ProTaper rotary root canal preparation: effects of canal anatomy on final shape analysed by micro CT

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Abstract

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Aim To evaluate the relative performance of ProTaper nickel–titanium (Ni–Ti) instruments shaping root canals of varying preoperative canal geometry.

Methodology Extracted human maxillary molars were scanned, before and after shaping with ProTaper, 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, 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 repeated-measures ANOVA and Scheffé posthoc tests.

Results Volume and surface area increased significantly and similarly in mb, db and p canals, and gross preparation errors were found infrequently. Root canal diameters, 5 mm coronal to the apex, increased from 0.38 to 0.65 mm, 0.42 to 0.66 mm and 0.57 to 0.79 mm for mb, db and p canals, respectively. Apical canal transportation ranged from 0.02 to 0.40 mm and was independent of canal type; 'wide' canals had a significantly higher ($P < 0.05$) proportion of unprepared surfaces than 'constricted' canals.

Conclusions Canals in maxillary molars were prepared *in vitro* using ProTaper instruments without major procedural errors. These instruments may be more effective in shaping narrow canals than wider, immature ones.

Keywords: canal geometry, ProTaper, shape, transportation.

Introduction

Modern engine-driven root canal preparation techniques claim to facilitate safe and efficient preparations. Such techniques have been evaluated in several studies using various experimental designs. Conventional analytical methods may employ reassembly techniques (Bramante *et al.* 1987) which evaluate cross-sections of root canals before and after preparation (Deplazes *et al.* 2001).

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Recently, micro computed tomography (μCT) was introduced to evaluate not only cross-sections of roots, but also three-dimensional shapes of canals at resolutions as high as 36 μm (Peters *et al.* 2000, Rhodes *et al.* 2000, Bergmans *et al.* 2001, Gluskin *et al.* 2001). This innovation was achieved because new hardware and software was 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).

Evidence suggests that canal anatomy influences preparation outcomes: significantly more aberrations are recorded when preparing simulated canals with more acute curves in plastic blocks using various nickel–titanium (Ni–Ti) rotary instruments (Bryant *et al.* 1999). In

addition, three-dimensional analysis using μCT indicated that canal transportation was more pronounced when shaping narrow curved canals than wider specimens (Peters *et al.* 2001a).

Nickel–Titanium rotary instruments such as ProTaper (Dentsply Maillefer, Ballaigues, Switzerland) 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 torsional loads (Ruddle 2002). However, more aggressive cutting could produce increased canal transportation and, aside from clinical guidelines (Ruddle 2001), little information exists about these instruments. Consequently, the aim of this study was to assess the shaping potential of ProTaper instruments, and to evaluate the effect of normal canal anatomy on the final outcome of the shaped canal using different variables.

Materials and methods

Preparation of specimens

Eleven three-rooted maxillary molars were selected from a pool of extracted teeth and stored in 0.1% thymol until used. Outer root surfaces were sealed from their apices to the cemento–enamel junctions, and the specimens were mounted on SEM stubs (014001-T, Balzers Union AG, Balzers, Liechtenstein). 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 the 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 using a set of ProTaper instruments, consisting of Shaping Files 1 and 2 (S1 and S2) and the Finishing Files 1 through 3 (F1–F3). Shaper X instruments were not available during the course of the study. Canals were prepared in a special torque-testing device (rotational speed 250 r.p.m.), which is described in detail elsewhere (Peters & Barbakow 2002). The operator was an endodontist with expertise in rotary techniques, and after a training period with ProTaper instruments and the torque-testing device (C.I.P.). During that phase, four S1 instruments fractured and subsequently, care was taken to enlarge the apical extent of the canals with a K-Flexofile size 015, prior to the use of ProTaper instruments.

Canal orifices were enlarged with Gates Glidden burs (insertion depth 3 mm, nos. 3 and 2; Dentsply Maillefer), and pulp chambers were irrigated with 5 mL of tap water. Working lengths were then set by subtracting 0.5 mm from the lengths of size 010 K-Flexofiles
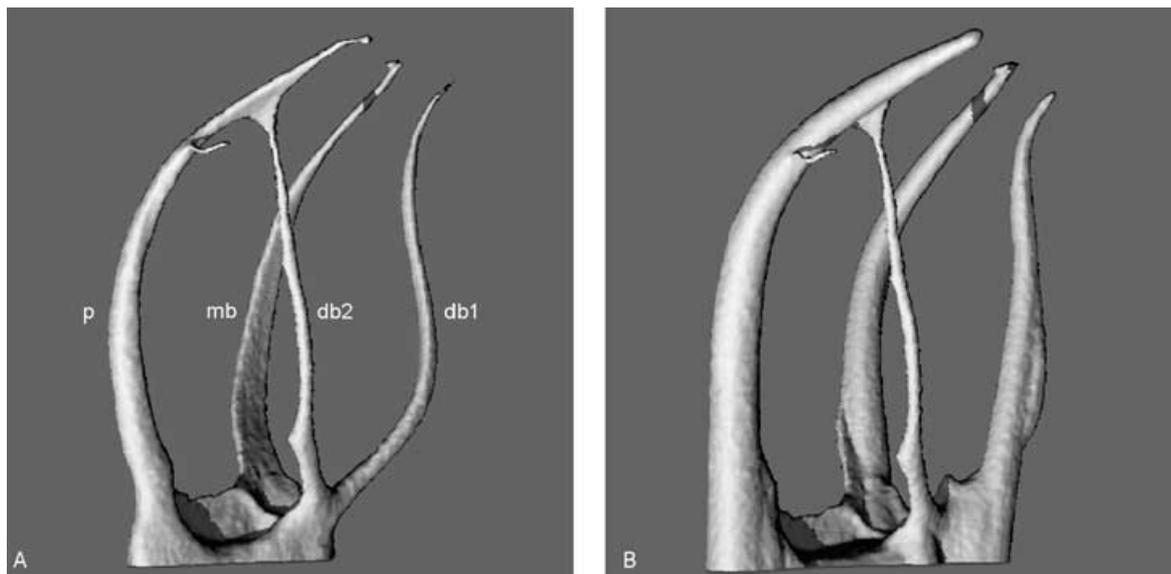
Figure 1 Images of unshaped (A) and prepared (B) systems reconstructed from micro computed tomography (μCT) data. Note unusual canal configuration with mesiobuccal (mb), distobuccal (db) canals and second distobuccal (db2) system merging into the palatal (p).

(Dentsply Maillefer, Ballaigues, Switzerland) when their tips were just visible at the main apical foramina. Digital radiographs (Digora, Soredex, Helsinki, Finland) were also taken of each canal to verify file position and canal anatomy. Apical preparations began with size 015 K-Flexofiles, using Glyde (Dentsply Maillefer) as the lubricant. Subsequently, canals were enlarged with instruments S1 and S2 used in a gentle pumping and brushing action. The mb and distobuccal (db) canals were prepared to a F2 (D1 diameter 0.25 mm), whilst palatal (p) canals were shaped to a F3 (D1 diameter 0.3 mm). Tap water served as the irrigant after each instrument, delivered by means of a gauge 27 needle, allowing for adequate back flow. After preparing one specimen (three canals), each set of ProTaper instruments was discarded and replaced by a new set.

## Micro CT measurements and evaluations

Scanning and evaluation procedures have been described elsewhere in detail (Peters *et al.* 2000, 2001a). Briefly, specimens were scanned at an isotropic resolution of 36 μm using a μCT system (μCT-20, Scanco Medical, Bassersdorf, Switzerland), and then, binary 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.

Whilst a special mounting device ensured almost exact repositioning of the pre- and postpreparation images, precision was perfected by superimposing both sets of segmented root canals manually over each other. Finally, the best superimposition was automatically detected, with a precision better than one voxel, by varying the relative translation in x-, y-, and z-directions.

Subsequently, matched root canals were evaluated as follows: changes in volume and surface area of the root canals were determined from the triangulated data. The same models were also used to determine the Structure Model Index (SMI) of the 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 of 3. Furthermore, 'thickness' of the canals were determined using recently described distance transformation techniques (Peters *et al.* 2000) and related to canal length in order to construct 'thickness' profiles (Fig. 2). Canal tapers, as line slopes, were determined from thickness profiles by fitting simple regressions.

Based on an overall median canal volume of 2.94 mm^3, 32 canals in 11 of 15 teeth were divided into 'wide' (mean volume: 5.54 ± 2.04 mm^3) and 'constricted' (mean volume: 2.03 ± 0.66 mm^3) groups. One p canal was not included in this analysis due to ambiguous surface area scores. Then, 'centres of gravity' of the canals, calculated for each slice, were connected along the z-axis by a fitted line. Canal transportations (CM shifts in millimetres, Fig. 3), were calculated by comparing the centres of gravity before and after treatment for the
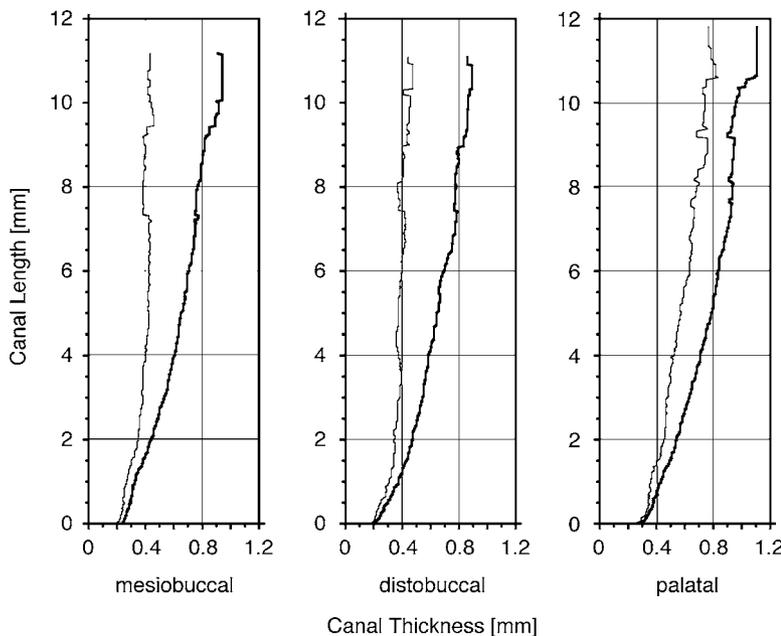
Figure 2 Canal 'thickness' profiles detailing clinical diameters along canal length (mean scores from 11 canals each).
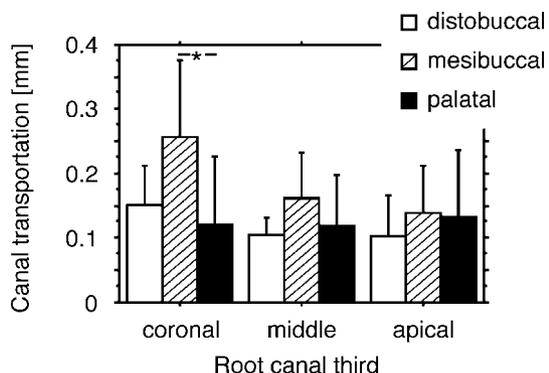
Figure 3 Canal transportation (CM) shift in mesiobuccal (mb), distobuccal (db) and palatal (p) canals, split by canal third (mean ± SD, $n = 11$ in each group). $^*P < 0.05$, two-way ANOVA.
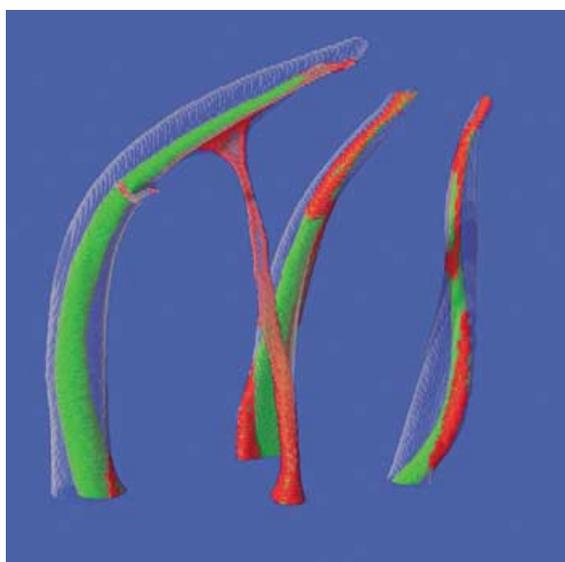
Figure 4 Matched and superimposed root canal systems shown in Fig. 1. Prepared canal areas indicated by green colour.

apical-, mid- and coronal-thirds of the canals. From a polynomic 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). This parameter was calculated by subtracting the number of static surface voxels from the total number of surface voxels. Scores expressed as mean ± SD were compared using one- and two-way ANOVAs with Scheffé

tests for posthoc comparisons. When appropriate, repeated-measures ANOVAs were constructed. A level of $P < 0.05$ was considered significant.

Results

Scanning of unprepared and instrumented canals yielded highly detailed three-dimensional canal images (Fig. 1). No obvious procedural errors such as apical zips perforations or ledges were detected after canal preparation with ProTaper. In addition, no clear changes in overall shape were detected in eight of 32 canals. This phenomenon was most prevalent in the apical parts of wider canals. However, distinct changes were recorded in the coronal parts of all canals, and were most likely due to preflaring the canal orifices.

Overall, median initial canal volume and surface area were 2.94 mm^3 and 24.15 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).

Table 1 Morphometric data determined for untreated maxillary root canals (mean ± SD)

	Mesiobuccal ($n = 11$)	Distobuccal ($n = 11$)	Palatal ($n = 11$)
Volume (mm^3)	3.48 ± 2.17	2.42 ± 1.52[a]	5.27 ± 2.35[a]
Area (mm^2)	29.41 ± 9.23[b]	17.61 ± 5.74[b,c]	27.27 ± 5.74[c]
SMI*	2.19 ± 0.65[d]	3.01 ± 0.36[d,e]	2.93 ± 0.64[e]

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

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

	Mesiobuccal ($n = 11$)	Distobuccal ($n = 11$)	Palatal ($n = 11$)
Volume (mm^3)	1.56 ± 0.65	1.74 ± 1.15[a]	1.40 ± 1.11[a]
Area (mm^2)	3.96 ± 2.29[b]	4.96 ± 4.14[b,c]	2.77 ± 3.41[c]
SMI**	0.57 ± 0.29[d]	0.33 ± 0.28[d]	0.44 ± 0.55

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

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 whilst canals were prepared, and resulting profiles indicated smooth tapers of .08 for the apical 5 mm in mb and db canals as well as .10 for p canals. Canal 'thickness' at the 5-mm level increased from 0.38 to 0.65, 0.42 to 0.66 and 0.57 to 0.79 mm, for mb and db and p canals, respectively.

Using superimposed canal models, mean centre of mass shift (CM shift) scores were calculated for the coronal, middle and apical thirds, and scores ranged from 0.021 to 0.407 mm. Figure 3 shows mean scores for canals that were further grouped into 'constricted' and 'wide' groups with the former comprising seven of 11 mb canals, seven of 11 db canals and two of 10 p canals. The 'wide' group included the remaining 16 canals. Two-way ANOVA indicated a significant difference between the 'wide' and 'constricted' groups in the coronal two thirds, whilst CM shifts in the apical thirds were similar (0.120 ± 0.07 vs. 0.135 ± 0.09 mm, Fig. 3).

Most canals used in this study were 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, which had higher initial degrees of curvature (Fig. 1, note curved p canal). Statistically, no significant differences were recorded when comparing the 'wide' and 'constricted' groups or between mb, db and p canals.

Superimposed images, with colour-coded static areas, designated relatively large untreated areas (Fig. 4). These areas tended to be mid-root at the convex side and apically at the concave side of the curvature. Finally, amounts of static surface voxels, or untreated areas were calculated (Table 4). The db canals had the lowest numbers of untreated voxels when compared to mb and p canals. This difference was not significant whilst constricted canals had a significantly lower number of

Table 3 Relative degree of canal straightening[*] (mean $\pm$ SD)

	Mesiobuccal ($n = 11$)	Distobuccal ($n = 11$)	Palatal ($n = 11$)
Straightening (%)	17.4 ± 16.7	30.0 ± 19.5	13.3 ± 19.6

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

Table 4 Numbers and percentages of static voxels recorded by superimposing matched images, before and after preparation (mean $\pm$ SD)

	Mesiobuccal ($n = 11$)	Distobuccal ($n = 11$)	Palatal ($n = 11$)
Voxels ($\times 10^3$)	12.2 ± 9.00	5.60 ± 3.70	11.4 ± 7.50
Voxels[*] (%)	43.0 ± 29.2	33.2 ± 18.9	49.0 ± 29.0

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

static voxels in comparison to large canals ($32 \pm 22\%$ vs. $52 \pm 26\%$, $P < 0.05$).

Discussion

ProTaper instruments were recently introduced and embody two new concepts. Firstly, in cross-section, the instruments do not have a U-file design and secondly, the instrument's shaft has variable tapers along its cutting surface (Ruddle 2001). This concept minimizes the number of instruments per set and is claimed to decrease torsional loads by reducing the frictional surface, thereby increasing cutting efficiency. No previous reports have evaluated the shaping ability of ProTaper Ni–Ti instruments using μCT. The 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.* 2001b). 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 & Barbakow 2002).

Originally, ProTaper sets included five instruments, namely, Shaping files 1 and 2 and Finishing files 1–3, and such sets were used in the present study. However, an additional instrument (Shaper X) was subsequently introduced, whose task is to relocate canal orifices and shape the coronal part of a canal. In the present study, this coronal preflaring was completed with Gates Glidden drills. Whilst the modified cutting flute of ProTaper instruments might reduce friction and consequently torque (Blum *et al.* 1999), this design may also 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 four other Ni–Ti preparation systems were evaluated using μCT (Peters *et al.* 2001a,b). However, when transportation was expressed as CM shifts, varying degrees of canal straightening were recorded with ProTaper, as was the case with other previously described preparation techniques (Peters *et al.* 2001a,b).

Overall canal anatomy, as described by volumes, surface areas and SMI, was statistically similar in the present study, compared to canals evaluated earlier using the same analytical methods (Peters *et al.* 2001a,b). ProTaper preparation removed dentine volumes varying from 1.40 to 1.76 mm^3 compared to a preoperative canal volume of 2.42–5.27 mm^3. Whilst some of these values for individual canals are lower than those previously described (Nielsen *et al.* 1995), the differences are probably due to varying regions of interest (ROI). However, calculations for a perfect 10-mm long cone with a 0.25-mm tip diameter and a .10 taper result in a theoretical file volume of 4.42 mm^3. This result should correspond to the volume of a perfectly prepared canal of similar dimensions. In principle, it seems intriguing to refer to these volumes when deciding on irrigation parameters (Yamada *et al.* 1983).

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, 2001a). Specifically, maximum local sphere diameter relates to a specific file tip size, which a clinician would select to gauge the apical region (Ruddle 2002). ProTaper instruments adequately opened canals 5 mm from their apices, with sizes varying from 0.65 to 0.79 mm. Spreaders and pluggers with size 0.5-mm tips could readily be used during obturation of root canals with such apical preparations. Deep instrument penetration is considered critical for both lateral (Alison *et al.* 1979) and vertical (Ruddle 2002) compaction. Canal 'thickness' is also an important parameter when considering how far into a canal irrigation needles can be safely inserted to allow for back flow.

Although procedural errors were not obvious, some canal transportation was evident in the present study. In fact, CM shifts were slightly larger than those reported previously (Peters *et al.* 2001a) for rotary instruments with a U-file cross-sectional geometry. This is possibly significant when the smaller apical sizes of ProTaper instruments (0.25–0.30 mm) are considered. Importantly, there was no significant difference in apical transportation when the findings for 'wide' canals were compared to those of their 'constricted' counterparts. However, results suggested that coronal preflaring with relocation of canal orifices was sufficient to avoid apical preparation errors. Whilst some canal straightening occurred, there was again no difference between the various canal types (p, db, mb) when graded as 'wide' or 'constricted'.

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; Table 4), amounting to 43–49% of their total compared to their 'constricted' counterparts. Similar findings have been reported earlier for other techniques using μCT reconstructions (Peters *et al.* 2001a) as well as from canal cross-sections (Tucker & Wenckus 1997). It has been proposed that canals be prepared to sufficiently large apical sizes, firstly to optimize irrigation and disinfection (Ruddle 2002), and to facilitate elimination of microbes mechanically (Dalton *et al.* 1998). However, the clinical significance of the parameter 'prepared surface' is not yet clarified considering that viable microbes penetrate deeper into dentinal tubules and may persist during root canal treatments (Peters *et al.* 2002).

Conclusions

ProTaper instruments prepared canals in extracted human maxillary molars without obvious procedural errors to a smooth tapered shape of appropriate sizes. However, some apical canal transportation was evident, which was independent of preoperative canal anatomy. In general, canal anatomy had an insignificant impact on preparation indicating that ProTaper instruments were able to shape 'constricted' canals. In contrast, 'wide' canals were less well prepared by ProTaper, suggesting that these new Ni–Ti instruments might be better suited for curved and constricted canals than wide, immature ones. Further clinical research is necessary to evaluate the outcome of root canal treatments, not only with ProTaper, but also with other currently available rotary Ni–Ti instruments.

Acknowledgements

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