## Title
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# Root-canal preparation with FlexMaster: canal shapes analysed by micro-computed tomography

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### Abstract

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**Aim** To evaluate the relative performance of FlexMaster nickel–titanium instruments shaping maxillary molar root canals *in vitro*.

**Methodology** Extracted human maxillary molars were scanned, before and after root-canal shaping, with FlexMaster, employing micro-computed tomography (μCT) at a resolution of 36 μm. Canals were three-dimensionally reconstructed and evaluated for volume, surface area, 'thickness' (diameter), canal transportation and prepared surface. Based on median canal volume, the canals were divided into 'wide' and 'constricted' groups. Comparisons were made between mesiobuccal (mb), distobuccal (db) and palatal (p), as well as 'wide' and 'constricted' canals, using ANOVA and Scheffé post-hoc tests.

**Results** Volume and surface area increased significantly and similarly in mb, db and p canals, and no gross preparation errors were found. Mean root-canal diameters, 5 mm coronal to the apex, increased from 0.45 to 0.65 mm, from 0.41 to 0.56 mm and from 0.79 to 0.85 mm for mb, db and p canals, respectively. Apical canal transportation ranged from 0.01 to 0.29 mm and was independent of canal type; 'wide' canals had a significantly higher ($P < 0.05$) proportion of unprepared surfaces than 'constricted' canals had.

**Conclusions** FlexMaster instruments shaped curved and narrow root canals in maxillary molars to sizes 40 and 45 without significant shaping errors. Canal anatomy had an insignificant impact on preparation, indicating that FlexMaster instruments were able to shape 'constricted' canals as well as 'wide' ones.

**Keywords:** canal shape, FlexMaster, micro-computed tomography (μCT), transportation.

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## Introduction

Modern engine-driven root-canal preparation techniques employ nickel–titanium instruments and claim to facilitate safe and efficient preparations. In particular, experiments using simulated canals in plastic blocks and extracted human teeth suggest that canal transportation can be minimized using these endodontic instruments (Glosson *et al.* 1995, Bryant *et al.* 1999, Schäfer & Lohmann 2002a). Recently, micro-computed tomography (μCT) was introduced to evaluate three-dimensional shapes of canals at resolutions as high as 34 μm (Peters *et al.* 2000, 2001a, Rhodes *et al.* 2000, Bergmans *et al.* 2001, Gluskin *et al.* 2001). This innovation was achieved because new hardware and software were available to evaluate the metrical data created by μCT, thus allowing geometrical changes in prepared canals to be determined in more detail (Peters *et al.* 2000).

FlexMaster (VDW, Munich, Germany) rotary instruments have a modified cross-sectional design that resembles a K-File configuration instead of the U-shape common to many other rotary instruments. Rotary instruments with this geometry are claimed to cut dentine more effectively and may therefore reduce stress on individual instruments. However, more aggressive cutting could produce increased canal transportation.

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Another recent modification in instrument design is the addition of .02 taper instruments to the sets containing instruments with conicities greater than the ones stipulated by the ISO norm. FlexMaster instruments are available in .02, .04 and .06 taper and in sizes ranging from 20 to 45.

Little is known about the impact of these design modifications on canal-shaping ability, and consequently, the aim of this study was to assess the shaping potential of FlexMaster instruments and to evaluate the effect of normal canal anatomy on the final outcome of the shaped canals.

## Materials and methods

### Preparation of specimens

Eleven three-rooted maxillary molars were selected from a pool of extracted teeth and were stored in 0.1% thymol until used. Outer root surfaces were sealed from their apices to the cemento-enamel junctions (Syntac Classic, Vivadent, Schaan, Liechtenstein, Germany) and the specimens were mounted on SEM stubs (014001-T, Balzers Union AG, Balzers, Liechtenstein, Germany). The canals were then scanned by μCT (see below) without probing the canals for patency, to avoid modifying the canals' apical anatomy. No attempt was made to locate or shape second mesiobuccal (mb) canals because their anatomy was too variable for the purpose of this study (Fig. 1). However, the μCT analysis indicated that a fourth canal was present in nine of the 11 specimens in this sample.

Canals were prepared in a special torque-testing device (rotational speed 240 r.p.m.), which is described in detail by Peters & Barbakow (2002). The operator was an undergraduate student with clinical expertise in rotary techniques, who had completed an extensive training period with FlexMaster instruments using the audiovisual material supplied by the manufacturer.

Canal orifices were enlarged with Gates Glidden burs (insertion depth 3 mm, nos. 3 and 2; Dentsply Maillefer, Ballaigues, Switzerland), and pulp chambers were irrigated with 5 mL of tap water. Working lengths were then set by subtracting 1 mm from the lengths of size 010 K-Flexofiles (Dentsply Maillefer) when their tips were just visible at the main apical foramina. Digital radiographs (Digora, Soredex, Helsinki, Finland) of each canal were also taken to verify file position and canal anatomy. Apical preparations with rotary instruments began after working lengths had been reached with a size 015 K-Flexofile using Glyde (Dentsply Maillefer) as a lubricant.

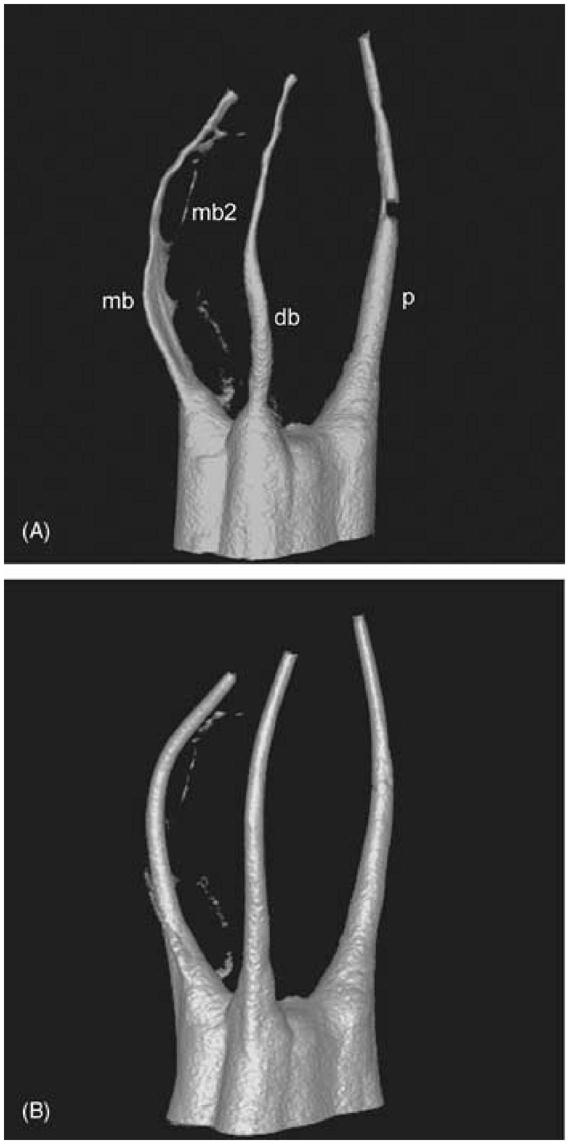


**Figure 1** Images of unshaped (A) and prepared (B) mb, db and p systems reconstructed from μCT data. Note the very fine second mb canal system (mb2).

Subsequent canal preparation using FlexMaster instruments differed slightly from the manufacturer's instructions: generally the sequence indicated for large canals was used initially and, on encountering resistance, was modified for smaller canals. In detail, the instruments used were:

- .06 taper size 30 in the coronal third,
- .06 taper sizes 25 and 20 in the middle third,
- .06 taper size 20,
- .04 taper size 30, size 25 and 20 and
- .02 taper sizes 25, 30, 35, 40 and 45 in the apical third.

 

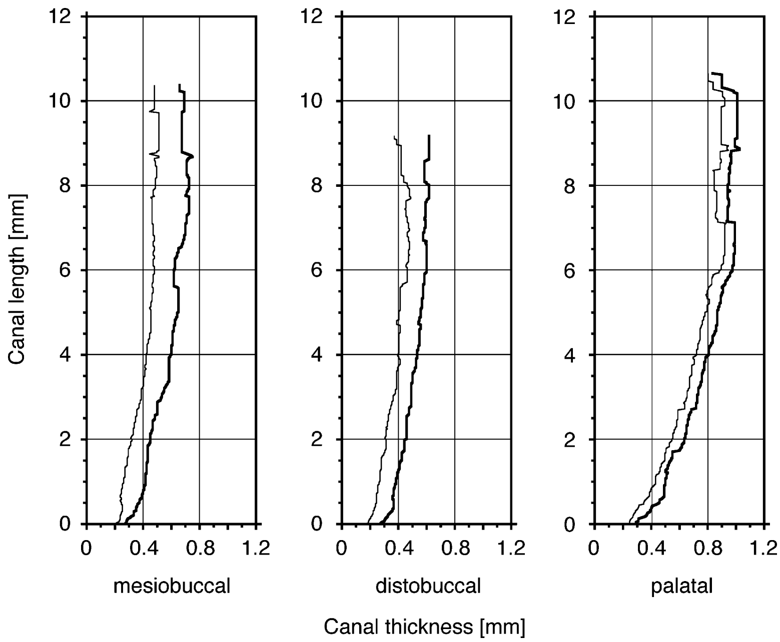


**Figure 2** Canal 'thickness' profiles detailing clinical diameters along canal length (mean scores from 11 p, 10 mb and 9 db canals).

The aim of this preparation sequence was to shape an apical stop to facilitate obturation by lateral compaction of gutta percha.

Mesiobuccal and distobuccal (db) canals were then prepared to an apical size 40, while palatal (p) canals were shaped to a size 45. Tap water served as the irrigant after each instrument, delivered by means of a conventional gauge 27 injection needle, allowing for adequate back-flow. After preparing one specimen (three canals), each set of FlexMaster instruments was discarded and replaced by a new set.

### Micro-computed tomography measurements and evaluations

Scanning and evaluation procedures have been described elsewhere in more detail (Peters *et al.* 2000, 2001a, 2003a). Briefly, specimens were scanned at an isotropic resolution of 34 μm, using a μCT system (μCT-20; Scanco Medical, Bassersdorf, Switzerland), and three-dimensional images of the root canals were constructed (Fig. 1) after filtering and thresholding. The canals were again scanned as above after shaping, so that each canal served as its own control.

Canals were superimposed with a precision better than one voxel, and matched root canals were evaluated for changes in volume and surface area. The same models were also used to determine the Structure Model Index (SMI) of the root canals. This index characterizes the structure of an object as having an ideal ribbon-like shape, corresponding to an SMI score of 0, or cylindrical shape, corresponding to an SMI score of 3. Furthermore, 'thicknesses' of the canals were determined using recently described distance transformation techniques (Peters *et al.* 2000) and related to canal lengths in order to construct 'thickness' profiles (Fig. 2).

Based on an overall median canal volume of 2.33 $mm^3$, all 33 canals of the current sample were divided into 'wide' (mean volume 4.67 $\pm$ 1.97 $mm^3$) and 'constricted' (mean volume 1.17 $\pm$ 0.55 $mm^3$) groups. Then, 'centres 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 centre-of-mass (CM) shifts in millimetres (Fig. 3) before and after

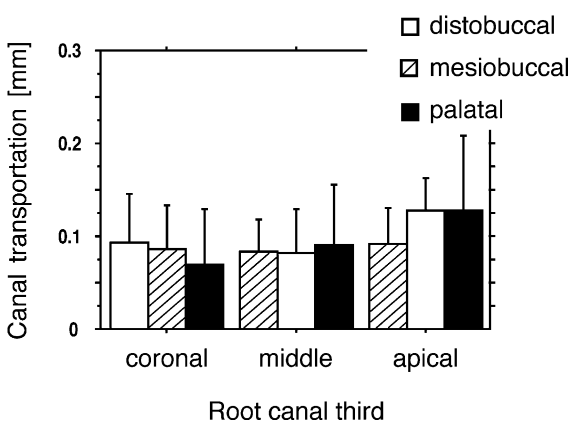


**Figure 3** Canal transportation (CM shift) in mb, db and p canals, split by canal third (means $\pm$ SD; $n = 10$).

 

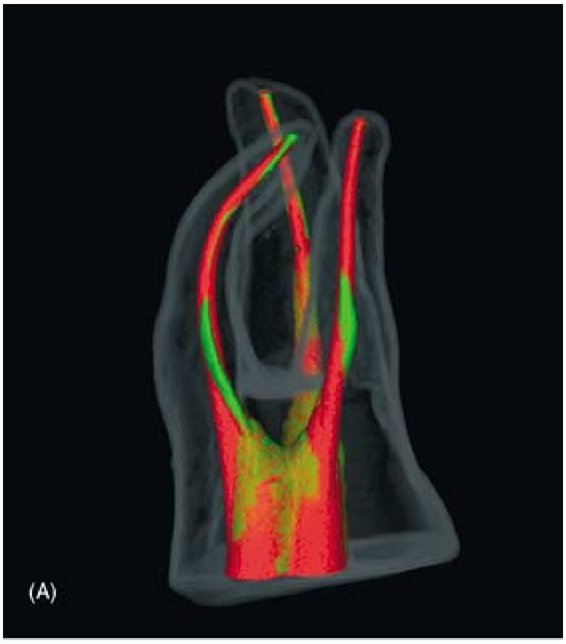



**Figure 4** Root contours with matched and superimposed root-canal systems shown in Fig. 1 in clinical (A) and mesiodistal projections (B). Unprepared canals are shown in green, and prepared areas are shown in red. Mixed red/green areas demonstrate overlapping images, i.e. unchanged canal wall sections. Pure green areas indicate dentine debris deposition.

treatment for the apical, mid and coronal thirds of the canals. From a polynomial equation, describing a fitted line for each canal, curvatures were calculated as second derivatives.

Finally, matched images of the surface area voxels of the canals, before and after preparation, were examined to evaluate the amount of uninstrumented surface (Fig. 4), using volume-rendering software (VGStudio Max Volume Graphics, Heidelberg, Germany). This parameter was calculated by subtracting the number of static surface voxels from the total number of surface voxels. Scores expressed as means ± SD were compared using one- and two-way ANOVAs with Scheffé tests for post-hoc comparisons. When appropriate, repeated-measures ANOVA was constructed. A level of $P < 0.05$ was considered significant.

## Results

Scanning of unprepared and instrumented canals yielded detailed three-dimensional canal images (Fig. 1A,B). Volume rendering was used to illustrate the relationship between root canals and outer root contour (Fig. 4). No obvious procedural errors such as apical zips, perforations or ledges were detected after canal preparation with FlexMaster. Apical stops of varying degrees were visible in some cases (p canal in Figs 1B and 2).

Overall, median initial canal volume and surface area were 2.33 $mm^3$ and 16.91 $mm^2$, respectively. Table 1 details preoperative mean scores, indicating that mb canals were significantly ($P < 0.05$) more ribbon-shaped than the other two canal types, as shown by respective SMI scores. Repeated-measures ANOVA revealed that preparation significantly increased canal volumes, surface areas and SMI scores (Table 2). At the same time, SMI increase was highest in mb canals, and ANOVA indicated significant differences between canal types in this respect ($P < 0.05$; Table 2).

Figure 2 illustrates diameters of canals, evaluated as 'thickness', by plotting means against canal lengths and yielding canal-dimension estimates before and after preparation. Overall 'thickness' increased significantly while canals were prepared. Apically, the attempt to

**Table 1** Morphometric data determined for untreated maxillary molar root canals (means ± SD)

| | Mesiobuccal ($n = 11$) | Distobuccal ($n = 11$) | Palatal ($n = 11$) |
|---|---|---|---|
| Volume ($mm^3$) | 3.06 ± 2.09 | 1.36 ± 0.79$^{a}$ | 4.50 ± 2.52$^{a}$ |
| Area ($mm^2$) | 21.73 ± 10.14$^{b}$ | 11.10 ± 4.60$^{b,c}$ | 20.95 ± 7.31$^{c}$ |
| SMI* | 2.63 ± 0.43$^{d,e}$ | 3.23 ± 0.20$^{d}$ | 3.57 ± 0.25$^{e}$ |

Significant differences between canal type ($P < 0.05$, one-way ANOVA) indicated by superscript alphabets.
*SMI: Structure Model Index ranging from 0 to 4.

 

**Table 2** Increase* in morphometric scores after preparation of maxillary molar root canals (means ± SD)

| | Mesiobuccal ($n = 10$) | Distobuccal ($n = 9$) | Palatal ($n = 11$) |
|---|---|---|---|
| Volume ($mm^3$) | $1.25 \pm 0.33^a$ | $0.88 \pm 0.21$ | $0.82 \pm 0.43^a$ |
| Area ($mm^2$) | $3.43 \pm 1.52$ | $3.23 \pm 1.30$ | $2.71 \pm 2.70$ |
| SMI** | $0.26 \pm 0.37^b$ | $0.04 \pm 0.22$ | $-0.07 \pm 0.133^b$ |

Significant differences between canal types ($P < 0.05$, Scheffé test) indicated by superscript alphabets.
*Significant, $P < 0.001$, repeated-measures ANOVA.
**SMI: Structure Model Index.

**Table 4** Numbers and percentages of static voxels recorded by superimposing matched images before and after preparation (means ± SD)

| | Mesiobuccal ($n = 10$) | Distobuccal ($n = 9$) | Palatal ($n = 11$) |
|---|---|---|---|
| Voxels ($\times 10^3$) | $9.77 \pm 4.88$ | $4.95 \pm 3.92$ | $7.39 \pm 4.82$ |
| Voxels* (%) | $47.43 \pm 16.9$ | $37.83 \pm 22.9$ | $39.29 \pm 20.4$ |

*Relative findings are expressed as percentages calculated in relation to surface areas after preparation. No differences between canal types (ANOVA).

create apical stops was indicated by a small artificially created ledge between the 0.75- and 1-mm mark in 'thickness' profiles (Fig. 2). Canal 'thickness' at the 5-mm level increased from 0.45 to 0.65 mm, from 0.41 to 0.57 mm and from 0.76 to 0.85 mm, for mb, db and p canals, respectively.

Using superimposed canal models, mean CM shift scores were calculated for the coronal, middle and apical thirds, and the scores ranged from 0.008 to 0.287 mm. Figure 3 details mean scores for db, mb and p canals. Two-way ANOVA indicated no differences between root-canal types and the 'wide' and 'constricted' groups, with almost identical CM shifts in the apical thirds ($0.115 \pm 0.07$ mm vs. $0.119 \pm 0.04$ mm in the 'wide' and 'constricted' groups, respectively). Furthermore, no significant differences were found with respect to canal level (Fig. 3).

Most canals used in this study were slightly to moderately curved, curvature being metrically described as the second derivative of a fitted line through successive canal centres. However, canal preparation led to various degrees of straightening (Table 3). This effect was most pronounced in those canals that had higher initial degrees of curvature. db canals that had also on average the smallest initial canal volumes (Table 1), showed the largest degree of canal straightening. However, this difference was not statistically significant nor were significant differences recorded when comparing the 'wide' and 'constricted' groups.

**Table 3** Relative degree of canal straightening* (means ± SD)

| | Mesiobuccal ($n = 10$) | Distobuccal ($n = 9$) | Palatal ($n = 11$) |
|---|---|---|---|
| Straightening (%) | $4.0 \pm 16.1$ | $16.3 \pm 16.6$ | $8.1 \pm 7.1$ |

No significant differences between canal types, but significant straightening during preparation ($P < 0.01$, repeated measures ANOVA).
*Expressed as decrease in second derivative scores, calculated from a polynomial equation fitted through respective canal centre of mass.

Superimposed images, with colour-coded static voxels, were designated untreated areas (Fig. 4). These areas tended to be mid-root at the inner canal walls and apically at the outer walls of the curvature. Interestingly, the summation allowed also to detect areas that were only visible in the preoperative scan and not in the post-operative image (green areas in Fig. 4). These are likely fins of oval canals that are partially blocked by dentine dust while static voxels (untreated areas) are designated by a mixed red/green colour.

Finally, amounts of static surface voxels or untreated areas were calculated (Table 4). db canals had the lowest numbers of untreated voxels when compared to mb and p canals. This difference was not significant while constricted canals had a significantly lower number of static voxels in comparison with large canals ($32 \pm 22\%$ vs. $52 \pm 26\%$; $P < 0.05$).

## Discussion

FlexMaster instruments were recently introduced, and they employ two new design features. First, in cross-section, the instruments do not have a U-file design, and second, less conical instruments (.02 taper) are included in the sequence. This concept is felt to allow efficient apical preparation to larger sizes than the previous systems did. Previous authors have evaluated the shaping ability of FlexMaster instruments using simulated canals in plastic blocks (Schäfer & Lohmann 2002a) and extracted teeth (Weiger *et al.* 2002a, Schäfer & Lohmann 2002b). However, these analyses were two-dimensional, looking at canal cross-sections or lateral aspects, while three-dimensional canal shapes can be compared using μCT. μCT is emerging in several endodontic research facilities as a nondestructive and accurate method to analyse canal geometry and the relative effects of shaping techniques (Rhodes *et al.* 2000, Bergmans *et al.* 2001, Gluskin *et al.* 2001, Peters *et al.* 2001a,b, 2003a). Accuracy and reproducibility of the system used in this study has been verified previously (Peters *et al.* 2000). This project is part of a larger study testing torque and force produced when canals are shaped using extracted human maxillary molars in a special testing device (Peters *et al.* 2002, 2003b).

The ultimate goal of root-canal preparation is canal debridement to promote apical healing (Byström *et al.* 1987) and, in vital cases, to retain apical health. In this regard, apical root-canal enlargement by mechanical canal shaping has an antimicrobial effect via canal debridement (Byström & Sundqvist 1981). However, irrigation with antimicrobial solutions is required to lower bacterial counts to clinically acceptable levels (Shuping *et al.* 2000). While larger apical shapes should favour reduction in bacteria, there is some evidence that this goal can be also achieved without enlargement (Coldero *et al.* 2002). In the present study, tap water was used for irrigation to study the effect of mechanical canal preparation and, specifically, the effects of shaping with a novel instrument.

The incorporation of less tapered instruments into the instrument sequence allows the clinician to use larger rotary instruments to full working length. However, larger instruments are less flexible and thus may increase the incidence of procedural errors and overall canal transportation. The present study addressed this question and furthermore evaluated the effect of canal anatomy on preparation outcome.

No obvious procedural errors were detected in this study, confirming findings reported in two earlier studies in which five other nickel–titanium preparation systems were evaluated using μCT (Peters *et al.* 2001a,b, 2003a). In fact, when transportation was expressed as CM shifts, lesser degrees of canal straightening were recorded with FlexMaster compared to previous studies (Peters *et al.* 2001a, 2003a). Furthermore, CM shifts were similar and small in 'wide' and 'constricted' canals after FlexMaster preparation, even though apical size 40 or 45 was reached. These large apical sizes were created in an attempt to facilitate canal debridement (Shuping *et al.* 2000), irrespective of initial canal sizes. Clinically, apical canal diameters would be gauged to determine master apical file diameters, but this was not feasible in this study as it would decrease the number of observations in each subgroup, invalidating any statistics.

Overall canal anatomy, as described by volumes, surface areas and SMIs, was statistically similar in the present study compared to canals evaluated earlier using the same analytical methods (Peters *et al.* 2001a,b, 2003a). However, db canals in the present sample tended to have lesser volume and 'thickness' than those analysed previously. Overall, FlexMaster preparation removed dentine volumes varying from 0.82 to 1.25 $mm^3$ compared to a preoperative canal volume of 1.36–4.50 $mm^3$. While some of these values for individual canals are lower than those previously described (Nielsen *et al.* 1995), the differences are probably because of varying regions of interest (ROI).

In this study, canal diameters were described as 'thickness', which was calculated by fitting spheres into reconstructed canals as described previously (Peters *et al.* 2000). Specifically, maximum local sphere diameter relates to a specific file tip size, which a clinician would select to gauge the apical region (Ruddle 2002). FlexMaster instruments adequately opened canals 5 mm from their apices with sizes varying from 0.57 to 0.85 mm. Spreaders and pluggers with size 0.5-mm tips might not be able to reach the 5-mm level in some of the smaller canals in the present sample. Deep instrument penetration is considered critical for both lateral (Alison *et al.* 1979) and vertical (Ruddle 2002) compaction. Therefore, in accordance with the manufacturer's instructions, canal shapes might be finished using a more tapered instrument into the apical third. Canal 'thickness' is also an important parameter when considering how far into a canal irrigation needles can be safely inserted for optimized irrigation delivery.

Because of the limited amount of cross-sectional enlargement following current standards, apical stops should not be assumed to have a clear box-like shape as pointed out by Kast'akova *et al.* (2001). This fact is further illustrated by thickness profiles in the present study, which represent average scores of several root canals with their individual shapes. Therefore, length measurement errors and the averaging process by itself might blur existing apical stops in small canals.

Procedural errors were not obvious, and only limited canal transportation was evident in the present study. Furthermore, as indicated above, CM shifts were similar or smaller than those recorded for rotary instruments with a U-file cross-sectional geometry. This finding is corroborated by radiographic studies in extracted teeth where FlexMaster preparation preserved canal curvatures significantly better than K-Flexofiles (Schäfer & Lohmann 2002a).

Importantly, there was no significant difference in apical transportation when the findings for 'wide' canals were compared to those of their 'constricted' counterparts. While some canal straightening occurred, there was again no difference between the various canal types (p, db, mb) when graded as 'wide' or 'constricted'. This result is similar to that reported earlier for ProTaper instruments (Peters *et al.* 2003a).

The impact of preoperative canal anatomy was most prominent when assessing the amount of uninstrumented canal areas after preparation. Canals graded as 'wide' had significantly larger untouched areas (Fig. 4), amounting to 42–61% of their total area, compared to their 'constricted' counterparts. Similar findings have been reported earlier for other canal-preparation techniques using µCT reconstructions (Peters *et al.* 2001a, 2003a) as well as from canal cross-sections (Tucker & Wenckus 1997, Weiger *et al.* 2002b). In fact, Weiger *et al.* (2002a) found that on average 45% of canal cross-section outlines, 3 mm short of working length, were unprepared after FlexMaster preparation. In the latter study, statistically similar scores were found after Lightspeed and nickel–titanium hand-file preparations. These findings, together with incompletely debrided root-canal surfaces seen in SEM studies (Schäfer & Lohmann 2002a), underline the need to use an efficient irrigation and shaping regime to clean root canals. Conversely, small apical dimensions encumber the use of ultrasonically activated irrigation by constraining the instrument's oscillations (Ahmad *et al.* 1990).

However, the relation of *in vitro* instrument performance, as assessed in the present study by µCT, to clinical efficiency should be further addressed by long-term clinical trials.

## Conclusions

In summary, FlexMaster instruments shaped curved and narrow root canals in maxillary molars to sizes 40 and 45 without significant shaping errors. However, a small degree of apical canal transportation was evident, which was independent of preoperative canal anatomy. In general, canal anatomy had an insignificant impact on preparation, indicating that FlexMaster instruments were able to shape 'constricted' canals to an apical size of 40. Further, clinical research is necessary to evaluate the outcome of root-canal treatments, not only with FlexMaster, but also with other currently available rotary nickel–titanium instruments.

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