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In-depth morphological study of mesiobuccal root canal systems in maxillary first molars: review

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A common failure in endodontic treatment of the permanent maxillary first molars is likely to be caused by an inability to locate, clean, and obturate the second mesiobuccal (MB) canals. Because of the importance of knowledge on these additional canals, there have been numerous studies which investigated the maxillary first molar MB root canal morphology using *in vivo* and laboratory methods. In this article, the protocols, advantages and disadvantages of various methodologies for in-depth study of maxillary first molar MB root canal morphology were discussed. Furthermore, newly identified configuration types for the establishment of new classification system were suggested based on two image reformatting techniques of micro-computed tomography, which can be useful as a further 'Gold Standard' method for in-depth morphological study of complex root canal systems. (*Restor Dent Endod* 2013;38(1):2-10)

Key words: Clearing technique; Mesiobuccal root; Micro-computed tomography; Minimum-intensity projection; Three-dimensional volume rendering

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Introduction

Understanding of the complex root canal anatomy is essential for the success of endodontic treatment.[1-3] Many studies demonstrated that mesiobuccal (MB) root canal system is not simple, but include very fine and complex structures, such as accessory canals, inter-canal communications, apical fins, deltas, and ramifications.[4-6] Because of the importance of knowledge on these micro-structures, there have been numerous studies which investigated the maxillary molar MB root canal morphology by *in vivo* and laboratory methods.[7-11] These studies reported that the incidence of second MB canals were 62%, 68.5%, 80.8%, and 90% in maxillary first molars.[7,8,10,11]

Traditionally, clearing technique has been used for study of root canal morphology.[12,13] This method uses various acids to make tooth transparent, and dying solution to make the root canal systems visible. As a result, the whole root canal system could be observed and investigated through the transparent tooth structure. Another method of root canal morphology study was the tooth sectioning method.[14] In this method, the teeth are sectioned into slices and re-assembled to be investigated tomographically. Recent advances in imaging technology enabled the use of cone-beam computed tomography (CBCT) in endodontic practice and studies.[15,16] CBCT could visualize the internal anatomy of dental hard tissues and requires lower radiation compared to conventional CT.[15] However, CBCT has limitations in resolution to reproduce detailed root canal morphology. In this reason, micro-computed tomography (MCT) was introduced in the study of root canal morphology. The current development of MCT

technology reproduces voxel resolution up to 1 µm though around 10 - 30 µm resolution of MCT devices were used in root canal studies.[17] The images obtained by MCT could be analyzed with various methods, including two-dimensional thin-slab minimum-intensity projection (TS-MinIP) technique and three-dimensional (3D) rendering techniques.[18] The objective of this study was to discuss the protocols, advantages, and disadvantages of methodologies used for root canal morphology study and to suggest the 'Gold Standard' method for in-depth root canal morphology study.

Search methodology

The PubMed search was used to file up the articles with the search keyword of 'mesiobuccal morphology, morphology study methods, and maxillary first molars' The articles written in language other than English were excluded. Some hand searched articles were included if necessary.

Methods for root canal morphology study

Clearing technique

Clearing technique is a traditional method which was used for more than 50 years.[19] This technique uses various acids to make teeth transparent. At first, access cavities were prepared on the sample tooth which serves as a venue for dye infiltration into the root canal system. And then, the root canal is negotiated to the apex with a #10 K-file to confirm the apical foramen. In a study of MB root canal system of maxillary first molars, it is better to resect the distobuccal roots and palatal roots for convenience of observation. Thereafter, pulp tissues and organic debris are dissolved from root canal by immersing the teeth in 5% sodium hypochlorite for 12 hours at room temperature. And then, teeth are washed by running tap water. After this procedure, the teeth are decalcified for five days in 5% nitric acid at room temperature. The nitric acid solution should be changed every two days and agitated at least two times a day. After the acid treatment, teeth are placed in running tap water for washing. These, decalcified teeth are placed in acetic acid for 24 hours for enhanced dentin matrix. Finally, the specimens are sequentially dehydrated in ascending concentrations of ethyl alcohol (70%, 90%, and 100%, for 12 hours, 6 hours, and 6 hours, respectively). Decalcified and dehydrated teeth are placed in a methyl salicylate solution for 24 hours. Through this whole procedures, tooth become transparent and the internal root canal morphology could be observed outside the tooth. After the completion of tooth clearing treatment, the root canals inside the tooth should be visualized with use of dying solution (Figure 1).
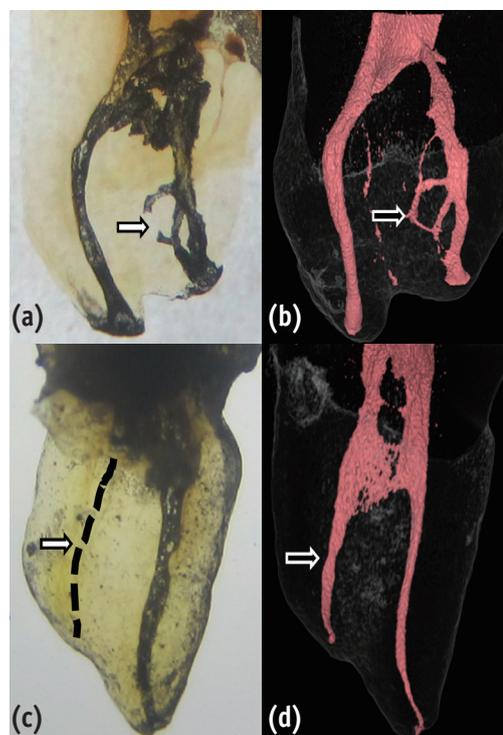

Figure 1. Representative images by (a, c) clearing technique; (b, d) Three-dimensional (3D) volume rendering technique of micro-computed tomography (MCT) showed restricted penetration of dye solution into a root canal system (a, c, white arrows with black outline).

Although this technique allows detailed investigation of the delicate root canal systems, it has several disadvantages. First, tooth morphology is apt to be distorted in the clearing process, because the tooth structures are weakened during demineralization process. The weakened tooth could be bent during the handling process of the specimen. Although, the amount of distortion is slight, small structures like accessory canals or isthmuses could be affected by slight distortion. This morphological distortion could result in closure or narrowing of accessory canals. The second problem with this technique is that dying solution tends not to fully infiltrate into the small accessory canals (Figure 1a, white arrow with black outline). When the root canals were severely narrowed in coronal portion, they could not be visualized in clearing technique because of the limited dye penetration. To solve this problem, Yoshioka et al. removed coronal dentine by troughing.[20] This problem also could be evaded in modified clearing technique.[21] The third problem with this technique is that root canal blockage resulting from narrowing and calcification below the grain size of dye solution could hinder the infiltration of the dye solution (Figure 1c, white arrow with black outline).

Endodontic cube technique

The Endodontic Cube usually consisted of brass components with hexed screws which enables the disassembly and reassembly of the cubes.[22] In this method, the tooth specimen is placed to appropriate position in the Endodontic Cube and acrylic resin is poured into the Endodontic Cube. The Endodontic Cube is then placed in a pressure container where the acrylic resin is cured. Thereafter, using the horizontal grooves on surfaces as a guide, the resin block is sectioned using slow speed saw into 1 mm slice. After this sectioning procedure, the specimens are observed under illumination with a surgical microscope and photographed with a digital camera with high resolution. With this method, the topographical cross-sectional images of root and root canal morphology could be obtained. Although, this technique enables tomographic analysis of root canal morphology without costly equipment such as MCT, this technique has some disadvantages, too. The main disadvantage of this technique is that the tooth structure loss is inevitable. In this reason, the images obtained with this technique are not continuous but interrupted images. Furthermore, some small accessory canals could be removed in the tooth slicing process.

Cone-beam computed tomography

CBCT scanners are accurate for the evaluation of root canals and their morphology.[23-26] The ability to reduce or eliminate the superimposition of surrounding structures and 3D reconstruction imaging make CBCT superior to conventional periapical radiography.[27] Compared with conventional medical CT, limited-volume CBCT has many advantages, such as its high-resolution imaging, minimal dose of radiation and rapid scan time.[23,28] Limited-volume CBCT can provide noninvasive 3D images or simultaneously axial, coronal and sagittal two dimensional (2D) sections of target objects (Figure 2) that can be applied in endodontic diagnosis morphologic analysis, endodontic epidemiologic investigation and clinical outcome study.[16,23,25,26,28-31]
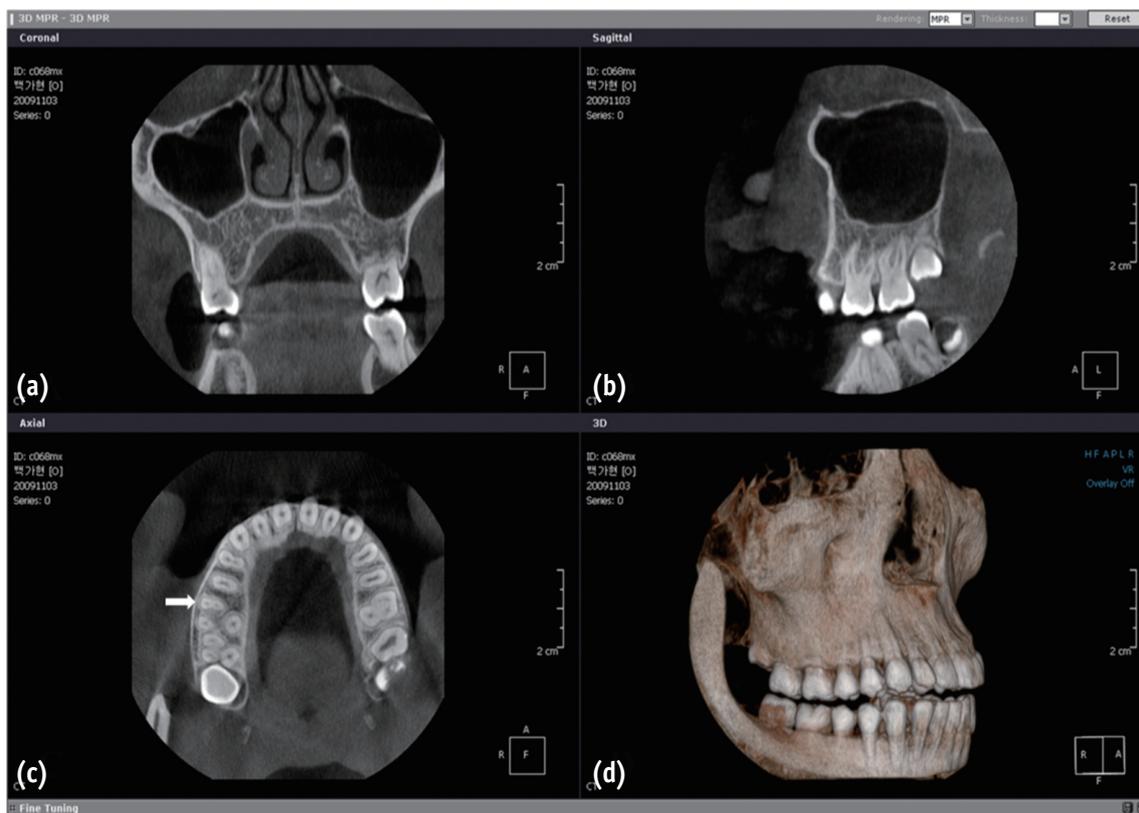

Figure 2. Original cone-beam computed tomography (CBCT) images of a maxillary first molar with two canals in the mesiobuccal (MB) root as viewed coronal, sagittal, axial direction by using OnDemand3D software. (a) Coronal view with the MB root exhibiting Type III canal configuration; (b) Sagittal view; (c) Axial view (arrow indicates the existence of two canals in MB root); (d) Three-dimensional (3D) reconstruction image.

Because there is a strong correlation between the data acquired by CBCT and histology, CBCT is a precise, nondestructive technique for endodontic research that allows the canal system to be explored both qualitatively and quantitatively.[24] However, because of its relatively low resolution to reproduce canal structures, there may be limitation in detailed reproduction of fine root canal morphology images. Furthermore, CBCT uses ionizing radiation and is not without risk. Therefore, patients' exposure to radiation should be kept as low as reasonably achievable (ALARA), and evidence-based selection criteria for CBCT should be developed.[32,33]

Micro computed tomography with thin slab-minimum intensity projection (TS-MinIP)

MCT is a result of recent innovations in dental imaging. MCT has voxel resolution of 50 to 1 μm. In this reason, it is possible to reproduce very fine and complex structures with MCT. With these advantages, MCT has been used widely in dental field. It was proved that the MCT is a very suitable and effective tool to study and visualize the complex root canal morphologies by various previous studies.[1,2,9,10,18]

A curved TS-MinIP technique is widely used in medical diagnosis and research.[34,35] The TS-MinIP technique has been used for investigation of biliary system and emphysema in medical field, but seldom used in dental field. This is a relatively simple, straightforward method without any chance of artificial manipulation, and the curved TS-MinIP technique easily detects low attenuated structures with very small lumen like accessory canals, fins, deltas and apical ramifications, which were difficult to illustrate with conventional multiplanar reconstruction.[36,37] Curved TS-MinIP images of the roots can be constructed with the use of dental image processing software (e.g., OnDemand3D, Cybermed, Seoul, Korea) with the following procedure. At first, the volume image of the tooth is positioned with the root apex upward. Subsequently, it is rotated so that the MB1 and MB2 canals overlapped as much as possible in the sagittal view. The canal axis is set according to the curvature of the MB canal. In the sagittal view, the thickness of the slab through which the virtual ray to be transmitted is determined to include the width of the canal. The slab thickness is dependent on the size of the canals and usually range from 0.5 to 1.0 mm. Using the software, a virtual ray is transmitted orthogonal to the curved slab (from mesial to distal direction), and the smallest pixel value is recorded to obtain the TS-MinIP image. The representative image obtained with TS-MinIP technique was illustrated below as Figure 3.

The greatest advantage of TS-MinIP technique is that air or low-attenuation structure is emphasized in contrast to surrounding high-attenuation structure. Even when anatomic structures are tortuous or twisted, in the TS-MinIP images, the lumen is seen as patent and continuous. However, depending on the direction of beam projection, overlapping minute canals may be missed and the 3D direction of the exit or the location of the apical foramen, accessory and lateral canals may be difficult to be observed compared with 3D image (Figure 3c). In addition, if the slab extends beyond the extent of the root due to root concavity or severe curvature, the pixel value outside the root is recognized as the minimum value and thus can result in a pseudo canal image (Figure 4).[38] Therefore, thin slabs of the target area should be appropriately set using information from axial, coronal, and sagittal images, minimizing any chance of false positive canal, such as pseudo-lumen.
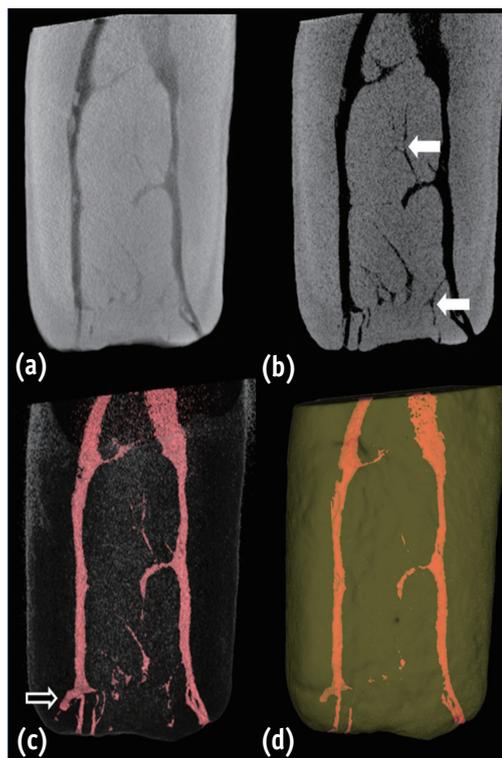

Figure 3. Canal images with different reformatting methods. (a) Simulation of conventional ray projection image; (b) Curved thin slab-minimum intensity projection (TS-MinIP) image; (c) Volume rendered image with segmentation of canal structure; (d) Surface rendered image. TS-MinIP image shows the most clear view of fine canal structures (b, white arrow), while an accessory canal hiding behind main root canal is shown only in three-dimensional (3D) volume rendered image (c, black arrow with white outline).
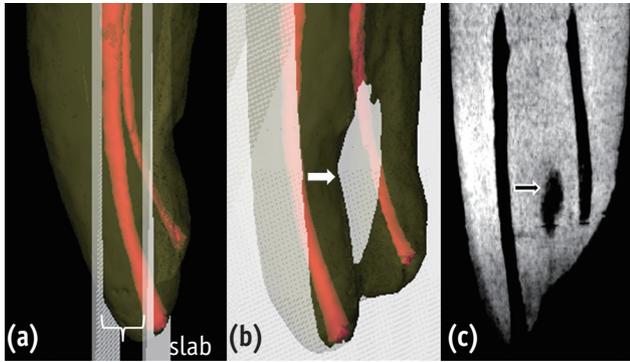
Figure 4. The slab is defined between two planes in (a), and (b) is a rotated image of (a) which shows root surface concavity included in the slab. (c) is a resultant thin slab-minimum intensity projection (TS-MinIP) image with pseudo-canal. If the slab extends beyond the extent of the root due to root concavity or severe curvature (b, white arrow), the pixel value outside the root is recognized as the minimum value and thus can result in a pseudo-canal image (c, black arrow with white outline).

Micro-computed tomography with 3D volume rendering

Three dimensionally rendered model of canal with MCT data shows spatial relationship among canal structures. In general, there are two types for 3D rendering technique according to reformatting method: volume rendering and surface rendering. Volume rendering projects 3D voxels directly onto a 2D image plane with consideration of opacity.[39] In contrast, surface rendering only has to traverse the 3D volume data once, in a preprocessing step, to extract surface model then display 2D image of the surface model.[40,41] The quality of surface model is highly dependent on a segmentation process which is difficult and highly sensitive to noise.

For volume rendering of canal structure, MCT data is just loaded into volume visualization software such as Ondemand3D or V-works (CyberMed), and then opacity is changed to observe the canals. Pre-processing like volume segmentation enhances visualization of the fine root canal structures. With segmented volumes, canal structure could be represented by an opaque red color and the external morphology of the root could be rendered transparent. For surface rendering of canal structure, the root and canal areas were first segmented from each MCT slice image using thresholding and in part manually. Then, stacking the segmented slices with image processing software such as V-works produce surface model of canal. The advantage of 3D volume rendering over TS-MinIP is that this method could visualize the small accessory canals and minute root canal structures without missing.

Furthermore, 3D volume rendering technique could give information on the 3D direction of small accessory canals and portal of exit. However, low attenuation structures could be less distinctively observed in 3D rendering technique than in TS-MinIP technique. Another advantage of this method is that we can calculate the surface area and total volume of root canal systems using this 3D volume rendering methods.

Root canal configuration classification systems

Weine's classification
Weine's classification system has long history of use and classified the root canals into four types.[14] Type I is one continuous root canal with one orifice and one exit. Type II is a canal with two orifices which combines into one before reaching the portal of exit. Type III refers to two distinct canals which has two distinct orifices and two distinct portal of exit. Type IV refers to canal which has one orifice and diverges into two canals which has separate portal of exit.

- Weine type I: One single canal with one orifice and portal of exit
- Weine type II: Two separate canals leave the pulp chamber and join short of the apex to form one canal.
- Weine type III: Two separate and distinct canals extend from the pulp chamber to the apex.
- Weine type IV: One canal leaves the pulp chamber and divides short of the apex into two separate and distinct canals with separate apical foramina.

Vertucci's classification
Vertucci's classification encompasses originally 8 types of canal configurations as described below.[42]
- Vercucci type I: One single canal with one orifice and portal of exit
- Vertucci type II: Two separate canals leave the pulp chamber and join short of the apex to form one canal.
- Vertucci type III: One canal leaves the pulp chamber, divides into two within the root, and then merges to exit as one canal.
- Vertucci type IV: Two separate and distinct canals extend from the pulp chamber to the apex.
- Vertucci type V: One canal leaves the pulp chamber and divides short of the apex into two separate and distinct canals with separate apical foramina.
- Vertucci type VI: Two separate canals leave the pulp chamber, merge in the body of the root, and redivide short of the apex and exit as two distinct canals.
- Vertucci type VII: One canal leaves the pulp chamber, divides and then rejoins within the body of the root, and finally redivides into two distinct canals short of the apex.

• Vertucci type VIII: Three separate and distinct canals extend from the pulp chamber to the apex.

However, its modification by Ng *et al.* suggested 7 additional types of root canals.[43]

The unclassifiable canal configuration types identified in previous studies

Although Weine's classification and modified Vertucci's classification suggested by Ng *et al.* encompasses wide variety of canal configurations, there are still canals that could not be classified with these classifications.[14,43] Gu *et al.* investigated the root canal morphology of 101 Korean maxillary first molars using both TS-MinIP technique and 3D rendering technique of micro CT.[18] They reported that 39 roots (38.6%) could not be classified according to Weine's classification and 11 roots (10.9%) were still non-classifiable with Modified Vertucci's classification.[14] Figure 5 shows the six non-classifible root canal configurations.[1]

Another previous study of Kim *et al.* showed the existence of non-classifiable MB root canal configurations in which

3D rendering of micro CT-obtained images was used.[1] In this study, they found 12 non-classifiable configuration types that were not included in the modified Vertucci's classification. Moreover, among these, three configurations (types 1–3, 2–3–2–3–2, and 2–3–4–3–2) have never been reported for maxillary first molar MB roots (Figure 6). These suggest that any of current MB canal configuration classification and its modified version cannot fully reflect the anatomical complexity of the maxillary first molar MB roots. Furthermore, the root canals with non-classifiable configurations branched, divided, and rejoined again in mid-root, or vice versa.

Clinical relevance

The series of studies which reported the maxillary first molar MB root canal configurations of Korean populations showed two interesting and clinically important findings.[1,11,18,25,44] One is that they showed the ethnic differences in the root canal morphology of MB root canals in maxillary first molars. Previous studies carried out for Caucasian population reported that the most prevalent root canal configuration in maxillary first molar MB roots is Weine's type II (Vertucci's type II).[42,45] On the contrary, the most prevalent root canal configuration in maxillary first molar MB roots in Korean population was Weine's type III (Vertucci's type IV). Considering these results, it could be stated that more effort to find the hidden second MB canals should be taken for the treatment of Korean patients, because Weine's type III canal has two separate portals of exits, which could allow micoleakage more readily. The other important finding of these studies is that

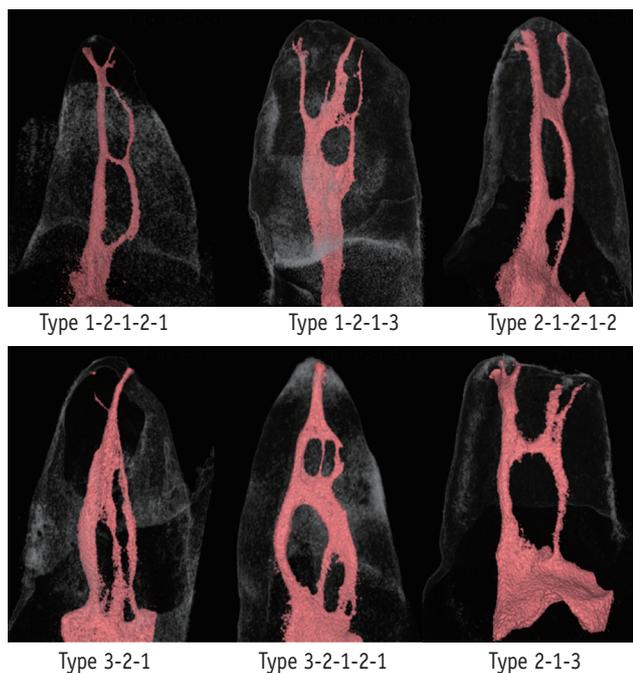| Type 1-2-1-2-1 | Type 1-2-1-3 | Type 2-1-2-1-2 |
| Type 3-2-1 | Type 3-2-1-2-1 | Type 2-1-3 |

Figure 5. Representative images obtained by three-dimensional rendering which shows six non-classifiable configuration types when the modified Vertucci's classification is applied (Reprinted with the permission of the Clin Oral Investig. Originally published as: Clin Oral Investig 2012, 10.1007/s00784-012-0725-1.).

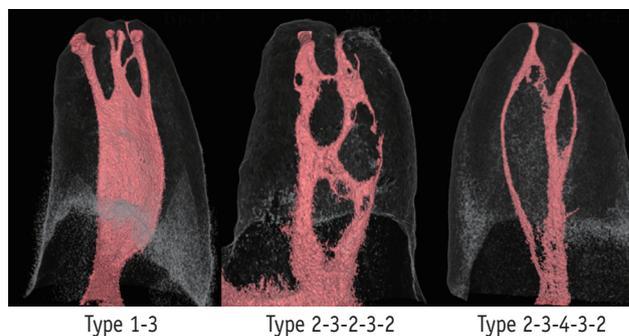| Type 1-3 | Type 2-3-2-3-2 | Type 2-3-4-3-2 |

Figure 6. Three-dimensional reconstructed images of 3 non-classifiable configuration types when modified Vertucci's classification was applied. The configuration types were not reported in maxillary first molar MB roots in the literature (Reprinted with the permission of the Clin Oral Investig. Originally published as: Clin Oral Investig 2012, 10.1007/s00784-012-0725-1.).

Table 1. Numbers and frequency of additional root canals in the MB roots of Korean maxillary first molars by age

Age (yr)	10 - 20	20 - 30	30 - 40	40 - 50	50 - 60	> 60
No. of teeth	44/54	129/178	59/69	41/58	42/71	14/28
(%)	(81.5)	(72.5)	(85.5)	(70.7)	(59.2)	(50)

Values indicate number of teeth in which each of the features was identified.
Values within parentheses are percentages (% of total number of teeth examined).
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the incidence of the second MB canals is varying according to age. The study of Lee *et al.* using CBCT, showed that the incidence of second MB canal in the population at the age of 20s is as high as approximately 80% in maxillary first molar, whereas that in population at the age of 60s is as low as 50% (Table 1).[25] This result is consistent with the previous study.[46] This large variation of incidence is due to the calcification and dentin deposition and should be considered in mind in clinical practice.[47]

Gold standard method for in-depth morphology study

Eder *et al.* reported that computed tomography could describe the exact canal configuration, verify information identical to histology, and thus serve as the 'gold standard' *in vitro*.[48] However, their study compared cross-sectional CT images with low resolution with the histologic section images of MB roots and could offer limited information confined to the number and configuration types of main root canals. A previous MCT study, which employed TS-MinIP technique along with 3D modeling analysis, demonstrated and reestablished a more accurate morphology classification of the complex maxillary first molar MB root canal system.[18] Additionally, TS-MinIP can serve as a promising adjunct to 3D modeling analysis. Since 3D rendering could find every detail in complex root canal system and TS-MinIP technique could show more accurately the low attenuation images than 3D volume rendering technique, the combined techniques of both can be a gold standard for in-depth morphological study.

Conclusions

MCT study more clearly showed the fine anatomical structures such as loop, accessory canals, and intercanal communication in the MinIP images than 3D rendering images. This means that MinIP may serve as a valuable adjunct for solving 3D problems for in-depth morphology study. Therefore, TS-MinIP combined with 3D volume rendering analysis can be a gold standard for in-depth morphology study of complex root canal system in experimental endodontology.

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