JOURNAL OF ENDODONTICS

Printed in U.S.A.
VOL. 27, NO. 1, JANUARY 2001

SCIENTIFIC ARTICLES

Changes in Root Canal Geometry after Preparation Assessed by High-Resolution Computed Tomography

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Root canal morphology changes during canal preparation, and these changes may vary depending on the technique used. Such changes have been studied in vitro by measuring cross-sections of canals before and after preparation. This current study used nondestructive high-resolution scanning tomography to assess changes in the canals' paths after preparation. A microcomputed tomography scanner (cubic resolution 34 μm) was used to analyze 18 canals in 6 extracted maxillary molars. Canals were scanned before and after preparation using either K-Files, Lightspeed, or ProFile .04 rotary instruments. A special mounting device enabled precise repositioning and scanning of the specimens after preparation. Differences in surface area (ΔA in mm^2) and volume (ΔV in mm^3) of each canal before and after preparation were calculated using custom-made software. ΔV ranged from 0.64 to 2.86, with a mean of 1.61 ± 0.7, whereas ΔA varied from 0.72 to 9.66, with a mean of 4.16 ± 2.63. Mean ΔV and ΔA for the K-File, ProFile, and Lightspeed groups were 1.28 ± 0.57 and 2.58 ± 1.83; 1.79 ± 0.66 and 4.86 ± 2.53; and 1.81 ± 0.57 and 5.31 ± 2.98, respectively. Canal anatomy and the effects of preparation were further analyzed using the Structure Model Index and the Transportation of Centers of Mass. Under the conditions of this study variations in canal geometry before preparation had more influence on the changes during preparation than the techniques themselves. Consequently studies comparing the effects of root canal instruments on canal anatomy should also consider details of the preoperative canal geometry.

Manual (Balanced-Force) and engine-driven (Lightspeed, ProFile, GT-Files, Quantec) root canal preparation techniques claim to provide safe and efficient preparations. These techniques have been evaluated in several studies using different experimental designs (1–5). One analytical method used a reassembly technique (6), which examined cross-sections of root canals before and after preparation (3, 4). On the other hand simulated canals in plastic blocks may be evaluated using impressions (1) and/or captions of the canals' outlines (2). These studies yielded important results on canal transportation and on the incidence of procedural errors, such as zipping and ledging. The vast majority of the previously described analytical procedures assess the changes in two dimensions only. However root canal anatomy is altered in three dimensions during preparation.

Researchers have previously used computed tomography (CT) to assess three-dimensional changes in root canal geometry (7–9). However authors frequently stated that the resolution of conventional CT was inadequate to detect subtle changes in canal anatomy after preparation (10). In the interim new hardware has been developed and the metrical data, inherent to micro-CT (μCT) (10–12), can accurately measure geometrical changes in prepared canals.

The aim of this study was to construct detailed three-dimensional images of root canal systems before and after canal preparation. In addition high precision measurements were made of the changes in root canal volumes and surface areas before and after preparations. Finally other detailed calculations were made of the instrumented surface areas and three-dimensional displacement of root canals' axes.

MATERIALS AND METHODS

Preparation of Specimens

Six three-rooted maxillary molars were selected from a pool of extracted teeth and stored in 0.1% thymol until used. The outer root surfaces were sealed from the apices to the cementoenamel junctions using a dentin bonding system (Syntac Classic; Vivadent, Schaan, Liechtenstein). The bonding resin was cured for 1 min using an Optilux 500 curing lamp (Demetron Res., Danbury, CT). Access cavities were then prepared and the specimens mounted on SEM carriers (Balzers, Balzers, Liechtenstein) fitted to custom-made molds with an internal diameter of 15 mm, into which the self-curing resin (Stycast, Emerson & Cuming, Oevel, Belgium) was poured. Finally a specially designed attachment was fitted to subsequently ensure precise repositioning of the specimens into the scanning system.

The specimens were divided into three groups of two each. The six canals were assigned for preparation by either stainless-steel K-Files (Dentsply-Maillefer, Ballaigues, Switzerland), Lightspeed (Lightspeed, Inc., San Antonio, TX), or ProFile .04 instruments (Dentsply-Maillefer). In this way two mesiobuccal (mb), two distobuccal (db), and two palatal (p) canals were prepared by each of the three types of endodontic instruments tested. Apical stops for the mb and db canals were prepared to size 40, whereas the apical stops for the palatal canals were shaped to size 45. The second mb canals were not included in this study because they did not always present as separate canals along the entire length of the root.

All canals were first stepped-down using Gates-Glidden burs (Dentsply-Maillefer) #4 through #1 sequentially. Each bur prepared ~1 mm into the canals, which were copiously irrigated throughout the entire preparation using 2.5% NaOCl. Working lengths for each canal were set to be 1 mm short of the main portal of exit. The working lengths were determined during the preparation at an appropriate point for the specific preparation technique used and were verified by digital radiographs (Digora, Soredex, Helsinki, Finland).

Canals assigned to group 1 were prepared with stainless-steel K-Files used in a quarter turn-pull motion. These canals were all stepped-back to a size 80 file and a recapitulation with the master file concluded the preparation. Canals assigned to group 2 were prepared using nickel-titanium Lightspeed instruments used strictly according to the manufacturers' instructions. These canals were all stepped-back to a size 80 or 100 instrument and a recapitulation with the master apical rotary concluded the preparation. Canals assigned to group 3 were prepared in a crown-down fashion using nickel-titanium ProFile .04 instruments from sizes 60 through 15. Apical stops were shaped to a size 40 or 45 and the canals then stepped-back to size 60. Again the preparation was concluded by recapitulating with the master apical rotary. Canals were purposely not probed for patency before the scanning process to avoid changing the canals' apical anatomy.

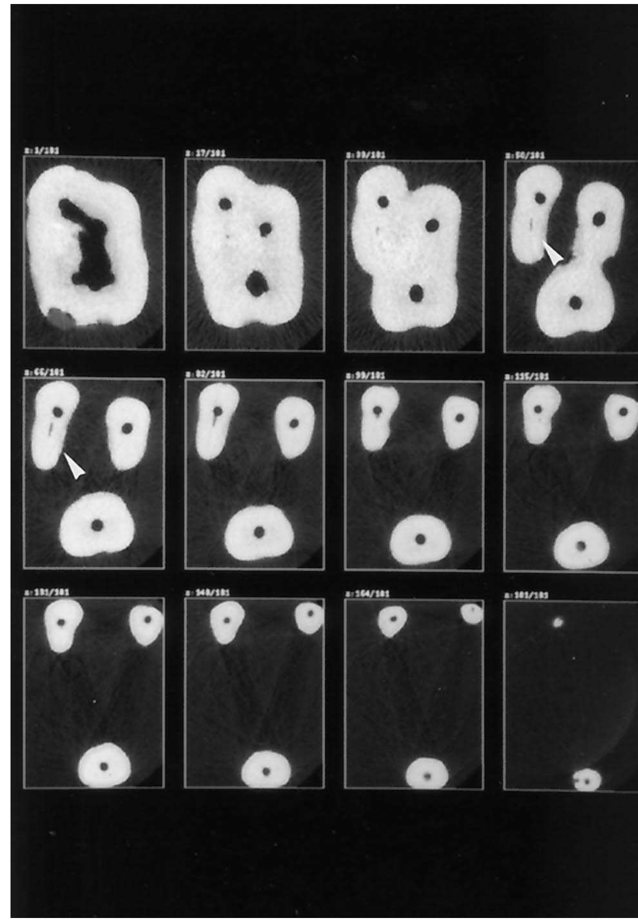

FIG 1. μCT slices, extending from the pulp chamber to the root apices of an extracted maxillary first molar whose p, db, and mb canals were shaped with K-Files, Lightspeed, and ProFile .04 instruments, respectively. Note the unprepared mb 2 canal identified by *arrowheads*.

μCT Measurements and Evaluations

A commercially available μCT system was used (μCT-20; Scanco Medical, Bassersdorf, Switzerland) at 50 kV to scan the specimens before and after preparation. Typically 150 to 300 slices with a voxel size of $34 \times 34 \times 34$ μm or $34 \times 34 \times 68$ μm were scanned, with each scanning procedure requiring 4 to 6.5 h. Initial experiments had shown that 68 μm slices in the axial direction were sufficient for the scanning, because the canals changed gradually in this direction.

The volume of interest selected extended from the furcation to the apex of the roots. The original gray-scale images were then processed with a slight gaussian low-pass filtration for noise reduction and a fixed threshold to separate root dentin from the root canals. These procedures produced binary images of the root canals. The high contrast of dentin to thymol-filled root canals with a linear attenuation ratio of roughly eight yielded excellent segmentation of the specimens (Fig. 1).

Although the special mounting device ensured almost exact repositioning of the samples, the precision was perfected by superimposing two sets of segmented root canals manually over each other. Then by varying the relative translation in all three directions the best superimposition was automatically detected with a precision better than one voxel.

The matched root canals were then evaluated as follows: volumes and surface areas of the root canals were determined from the triangulated data (13) using the "Marching Cubes" algorithm. Increases in volume and surface area were calculated by subtracting the scores for the treated canals from those recorded for the untreated counterparts.

Triangulated data were also used to determine the Structure Model Index (SMI) of the canals (14). This index characterizes the structure of trabecular bone as having a plate-like shape, assigned an SMI score of 0 or a rod-like shape, assigned an SMI of 3. The SMI is determined from infinitesimally minute increases of the surface area, whereas the change in volume is related to the changed surface area (i.e. to the convexity of the structure). When

FIG 2. Three-dimensional views of the p, mb, and db canal system of an extracted maxillary molar before *(A)* and after *(B)* preparation with K-Files, Lightspeed, and ProFile .04 instruments, respectively. Models of the root canal systems were reconstructed from μCT data.

TABLE 1. Mean increases (±SD) in canal volumes, surface areas, and the SMI grouped into db, mb, and p canals

	db (n = 6)	mb (n = 6)	p (n = 6)	Total (n = 18)
ΔVolume (mm^3)	1.74 ± 0.66	2.02 ± 0.57	1.05 ± 0.54	1.61 ± 0.70
	+87.2 ± 58.6%	+84.4 ± 50.4%	+18.6 ± 16.2%	+64.7 ± 54.4%
ΔArea (mm^2)	4.53 ± 3.03	5.53 ± 2.18	2.37 ± 1.71	4.16 ± 2.63
	+27.6 ± 22.7%	+22.2 ± 12.1%	+8.8 ± 7.9%	+20.0 ± 17.2%
ΔSMI	0.34 ± 0.24	0.40 ± 0.18	0.01 ± 0.14	0.26 ± 0.25
	+13.0 ± 10.8%	+15.8 ± 4.4%	+0.8 ± 4.8%	+10.0 ± 9.7%

Absolute scores and relative findings, expressed as percentages of the initial values.

a perfect plate is dilated the surface area does not increase and the SMI is 0. In contrast if a rod is dilated the surface area does increase accordingly, and the SMI is normed so that perfect rods have a score of 3.

The Thickness of a canal was determined using recently described Distance Transformation Techniques (15). In this procedure, the canals or other volumes of interest are inscribed with spheres, which are sized to fit into the maximal diameter. The mean diameters of these spheres is termed "Thickness" of the canal.

Images of the untreated and the instrumented canals were not superimposed when using the μCT technique to assess volume, surface, SMI, and Thickness. These parameters were evaluated separately for the exactly matched volumes of interest. However exact superimposition is required, before and after canal preparation, to obtain reproducible results for "centers of gravity" because the datasets are then compared voxel by voxel in each slice. Each slice was defined by a series of coordinated data for the x-, y- and z-axes. The first two axes were parallel to the slice, whereas the z-axis is at right angles to each slice.

The "centers of gravity" of the canals, calculated for each slice, were connected along the z-axis by a fitted line. Canal transportations were calculated by comparing the centers of gravity before and after treatment for the apical, mid, and coronal thirds of the canals. Canal transportation, in μm, was expressed in relation to the coordinates and also correlated to the canals' greatest curves.

Finally matched images of the surface area voxels of the canals, before and after preparation, were examined to evaluate the amount of uninstrumented surface. It was assumed that surface voxels remaining in the same place, before and after treatment, represented uninstrumented parts of the canal walls. The amount of uninstrumented surface could be calculated by subtracting the number of static surface voxels from the total number of surface voxels. All scores were expressed as means ± SD, but no statistical analysis was done because of the small sample sizes.

RESULTS

Scanning of unprepared and instrumented canals yielded highly detailed cross-sectional images (Fig. 1) that were subsequently three-dimensionally reconstructed. Figure 2 compares two root canals systems before and after canal preparation using these three-dimensional models, and the images detail varying amounts of change in canal geometry in the mb, db, and canals. These changes were quantified using triangulated three-dimensional canal models.

Canal Volume and Surface

When grouped by canal type, the absolute and relative changes in canal volumes and surface areas were higher in mb and db canals, compared with palatal canals (Table 1). Generally mean increases in canal surface area were similar to the mean volume scores, but differences between canal types were considerably smaller (Table 1). For example relative volume scores for db and mb canals were 87.2% and 84.4%, respectively, compared with 18.6% for palatal canals. When grouped according to the preparation technique (Table 2), mean increases in canal volume and surface area were similar for Lightspeed and ProFile .04 instruments (groups 2 and 3), but were lower for canals prepared using

TABLE 2. Mean increases (±SD) in canal volumes, surface areas, and the SMI after preparation using Lightspeed, K-Files, and ProFile .04 instruments

	Lightspeed ($n = 6$)	K-File ($n = 6$)	ProFile .04 ($n = 6$)
ΔVolume (mm^3)	1.81 ± 0.83	1.28 ± 0.57	1.79 ± 0.66
	+86.9 ± 71.1%	+31.4 ± 16.4%	+81.2 ± 52.9%
ΔArea (mm^2)	5.31 ± 2.98	2.58 ± 1.83	4.86 ± 2.53
	+27.8 ± 22.5%	+9.7 ± 7.9%	+24.1 ± 15.5%
ΔSMI	0.25 ± 0.30	0.25 ± 0.27	0.27 ± 0.23
	+8.8 ± 10.0%	+10.2 ± 10.3%	+11.1 ± 10.3%

Absolute scores and relative findings, expressed as percentages of the initial values.

K-Files (group 1). Under these conditions relative volume scores for Lightspeed and ProFile .04 were 86.9% and 81.2%, respectively, compared with 31.4% for K-Files.

SMI

The ability of a preparation technique to produce more rounded canals was assessed using the SMI. With this method of evaluation, the roundness of palatal canals did not change. In contrast SMI scores for db and mb canals increased by 13.0% and 15.8%, respectively, indicating more rounded canals (Table 1). Using the SMI evaluating method no differences were detected between the three preparation techniques investigated (Table 2).

Uninstrumented Root Canal Surface

The number of static voxels recorded by superimposing matched images of the unprepared and instrumented canal walls is listed in Table 3. In Fig. 3 superimposed canal segments in cross-section detail uninstrumented portions of the canal outlines. The highest score for uninstrumented voxels was recorded in group 1 in which the canals were shaped with K-Files (53.5%), compared with groups 2 and 3 whose corresponding scores were 38.8% and 42.8%, respectively. The highest score for static voxels was recorded in palatal canals compared with db and mb canals (Table 3).

Canal Transportation

Superimposing datasets before and after canal preparation yielded indicators for three-dimensional canal transportation by connecting the respective centers of gravity (Fig. 4). The resulting profiles showed that convexities on the canal walls were reduced in addition to straightening of the canals (Fig. 4). Mean absolute scores indicated that canal transportation was highest apically (Fig. 5) and in group 3 in which the canals were shaped using ProFile .04 instruments (Table 4). The mean scores varied from 50 μm to 1.8 μm. Transportation occurred outward in relation to the greater curvature in the apical third, regardless of the instrumenting technique used (Fig. 5 and Table 4).

DISCUSSION

Each of the recently marketed nickel-titanium preparation techniques may afford a better canal preparation than the previous methods. Consequently analytical methods are required to confirm or reject this fact by exactly comparing canal geometry in three dimensions, before and after preparation (6). To date the degree of changes in canal shape and the incidence of procedural errors caused by different instruments have been analyzed by a variety of experimental methods (1, 3–5). The current paper describes a comprehensive method to analyze changes in canal geometry in three dimensions using μCT. Generally μCT has recently evolved as a promising tool in experimental endodontology (7, 16), particularly because the resolution has increased from 1 mm slices (8) to 34 μm in the present study.

Furthermore previous authors reported difficulties in metrical assessment because of the projection errors they encountered (9). However a recent paper reported a high correlation between canal outlines obtained by μCT and videomicroscope tracings (16). The stacked-fan beam technology used in the current study yields images without significant projection errors (11).

Unfortunately previous attempts in metrically correct three-dimensional description of canal geometry failed because of technical problems and the lack of appropriate algorithms (8). Recently relationships between internal and external canal shapes were described using fractal geometry as a two-dimensional parameter applied to canal cross-sections (7).

The current paper describes root canals in terms of volume and surface area based on triangulation of reconstructed canal models using the “Marching cubes algorithm” (13). Using this method the current findings indicate changes in root canal geometry after preparation are more dependent on the type of canal than on the technique or instruments used to shape the canals. For example palatal canals whose apical stops were shaped to a size 45 produced smaller changes in volume and surface area than the mb and db canals shaped to size 40. It was difficult to compare the absolute scores for volume and surface area with those recorded by Nielsen et al. (9), because they did not state the exact outline of the volume of interest. In addition, they found greater changes in canal volume (238 to 1211%) and surface area (94 to 216%) using measuring algorithms (17) different from those used in the current study. Other authors (8) using a similar approach with conventional medical CT yielded canal volume scores varying from 5 to 9.25 mm^3. These findings were in agreement with the current results, but more dentin was removed in that study (8).

Canal roundness was assessed using the recently defined SMI, which is used to quantify cancellous bone morphology (14). As anticipated the current μCT analysis showed that the mean roundness along the palatal canal was virtually unaltered. In contrast, mb and db canals were rounded and thus well shaped after canal preparation, whereas the palatal canals appeared poorly shaped. This possible lack of canal preparation in the palatal canals occurred irrespective of the preparation technique used. Earlier fractal dimension analyses indicated that db roots were more rounded than their mb counterparts (7). In contrast the SMI in the present study addressed the structure of root canals rather than comparing roots and root canals as fractal dimension analyses.

Based on the three-dimensional models, the amounts of static voxels varied from 36 to 57%, before and after instrumentation. However this finding should be carefully interpreted because if the amount of dentin removed were $<$34 μm, it would not be registered. Both voxel size and the exactness of the repositioning of the images, before and after treatment, influenced the precision of this finding. Consequently only removing $>$34 μm of dentin would be reflected by the lack of superimposition as detailed by the darker lines in Fig. 4. However microorganisms may penetrate up to 150 μm into dentinal tubules (18); therefore it may not be adequate to

TABLE 3. Nos. and percentages of static voxels recorded by superimposing matched images, before and after instrumentation, of db, mb, and p canals

	db (n = 6)	mb (n = 6)	p (n = 6)	Total (n = 18)
Voxels ($\times 10^3$)	3.40 ± 2.41	6.15 ± 2.86	7.01 ± 2.90	5.41 ± 3.24
Voxels (%)	36 ± 23%	45 ± 16%	57 ± 22%	46 ± 21%

Relative findings are expressed as percentages calculated in relation to surface areas after canal preparation.

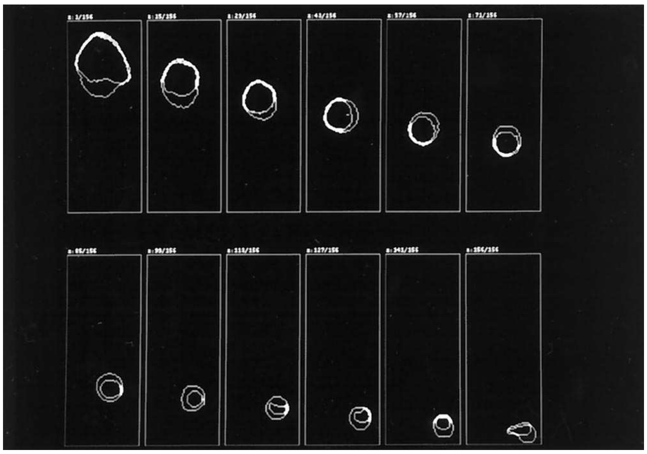

FIG 3. Superimposed μCT slices of a mb canal of the extracted maxillary first molar shown in Fig. 1, before and after canal preparation using ProFile .04 instruments, in which static voxels are highlighted by bright gray levels.

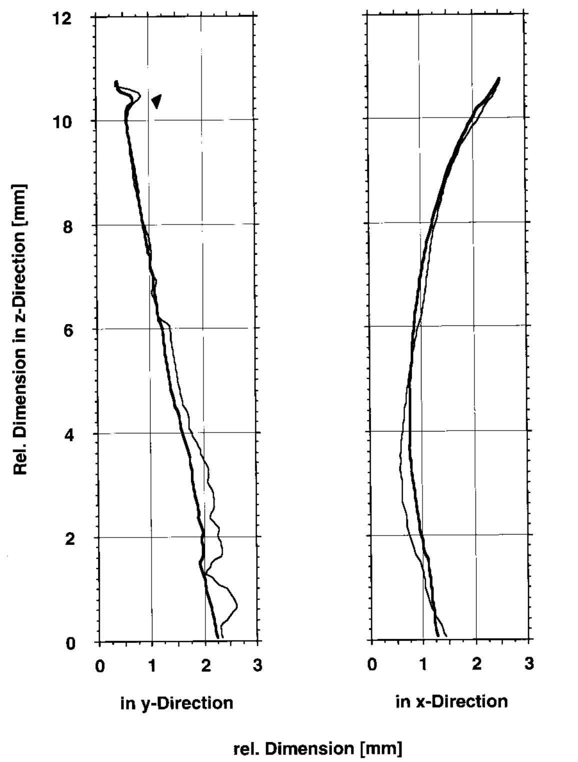

FIG 4. Diagram detailing displacement of the canal centers of a mb root canal, reconstructed from μCT data, relative to the x- and y-axes. The canal had been prepared with ProFile .04 instruments. Note that access to the canal is partially hindered by overhanging dentin *(arrowhead)*.

remove only 34 μm of dentin chemomechanically from the canal walls.

Canal transportation is a procedural error common to all preparation techniques and the current three-dimensional evaluation yielded absolute scores that were similar to results of previous CT (8, 9) or reconstruction techniques (4). However the terminology "canal transportation" and "ability to stay centered" used in some publications is confusing. In the current paper "canal transportation" refers to movement of centers of gravity, in absolute numbers, and also in relation to the canal's main curvature. Apically canals were transported not only outward from the canal centers, but also in other directions as well. This is in agreement with other recent findings investigating ProFile Series 29 and Quantec 2000 instruments (19).

Although the potential for μCT in experimental endodontology is repeatedly graded as being excellent (10, 16, 20), the reconstruction and measurement of each slice is time-consuming. For example scanning and reconstructing an upper molar require at least 3 h of operator time using the most modern systems available. This accounts for the low number of specimens evaluated in the current study. However a recent improvement in scanner technology now enables a single 10-min sweep when scanning a block 6 mm long and with a 17 mm diameter (Rüegsegger, personal communication). Such improvements will without doubt further increase the use of μCT as a nondestructive method to evaluate root canal geometry.

Under the conditions of this study, variations in canal geometry before preparation had more influence on the changes during

TABLE 4. Mean canal transportation (μm, ±SD) and range determined for the coronal, middle, and apical thirds after preparation using Lightspeed, K-Files, and ProFile .04 instruments

	Lightspeed (n = 6)	ProFile (n = 6)	K-File (n = 6)	Total (n = 18)
Coronal third	16.2 ± 63.4	6.8 ± 59.3	−14.7 ± 37.0	1.8 ± 52.3
	−41–134	−75–94	−89–31.1	−89–134
Middle third	−4.1 ± 52.3	15.9 ± 48.3	5.6 ± 25.7	5.8 ± 41.2
	−74–71	−21–87	−13–45	−74–87
Apical third	−28.6 ± 28.6	−50.0 ± 82.9	−10.3 ± 32.0	−28.6 ± 57.7
	−112–48	−154–70	−58.8–33	−154–70

Positive and negative values indicate transportation inwards and outwards, respectively, relative to the main curve of the canals.

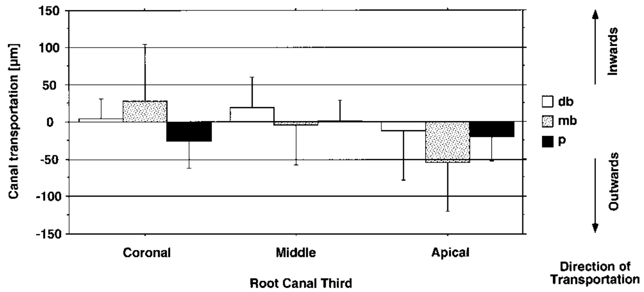

FIG 5. *Bar diagram* showing mean canal center displacements (±SD) for prepared canals grouped into db, mb, and p types. Displacement is grouped as occurring in the coronal, middle, and apical thirds. Positive and negative values represent displacement inwards and outwards, respectively, relative to the mean curvature.

preparation than the techniques themselves. Consequently studies comparing the effects of root canal instruments on canal anatomy should also consider details of the preoperative canal geometry. Data from μCT studies will add to the knowledge of root canal anatomy and may also confirm or refute claims made by the manufacturers of rotary instruments that their product provides the optimally prepared canal.

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