

# Shaping ability of progressive versus constant taper instruments in curved root canals of extracted teeth

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## Abstract

**Yang GB, Zhou XD, Zheng YL, Zhang H, Shu Y, Wu HK.**

Shaping ability of progressive versus constant taper instruments in curved root canals of extracted teeth. *International Endodontic Journal*, **40**, 707–714, 2007.

**Aim** To compare the shaping ability of progressive versus constant taper shaft instruments in curved root canals of extracted human teeth.

**Methodology** A total of 40 root canals of mandibular molars with curvatures ranging between 20° and 40° were divided into two groups of 20 canals each and embedded in a muffle system. The root canals sectioned horizontally at three levels before preparation and then remounted into the mould. All root canals were prepared with ProTaper (progressive taper) or Hero Shaper (constant taper) instruments. Pre- and post-instrumentation radiographs and cross-sectional images were obtained. The parameters evaluated were: working safety (instrument failure, apical blockage and loss of working length) and shaping ability (straightening, cross-sectional area, transportation and centring ability). The data were analysed statistically using Student's *t*-test.

**Results** No instrument fractured during preparation. One Hero Shaper instrument permanently deformed. Both instrument systems maintained working length well. The canals prepared with Hero Shaper instruments were straightened to a lesser degree ( $P < 0.05$ ). ProTaper instruments removed more dentine in the coronal and the middle sections of the canals. Canals prepared with Hero Shaper instruments had less transportation ( $P < 0.01$ ) and better centring ability ( $P < 0.05$ ) in the apical section.

**Conclusions** Both instrument systems were safe to use and maintained working length well. The canals prepared with Hero Shaper had less transportation and were better centred in the apical region, possibly because their smaller taper reduced instrument stiffness.

**Keywords:** canal transportation, curved root canal, Hero Shaper, nickel-titanium, ProTaper, rotary instruments.

Received: 28 September 2006; accepted: 11 April 2007

## Introduction

Canal preparation is one of the major components of root canal treatment and is directly related to subsequent disinfection and filling (Peters *et al.* 2001). The aim of root canal preparation is to form a continuously tapered shape with the smallest diameter at the apical

foramen and the largest at the orifice to allow effective irrigation and filling. Many instruments have been recommended but only a few seem to be capable of achieving these primary objectives of root canal preparation consistently (Schäfer *et al.* 2006). During the last decade, root canal preparation with rotary nickel-titanium (Ni-Ti) instruments became popular as it facilitates the difficult and time-consuming process of shaping and improves the final quality of root canal preparation. It has been demonstrated that rotary Ni-Ti instruments are able to maintain canal shape even in severely curved canals (Thompson & Dummer 1997, Schäfer 2001, Schäfer & Lohmann 2002). However,

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despite these positive results, manufacturers continue to introduce Ni-Ti systems with new blade designs and tapers, claiming increased safety and ease of use.

The Ni-Ti rotary instruments currently available commercially vary considerably in their design. Various designs for taper, blades, grooves and tips have been suggested (Bergmans *et al.* 2002). The shaft design can be grouped according to taper into two categories: progressive or constant. It has been reported that instruments with progressive taper can shape canals more quickly than constant taper instruments (Veltri *et al.* 2005).

In the progressive ProTaper system (Dentsply Maillefer, Ballaigues, Switzerland), the shaping files (S) have an increasing taper from tip to coronal, whereas the finishing files (F) have a decreasing taper. It has been claimed that the increasing taper instruments have enhanced flexibility in the middle region and at the tip, and that the decreasing taper instruments provide a larger taper in the important apical region but make them stiff (Bergmans *et al.* 2003).

The Hero Shaper (Micro-Mega, Besançon, France) is a new system that supplements the existing Hero 642 system (Micro-Mega). The Hero Shaper helix angle increases from the tip to the shank, and this has been claimed to reduce threading, whilst the pitch varies according to the taper with a reported increase in efficiency, flexibility and strength (Veltri *et al.* 2005).

In a previous study, the shaping ability of progressive taper (ProTaper) versus constant taper (Hero 642) instruments in simulated root canals was compared (Yang *et al.* 2006). However, the outcome in simulated root canals may not reflect the results in root canals of real teeth (Kum *et al.* 2000). Thus, the aim of the present study was to evaluate the working safety and shaping ability of ProTaper and Hero Shaper instruments in real root canals of extracted human teeth using several parameters. The parameters evaluated were: instrument failure, apical blockage, loss of working length, straightening, cross-sectional area, transportation and centring ability.

## Materials and methods

### Selection of root canals

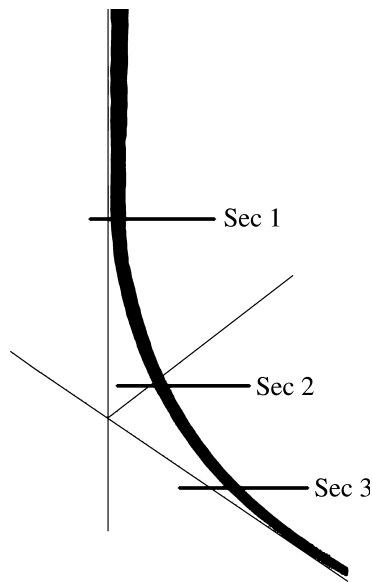
Fifty freshly extracted human permanent mandibular molars, with at least one curved root and curved root canal, were selected. The teeth were stored in 0.1% thymol solution until further use. Coronal access cavities were achieved using diamond burs, and the canals

were controlled for apical patency with size 10 K-files (Dentsply Maillefer, Ballaigues, Switzerland). Only teeth with fully formed root apices and those whose canal width near the apex was approximately size 15 were included; this was evaluated with size 15 K-file.

Standardized preoperative radiographs were exposed in order to determine the degree and radius of the curvature. A size 15 K-file was inserted into the root canal and a series of radiographs was taken with a Heliodent 70 X-ray machine (Siemens, Bensheim, Germany) connected to a digital sensor (Trophy Radiologie Inc., Croissy-Beaubourg, France) operating at 0.08 s, 70 kV and 4 mA. Following each exposure, the tooth was rotated incrementally until the file in the root canal appeared almost straight. The tooth was then rotated 90° to reveal the maximum curvature of the root canal (Iqbal *et al.* 2003). The position of maximum curvature was obtained, and all subsequent radiographs of the sample were taken at the same position. The degree and radius of canal curvature were determined from these preoperative radiographs with a computer program IMAGE PRO PLUS 5.0 (Media Cybernetics, Silver Spring, MD, USA). Only canals whose angles of curvature, according to Schneider method (Schneider 1971), ranged between 20° and 40° and radii of curvature, according to the method of Pruett (Pruett *et al.* 1997), ranged between 4.0 mm and 15.0 mm were included. Thus, a total of 40 canals were selected. All teeth were shortened to the same length of 17 mm by removing coronal tooth tissue.

### Preparation of the model

A modified Bramante muffle system (Hülsmann *et al.* 1999) was used to evaluate the shaping ability. The muffle-block consisted of a U-formed middle section and two lateral walls that were fixed with three screws as described previously (Hülsmann *et al.* 1999). A modified radiographic platform was constructed as described by Sydney *et al.* (1991). A positioner for the X-ray tube was fixed to the front side of the muffle block, and on the back side a holder for the digital X-ray sensor was fixed to the muffle block. This allowed the exposure of radiographs under standardized and reproducible conditions. After sealing the apices with wax, the canals were mounted in the muffle-block using transparent acrylic resin (Orthoplast; Vertex, Zeist, the Netherlands) with the position of maximum curvature facing the radiographic platform. After complete polymerization of the resin, the block was removed from the model, the wax removed and the apical foramen exposed. The root



**Figure 1** The three levels at which root canals were sectioned horizontally.

canals were sectioned horizontally at three sites (coronal, middle and apical) as follows (Fig. 1):

- Section 1 (coronal): the beginning of the curvature (BC)
- Section 2 (middle): the apex of the curve of the original canal (AC), determined by the intersection of two lines (one along the coronal aspect of the central line, and the second along the apical portion of the central line)
- Section 3 (apical): a point half-way from the canal orifice to the apex of the curve (HO)

The root canals were remounted into the muffle system in readiness for preparation.

**Root canal instrumentation**

On the basis of the degree and radius of curvature, the canals were randomly divided into two groups of 20 canals each. The homogeneity of the two groups with respect to the angle and radius of curvature was assessed using a *t*-test (Table 1). Group A was assigned for preparation with ProTaper instruments and group B with Hero Shaper instruments.

The working length for all canals was determined by subtracting 0.5 mm from the length at which the tip of a size 15 file could be visualized at the apical foramen when viewed under a stereomicroscope (Nikon SMZ1000, Tokyo, Japan).

**Table 1** Characteristics of curved root canals (*n* = 20 canals each group)

Instrument	Curvature (°)			Radius (mm)		
	Mean ± SD	Min	Max	Mean ± SD	Min	Max
ProTaper	27.8 ± 8.6	20.0	40.0	9.34 ± 4.76	4.42	15.00
Hero Shaper	29.2 ± 9.4	20.8	39.2	8.44 ± 4.35	4.61	14.20
<i>P</i> -value ( <i>t</i> -test)	0.705			0.626		

**Table 2** Details of the instruments for each system

ProTaper		Hero Shaper		
Type	Length	Taper	Size	Length
S1	WL	0.06	30	Meet resistance
SX	1/2 WL	0.06	25	Meet resistance
S1	WL	0.06	20	WL-2 mm
S2	WL	0.04	20	WL
F1	WL	0.04	25	WL
F2	WL	0.04	30	WL
F3	WL			

WL, working length.

Both ProTaper and Hero Shaper instruments were set into permanent rotation (300 rev min<sup>-1</sup>) with a 16 : 1 reduction handpiece (ATR Tecnika vision; Dentsply Maillefer, Ballaigues, Switzerland) powered by a torque-limited electric motor (ATR Tecnika vision; Dentsply Maillefer). The preparation was completed in a crown-down manner according to manufacturers' instructions using a brushing technique. Once the instrument had negotiated working length and rotated freely, it was withdrawn and changed for the next one. The instrument sequence for each group is described in Table 2. The sequence used in the present study for Hero Shaper was based on the recommendation by the manufacturer for severely curved canals but with modification.

Each instrument was used to enlarge five canals only and then discarded. Before being used, each instrument was coated with EDTA cream (Meta Biomed, Choon Chong Buk-Do, Korea) to act as a lubricant. In all the groups, irrigation was performed after each change of instrument with 2.0 mL of a 5.25% NaOCl solution followed by 2.0 mL of a 17% EDTA solution and a final rinse with 2.0 mL saline using a plastic syringe with a 27-gauge closed-end needle (Hawe Max-I-probe; Hawe-Neos, Bioggio, Switzerland). The needle was inserted as deeply as possible into the root canal without binding. Upon completion of instrumentation, the root canal was finally flushed for 1 min each with 2.0 mL of 17% EDTA solution and 2.0 mL of 5.25% NaOCl solution followed by rinsing with 4.0 mL saline. Finally, the

canals were dried with paper points. All canals were prepared by one operator experienced with both ProTaper and Hero Shaper instruments.

Standard radiographs were taken after instrumentation with the master instruments *in situ* using the muffle system. Three cross-sectional images of each canal were also taken before and after instrumentation under a stereomicroscope connected to a charge-coupled device (CCD) camera (Nikon digital sight DS-U1, Tokyo, Japan) at a fixed position and magnification using a special mounting device that enabled exact repositioning of the pre- and post-instrumentation cross-sectional images. The images per cross-section were coloured and superimposed with the IMAGE PRO PLUS 5.0 program. Precision was achieved by manually superimposing both margins of the cross-sections over each other. Finally, the best superimposition was automatically detected. Measurement of the canals was carried out by a second examiner who was uninformed of the experimental groups.

#### Assessment of canal preparation

Parameters used to evaluate the working safety were: instrument failure, apical blockage and loss of working length.

- 1. Instrument failure:** instruments that deformed or fractured during preparation were noted.
- 2. Apical blockage:** the apical part of the canal became blocked with dentine debris during preparation.
- 3. Loss of working length:** the final length of each canal was determined following the preparation. An F3 ProTaper instrument of group A or a size 30, 0.04-taper Hero Shaper instrument of group B was inserted into the prepared canal. Variations of working length were determined by subtracting the final length from the original length to an accuracy of 0.02 mm.

The shaping ability of the instruments was assessed for longitudinal (straightening) and cross-sectional (cross-sectional area, transportation and centring ability) planes using the computer program IMAGE PRO PLUS 5.0.

**1. Straightening:** straightening was assessed by changes to the degree and radius of the curvature after instrumentation on the basis of radiographs with the final instrument inserted into the canal compared with the initial curvature degree and radius.

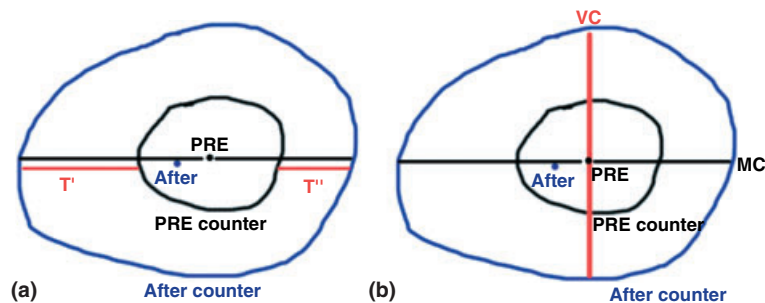
**2. Cross-sectional area:** cross-sectional area of each section was measured before and after preparation.

**3. Transportation:** transportation (Fig. 2a) after instrumentation was measured according to the method described by Bergmans *et al.* (2003). Transportation was calculated on each section in two directions (Fig. 2b): the direction of maximum curvature (MC) and the direction vertical to the maximum curvature (VC).

**4. Centring ability:** centring ability (Fig. 2a) of the instrument towards the original canal was calculated by the ratio of  $T'/T''$  or  $T''/T'$  according to the method developed by Gambill *et al.* (1996). If these numbers were not equal, the lower figure was considered as the numerator of the ratio. Centring ability was also calculated in two directions (Fig. 2b): MC and VC. If an uninstrumented canal wall remained in that direction, the centring ability was assigned '0'. Thus, a result of '1' indicates perfect centring ability, and '0' indicates worst centring ability.

#### Analysis of data

All data were recorded and stored in a PC. Following the error and range checks, the data were analysed with Student's *t*-test at a significance level of 0.05 using SPSS 11.0 (SPSS Inc., Chicago, IL, USA).



**Figure 2** (a) Definition of transportation ( $T = T' - T''$ ) and centring ability (ratio =  $T'/T''$  or  $T''/T'$ ). (b) Representation of the two measurement directions: MC, direction of maximum curvature; VC, direction vertical to the maximum curvature.

**Results**

**Working safety**

No instrument fractured during the preparation, and only one Hero Shaper instrument (0.04 taper, size 25) deformed permanently. All canals remained patent following the instrumentation; thus none of the canals were blocked with dentine debris. A mean loss of working length of 0.58 mm (SD 0.25 mm) for ProTaper and 0.54 mm (SD 0.21 mm) for Hero Shaper was recorded; the difference was not significant ( $P = 0.648$ ,  $t$ -test).

**Shaping ability**

*Straightening*

The mean straightening (changes to the degree and radius of curvature) of the curved canals is summarized in Table 3. The use of Hero Shaper instruments resulted in significantly less straightening during

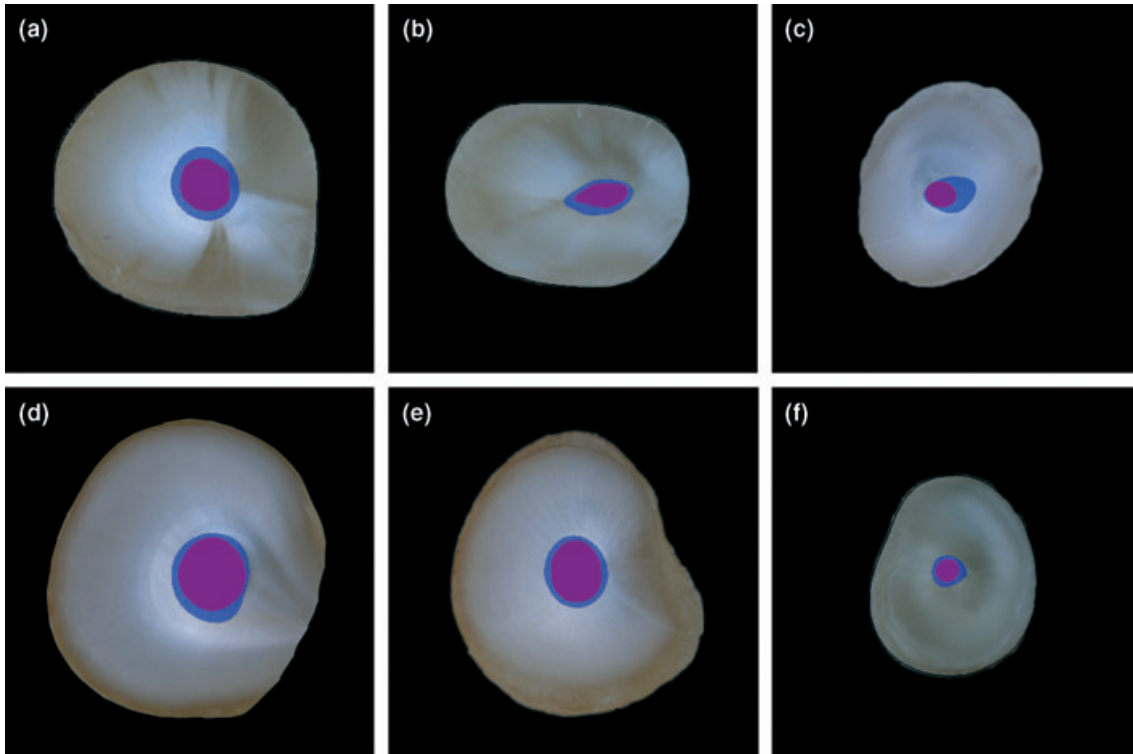
**Table 3** Mean degree of straightening (changes of degree and radius of the curvature) (mean  $\pm$  SD)

Instrument	Straightening	
	Degree ( $^{\circ}$ )	Radius (mm)
ProTaper	1.20 $\pm$ 0.74	1.24 $\pm$ 0.21
Hero Shaper	0.74 $\pm$ 0.56	0.83 $\pm$ 0.24

instrumentation compared with ProTaper in terms of both degree and radius of curvature ( $P < 0.05$ ).

*Superimposed cross-sectional images – qualitative analysis*

Representative superimposed cross-sectional images are shown in Fig. 3. In general, most of the canals in both groups had a centred enlargement in the coronal (section 1) and middle (section 2) regions. ProTaper instruments removed dentine asymmetrically in the apical region (section 3), which resulted in transportation towards the outer aspect of the curve. However, Hero Shaper instruments removed dentine symmetrically at this region. In the coronal region, there were



**Figure 3** Superimposed cross-sectional images of the two groups. The red regions define the cross-section before instrumentation and the blue regions define the cross-section after instrumentation. (a, b and c: section 1, 2 and 3 with ProTaper; d, e and f: section 1, 2 and 3 with Hero Shaper).

no uninstrumented areas. In the middle, two canals in each group revealed uninstrumented areas. In the apical, five canals in ProTaper group and three canals in Hero Shaper group had uninstrumented areas.

*Cross-sectional area*

The mean area of each pre- and post-instrumentation cross-section is shown in Table 4. There was no statistical difference between the two groups with respect to the areas of section 1, 2 and 3 before instrumentation. However, canals after preparation using ProTaper instruments had larger areas in the coronal (section 1) and middle (section 2) parts, which indicated that ProTaper instruments removed more dentine in these regions.

*Transportation*

The mean absolute values for transportation after instrumentation on each section in two directions are detailed in Table 5. In the coronal (section 1) and middle (section 2) sections of the canals, there were no significant differences between the two groups for canal transportation in either direction ( $P > 0.05$ ). At the apical (section 3) region, the canals prepared by ProTaper instruments had a larger mean value for transportation in the direction of MC ( $P < 0.01$ ), but in the direction of VC there was no significant difference ( $P > 0.05$ ).

*Centring ability*

Centring ability (expressed by centring ratio) on each section in the two directions is detailed in Table 6. In the coronal and middle sections of the canals, there were no significant differences between the two groups for centring ability in either direction ( $P > 0.05$ ). In the apical region of the canals, the differences between the two groups were significant in both directions. In general, Hero Shaper instruments had a more centred enlargement compared with ProTaper instruments.

**Table 5** Absolute values (mean ± SD) for transportation (mm) after instrumentation at different sections in two directions

Transportation	Section		
	1	2	3
<b>Direction MC</b>			
ProTaper	0.052 ± 0.046	0.059 ± 0.036	0.069 ± 0.024
Hero Shaper	0.028 ± 0.023	0.039 ± 0.025	0.042 ± 0.021
<i>P</i> -value	0.317	0.122	**
<b>Direction VC</b>			
ProTaper	0.022 ± 0.015	0.024 ± 0.013	0.025 ± 0.015
Hero Shaper	0.018 ± 0.012	0.018 ± 0.017	0.020 ± 0.010
<i>P</i> -value	0.730	0.312	0.238

MC, maximum curvature; VC, vertical to the maximum curvature.  
\*\* $P < 0.01$ .

**Table 6** Absolute values (mean ± SD) for centring ability (ratio) at different sections in two directions

Centring ability	Section		
	1	2	3
<b>Direction MC</b>			
ProTaper	0.66 ± 0.21	0.60 ± 0.14	0.40 ± 0.08
Hero Shaper	0.60 ± 0.16	0.56 ± 0.12	0.52 ± 0.14
<i>P</i> -value	0.608	0.432	**
<b>Direction VC</b>			
ProTaper	0.77 ± 0.345	0.76 ± 0.17	0.70 ± 0.19
Hero Shaper	0.95 ± 0.296	0.89 ± 0.24	0.91 ± 0.26
<i>P</i> -value	0.325	0.117	*

MC, maximum curvature; VC, vertical to the maximum curvature.  
\* $P < 0.05$ ; \*\* $P < 0.01$ .

**Discussion**

The purpose of this study was to compare the shaping ability of a progressive taper (ProTaper) versus a constant taper (Hero Shaper) instrument system. For the evaluation of root canal preparation by different instruments, two experimental models often used are

Instrument	Section					
	1		2		3	
	Pre-	Post-	Pre-	Post-	Pre-	Post-
ProTaper	0.74 ± 0.37	1.11 ± 0.36	0.47 ± 0.24	0.93 ± 0.28	0.27 ± 0.14	0.47 ± 0.16
Hero Shaper	0.65 ± 0.54	0.75 ± 0.18	0.38 ± 0.16	0.53 ± 0.18	0.20 ± 0.12	0.40 ± 0.08
<i>P</i> -value ( <i>t</i> -test)	0.608	*	0.14	**	0.08	0.112

\* $P < 0.05$ ; \*\* $P < 0.01$ .

**Table 4** Values (mean ± SD) for area (mm<sup>2</sup>) of each cross-section of pre- and post-instrumentation

simulated root canals in clear resin blocks or root canals in extracted human teeth. The shaping ability of progressive versus constant taper instruments was compared previously in simulated canals (Yang *et al.* 2006). Using extracted teeth in the present study provides conditions close to the clinical situation (Schäfer & Vlassis 2004). Despite the variations in the morphology of natural teeth, efforts were made to ensure comparability of the experimental groups. For example, the teeth in both groups were balanced with respect to the angle and radius of canal curvature based on the initial radiograph.

The 'Serial Sectioning Technique' introduced by Bramante *et al.* (1987) is a commonly used method (Tasdemir *et al.* 2005). This technique was used in the present study. When comparing the shaping ability of different root canal instruments, it is of importance to have similar apical preparation diameters (Bergmans *et al.* 2003). In the present study, the final apical preparation diameter was size 30 – the maximum size of the sequences at the time the study was undertaken.

The sequence of Hero Shaper used in this study was modified based on the recommendation of the manufacturer for severely curved canals; it was more closely adapted to the crown-down approach. The modification allowed the larger and more tapered instruments to be used in the coronal and middle thirds of the canal (Veltri *et al.* 2005).

The main parameters used to evaluate shaping are to protect the curvature of the canal and to maintain good centring ability. Transportation is caused by the tendency of instrument to return to its original straight shape when inserted into a curved root canal (Willey *et al.* 1992). The comparison of the pre- and postoperative photographs of the root canal cross-sections enabled the evaluation of the most important parameters of root canal preparation, i.e. transportation, centring ability, cross-sectional area and uninstrumented areas (Hülsmann *et al.* 2003). Better compliance with original canal shape was obtained using the constant taper (Hero Shaper). The Hero Shaper produced good centring ability in the apical section, which is in accordance with the results of Veltri *et al.* (2005). However, transportation towards the outer aspect of the canals in the apical section after preparation with ProTaper was evident, which might be the result of the progressive tapers along the cutting surface of these instruments, in combination with the sharp cutting edges (Schäfer & Vlassis 2004). The final file of the ProTaper – F3 – has an apical taper of 0.09, which is much larger than the Hero Shaper that has a 0.04

taper. The large taper of the F3 instrument increases the stiffness of the tip (Schäfer & Vlassis 2004), and the use of larger and greater taper instruments in moderately to severely curved canals should be considered carefully (Kum *et al.* 2000). Canals prepared with ProTaper instruments had larger cross-sectional areas in the coronal and middle parts, which could be attributed to the large diameters of the instruments, especially F3. Hero Shaper removed smaller amounts of dentine compared with ProTaper in both coronal and middle parts of the canals, and this may compromise irrigation and infection control. There are very limited reports on Hero Shaper, which is a supplement to Hero 642 and shares some features with it, making the comparison feasible. For example, ProTaper resulted in more straightening during preparation than with Hero 642 (Hülsmann *et al.* 2003, Guelzow *et al.* 2005, Paqué *et al.* 2005). The number of specimens with no or only minimal contact between pre- and postoperative cross-sections was higher after preparation using Hero 642 than following the use of FlexMaster (Hülsmann *et al.* 2003). Good shaping ability concerning postoperative cross-sections has also been described for Hero 642 by Tasdemir *et al.* (2005).

## Conclusions

Within the limitation of this study, both ProTaper and Hero Shaper instrument systems were safe to use and maintained working length well. The canals prepared with Hero Shaper instruments had less transportation and were better centred in the apical region, probably because of their smaller taper that could tend to reduce instrument stiffness. Canals prepared with Hero Shaper were narrower; this may compromise irrigation.

## Acknowledgements

The authors state that they have no commercial interest associated with the Dentsply Maillefer and Micro-Mega companies. The only purpose of this study was to obtain data for clinical research. This research was supported in part by the National Key Technologies R&D Programme of the Tenth Five-Year Plan of the Ministry of Science and Technology, China (Grant No. 2004BA720A23) and a grant from Sichuan University, Chengdu, China (No. 0040305505030). The authors are extremely grateful to Dentsply Maillefer and Micro-Mega for their technical support and donation of instruments. The authors also thank Ms. Eugenie Fyfe for editing the manuscript.

## References

- Bergmans L, Van Cleynenbreugel J, Beullens M, Wevers M, Van Meerbeek B, Lambrechts P (2002) Smooth flexible versus active tapered shaft design using NiTi rotary instruments. *International Endodontic Journal* **35**, 820–8.
- Bergmans L, Van Cleynenbreugel J, Beullens M, Wevers M, Van Meerbeek B, Lambrechts P (2003) Progressive versus constant tapered shaft design using NiTi rotary instruments. *International Endodontic Journal* **36**, 288–95.
- Bramante CM, Berbert A, Borges RP (1987) A methodology for evaluation of root canal instrumentation. *Journal of Endodontics* **13**, 243–5.
- Gambill JM, Alder M, del Rio CE (1996) Comparison of nickel–titanium and stainless steel hand-file instrumentation using computed tomography. *Journal of Endodontics* **22**, 369–75.
- Guelzow A, Stamm O, Martus P, Kielbassa AM (2005) Comparative study of six rotary nickel–titanium systems and hand instrumentation for root canal preparation. *International Endodontic Journal* **38**, 743–52.
- Hülsmann M, Gambal A, Bahr R (1999) An improved technique for the evaluation of root canal preparation. *Journal of Endodontics* **25**, 599–602.
- Hülsmann M, Gressmann G, Schäfers F (2003) A comparative study of root canal preparation using FlexMaster and HERO 642 rotary Ni-Ti instruments. *International Endodontic Journal* **36**, 358–66.
- Iqbal MK, Maggiore F, Suh B, Edwards KR, Kang J, Kim S (2003) Comparison of apical transportation in four Ni-Ti rotary instrumentation techniques. *Journal of Endodontics* **29**, 587–91.
- Kum KY, Spångberg L, Cha BY, et al. (2000) Shaping ability of three ProFile rotary instrumentation techniques in simulated resin root canals. *Journal of Endodontics* **26**, 719–23.
- Paqué F, Musch U, Hülsmann M (2005) Comparison of root canal preparation using RaCe and ProTaper rotary Ni-Ti instruments. *International Endodontic Journal* **38**, 8–16.
- Peters OA, Schönenberger K, Laib A (2001) Effects of four Ni-Ti preparation techniques on root canal geometry assessed by micro computed tomography. *International Endodontic Journal* **34**, 221–30.
- Pruett JP, Clement DJ, Carnes DL (1997) Cyclic fatigue testing of nickel–titanium endodontic instruments. *Journal of Endodontics* **23**, 77–85.
- Schäfer E (2001) Shaping ability of Hero 642 rotary nickel–titanium instruments and stainless steel hand K-Flexofiles in simulated curved root canals. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics* **92**, 215–20.
- Schäfer E, Lohmann D (2002) Efficiency of rotary nickel–titanium FlexMaster instruments compared with stainless steel hand K-Flexofile. Part 2. Cleaning effectiveness and instrumentation results in severely curved root canals of extracted teeth. *International Endodontic Journal* **35**, 514–21.
- Schäfer E, Vlassis M (2004) Comparative investigation of two rotary nickel–titanium instruments: ProTaper versus RaCe. Part 2. Cleaning effectiveness and shaping ability in severely curved root canals of extracted teeth. *International Endodontic Journal* **37**, 239–48.
- Schäfer E, Erler M, Dammaschke T (2006) Comparative study on the shaping ability and cleaning efficiency of rotary Mtwo instruments. Part 1. Shaping ability in simulated curved canals. *International Endodontic Journal* **39**, 196–202.
- Schneider SW (1971) A comparison of canal preparation in straight and curved root canals. *Oral Surgery, Oral Medicine and Oral Pathology* **32**, 271–5.
- Sydney GB, Batista A, de Melo LL (1991) The radiographic platform: a new method to evaluate root canal preparation *in vitro*. *Journal of Endodontics* **17**, 570–2.
- Tasdemir T, Aydemir H, İnan U, Ünal O (2005) Canal preparation with Hero 642 rotary Ni-Ti instruments compared with stainless steel hand K-file assessed using computed tomography. *International Endodontic Journal* **38**, 402–8.
- Thompson SA, Dummer PMH (1997) Shaping ability of NT Engine and McXim rotary nickel–titanium instruments in simulated root canals. Part 1. *International Endodontic Journal* **30**, 262–9.
- Veltri M, Mollo A, Mantovani L, Pini P, Balleri P, Grandini S (2005) A comparative study of Endoflare-Hero Shaper and Mtwo NiTi instruments in the preparation of curved root canals. *International Endodontic Journal* **38**, 610–6.
- Willey WL, Senia ES, Montgomery S (1992) Another look at root canal instrumentation. *Oral surgery, Oral Medicine, and Oral Pathology* **74**, 499–507.
- Yang GB, Zhou XD, Zhang H, Wu HK (2006) Shaping ability of progressive versus constant taper instruments in simulated root canals. *International Endodontic Journal* **39**, 791–9.