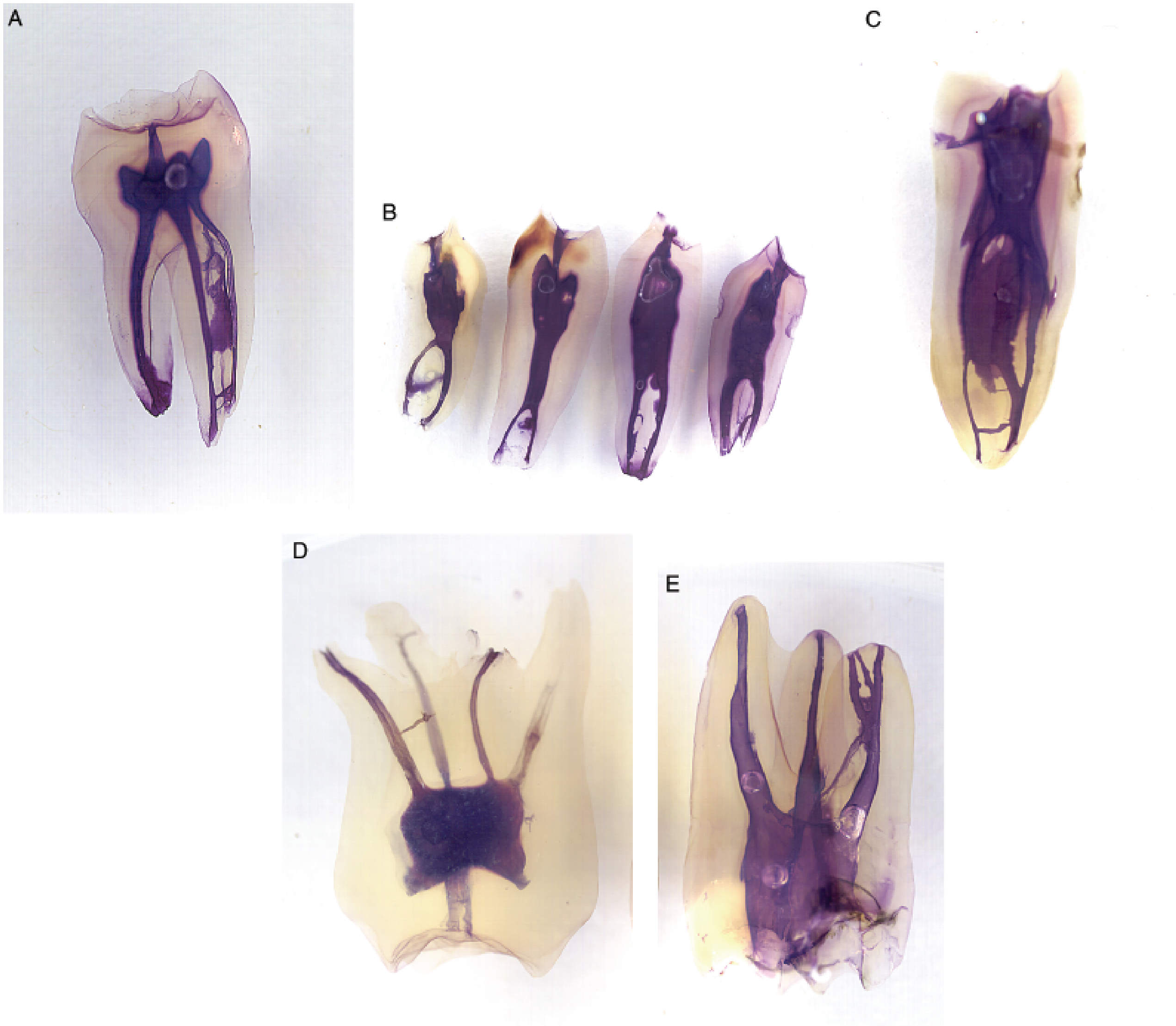

Fig. 7. Cleared teeth demonstrating root canal variation. (A) Mandibular second molar with three mesial canals. (B) Mandibular premolars with Vertucci type V canal configuration. (C) Mandibular premolars with three canals and intercanal connections. (D) Maxillary second molar with two palatal canals. (E) Maxillary first molar with two canals separating into three in mesiobuccal root. MB-2 orifice close to palatal orifice.

3. '*Law of color change*: The color of the pulp chamber floor is always darker than the walls.'
4. '*Law of orifices location 1*: the orifices of the root canals are always located at the junction of the walls and the floor.'
5. '*Law of orifices location 2*: The orifices of the root canals are located at the angles in the floor–wall junction.'
6. '*Law of orifices location 3*: The orifices of the root canals are located at the terminus of the root developmental fusion lines.'

The above laws were found to occur in 95% of the teeth examined. Five percent of mandibular second and third molars did not conform to these laws because of the presence of C-shaped canal anatomy.

The pulp cavity generally decreases in size as an individual ages. Dentine formation is not uniform throughout life and is more rapid on the roof and floor than on the walls of pulp chambers of posterior teeth. Such calcifications result in a flattened pulp chamber (Fig. 10). A root always contains a root canal even though one is not visible on a radiograph and is difficult to locate and negotiate. If there is only one canal, it will lie in the center of the root. When beginning an access preparation on a tooth with a calcified pulp cavity, it is

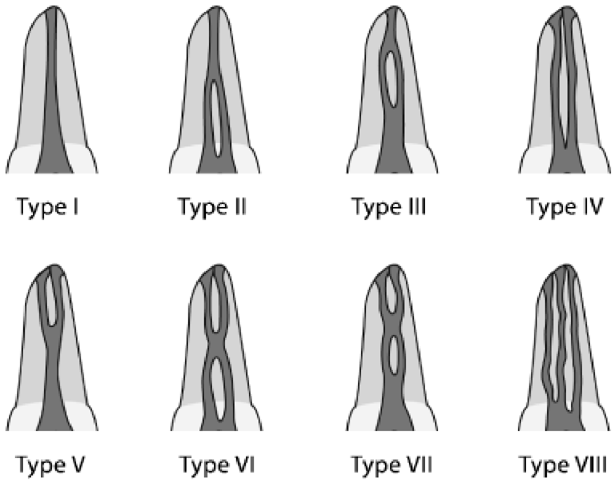

Fig. 8. Diagrammatic representation of Vertucci's canal configurations.

helpful to do so before placing the dental dam. This enables the dentist to evaluate root relationships and work more effectively in the long axis of the tooth. However, once the canal is located, the dental dam must be placed before proceeding further. When searching for a calcified canal, magnification and illumination are absolute prerequisites for evaluating color changes and working deep inside the tooth. It is also helpful to occasionally stop and take additional radiographic views. The straight facial radiograph provides information about the mesial-distal penetration while an angled radiograph provides information about the facial-lingual penetration. These radiographs help determine the correctness of the penetration angle and its proximity to the elusive canal. The LN bur (Caulk/Dentsply, Tulsa, OK, USA), the Mueller bur (Brasseler, Savannah, GA, USA) and thin ultrasonic tips are especially useful for locating calcified root canals. Locating canals and initial penetration under the microscope is aided by fine instrument like the Micro-Orifice Opener (Dentsply Maillefer, Ballaigues, Switzerland).

An examination of the floor of the pulp chamber offers clues to the location of orifices and to the type of canal system present. When there is only one canal, it is usually located in the center of the access preparation. All such orifices particularly if oval in shape must be thoroughly explored with apically precurved small K-type files to determine if more than one canal is present. If only one orifices is found that is not in the center of the preparation, it is probable that another is present and one should be searched for on the opposite side. The relationship of the two orifices to each other is also significant. The closer they are to each other the greater the chance that the two canals join at some point within the body of the root. The direction that a file takes upon introduction into an orifices is also important. If the initial file placed into the distal canal of a mandibular molar for example points to either the buccal or lingual, one should suspect a second canal. If two canals are present each will be smaller than a single canal.

Whenever a root contains two canals which join, the palatal/lingual canal is generally the one with straight line access to the apex. This anatomy is best treated by preparing and obturating the palatal/lingual canal to the apex and the buccal canal to the point of juncture (90). If both canals are enlarged to the apex, an 'hour-glass' preparation results. The point at which the two canals join would be more constricted than the preparation at the apex. Filling such a situation leaves voids in the apical third and invites failure particularly if bacteria remain in the canal. Rotary nickel titanium files must also be used with caution when this type of anatomy is present because instrument separation can occur as the file transverses the sharp curvature into the common part of the canal. When one canal separates into two, the division is buccal and lingual with the lingual canal generally splitting from the main canal at a sharp angle; sometimes at nearly a right angle (Fig. 11). Slowey (91) recommends 'that it is helpful to visualize this canal configuration as a lower case letter 'h'. The buccal canal would be the straight line portion of the letter 'h' whereas the lingual canal exists about mid-root at a sharp angle from the straight buccal canal.' This necessitates a modification in access toward the lingual in order to achieve unobstructed passage of instruments into the lingual canal (91).

Maxillary molars generally have three roots and can have as many as three mesial canals, two distal canals and two palatal canals. The mesiobuccal root of the maxillary first molar has generated more research and clinical investigation than any root in the mouth. It generally has two canals but a third canal has been reported. When there are two, they are called mesiobuccal (MB-1) and second mesiobuccal (MB-2). Görduysus et al. (7) studied the location and pathway of the MB-2 canal in maxillary first and second molars using the DOM and found that the location of this canal varies greatly. It was consistently located mesial to or directly on a line between the MB-1 and the palatal orifices (Fig. 12), within 3.5 mm palatally

Table 3. Classification and percentage of root canals of the maxillary teeth*

Teeth	No. of teeth	Type I, 1 canal	Type II, 2-1 canals	Type III, 1-2-1 canals	Total with one canal at apex	Type IV, 2 canals	Type V, 1-2 canals	Type VI, 1-2-1 canals	Type VII, 1-2-1-2 canals	Total with two canals at apex	Type VIII, 3 canals	Total with three canals at apex
Maxillary central	100	100	0	0	100	0	0	0	0	0	0	0
Maxillary lateral	100	100	0	0	100	0	0	0	0	0	0	0
Maxillary canine	100	100	0	0	100	0	0	0	0	0	0	0
Maxillary first premolar	400	8	18	0	26	62	7	0	0	69	5	5
Maxillary second premolar	200	48	22	5	75	11	6	5	2	24	1	1
Maxillary first molar												
Mesiobuccal	100	45	37	0	82	18	0	0	0	18	0	0
Distobuccal	100	100	0	0	100	0	0	0	0	0	0	0
Palatal	100	100	0	0	100	0	0	0	0	0	0	0
Maxillary second molar												
Mesiobuccal	100	71	17	0	88	12	0	0	0	12	0	0
Distobuccal	100	100	0	0	100	0	0	0	0	0	0	0
Palatal	100	100	0	0	100	0	0	0	0	0	0	0

*Results published previously in: Vertucci FJ. Root canal anatomy of the human permanent teeth. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1984: 58:589–599.

Table 4. Classification and percentage of root canals of the mandibular teeth*

Teeth	No. of teeth	Type I, 1 canal	Type II, 2-1 canals	Type III, 1-2-1 canals	Total with one canal at apex	Type IV, 2 canals	Type V, 1-2 canals	Type VI, 1-2-1 canals	Type VII, 1-2-1-2 canals	Total with two canals at apex	Type VIII, 3 canals	Total with three canals at apex
Mandibular central incisor	100	70	5	22	97	3	0	0	0	3	0	0
Mandibular lateral incisor	100	75	5	18	98	2	0	0	0	2	0	0
Mandibular canine	100	78	14	2	94	6	0	0	0	6	0	0
Mandibular first premolar	400	70	0	4	74	1.5	24	0	0	25.5	0.5	0.5
Mandibular second premolar	400	97.5	0	0	97.5	0	2.5	0	0	2.5	0	0
Mandibular first molar												
Mesial	100	12	28	0	40	43	8	10	0	59	1	1
Distal	100	70	15	0	85	5	8	2	0	15	0	0
Mandibular second molar												
Mesial	100	27	38	0	65	26	9	0	0	35	0	0
Distal	100	92	3	0	95	4	1	0	0	5	0	0

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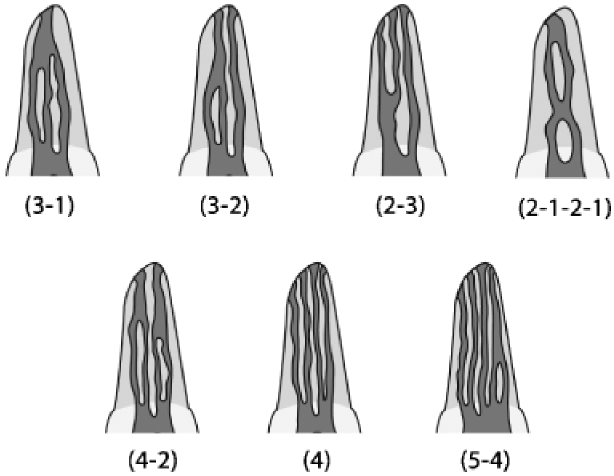

Fig. 9. Diagrammatic representation of Gulabivala et al.'s supplemental canal configurations to those of Vertucci.

and 2 mm mesially from the MB-1 orifices. Not all MB-2 orifices lead to a true canal. An 'apparent' MB-2 canal could not be traced far beyond the orifices in 16% of the teeth.

Negotiation of the MB-2 canal is often difficult due to a ledge of dentine that covers its orifices, the mesiobuccal inclination of its orifices on the pulpal floor (Fig. 13A) and its pathway which often takes one or two abrupt curves in the coronal part of the root. Most of these obstructions can be eliminated by 'troughing or countersinking' with ultrasonic tips mesially and apically along the mesiobuccal-palatal groove (Fig. 13B). This procedure causes the canal to shift mesially necessitating moving the access wall further mesially. Troughing may have to extend 0.5–3 mm deep. Care must be taken to avoid furcal wall perforation of this root as a concavity

Table 5. Case reports of apical canal configurations for maxillary anterior and premolar teeth

Authors	Tooth	1 canal	2 canals	4 canals
Mangani and Ruddle (32)	Central incisor	–	–	X
Todd (33)	Central incisor	–	X	–
Genovese and Marsico (34)	Central incisor	–	X	–
Sinai and Lustbader (35)	Central incisor	–	X	–
Von der Vyver and Traub (36)	Central incisor	–	X	–
Cabo-Valle and Gonzalez-Gonzalez (37)	Central incisor	–	X	–
Mader and Konzelman (38)	Central incisor	–	X	–
Pecora et al. (39)	Lateral incisor	–	X	–
Thompson et al. (40)	Lateral incisor	X*	–	–
Fabra-Campos (41)	Lateral incisor	–	X	–
Christie et al. (42)	Lateral incisor	–	X	–
Walvekar and Behbehani (43)	Lateral incisor	–	–	X
Collins (44)	Lateral incisor	–	X	–
Soares and Leonardo (45)	Maxillary first premolar	–	–	X
Soares and Leonardo (45)	Maxillary second premolar	–	–	X
Ferreira et al. (46)	Maxillary second premolar	–	–	X
Barkhordar and Sapone (47)	Maxillary second premolar	–	–	X
Low (48)	Maxillary second premolar	–	–	X

*Two canals join into one.

Table 6. Case reports of apical canal configurations for maxillary molar teeth

Authors	Tooth	1 canal	2 canals	4 canals
Bond et al. (49)	Mesiobuccal first molar	–	–	Case report
Beatty (50)	Mesiobuccal first molar	–	X	–
Maggiore et al. (51)	Mesiobuccal first molar	–	X	–
Cecic et al. (52)	Mesiobuccal first molar	–	X	–
Baratto-Filho et al. (53)	Mesiobuccal first molar	–	X	–
Wong (54)	Mesiobuccal first molar	–	X	–
Martinez-Berna et al. (55)	Distobuccal first molar		3	–
Hülsmann (56)	Distobuccal first molar		X	–
Bond et al. (49)	Distobuccal first molar	–	X	–
Beatty (50)	Distobuccal first molar	X	–	–
Maggiore et al. (51)	Distobuccal first molar	X	–	–
Cecic et al. (52)	Distobuccal first molar	X	–	–
Baratto-Filho et al. (53)	Distobuccal first molar	X	–	–
Wong (54)	Distobuccal first molar	X	–	–
Martinez-Berna et al. (55)	Palatal first molar	3	–	–
Hülsmann (56)	Palatal first molar	X	–	–
Bond et al. (49)	Palatal first molar	X*	–	–
Beatty (50)	Palatal first molar	X	–	–
Maggiore et al. (51)	Palatal first molar	–	–	X
Cecic et al. (52)	Palatal first molar	–	X	–
Baratto-Filho et al. (53)	Palatal first molar	–	X	–
Wong (54)	Palatal first molar	–	–	X
Thews et al. (57)	Palatal first molar	–	2	–
Benenati (58)	Mesiobuccal second molar	X	–	–
Fahid and Taintor (59)	Mesiobuccal second molar	X	–	–
Benenati (58)	Distobuccal second molar	X	–	
Fahid and Taintor (59)	Distobuccal second molar	–	X	–
Benenati (58)	Palatal second molar	–	X	–

*Two canals join into one.

exists on its distal surface. Apical to the troughing level the canal may be straight or curve sharply to the distobuccal, buccal or palatal.

Mandibular molars usually have two roots. However, occasionally three roots are present with two or three canals in the mesial and one, two, or three canals in the

Table 7. Case reports of apical canal configurations for mandibular anterior and premolar teeth

Authors	Tooth	1 canal	2 canals	3 canals	4 canals
Funato et al. (60)	Central incisor	–	X	–	
D'Arcangelo et al. (61)	Canine	–	X	–	
Orguneser and Kartal (62)	Canine	–	X*	–	
Heling et al. (63)	Canine	–	–	X	
Holtzman (64)	Second premolar	–	–	–	X
El Deeb (65)	Second premolar	–	–	X	–
Rödig and Hülsmann (66)	Second premolar	–	–	X	–
Bram and Fleisher (67)	Second premolar	–	–	–	X
Rhodes (68)	Second premolar	–	–	–	X
Macri and Zmener (69)	Second premolar	–	–	–	X†

*Three canals join into two.
†Five canals join into four.

distal root (Table 8). De Moor et al. (92) reported that mandibular first molars occasionally have an additional distolingual root (radix entomolaris, RE). The occurrence of these three-rooted mandibular first molars is less than 3% in African populations, 4.2% in Caucasians, less than 5% in Eurasian and Asian populations and higher than 5% in populations with Mongolian traits. The distal surface of the mesial root and mesial surface of the distal root have a root concavity which makes this wall very thin. Overzealous instrumentation of the concavity can lead to a strip perforation of the root. A middle mesial (MM) canal is sometimes present in the developmental groove between MB and ML canals (Fig. 14). The incidence of occurrence of a MM canal ranges from 1% (13) to 15% (93). It must always be looked for during access preparation. A bur is used to remove any protuberance from the mesial axial wall which would prevent direct access to the developmental groove between MB and ML orifices. With magnification, this developmental groove should be carefully explored with the sharp tip of an endodontic explorer. If a depression or orifices is located, the groove can be troughed with ultrasonic tips at the expense of its mesial aspect until a small file can negotiate this intermediate canal. The canals in the distal root are the distal (D) if there is one canal and the distobuccal (DB), distolingual (DL) and middle distal (MD) canal if there are more than one canal.

The C-shaped canal configuration was first reported by Cooke and Cox (94). While most C-shaped canals occur in the mandibular second molar, they have also been reported in the mandibular first molar, the maxillary first and second molars and the mandibular first premolar. C-shaped mandibular molars are so named for the cross-sectional morphology of its root and root canal. Instead of having several discrete orifices, the pulp chamber of the C-shaped molar is a single ribbon-shaped orifices with a 180° arc (or more), starting at the mesiolingual line angle and sweeping around either the buccal or lingual to end at the distal aspect of the pulp chamber. Below the orifices level, the root structure of a C-shaped molar can harbor a wide range of anatomic variations. 'These can be classified into two basic groups: (1) those with a single, ribbon-like, C-shaped canal from orifices to apex and (2) those with three or more distinct canals below the usual C-shape orifices.' Fortunately C-shaped molars with a single swath of canal are the exception rather that the rule. More common is the second type of C-shaped canal, with its discrete canals having unusual forms (94).

There is significant ethnic variation in the incidence of C-shaped molars. This anatomy is much more common in Asians, than in Caucasians. Investigations in Japan and China showed a 31.5% incidence of C-shaped canals (95–96). Haddad et al. (97) found a 19.1% rate in Lebanese subjects while Seo and Park

Table 8. Case reports of apical canal configurations for mandibular molar teeth

Authors	Tooth	1 canal	2 canals	3 canals	4 canals
Beatty and Krell (70)	Mesial first molar	–	–	X	–
Martinez-Berna and Badanelli (71)	Mesial first molar	–	–	X	–
Fabra-Campos (72)	Mesial first molar	–	–	X	–
Baugh and Wallace (73)	Mesial first molar	–	X*	–	–
Ricucci (74)	Mesial first molar	–	X*	–	–
DeGrood and Cunningham (75)	Mesial first molar	–	X*	–	–
Jacobsen et al. (76)	Mesial first molar	–	X*	X	X
Reeh (77)	Mesial first molar	–	–	–	X
Ricucci (74)	Distal first molar	X	–	–	
DeGrood and Cunningham (75)	Distal first molar	–	X*	–	–
Martinez-Berna and Badanelli (71)	Distal first molar	X†	X*	–	–
Beatty and Krell (70)	Distal first molar	–	X	–	–
Reeh (77)	Distal first molar	–	–	X	–
Beatty and Interian (78)	Distal first molar	–	–	X	–
Friedman et al. (2)	Distal first molar	–	–	X	–
Stroner et al. (79)	Distal first molar	–	–	X	–
Wells and Bernier (80)	Distal second molar	X	–	–	–
Beatty and Krell (70)	Distal second molar	–	–	X	–
Beatty and Krell (70)	Distal second molar	–	X	–	–
Wells and Bernier (80)	Distal second molar	X‡	–	–	–

*Three canals join into two.
†Three canals join into one.
‡Mesial and distal canals join.

(98) found that 32.7% of Korean's had C-shaped mandibular second molars. Although the C-shaped canal anatomy creates considerable technical challenges, the use of the DOM, sonic and ultrasonic instrumentation and thermoplastic obturation techniques have made treatment more predictable.

Apical region of the root

The classic concept of apical root anatomy is that there exists three anatomic and histologic landmarks namely the apical constriction (AC), the cemento-dentinal junction (CDJ) and the apical foramen (AF). The anatomy of the root apex as described by Kuttler (99) (Fig. 15) shows the root canal tapering from the canal orifices to the AC which is generally 0.5–1.5 mm inside the AF. It is generally considered to be the part of the root canal with the smallest diameter. It is the reference point most often used by dentists as the apical termination of shaping, cleaning and obturation procedures.

The CDJ is the point in the canal where cementum meets dentine. It is the point where pulp tissue ends

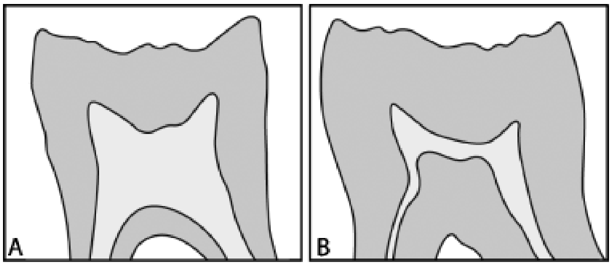

Fig. 10. Comparison in size of the pulps of two mandibular first molars at different ages. (A) Age, 7 years. The pulp chamber is large. (B) 55 years. The pulp chamber is greatly reduced in size through reparative dentin formation mainly on the pulpal floor.

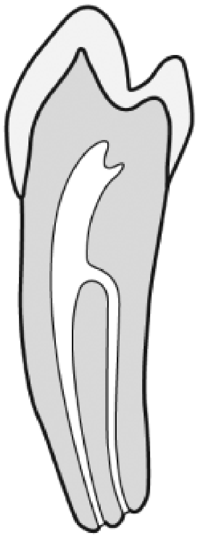

Fig. 11. Mesial view of a mandibular premolar with Vertucci Type V canal configuration. Lingual canal separates from main canal at nearly a right angle necessitating widening of the access to the lingual. This should be preformed utilizing the DOM.

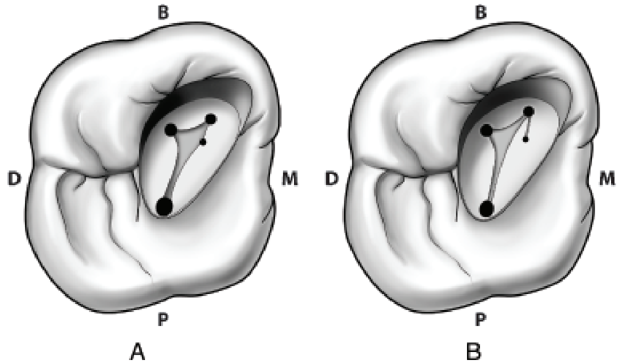

Fig. 12. Diagrammatic representation of position of MB-2 canal orifi in maxillary molars.

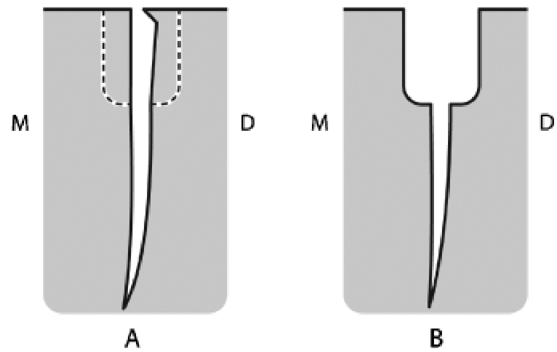

Fig. 13. Diagrammatic representation of the orientation of MB-2 orifice before (A) and after (B) troughing procedure. Removing obstructions facilitates access into this orifice.

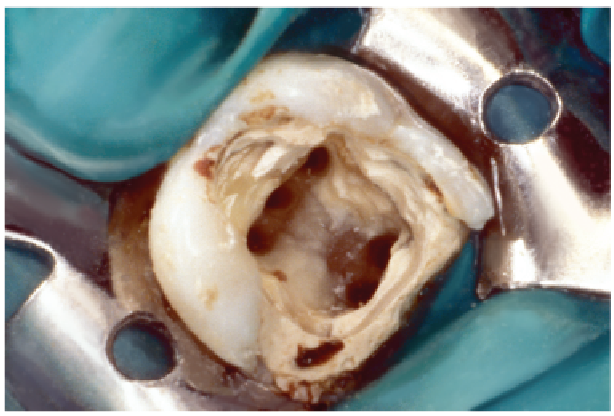

Fig. 14. Mandibular first molar access with three mesial canals. Approximately half of the middle mesial canals terminate in a separate foramen.

and periodontal tissues begin. Its location in the root canal is highly variable. It generally is not the same area as the AC and is not a fixed point in population of different countries (100). Smulson et al. (101) estimated that the CDJ is located approximately 1.0 mm from the AF.

From the AC or minor diameter (102) the canal widens as it approaches the AF or major diameter. The shape of the space between the major and minor diameters has variously been described as funnel-shaped, hyperbolic or 'morning glory'. The mean distance between the major and minor diameters has been determined to be 0.5 mm in a young person and 0.67 mm in an older individual. The increased length in older individuals is due to the increased buildup of cementum. The AF is the 'circumference or rounded edge, like a funnel or crater, that differentiates the termination of the cemental canal from the exterior

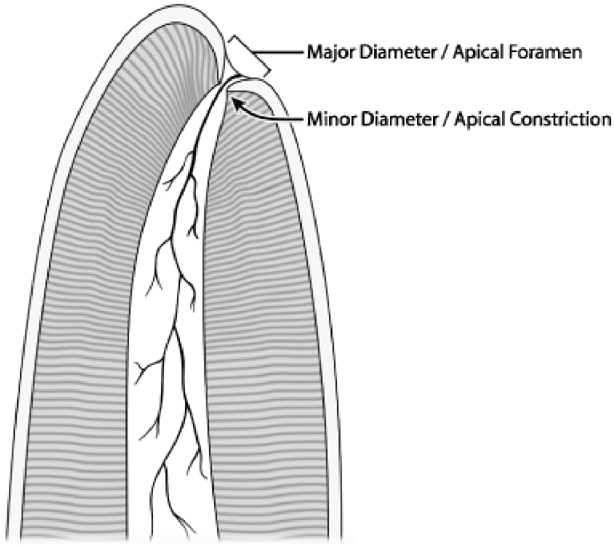

Fig. 15. Morphology of the root apex. From its orifice, the canal tapers to the apical constriction or minor diameter which is generally considered the narrowest part of the canal. From this point the canal widens as it exits the root at the apical foramen or major diameter. The space between the minor and major diameters is funnel shaped.

Table 9. Mean perpendicular distance from the root apex to the apical constriction and both mesiodistal and labiolingual diameters at the constriction*

Teeth	Mesiodistal (mm)	Labiolingual (mm)	Vertical (mm)
Central incisor	0.370	0.428	0.863
Lateral incisor	0.307	0.369	0.825
Canine	0.313	0.375	1.010

*Results published previously in: Mizutani T, Ohno N, Nakamura H. Anatomical study of the root apex in the maxillary anterior teeth. J Endod 1992: 18(7): 344–347.

Table 10. Size of main apical foramina*

Teeth	Mean values (*u*)
Maxillary incisors	289.4
Mandibular incisors	262.5
Maxillary premolars	210.0
Mandibular premolars	268.25
Maxillary molars	
Palatal	298.0
Mesiobuccal	235.05
Distobuccal	232.20
Mandibular molars	
Mesial	257.5
Distal	392.0

*Results published previously in: Morfis A, Sylaras SN, Georgopoulou M, Kernani M, Prountzos F. Study of the apices of human permanent teeth with the use of a scanning electron microscope. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1994: 77(2):172–176.

surface of the root'. Kuttler (99) determined that the diameter of the AF in individuals in the age range of 18–25 was 502 μm and in those over 55 years of age was 681 μm, demonstrating its growth with age. The AF does not normally exit at the anatomic apex but is offset 0.5–3.0 mm. This variation is more marked in older teeth through cementum apposition. Studies have demonstrated that the AF coincides with the apical root vertex 17–46% of the time (12–16).

Ponce and Vilar Fernandez (103) evaluated serial histologic sections of maxillary anterior teeth to determine the location and diameter of the CDJ and the diameter of the AF. They found that the extension of cementum from the AF into the root canal differed considerably on opposite canal walls. Cementum reached the same level on all canal walls only 5% of the time. The greatest extension generally occurred on the concave side of the canal curvature. This variability reconfirmed that the CDJ and AC are generally not the same area and that the CDJ should be considered just a point at which two histologic tissues meet within the root canal. The diameter of the canal at the CDJ was highly irregular and was determined to be 353 μm for maxillary centrals, 292 μm for lateral incisors and 298 μm for canines.

Mizutani et al. (104) prepared serial cross-sections of 90 maxillary anterior teeth and found that the root apex and main AF coincided in 16.7% of central incisors and canines and in 6.7% of lateral incisors. Both the root apex and AF of the central incisors and canines were displaced distolabially while those of the lateral incisors were displaced distolingually. The perpendicular dis-

Table 11. Median canal diameter (in mm) at 1, 2 and 5 mm from the apex*

Tooth (canal) Position	Buccal/lingual 1 mm	2 mm	5 mm	Mesial/distal 1 mm	2 mm	5 mm
Maxillary						
Central Incisor	0.34	0.47	0.76	0.30	0.36	0.54
Lateral Incisor	0.45	0.60	0.77	0.33	0.33	0.47
Canine	0.31	0.58	0.63	0.29	0.44	0.50
Premolar						
Single canal	0.37	0.63	1.13	0.26	0.41	0.38
Bucccal	0.30	0.40	0.35	0.23	0.31	0.31
Palatal	0.23	0.37	0.42	0.17	0.26	0.33
Molar						
Single Mesiobuccal	0.43	0.46	0.96	0.22	0.32	0.29
1st Mesiobuccal	0.19	0.37	0.46	0.13	0.27	0.32
2nd Mesiobuccal	0.19	0.31	0.38	0.16	0.16	0.16
Distobuccal	0.22	0.33	0.49	0.17	0.25	0.31
Palatal	0.29	0.40	0.55	0.33	0.40	0.74
Mandibular						
Incisor	0.37	0.52	0.81	0.25	0.25	0.29
Canine	0.47	0.45	0.74	0.36	0.36	0.57
Premolar						
Single	0.35	0.40	0.76	0.28	0.32	0.49
Buccal	0.20	0.34	0.36	0.23	0.29	0.41
Palatal	0.13	0.32	0.37	0.18	0.21	0.17
Molar						
Single Mesial	0.45	0.80	2.11	0.22	0.30	0.29
Mesiobuccal	0.40	0.42	0.64	0.21	0.26	0.32
Mesiolingual	0.38	0.44	0.61	0.28	0.24	0.35
Distal	0.46	0.50	1.07	0.35	0.34	0.59

*Results published previously in: Wu MK, R'Oris A, Barkis D, Wesselink P. Prevalence and extent of long oval canals in the apical third. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000: 89(6):739–743.

tance from the root apex to the AC and both mesiodistal and labiolingular root canal diameters at the AC are shown in Table 9. The labiolingual diameter in all maxillary anterior teeth is approximately 0.05 mm larger than the mesiodistal diameter. This has definite implications on shaping and cleaning procedures as only the mesiodistal diameter is evident on the radiograph.

Morfis et al. (105) studied the apices of 213 permanent teeth with the use of a scanning electron microscope and determined the number and size of AF, its distance from the anatomic apex, and the size of accessory foramina. More than one main AF was observed in all teeth except for the palatal root of maxillary molars and the distal root of mandibular molars. Twenty-four percent of maxillary premolars and 26% of maxillary incisors showed no main AF. The mesial roots of mandibular molars (50%), the maxillary premolars (48.3%) and the mesial root of maxillary molars (41.7%) showed the highest percentage of multiple AF. This finding is consistent with observations that blunted roots usually have more than one root canal. The mean values of the size of the main AF are listed in Table 10. They varied from 210 μm for the maxillary premolars to 392 μm for the distal roots of mandibular molars. All groups of teeth demonstrated at least one accessory foramen. The maxillary premolars had the largest number and size of accessory foramen (mean value 53.4 μm) and the most complicated apical morphologic makeup. This was followed closely by the mandibular premolars and may be a reason why root canal therapy may fail in this group of teeth.

Briseno Marroquin et al. (106) investigated the apical anatomy of 523 maxillary and 574 mandibular molars from an Egyptian population by means of a computer-aided stereomicroscope (× 40 magnification). The most common physiological foramen (apical constriction) shape was oval (70%); the mean of the narrow and wide physiological foramen diameters was 0.20–0.26 mm in mandibular molars, 0.18–0.25 mm in maxillary mesio-buccal and distobuccal roots and 0.22–0.29 mm in the maxillary palatal root. There was a high percentage of two physiological foramina in mesial (87%) and mesiobuccal (71%) roots of mandibular and maxillary first molars, respectively; there was a high frequency of accessory foramina in maxillary mesiobuccal (33%) and mandibular mesial (26%) roots.

Mjör et al. (107,108), found tremendous variation in the morphology of the apical root including numerous accessory canals, areas of resorption and repaired resorption, attached, embedded and free pulp stones and varied amounts of irregular secondary dentine. Primary dentinal tubules were found less frequently than in coronal dentine and were more or less irregular in direction and density. Some areas were completely devoid of tubules. Fine tubular branches (300–700 mm in diameter) which run at 45° to the main tubules and microbranches (25–200 mm diameter) which run at 90° to the main tubules were frequently present. This variable structure in the apical region presents challenges for root canal therapy. Obturation techniques which rely on the penetration of adhesives into dentinal tubules may not be successful. These authors concluded that the hybrid layer may become a very important part of adhesive systems in the apical part of the root canal.

Although debated for decades, there is considerable controversy concerning the exact termination point for root canal therapy procedures (109–110). Clinical determination of apical canal morphology is difficult at best. The existence of an AC may be more conceptual than actual. Dummer et al. (111) determined that a traditional single AC was present less than half the time. Frequently, the apical root canal is tapered or parallel or contained multiple constrictions. Other authors (112–113) have suggested that an apical constriction is usually not present, particularly when there is apical root resorption and periradicular pathology. Weine (114) recommends the following termination points for therapy: 1 mm from the apex when there is no bone or root resorption; 1.5 mm from the apex when there is only bone resorption and 2 mm from the apex when there is bone and root resorption.

Wu et al. (115) feel that it is difficult to locate the AC and AF clinically and that the radiographic apex is a more reliable reference point. These authors recommend that root canal procedures terminate 0–3 mm from the radiographic apex depending upon the pulpal diagnosis. For vital cases, clinical and biologic evidence (116–117) indicates that a favorable point to terminate therapy was 2–3 mm short of the radiographic apex. This leaves an apical pulp stump which prevents the extrusion of irritating filling materials into the periradicular tissues. With pulp necrosis, bacteria and their byproducts may be present in the apical root canal and jeopardize healing. In these cases, a better success rate was achieved (116–117) when therapy ended at or within 2 mm of the radiographic apex. When therapy ended shorter than 2 mm or extended past the radiographic apex, the success rate decreased by 20%. For retreatment cases, therapy should extend to or preferably 1–2 mm short of the radiographic apex to prevent overextension of instruments and filling materials into the periradicular tissues.

Langeland (118–121) and Ricucci and Langeland (122) concluded after evaluating apical and periradicular tissues following root canal therapy, that the most favorable prognosis was obtained when procedures were terminated at the AC while the worst was obtained when working beyond the AC. The second worst prognosis occurred when procedures were terminated more than 2 mm from the AC. These findings occurred in vital and necrotic tissue and when bacteria were present beyond the AF. The presence of sealer and/or gutta-percha into the periradicular tissues, into lateral canals and into apical ramifications always produced a severe inflammatory reaction (123–125). These authors, however, admit that it is difficult at best to clinically locate the AC. Finally, Schilder (126) recommended a termination point for all therapy at or beyond the radiographic apex and advocated the filling of all apical ramifications and lateral canals. The apical limit of instrumentation and obturation continues to be one of the major controversies in root canal therapy.

A hallmark of the apical region is its variability and unpredictability. Because of the tremendous variation in canal shapes and diameters there is concern about a clinicians ability to shape and clean canals in all dimensions. The ability to accomplish this depends upon the anatomy of the root canal system, the dimensions of canal walls and the final size of enlarging instruments.

The initial file that explores canal anatomy and binds in the canal is sometimes used as a measure of apical root canal diameter. Attempting to gauge the size of oval-shaped apical root canals, Wu et al. (127) demonstrated that in 75% of the cases the initial file contacted only one side of the apical canal wall; in the remaining 25% the instrument failed to contact any wall. In 90% of the canals, the diameter of the initial instrument was smaller than the short diameter of the canal. Consequently, using the first file to bind for gauging the diameter of the apical canal and as guidance for apical enlargement is not reliable. Leeb (128) recognized this problem and determined that it could be remedied by removing the interferences in the coronal and middle thirds of the canal. Contreras et al. (129) concluded that radicular flaring before canal exploration removed interferences and increased the initial file size that was snug at the apex (almost two file sizes greater). Early flaring gives the dentist a better sense of apical canal size so that better decisions can be made concerning the appropriate final diameter needed for apical shaping and cleaning.

Gani and Visvisian (130) compared the shape of the apical portion of the root canal system of maxillary first molars with the D_0 diameter of endodontic instruments and found that correlations between maximum canal diameters and instrument diameters were highly variable. Evaluation of the root canal diameter showed that a circular shape (both diameters are equal) predominates in the palatal and MB-2 canals; a flat shape (largest diameter exceeds the smallest by more than the radius) occurs most often in the MB-1 canal; both circular and flat shapes are found in the distobuccal canal. Flat and ribbon shaped canals persist near the apex even in elderly patients and mainly in the MB-1 canal. This finding was believed to be due to the concentric narrowing of ribbon shaped canals primarily along their smallest diameter. Oval canals narrow mainly along their largest diameter and tend to become circular. These authors concluded that the maxillary first molar shows a very complicated canal shape at the apical limit of its canal system and this anatomy makes shaping, cleaning and obturation difficult. This is particularly true of the MB-1 and distobuccal canals. Because of this great variability it was virtually impossible for them to establish guidelines for instrument calibers that would guarantee adequate canal preparation.

Wu et al. (131) studied the apical root canal diameters and tapers of each tooth group and demonstrated that root canals are frequently long oval or ribbon-shaped in the apical 5 mm (Table 11). These authors defined a long oval canal as one that has a ratio of long to short canal diameter that is greater than 2. This type of canal morphology was found to occur in 25% of the cross-sections studied. They have a buccal/lingual diameter which is larger than its mesial/distal diameter. This was found to be true for all canals except the palatal canal of maxillary molars. The canal measurements suggest that apical preparations need to be taken to larger sizes than previously recommended (132). These authors concluded that 'because of long oval canals, larger canal tapers in the buccal-lingual direction, wider ranges in the apical diameters of canals, and the lack of technology to measure these diameters, it is very difficult if not impossible to adequately debride all canals by instrumentation alone.' This fact was further emphasized by Wu and Wesselink (133) when they reported uninstrumented extensions in 65% of oval canals prepared with files utilizing the balanced force technique and by Rodig et al. (134) who determined that nickel–titanium rotary instruments did not allow controlled preparation of the buccal and lingual extensions of oval canals. The instruments created a round bulge in the canal leaving the extensions unprepared and filled with smear layer and debris.

The complete shaping and cleaning of root canals is often difficult to achieve because of variations in canal cross-sectional shapes (135–137) and the presence of canal irrigularities and curvatures. Stainless steel hand files and tapered nickel–titanium rotary files are currently used for root canal enlargement. Excessive flaring with these instruments particularly in curved roots pose the danger of thining or perforating the root canal wall on the concave surface of a root (138). Furthermore, the risk of iatrogenic mishaps increase because root canals tend to be closer to the inner (concave) part of curved roots (139–140). Abou-Rass et al. (141) recommended 'anticurvature filing' when preparing curved canals. 'This is a controlled and directed canal preparation into the bulky portions or safety zones and away from the thinner portions or danger zones of root structure where root perforation or stripping of the canal walls can occur.'

Lim and Stock (142) compared anticurvature filing using the step back technique with a standard circumferential step back method in curved molar root canals and showed that anticurvature filling reduces the risk of perforation through the furcal or curved root surface. These authors designated that an arbitrary value of 0.3 mm of dentine is the minimal canal wall thickness that should remain after preparation inorder to provide sufficient resistance to obturation forces and to forces exerted during function. Gluskin et al. (143) showed that canal shapes prepared with nickel–titanium rotary GT files (Dentsply-Tulsa Dental, Tulsa, USA) were better centered and conserved more dentine in the danger zone region of curved molars than hand instruments. Garala et al. (144) determined that significant differences in remaining canal wall thickness were not present when either the ProFile rotary system (Maillefer) or the Hero 642 system

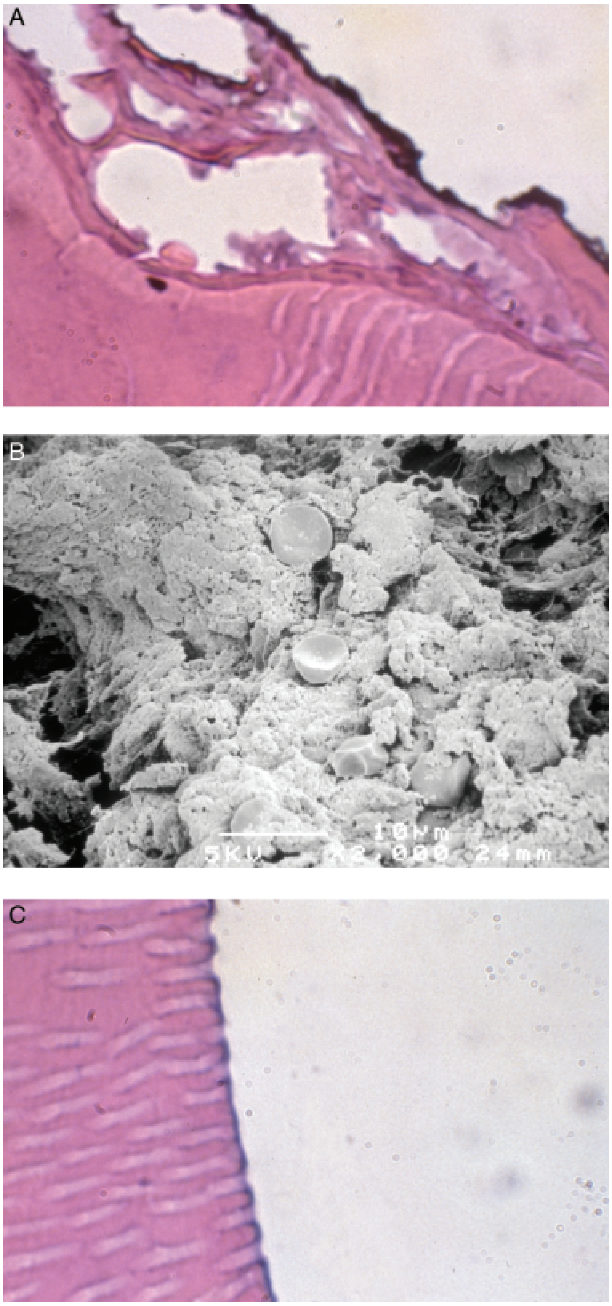

Fig. 16. (A) X-section of mandibular anterior tooth showing pulp remnants remaining in recesses of root canal walls in apical 1 mm. Rotary nickel titanium preparation (size 40, 0.08 taper) and manual irrigation [6% NaOCL and RC prep (Premier)]. (B) Electron photomicroscopy of canal wall in (A) illustrating much debris. (C) X-section of mandibular anterior tooth showing clean canal walls in the apical 1 mm following rotary nickel titanium preparation (size 40, 0.08 taper) and sonic accoustic irrigation with 6% NaOCL.

(Micromega, Besancon, France) were used according to manufacturers directions. Canal wall structure removed during preparation never exceeded 60%.

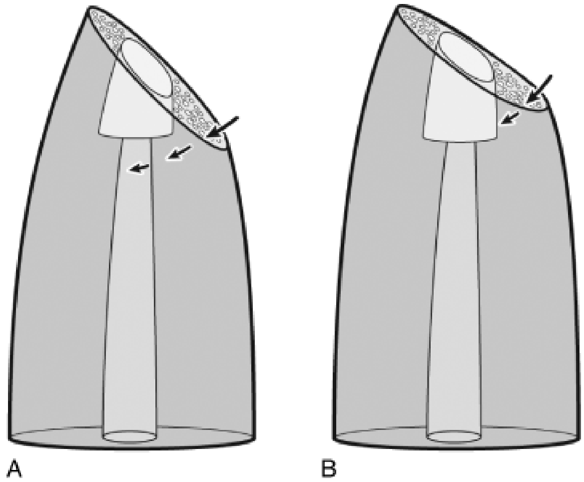

Fig. 17. Leakage through dentinal tubules originating at beveled root surface. (A) Reverse filling does not extend coronally to height of bevel. Arrows indicate potential pathway for fluid penetration. (B) Reverse filling extends coronally to height of bevel and blocks fluid penetration (arrows) into the root canal space. From Vertucci FJ and Beatty RG. Apical leakage associated with retrofilling technique: a dye study. J Endod 1986: 12(8): 335.

Neither system over-prepared canals or compromised the integrity of the root by excessive removal of the canal wall. However, the authors found that the apical preparations showed the least amount of preparation. Many apical and coronal preparations were seen where only a portion of the canal wall was instrumented. Further apical canal enlargement seems necessary inorder to incorporate the original canal into the final preparation. Peters et al. (145–146) came to similar conclusions in studying the effect of five nickel–titanium rotary instrumentation systems on canal debridement. They found that all techniques left 35% or more of the canal surface area unchanged. All of these results are fairly predictable considering the highly variable and unfriendly environment that the root canal system provides and the current state of endodontic intracanal instruments which are unable to contact all of the recesses present along canal walls. They do a good job in shaping the canal but a poor job in accomplishing total canal debridement.

When attempting to find better ways to clean and sterilize root canals, Card et al. (147) determined that enlarging canals above the traditional recommended apical sizes was the only way to effectively remove culturable bacteria from the canal. The larger apical sizes optimized irrigation and disinfection and facilitated the mechanical elimination of microbes. Usman

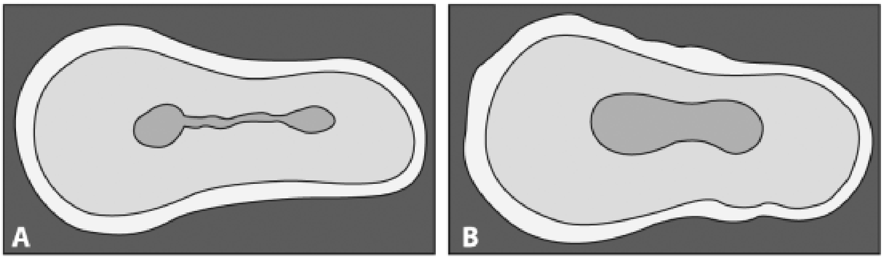

Fig. 18. (A) Complete isthmus on beveled root surface between two canals. (B) Isthmus has become part of the retropreparation which should have a uniform depth of 3 mm.

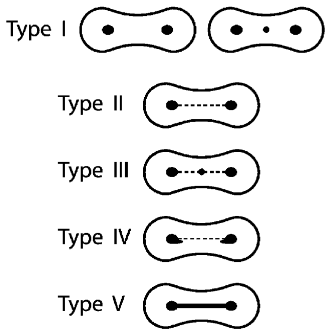

Fig. 19. Types of canal isthmi.

et al. (148) similarly concluded that an increase in size of canal instrumentation at working length produced an increase in canal cleanliness. However, irrigant volume, number of instrument changes and depth of penetration of irrigant needles had a much less effect on canal debridement. The price of increasing apical canal diameter may be procedural errors and/or root fractures. As a supplement to these techniques, acoustic microstreaming by sonic and ultrasonic irrigation appears to have a positive effect on the cleanliness of oval canals as demonstrated by Lumley et al. (149) and Jurecko et al. (150) (Fig. 16). However, further research needs to be conducted to determine the best treatment procedures for a highly variable root canal system.

Peters et al. (151) recently demonstrated a detailed three-dimensional model of the pulp cavity obtained by means of high-resolution computed tomography. This method holds great promise for further increasing our knowledge of root canal anatomy. Studying maxillary molars, these authors determined the volume, area and dimensions of the root canal systems. The mean canal diameters in the apical 0.5 mm were 188 ± 5, 174 ± 12 and $318 \pm 23\,\mu m$ for the mesiobuccal (MB-1), distobuccal and palatal canals. Such information goes a long way toward helping us establish final instrumentation sizes for cleaning and shaping procedures.

Taken together, the *in vivo* studies and case reports discussed above underline the importance of a thorough knowledge of dental anatomy for non-surgical root canal treatment. However, the natural anatomy is altered during surgical procedures and additional anatomic features need to be addressed. As a result of their studies on apical anatomy, Morfis et al. (105) concluded that beveling the root apex 2–3 mm during surgical procedures removes the vast majority of unprepared and unfilled accessory canals and thereby eliminates the possibility of failure. This finding agrees with the results of Kim et al. (152) who determined that the amount of apical root resection depends upon the incidence of accessory and apical ramifications at the root end. Using a bevel perpendicular to the long axis of a root, they found that the removal of 1 mm of apex eliminated 52% of apical ramifications and 40 % of accessory canals. Removal of 2 mm of apex eliminated 78% of apical ramifications and 86% of the accessory canals. Removal of 3 mm eliminated 98% of apical ramifications and 93% of accessory canals. Consequently apical resections of 3 mm are most effective for eliminating the majority of these structures.

During apical root resection, a bevel perpendicular to the long axis of a root exposes a small number of microtubules (107–108). However, a 45° bevel exposes a significantly greater number. Vertucci and Beatty (153) theorized that beveling the root apex at such an angle increases the number of dentinal tubules and the chance of leakage into and out of the root canal. To prevent this from occurring, they recommended that retropreparations extend coronally to the height of the bevel (Fig. 17). Tidmarsh and Arrowsmith (154) corroborated their theory by examining the root ends of developed roots with a scanning electron microscope.

The root apex houses a variety of anatomic structures and tissue remnants. If surgery becomes necessary, an apical root resection can alter canal anatomy. Intercanal connections can become exposed and a single foramen may become multiple foramina. Results will be poor if this altered anatomy is not recognized and treated.

Wada et al. (155) evaluated the root apex of teeth with refractory apical periodontitis that did not respond to root canal therapy. They removed the root end and found that 70% contained significant apical ramifications. This frequency is highly suggestive of a close relationship between the anatomical complexity of the root canal system, persisting intracanal bacteria and the failure of periradicular pathology to heal (156–158).

Cambruzzi and Marshall (159) called an intercanal connection or transverse anastomosis an 'isthmus' and stressed the importance of preparing and filling it during surgery. An isthmus is a narrow, ribbon-shaped communication between two root canals that contains pulp or pulpally derived tissue. It can also function as a bacterial reservoir. Any root that contains two or more root canals has the potential to contain an isthmus (Fig. 18). Thus whenever multiple canals are present on a resected root surface an isthmus must be suspected. Cambruzzi and Marshall also advocate the *in vivo* use of methylene blue dye as an aid in visualizing the outline of the resected root surface and the presence of an isthmus.

Weller et al. (160) found that the highest incidence of isthmi in the mesiobuccal root of maxillary first molars occurred 3–5 mm from the root apex. The 4 mm level contained a complete or partial isthmus 100% of this time. The presence of a partial isthmus was reported by Teixeira et al. (161) who found that they occurred more frequently than a complete isthmus.

Identification and treatment of isthmi is vitally important for the success of surgical procedures. Hsu and Kim (162) identified five types of isthmi which can occur on a beveled root surface (Fig. 19).

Type I	Two or three canals with no communications.
Type II	Two canals with a definite connection between them.
Type III	Three canals with a definite connection between them
Type IV	Canals extend into the isthmus area.
Type V	Is a true connection or corridor throughout the section.

Isthmi are found in 15% of anterior teeth, 16% of maxillary premolar teeth at the 1 mm resection level and 52% at the 6 mm resection level. They occur 30% of the time at the 2 mm level in mandibular premolars and 45% at the 3 mm level and 50% at the 4 mm level in the mesiobuccal root of the maxillary first molar. The mesial root of the mandibular first molars contain isthmi 80% of the time at the 3–4 mm resection level while 15% of distal roots have isthmi at the 3 mm level. Microsurgical endodontic techniques have allowed the dentist to visualize the resected root surface and identify the isthmus, prepare it with ultrasonic tips and fill the preparation with acceptable filling materials. The recognition and microendodontic treatment of the canal isthmus is a factor that has significantly reduced the failure rate of endodontic surgery (163–164).

In conclusion, outcomes of non-surgical and surgical endodontic procedures are influenced by highly variable anatomic structures. Therefore clinicians ought to be aware of complex root canal structures, of cross-sectional dimensions and of iatrogenic alterations of canal anatomy.

Careful interpretation of angled radiographs, proper access preparation and a detailed exploration of the interior of the tooth, ideally under magnification, are essential prerequisites for a successful treatment outcome.

Acknowledgments

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