Comparative investigation of two rotary nickel–titanium instruments: ProTaper versus RaCe. Part 1. Shaping ability in simulated curved canals

E. Schäfer & M. Vlassis
Department of Operative Dentistry, University of Münster, Münster, Germany

Abstract

Schäfer E, Vlassis M. Comparative investigation of two rotary nickel–titanium instruments: ProTaper versus RaCe. Part 1. Shaping ability in simulated curved canals. *International Endodontic Journal*, **37**, 229–238, 2004.

Aim To compare the shaping ability of ProTaper with Reamer with Alternating Cutting Edges (RaCe) instruments. Part 1 of this two-part report describes the efficacy of these two nickel–titanium instruments in simulated curved root canals.

Methodology Simulated canals with 28° and 35° curves in resin blocks were prepared with ProTaper and RaCe instruments using a crown-down preparation technique ($n = 24$ canals in each case). Pre- and postinstrumentation images were recorded, and assessment of canal shape was completed with a computer image analysis program. Material removal was measured at 20 measuring points, beginning 1 mm from the apex. Incidence of canal aberrations, preparation time, changes of working length and instrument failures were also recorded. The data were analysed statistically using the Mann–Whitney *U*-test or the chi-square test.

Results On average, canals prepared with RaCe instruments remained better centred compared with those enlarged with ProTaper files. Three RaCe instruments and two ProTaper files fractured during preparation ($P > 0.05$). Between both the canal types, RaCe was significantly faster ($P < 0.001$) than ProTaper and maintained working length significantly better ($P < 0.05$).

Conclusion Both instruments prepared curved canals rapidly and were relatively safe. RaCe respected original canal curvature better than ProTaper, which tended to transport towards the outer aspect of the curve.

Keywords: canal transportation, curved root canals, nickel–titanium, resin blocks, root canal preparation, rotary instruments.

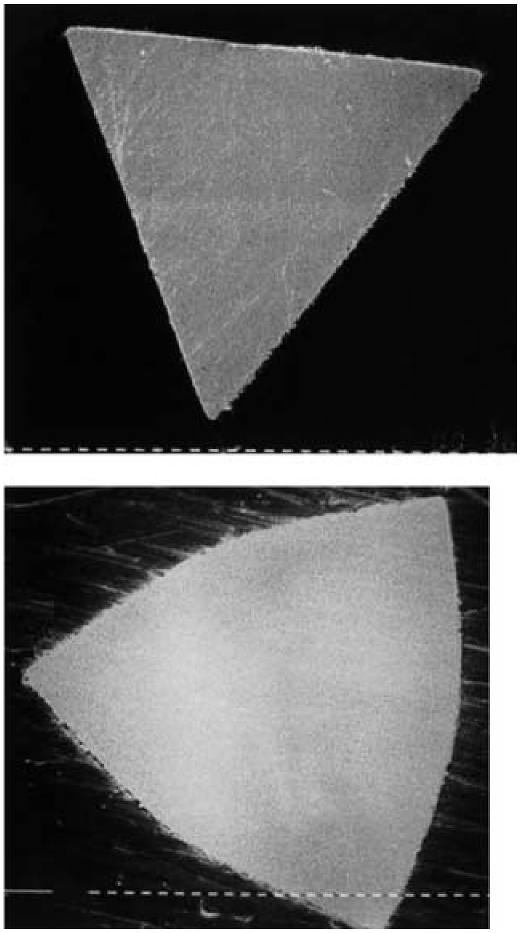
Received 15 September 2003; accepted 2 December 2003

Introduction

The aim of root canal instrumentation is to create a tapered shape with adequate volume to allow effective irrigation and obturation (European Society of Endodontology 1994). However, traditional hand instruments often failed in achieving these objectives, especially when used in severely curved canals (Briseño & Sonnabend 1991, Al-Omari *et al.* 1992, Schäfer *et al.* 1995). These instruments are stiff – a property that increases with increasing instrument size and results in canal aberrations such as ledges, perforations, zips and elbows (Schäfer *et al.* 1995, Bergmans *et al.* 2001). In order to eliminate some of the shortcomings of these traditional endodontic instruments, rotary nickel–titanium instruments have been developed. Most of the new systems incorporate instruments with a taper greater than the ISO standard .02 design (Thompson & Dummer 1997a, Bergmans *et al.* 2001). Besides variation in taper, nickel–titanium rotary instruments are characterized by different cross-sections and blade designs (Bergmans *et al.* 2001).

Two new file designs of rotary nickel–titanium instruments with sharp cutting edges were recently introduced as ProTaper (Dentsply Maillefer, Ballaigues, Switzerland) and Reamer with Alternating Cutting Edges (RaCe; FKG Dentaire, La-Chaux-de-Fonds, Switzerland). The ProTaper instruments have a convex triangular cross-sectional design (Fig. 1a), a noncutting safety tip (Fig. 2a)

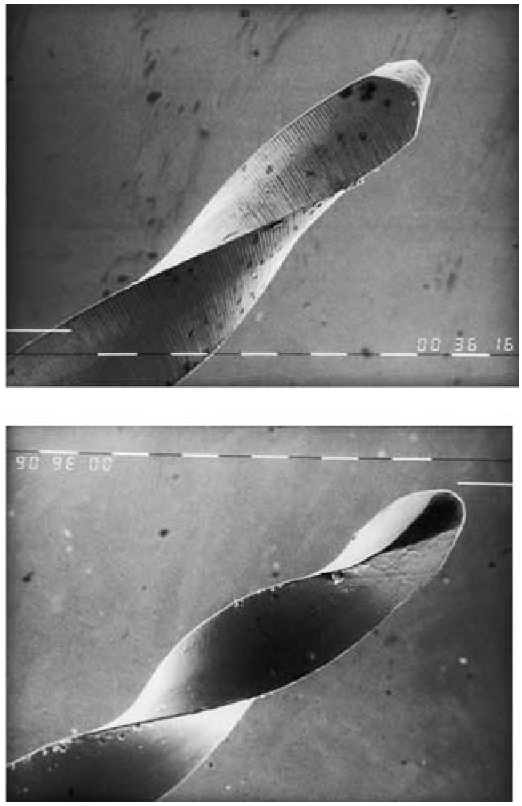
Correspondence: Prof. Dr Edgar Schäfer, Department of Operative Dentistry, Waldeyerstr. 30, D-48149 Münster, Germany (Fax: +49 251 834 70 40; e-mail: eschaef@uni-muenster.de).



(a)

(b)

Figure 1 Scanning electron microscope images of the cross-sections of the two nickel–titanium instruments showing sharp cutting edges. (a) ProTaper (F2; original magnification 160×). (b) RaCe (.04 taper size 25; original magnification 160×).



(a)

(b)

Figure 2 Scanning electron microscope images of the tip region of the two instruments showing a noncutting, flattened tip with rounded transitional angles. (a) ProTaper (F3; original magnification 80×). (b) RaCe (.06 taper size 30; original magnification 80×).

and a flute design that combines multiple tapers within the shaft. Root canal instruments with this cross-sectional design are claimed to cut dentine more effectively (Bergmans *et al.* 2001, Ruddle 2002). The basic series of ProTaper files comprises six instruments: three shaping and three finishing files. According to the manufacturer, the auxiliary shaping file (SX) should be used to produce more shape in the coronal portion of the root canal (Bergmans *et al.* 2003). The coronal one-third of the canal should be instrumented using the shaping file no. 1 (S1), whereas shaping file no. 2 (S2) is designed to prepare the middle one-third of the root canal. In addition, both instruments do progressively enlarge the apical one-third (Bergmans *et al.* 2003). The finishing files (F1–F3) should be used to finish the apical one-third of the root canal and to progressively expand the shape in the middle one-third (Bergmans *et al.* 2003). The F3 file has a size 30 at the tip of the instrument. The shaping files have a progressive taper sequence (increasing from tip to coronal) whereas the finishing files show a decreasing taper profile. It is claimed that the progressive taper sequence should enhance the flexibility of the files in the middle and at the tip region, and that the decreasing taper sequence should enhance the strength of the files (Bergmans *et al.* 2003).

The RaCe instruments have a triangular cross-sectional design (Fig. 1b) with sharp cutting edges, with the exception of the .02 taper size 20 files, which have a square cross-section. These sharp cutting edges would tend to result in an efficient chip dislodgement (Wildey *et al.* 1992, Bergmans *et al.* 2001). Moreover, RaCe files have alternating cutting edges (Fig. 3), and this design is alleged to have two functions: (i) to eliminate screwing in and blocking in continuous rotation; and (ii) to reduce the working torque. Finally, RaCe instruments possess

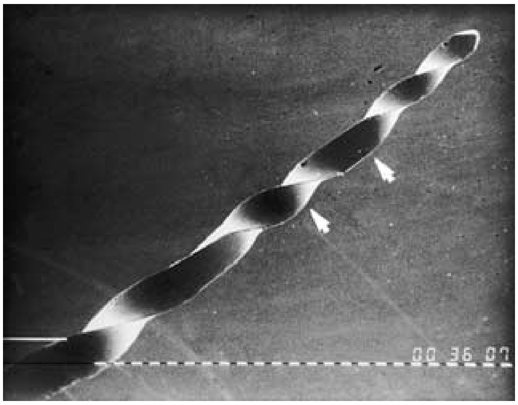


Figure 3 Scanning electron microscope image of the cutting surface of a RaCe instrument (.06 taper size 30; original magnification 20×) showing alternating cutting edges (indicated by arrows).

a noncutting tip (Fig. 2b). Five different PreRaCe and 11 RaCe nickel–titanium instruments are available. Two PreRaCe files (.10 taper size 40 and .08 taper size 35) are also available as stainless steel instruments.

To date, little information exists about these two instruments. The purpose of the present study was to compare ProTaper instruments with RaCe files during the shaping of simulated curved root canals in resin blocks using different parameters.

Materials and methods

Simulated canals

Simulated canals made of clear polyester resin (Viapal uP 004/64, Vianova Resins, Hamburg, Germany) with coloured canal walls were used to assess instrumentation. The degree of curvature was either 28° or 35°. The diameter and the taper of all simulated canals were equivalent to an ISO standard size 15 root canal instrument. The 28° canals were 13 mm long, the straight part being 5.5 mm and the curved part 7.5 mm. The curvature was defined mathematically with a radius of 7.5 mm, resulting in an angle of 28° according to the Schneider method (Schneider 1971). The 35° canals were 13 mm long, the straight part being 5 mm and the curved part 8 mm. The radius of the curvature was 6.5 mm.

Preparation of simulated canals

The simulated canals were prepared with either ProTaper or RaCe rotary nickel–titanium instruments. The transparent blocks were covered with adhesive tape during the preparation phase. All instruments were used to enlarge two canals only. Prior to use, each instrument was coated with glycerine to act as a lubricant, and copious irrigation with water was performed repeatedly after the use of each instrument. All canals were enlarged by an operator experienced in preparation with both ProTaper and RaCe instruments. Measurement of the canals was carried out by a second examiner who was unaware of the experimental groups. A randomly laid down sequence was used to avoid bias towards one of the two instrumentation techniques. Only, six resin blocks (three with 28° curves and three with 35° curves) were instrumented at a time to minimize operator fatigue and familiarity. These six resin blocks were defined as a set. The order of use of the two instrument types within a set was rotated.

Both types of instruments were set into permanent rotation with a 4 : 1 reduction handpiece (WD-66 EM, W&H, Buermoos, Austria) powered by a torque-limited electric motor (Endo IT motor, VDW, Munich, Germany). For each file, the individual torque limit and rotational speed programmed in the file library of the Endo IT motor were used. In a pilot study, the instrumentation sequences that allowed preparation of the different canals without difficulties were as follows:

Group A

ProTaper instruments were used in a crown-down manner according to the manufacturer's instructions using a gentle in-and-out motion. Instruments were withdrawn when resistance was felt and changed for the next instrument. The instrumentation sequence was:

1 An S1 file (shaping file no. 1; taper .02–.11; size 17) was used to 7 mm.

2 An SX (auxiliary shaping file; taper .035–.19; size 19) used to 7 mm.

3 An S1 file was used to 9 mm.

4 An S2 file (shaping file no. 2; taper .04–.115; size 20) was used to 11 mm.

5 An F1 file (finishing file no. 1; taper .07–.055; size 20) was used to 13 mm, the full length of the canal.

6 An F2 file (finishing file no. 2; taper .08–.055; size 25) was used to 13 mm, the full length of the canal.

7 An F3 file (finishing file no. 3; taper .09–.05; size 30) was used to 13 mm, the full length of the canal.

Once the instrument had negotiated to the end of the canal and had rotated freely, it was removed.

Group B

Reamer with Alternating Cutting Edges instruments were also used in a crown-down manner according to the manufacturer's instructions using a gentle in-and-out motion. Instruments were withdrawn when resistance was felt and changed for the next instrument. The instrumentation sequence was:

1 A .10 taper size 40 instrument was used to 5 mm.
2 A .08 taper size 35 instrument was used to 7 mm.
3 A .06 taper size 30 instrument was used to 9 mm.
4 A .04 taper size 25 instrument was used to 11 mm.
5 A .02 taper size 25 instrument was used to 13 mm, the full length of the canal.
6 A .02 taper size 30 instrument was used to 13 mm, the full length of the canal.
7 A .02 taper size 35 instrument was used to 13 mm, the full length of the canal.

Once the instrument had negotiated to the end of the canal and had rotated freely, it was removed.

Comparing the two instrumentation sequences, it has to be kept in mind that the final apical preparation diameter in the ProTaper group was a size 30 and in the RaCe group a size 35. In each of these two test groups, 24 canals with 28° and 24 canals with 35° curves were enlarged. Thus, a total of 96 canals were prepared.

Assessment of canal preparation and analysis of data

The time for canal preparation was recorded, and the total active instrumentation, instrument changes within the described instrumentation sequence and irrigation were included. Changes of working length were determined by subtracting the final length (measured to the nearest 0.5 mm) of each canal after preparation from the original length (13 mm). The preparation time and the loss of working length were analysed statistically using the Mann–Whitney *U*-test at a significance level of $P < 0.05$. The number of fractured and permanently deformed instruments during enlargement was also recorded. A chi-square test was used to determine whether there were significant differences between the two instruments for instrument failure and deformation.

The assessment of preparation shape was carried out with the computer program IMAGE 1.41 (National Institutes of Health public domain program). Therefore, pre- and postinstrumentation canal shapes were taken in a standardized manner and magnified 40 times by means of a charged coupled device (CCD) camera (SSC-M370CE, Sony Corporation, Tokyo, Japan) and stored in a computer (Macintosh Quadra 660 AV, Apple Computer, Ismaning, Germany). Thereafter, a composite image was produced of the pre- and postinstrumentation images and superimposed. The amount of resin removed, e.g. the difference between the canal configuration before and after instrumentation was determined for both the inner and the outer side of the curvature in 1-mm steps using the IMAGE 1.41 program. The amount of resin substance removed in all canals was measured one-dimensionally with a precision of ±0.01 mm. The first measuring point was 1 mm away from the apical ending of the canal, and the last measuring point was 10 mm from the apical end, resulting in 10 measuring points at the outer and 10 points at the inner side of the canal, and thus in a total of 20 measuring points (Schäfer *et al.* 1995). All measurements were made at right angles to the surface of the canal. The data were analysed by the Mann–Whitney *U*-test because for some measuring points the data was not distributed normally according to the Kolmogorov-Smirnov test.

Furthermore, based on the superimposition of pre- and postoperative images, assessments were made according to the presence of different types of canal aberrations, such as apical zip associated with elbow, ledge and perforation. These different types of canal aberration were defined according to the detailed descriptions published previously (Thompson & Dummer 2000b).

Results

During preparation of the 96 canals, a total of five instruments fractured. Therefore, the following results are based on the remaining 91 canals. One canal with 28° and four canals with 35° curves were excluded.

Instrument failure

Table 1 details the number of deformations and fractures of instruments that occurred during the study. All failures occurred at the tip region of the instruments. In the 28° curved canals, one RaCe instrument (.02 taper, size 25) and none of the ProTaper files fractured. In the 35° curved canals, two ProTaper (both F3 files) and two RaCe (both .02 taper, size 25) instruments fractured. The differences between the two instrument types were not statistically significant, in terms of either the number of separated instruments or the number of permanently deformed instruments (χ^2-test, $P > 0.05$).

Table 1 Number of fractured and permanently deformed instruments

	28° Curved canals		35° Curved canals	
Instrument	Fractured	Deformed	Fractured	Deformed
ProTaper	0	6	2	8
RaCe	1	7	2	6

Table 2 Mean preparation time (min) and SD with the two different instruments

	28° Curved canals		35° Curved canals	
Instrument	Mean	SD	Mean	SD
ProTaper	5.75	0.40	6.30	0.36
RaCe	4.59	0.74	5.52	0.54

Table 4 Incidence of canal aberrations by instrument types

	28° Curved canals		35° Curved canals	
Aberration type	ProTaper	RaCe	ProTaper	RaCe
Zip/elbow	3	1	4	1
Ledge	3	2	4	2
Perforation	0	0	0	0

χ^2-test, no significant differences ($P > 0.05$).

Preparation time

The mean time taken to prepare canals with the different instruments is shown in Table 2. Independent of the curvature of the canals, the shortest mean preparation time was recorded when RaCe instruments were used. Both in 28° and 35° curved canals, RaCe was significantly faster than ProTaper ($P < 0.001$). For both instruments, enlargement of 28° curved canals was significantly quicker than instrumentation of 35° curved canals ($P < 0.01$).

Change of working length

All canals remained patent following instrumentation; thus, none of the canals became blocked with resin debris. None of the canals had overextension of preparation, whereas a loss of working distance was found in several canals.

The mean losses of working length that occurred with the different instruments are listed in Table 3. With ProTaper files, a significantly greater loss of working length resulted than with RaCe instruments, in both the 28° and the 35° curved canals ($P < 0.05$). For RaCe, there were no significant differences between the mean loss of working length in 28° curved canals and in 35° curved canals ($P = 0.773$), whereas for ProTaper, the mean loss of working length was significantly greater in 35° curved canals than in 28° curved canals ($P < 0.05$).

Canal shapes

The results concerning the assessment of canal aberrations are summarized in Table 4. With respect to the different types of aberrations evaluated, in canals with both 28° and 35° curves, there were no significant differences between the two instrument types (χ^2-test, $P > 0.05$), even though more zips and more ledges were created with ProTaper.

Table 3 Mean loss of working length (mm) and SD with the two different instruments

	28° Curved canals		35° Curved canals	
Instrument	Mean	SD	Mean	SD
ProTaper	0.26	0.31	0.38	0.23
RaCe	0.16	0.31	0.20	0.35

On average, in the canals with 28° curves, RaCe instruments removed material more evenly on the outer, as well as on the inner side of curvature (Fig. 4b). At 13 out of 20 measuring points, significant differences ($P < 0.05$) occurred between resin removal achieved with the two different instruments (Table 5). The canals prepared with RaCe instruments remained better centred compared with those enlarged with ProTaper files (Fig. 4).

In the canals with 35° curves, RaCe instruments removed more material on the inner side of the curvature than ProTaper (Fig. 5). On average, only limited material removal occurred on the inner side of the curvature in the apical part of the canals when ProTaper files were used (Table 6). Canals shaped with ProTaper had material removed mainly in the last 1–5 mm along the outer side of the curvature, resulting in a slight outer widening of the canal (Fig. 5a). This effect was significantly different compared with the material removal achieved with RaCe files at these five measuring points ($P < 0.05$). At 16 out of 20 measuring points, significant differences ($P < 0.05$) occurred between resin removal achieved with the two different instruments (Table 6). In general, the RaCe instruments had a more centred enlargement compared with the ProTaper instruments (Fig. 5).

Discussion

The purpose of this study was to compare the relative efficiency and shaping ability of two recently introduced rotary nickel–titanium instruments: ProTaper and RaCe. The shaping abilities of these instruments was compared under strictly controlled laboratory conditions, using clear resin blocks. Use of simulated canals in resin blocks does not reflect the action of the instruments in root canals of real teeth. However, resin blocks allow a direct comparison of the shaping ability of different instruments (Schäfer *et al.* 1995). A major drawback of using

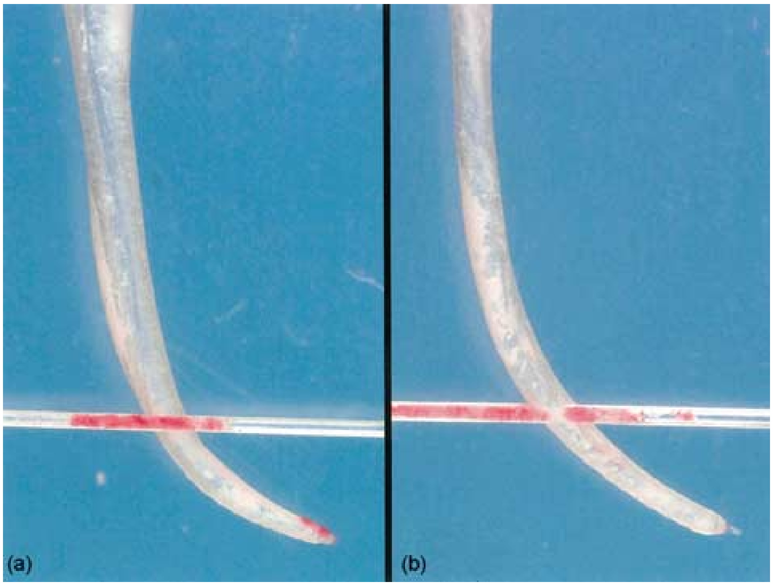


Figure 4 Representative examples of canal shapes of 28° curved canals as the result of instrumentation with (a) ProTaper files and (b) RaCe files. Notice the sections of red-coloured canal walls, indicating that nearly no resin has been removed on this canal wall areas.

rotary instruments in resin blocks is the heat generated, which may soften the resin material (Kum *et al.* 2000) and lead to binding of cutting blades, and separation of the instrument (Thompson & Dummer 1997c, Baumann & Roth 1999). Thus, because of the nature of the resin, care should be exercised in the extrapolation of the present results to the use of these instruments in real root canals, where dentine is involved (Thompson & Dummer 1997c).

When comparing the shaping abilities of different preparation techniques or different root canal instruments, it is of importance to have similar apical preparation diameters (Bergmans *et al.* 2003). In the present investigation, the final apical preparation diameter in the ProTaper group was a size 30 (finishing file no. 3) because finishing files with larger sizes are not available. However, the final apical diameter in the RaCe group was a size 35. This was done for one reason: the major objective of the present study was on the one hand to compare the shaping ability of the two rotary instruments tested. On the other hand, another objective was to compare the results for ProTaper and Race with those of previous studies investigating other rotary nickel–titanium instruments under identical experimental conditions (Table 7). As in these recent studies the apical preparation diameter was a size 35 in all cases, it was agreed to enlarge the canals assigned to the RaCe group up to size 35 also. Moreover, the results of the present investigation strongly indicate that the negligible difference between the apical preparation diameter in the ProTaper and the RaCe was not responsible for the final outcome of the shaped canals using the two different instruments.

In comparison with the ProTaper files, rotary RaCe instruments maintained original root canal curvature better and showed less straightening (Figs 4 and 5), especially in canals having 35° curves. These observations

Table 5 Mean material removed (mm) and SD at the different measuring points after instrumentation of simulated 28° curved canals

	Inner canal wall (mm from the apex)										Outer canal wall (mm from the apex)									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
ProTaper																				
Mean	0.04	0.06	0.08	0.11	0.26	0.45	0.61	0.72	0.67	0.52	0.15	0.26	0.33	0.32	0.25	0.16	0.08	0.04	0.04	0.06
SD	0.04	0.04	0.05	0.07	0.11	0.10	0.09	0.09	0.09	0.08	0.03	0.05	0.05	0.07	0.10	0.08	0.07	0.04	0.04	0.06
RaCe																				
Mean	0.06	0.10	0.15	0.17	0.23	0.29	0.37	0.44	0.42	0.32	0.18	0.18	0.22	0.23	0.24	0.20	0.12	0.04	0.03	0.03
SD	0.02	0.03	0.03	0.03	0.05	0.06	0.06	0.06	0.06	0.05	0.06	0.03	0.04	0.05	0.06	0.06	0.05	0.03	0.02	0.01
P-value	*	**	***	**	0.077	***	***	***	***	***	**	***	***	***	0.615	0.065	0.064	0.093	0.377	0.211

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

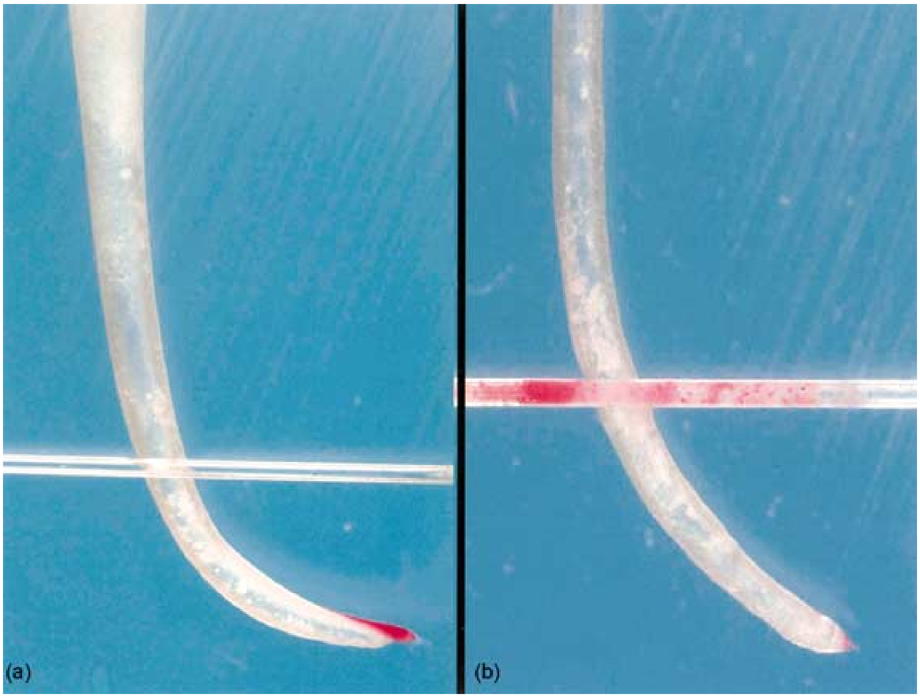


Figure 5 Representative examples of canal shapes of 35° curved canals as the result of instrumentation with (a) ProTaper files and (b) RaCe files. Notice the sections of red-coloured canal walls, indicating that nearly no resin has been removed on this canal wall areas.

are in accordance with two recently published studies (Elasaad *et al.* 2002, Peters *et al.* 2003), which demonstrated that varying degrees of canal straightening and transportation towards the outer aspect of the curvature were evident when curved canal were enlarged with ProTaper instruments. In contrast, Bergmans *et al.* (2003) reported that a transportation towards the outer side of the curvature was not observed for the ProTaper files in the apical part of the canals, but these files tended to transport towards the furcation in the coronal part of the canals.

The fact that some canal transportation towards the outer aspect of the canal was evident with ProTaper files may be because of the variable tapers along the cutting surface of these files, in combination with the sharp cutting edges because of their cross-sectional design. Certainly, the decreasing taper sequence of the finishing files enhances the strength of the files, but it increases the stiffness of their tips. For example, the taper at the tip of a ProTaper size 30 is 9% whereas the taper of a size 20 is only 7%. Considering these differences in the tapers of the tip region, thought should be given to whether

Table 6 Mean material removed (mm) and SD at the different measuring points after instrumentation of simulated 35° curved canals

	Inner canal wall (mm from the apex)										Outer canal wall (mm from the apex)									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
ProTaper																				
Mean	0.05	0.07	0.11	0.13	0.28	0.52	0.68	0.76	0.68	0.53	0.21	0.33	0.40	0.37	0.27	0.13	0.04	0.03	0.03	0.05
SD	0.03	0.05	0.06	0.07	0.09	0.10	0.09	0.10	0.10	0.07	0.06	0.11	0.10	0.09	0.08	0.06	0.04	0.02	0.02	0.04
RaCe																				
Mean	0.09	0.11	0.18	0.19	0.24	0.32	0.43	0.48	0.41	0.33	0.17	0.17	0.21	0.23	0.20	0.17	0.09	0.04	0.04	0.05
SD	0.05	0.05	0.07	0.07	0.09	0.10	0.10	0.09	0.09	0.10	0.04	0.06	0.06	0.07	0.08	0.09	0.07	0.04	0.04	0.04
P-value	**	**	**	*	0.015	***	***	***	***	***	*	***	***	***	*	*	*	0.366	0.459	0.613

$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

Table 7 Comparison of the results obtained in previous studies under identical experimental conditions using different rotary nickel titanium instruments

		Mean preparation time (min)		Mean loss of working length (mm)		Fracture rate (%)	
Instrument	Reference	28° Curved canals	35° Curved canals	28° Curved canals	35° Curved canals	Related to the number of files used	Related to the number of canals
ProFile	Schäfer & Fritzenschaft (1999)	14.47	14.80	0.34	0.40	2.4	29.2
Hero 642	Schäfer (2001)	8.00	12.95	0.15	0.22	6.9	6.3
FlexMaster	Schäfer & Lohmann (2002)	4.73	4.55	0.31	0.31	1.2	4.2
K3	Schäfer & Florek (2003)	6.92	6.49	0.28	0.35	2.9	22.9
ProTaper	Present study	5.75	6.30	0.26	0.38	1.2	4.2
RaCe	Present study	4.59	5.52	0.16	0.20	1.8	6.3

there is an absolute necessity to enlarge a curve up to size 30 with ProTaper instruments because the larger instruments are stiffer and cause high lateral forces in curved canals (Bergmans *et al.* 2001). These restoring forces attempt to return the file to its original shape and act on the outer side on the canal wall during preparation. The resulting transportation leaves a certain portion of the canal wall uninstrumented (Bergmans *et al.* 2001). In fact, it can be noted in the present study that in several cases no resin was removed on the inner side of the curvature in the apical part of the canals when ProTaper files were used (Figs 4a and 5a). This finding corroborates the results of previous studies (Bergmans *et al.* 2003, Cosby *et al.* 2003) and is consistent with an investigation of Peters *et al.* (2001) who reported that about 35% of the canal surface area was not prepared when different nickel–titanium preparation techniques were used.

RaCe instruments provided a centred apical preparation of the simulated canals and maintained the original shape of the curved canals (Figs 4 and 5). This finding is in agreement with recent preliminary reports (Elasaad *et al.* 2002, Baumann *et al.* 2003, Cosby *et al.* 2003). Nevertheless, in order to completely assess the shaping potential of RaCe instruments, further studies are required to focus on other criteria for canal preparation such as three-dimensional analysis of the prepared canal in order to assess smoothness, flow characteristics and taper of the enlarged canals.

In the present study, none of the canals became blocked with resin debris and none of the canals showed overextension of preparation. Thus, the only changes of working length was a loss of working distance. In general, it was possible with both types of instruments to control the working distance well (Table 3), although a significantly greater loss of working length resulted with ProTaper than with RaCe instruments, in both the 28° and the 35° curved canals ($P < 0.05$). This finding is in agreement with several observations of other studies in that only small mean changes in working distance occurred with rotary nickel–titanium instruments (Kum *et al.* 2000, Thompson & Dummer 2000a, Schäfer & Lohmann 2002, Schäfer & Florek 2003). On the whole, it is questionable whether the small changes in working length observed in the present study would have any clinical significance. These changes may be probably because of minor canal straightening during canal enlargement or lack of length control by the operator (Thompson & Dummer 2000a).

The mean time for canal preparation was recorded and included instrument changes within the instrumentation sequences. Both in the 28° and 35° curved canals, RaCe instruments were significantly faster than ProTaper files (Table 2). Nevertheless, compared with other rotary nickel–titanium files, instrumentation times with ProTaper instruments were more rapid than with several other rotary nickel–titanium instruments (Table 7).

During the present study, three RaCe and two ProTaper instruments fractured. It is worth emphasizing that all these were .02 taper size 25 instruments (RaCe) and F3 files (ProTaper). To date, no data is available on the torsional properties of these rotary instruments; therefore, no explanation can be given why these particular instruments were susceptible to fracture. Related to the total number of instruments used, a fracture rate of approximately 1.2% resulted for the ProTaper instruments (2 out of 168 files used when all instruments were used to enlarge two canals only) and approximately 1.8% (3 out of 168 files) for the RaCe instruments, respectively. Related to the total number of 48 simulated canals enlarged with each of these instruments, the separation rate ranged between 4.2 and 6.3%, respectively. In comparison with previously published studies conducted under the same experimental conditions as used in the present investigation, the separation rates of both instruments were lower compared to the fracture frequency of Hero 642, ProFile and K3 instruments and were nearly in the same range as that for FlexMaster instruments (Table 7). This relatively low incidence of instrument fracture may be related to the triangular cross-sectional design of the two instruments that results in sharper cutting edges and a larger core when compared to U-shaped files or to instruments having radial land reliefs (Hülsmann *et al.* 2003). Thus, when using ProTaper or RaCe files according to the instrumentation sequence described in the present study, the fracture rate of both instruments was comparable to previously reported fracture rates of newer rotary nickel–titanium instruments (Thompson & Dummer 1997a; 2000a, Baumann & Roth 1999, Kum *et al.* 2000).

Conclusions

The results of the present investigation confirm the results of previous studies on different rotary nickel–titanium instruments concerning their ability to maintain the original shape of severely curved canals (Thompson & Dummer 1997a,b,c,d, Baumann & Roth 1999, Kum *et al.* 2000, Schäfer 2001, Schäfer & Lohmann 2002, Schäfer & Florek 2003). Within the limitations of this present study, ProTaper and RaCe instruments prepared curved canals rapidly and were relatively safe. In both canal types, RaCe instruments maintained the original canal curvature better than ProTaper, which tended to transport towards the outer aspect of the curve in the apical part of the canals.

References

Al-Omari MAO, Dummer PMH, Newcombe RG (1992) Comparison of six files to prepare simulated root canals. Part 2. *International Endodontic Journal* **21**, 67–81.

Baumann MA, Roth A (1999) Effect of experience on quality of canal preparation with rotary nickel-titanium files. *Oral Surgery* **88**, 714–8.

Baumann MA, Leinbrock O, Hellmich M, Baumann-Giedziella UA (2003) Effectiveness of root canal instrumentation with RaCe: an SEM study. *Journal of Endodontics* **29**, 286 (Abstract).

Bergmans E, Van Cleynenbreugel J, Wevers M, Lambrechts P (2001) Mechanical root canal preparation with NiTi rotary instruments: rationale, performance and safety. Status report for the American Journal of Dentistry. *American Journal of Dentistry* **14**, 324–33.

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.

Briseño BM, Sonnabend E (1991) The influence of different root canal instruments on root canal preparation: an in vitro study. *International Endodontic Journal* **24**, 15–23.

Cosby VD, Apicella MJ, Yancich PP, Parker M (2003) Comparison of three instrumentation techniques in curved canals. *Journal of Endodontics* **29**, 288 (Abstract).

Elasaad MG, Isler AE, McDonald NJ (2002) An evaluation of root canal centering abilities of ProTaper and RaCe Ni-Ti rotary files and Flexofiles. *Journal of Endodontics* **28**, 247 (Abstract).

European Society of Endodontology (1994) Consensus report of the European Society of Endodontology on quality guidelines for endodontic treatment. *International Endodontic Journal* **27**, 115–24.

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.

Kum K-Y, Spångberg L, Cha BY, Young J, II, Seung-Jong L, Chan-Young L (2000) Shaping ability of three ProFile rotary instrumentation techniques in simulated resin root canals. *Journal of Endodontics* **26**, 719–23.

Peters OA, Schönenberger K, Laib A (2001) Effects of four Ni-Ti preparation techniques on root canal geometry assessed by micro computer tomography. *International Endodontic Journal* **34**, 211–30.

Peters OA, Peters CI, Schönenberger K, Barbakow F (2003) ProTaper rotary root canal preparation: effects of canal anatomy on final shape analysed by micro CT. *International Endodontic Journal* **36**, 86–92.

Ruddle C (2002) Cleaning and shaping the root canal system. In: Cohen S, Burns RC, eds. *Pathways of the Pulp*, 8th edn. St Louis, MO: Mosby, pp. 231–92.

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, Florek H (2003) Efficiency of rotary nickel-titanium K3 instruments compared with stainless steel hand K-Flexofile. Part 1. Shaping ability in simulated curved canals. *International Endodontic Journal* **36**, 199–207.

Schäfer E, Fritzenschaft F (1999) Vergleichende Untersuchung zweier permanent rotierender Wurzelkanalaufbereitungs-systeme auf Nickel-Titan-Basis. *Endodontie* **8**, 213–26.

Schäfer E, Lohmann D (2002) Efficiency of rotary nickel-titanium FlexMaster instruments compared with stainless steel hand K-Flexofile. Part 1. Shaping ability in simulated curved canals. *International Endodontic Journal* **35**, 505–13.

Schäfer E, Tepel J, Hoppe W (1995) Properties of endodontic hand instruments used in rotary motion. Part 2. Instrumentation of curved canals. *Journal of Endodontics* **21**, 493–7.

Schneider SW (1971) A comparison of canal preparations in straight and curved canals. *Oral Surgery* **32**, 271–5.

Thompson SA, Dummer PMH (1997a) Shaping ability of NT engine and McXim rotary nickel-titanium instruments in simulated root canals: part 1. *International Endodontic Journal* **30**, 262–9.

Thompson SA, Dummer PMH (1997b) Shaping ability of Lightspeed rotary nickel-titanium instruments in simulated root canals. Part 1. *Journal of Endodontics* **23**, 698–702.

Thompson SA, Dummer PMH (1997c) Shaping ability of ProFile .04 taper series 29 rotary nickel-titanium instruments in simulated canals. Part 1. *International Endodontic Journal* **30**, 1–7.

Thompson SA, Dummer PMH (1997d) Shaping ability of ProFile .04 taper series 29 rotary nickel-titanium instruments in simulated root canals. Part 2. *International Endodontic Journal* **30**, 8–15.

Thompson SA, Dummer PMH (2000a) Shaping ability of Hero 642 rotary nickel-titanium instruments in simulated root canals: part 1. *International Endodontic Journal* **33**, 248–54.

Thompson SA, Dummer PMH (2000b) Shaping ability of Hero 642 rotary nickel-titanium instruments in simulated root canals: part 2. *International Endodontic Journal* **33**, 255–61.

Wildey WL, Senia S, Montgomery S (1992) Another look at root canal instrumentation. *Oral Surgery, Oral Medicine, Oral Pathology* **74**, 499–507.

