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

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Abstract

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Aim To determine the cleaning effectiveness and shaping ability of ProTaper and RaCe nickel–titanium rotary instruments during the preparation of curved root canals in extracted human teeth.

Methodology A total of 48 root canals of mandibular and maxillary molars with curvatures ranging between 25° and 35° were divided into two groups of 24 canals each. Based on radiographs taken prior to instrumentation with the initial instrument inserted into the canal, the groups were balanced with respect to the angle and the radius of canal curvature. Canals were prepared using a crown-down preparation technique. After each instrument, the root canals were flushed with a 2.5% NaOCl solution and at the end of instrumentation with NaCl. Using pre- and post-instrumentation radiographs, straightening of the canal curvatures was determined with a computer image analysis program. After splitting the roots longitudinally, the amount of debris and smear layer was quantified on the basis of a numerical evaluation scale, using a scanning electron microscope (SEM). The data established for scoring the debris and the smear layer were separately recorded and analysed statistically using the Wilcoxon test.

Results Two ProTaper and three RaCe instruments fractured; there was no significant difference between instrument types ($P > 0.05$). Completely clean root canals were never observed. For debris removal, RaCe files achieved significantly better results ($P < 0.001$) than ProTaper instruments. The results for remaining smear layer were similar and not significantly different ($P > 0.05$). RaCe instruments maintained the original canal curvature significantly better ($P < 0.05$) than ProTaper instruments. No significant differences were detected between the instruments ($P > 0.05$) for the time taken to prepare the canals.

Conclusions Under the conditions of this study, RaCe instruments resulted in relatively good cleaning and maintained the original curvature significantly better than ProTaper did.

Keywords: canal curvature, canal straightening, debris, irrigation, smear layer.

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Introduction

Successful root canal treatment depends amongst other factors on the removal of microorganisms through chemo-mechanical instrumentation of the root canal system. This includes the removal of the infected dentine and organic tissue by shaping and dissolution. Thus, the cleaning ability of any root canal instrument is of importance for the outcome of root canal treatment.

Recently, rotary nickel–titanium root canal instruments have become an important part of the endodontic armamentarium. Most of these newly introduced systems have been investigated with regard to their shaping ability in simulated curved canals or curved canals in extracted teeth. These studies have shown that nickel–titanium rotary instruments can effectively produce a

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well-tapered root canal form sufficient for obturation, with minimal risk of transporting the original canal (Thompson & Dummer 1997, 1998, Bertrand *et al.* 2001, Hülsmann *et al.* 2001, 2003, Schäfer & Lohmann 2002, Schäfer & Schlingemann 2003). Nevertheless, another factor of major interest, the cleaning efficiency of rotary nickel–titanium instruments, requires further investigation, especially because only a few studies have focused on this parameter (Hülsmann *et al.* 2000; 2001; 2003, Schäfer & Zapke 2000, Gambarini & Laszkiewicz 2002, Versümer *et al.* 2002, Schäfer & Schlingemann 2003). Moreover, these investigations have shown that the different rotary nickel–titanium instruments produced inconsistent results and that variation in the debris-removal efficiency of different rotary nickel–titanium instruments may result from variation in flute designs. Obviously, instruments with sharp cutting edges seem to be superior to those having radial lands (Jeon *et al.* 2003).

Recently, two new rotary nickel–titanium instruments with sharp cutting edges (Schäfer & Vlassis 2003) were introduced, but little information exists about their cleaning ability. Consequently, the aim of this investigation was to compare the cleaning efficacy (residual debris, quality of the smear layer) after preparation of severely curved root canals with ProTaper instruments (Dentsply Maillefer, Ballaigues, Switzerland) and RaCe files (FKG, La Chaux-de-Fonds, Switzerland). Moreover, another purpose of this study was to assess whether instrumentation had an effect on canal curvature.

Materials and methods

Selection of teeth

A total of 48 extracted human maxillary and mandibular molars with intact crowns and with at least one curved root and canal were selected. Coronal access was achieved using diamond burs, and the canals were controlled for apical patency with a root canal instrument of size 10. Only teeth with intact root apices and those whose root canal width near the apex was approximately compatible with size 15 were included. This was checked with silver points sizes 15 and 20 (Antaeos, Munich, Germany).

Standardized radiographs were taken prior to the instrumentation with the initial root canal instrument of size 15 inserted into the curved canal. The tooth was placed in a radiographic mount made of silicone-based impression material (Silaplast Futur, Detax, Ettlingen, Germany) to maintain a constant position. The radiographic mount comprised a radiographic paralleling device embedded in acrylic resin. This device was attached to a Kodak Ultra-speed film (Kodak, Stuttgart, Germany) and was aligned so that the long axis of the root canal was parallel and as near as possible to the surface of the film. The X-ray tube, and thus the central X-ray beam, was aligned perpendicular to the root canal. The exposure time (0.12 s; 70 kV, 7 mA) was the same for all radiographs with a constant source-to-film distance of 50 cm and an object-to-film distance of 5 mm. The films were developed, fixed and dried in an automatic processor (Dürr-Dental XR 24 Nova, Dürr, Bietigheim-Bissingen, Germany).

The degree and the radius of canal curvature were determined using a computerized digital image-processing system (Schäfer *et al.* 2002). Only teeth whose radii of curvature ranged between 3.5 and 9 mm and those whose angles of curvature ranged between 25° and 35° were included (Table 1). On the basis of the degree and the radius of curvature, the teeth were allocated into two identical groups of 24 teeth each. The homogeneity of the two groups with respect to the degree and the radius of curvature was assessed using a *t*-test (Table 1). At the end of canal preparation, the canal curvatures were redetermined on the basis of a radiograph with the final root canal instrument inserted into the canal using the same technique (Schäfer *et al.* 2002) in order to compare the initial curvatures with those after instrumentation. Only one canal was instrumented in each tooth.

Root canal instrumentation

The working length for all groups was obtained by measuring the length of the initial instrument (size 10) at

Table 1 Characteristics of curved root canals ($n = 24$ teeth per group)

Instrument	Curvature (°)			Radius (mm)		
	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum
ProTaper	29.71 ± 3.23	25.0	35.0	6.54 ± 1.41	3.8	8.5
RaCe	30.04 ± 3.45	26.0	35.0	6.44 ± 0.98	3.7	7.9
P-value (*t*-test)	0.732			0.785		

the apical foramen minus 1 mm. Instruments were used to enlarge two canals only. After each instrument, the root canal was flushed with 5 mL of a 2.5% NaOCl solution and at the end of instrumentation with 5 mL of NaCl using a plastic syringe with a gauge 30 closed-end needle (Hawe Max-I-probe, Hawe-Neos, Bioggio, Switzerland). The needle was inserted as deep as possible into the root canal without binding.

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. The preparation sequences were the same as those described in Part 1 of this two-part report (Schäfer & Vlassis 2003).

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 one-third of the working length.
2 An SX (auxiliary shaping file; taper .035–.19; size 19) used to one-half of the working length.
3 An S1 file was used to one-half to two-thirds of the working length.
4 An S2 file (shaping file no. 2; taper .04–.115; size 20) was used to two-thirds of the working length.
5 An F1 file (finishing file no. 1; taper .07–.055; size 20) was used to the full working length.
6 An F2 file (finishing file no. 2; taper .08–.055; size 25) was used to the full working length.
7 An F3 file (finishing file no. 3; taper .09–.05; size 30) was used to the full working length.

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

Group B

RaCe 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 one-third to one-half of the working length.
2 A .08 taper size 35 instrument was used to one-half of the working length.
3 A .06 taper size 30 instrument was used to one-half to two-thirds of the working length.
4 A .04 taper size 25 instrument was used to two-thirds of the working length.
5 A .02 taper size 25 instrument was used to the full working length.
6 A .02 taper size 30 instrument was used to the full working length.
7 A .02 taper size 35 instrument was used to the full working length.

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

Evaluations

All root canal preparations were completed by one operator, while the scanning electron microscope (SEM; Philips PSEM 500X, Eindhoven, the Netherlands) evaluations and the assessment of the canal curvatures prior to and after instrumentation were carried out by a second examiner who was blind with respect of all to the experimental groups.

Canal cleanliness

After preparation, all root canals were flushed with NaCl and dried with absorbent paper points. Roots were split longitudinally, prepared for SEM investigation and examined under the SEM at 20–2500× magnification.

Separate evaluations were recorded for debris and smear layer. The cleanliness of each root canal was evaluated in three areas (apical, middle and coronal thirds of the root) by means of a numerical evaluation scale (Hülsmann *et al*. 1997). The following scheme was used:

- Debris (dentine chips, pulp remnants and particles loosely attached to the canal wall):
  - Score 1: clean canal wall, only very few debris particles.
  - Score 2: few small conglomerations.
  - Score 3: many conglomerations, less than 50% of the canal wall covered.
  - Score 4: more than 50% of the canal wall covered.
  - Score 5: complete or nearly complete covering of the canal wall by debris.
- Smear layer (dentine particles, remnants of vital or necrotic pulp tissue, bacterial components, and retained irrigant):
  - Score 1: no smear layer, orifice of dentinal tubules patent.
  - Score 2: small amount of smear layer, some open dentinal tubules.
  - Score 3: homogenous smear layer along almost the entire canal wall, only very few open dentinal tubules.

○ Score 4: the entire root canal wall covered with a homogenous smear layer, no open dentinal tubules.
○ Score 5: a thick, homogenous smear layer covering the entire root canal wall.

The data established for scoring the debris and the smear layer were separately recorded and analysed statistically. Because of the ordinal nature of the scores, the data were subjected to the Wilcoxon test ($P < 0.05$).

Instrumentation results

Based on the canal curvatures assessed prior to and after instrumentation, canal straightening was determined as the difference between canal curvature prior to and after the instrumentation. The *t*-test was used for comparison of the two groups. The level of statistical significance was set at $P < 0.05$.

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

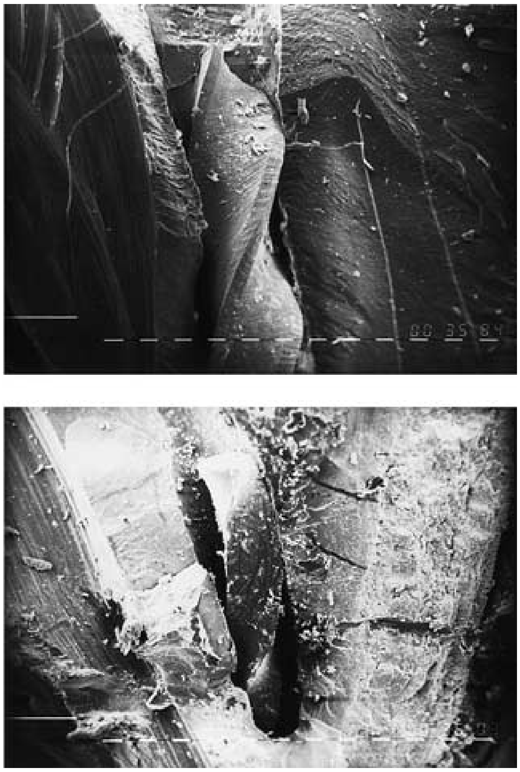
Results

Instrument failure

During the preparation of the curved canals, two ProTaper (S1 and F3) and three RaCe (two .02 taper size 25 and one .02 taper size 35) instruments fractured. All instruments separated at the tip region (Fig. 1). A total of 10 ProTaper and 12 RaCe instruments permanently deformed during instrumentation. The differences between the two instrument types were not statistically significant, in terms of the number of either separated instruments or permanently deformed instruments (χ^2-test; $P > 0.05$).

Canal cleanliness

The scores for debris and smear layer are detailed in Tables 2 and 3. Completely cleaned root canals were never found. On average, cleaning was significantly more effective in the coronal and middle thirds of canals ($P < 0.05$; Fig. 2).



(a)

(b)

Figure 1 Separated files in the apical portions of curved canals. Notice the agglomeration of debris (original magnification 40×). (a) ProTaper F3 file; (b) RaCe instrument .02 taper size 35.

In general, the use of RaCe instruments resulted in significantly less debris ($P < 0.001$) compared to canal preparation with ProTaper instruments (Table 2). In terms of smear layer (Fig. 3), the ProTaper files resulted in 27.3% and the RaCe system in 23.8% of specimens having scores 1 and 2 (Table 3); no statistically significant differences were apparent ($P = 0.416$).

Instrumentation results

The mean time taken to prepare the canals with the two types of instruments is shown in Table 4. There were no statistical significant differences between the two instruments ($P = 0.919$).

All canals remained patent following instrumentation; thus, none of the canals were blocked with dentine. With both types of instruments, no canal showed overextension of preparation, whereas a loss of working distance was found in four canals prepared with ProTaper

Table 2 Summary of scores for debris*

	Coronal third scores					Middle third scores					Apical third scores					Total scores				
Instrument	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ProTaper	4	5	8	3	2	2	5	10	4	1	1	3	5	8	4	7	13	24	15	7
RaCe	7	9	4	1	0	4	10	5	2	0	2	7	7	3	2	13	26	16	6	2
P-values	<0.05					<0.05					<0.05					<0.001				

*Listed are the number of canal areas evaluated as scores 1 to 5 ($n = 24$ teeth per group). Three canal areas (coronal, middle and apical thirds) have been evaluated per tooth, thus resulting in a total of 72 canal areas per each tooth. Because of two fractures of the ProTaper instruments, six canal areas could not be evaluated in this group. Because of three fractures of the RaCe files, nine canal areas could not be evaluated in this group. Score 1 indicates the best and score 5 the worst result.

Table 3 Summary of scores for smear layer*

	Coronal third scores					Middle third scores					Apical third scores					Total scores				
Instrument	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ProTaper	1	8	8	4	1	0	6	9	4	3	0	3	12	3	4	1	17	29	11	8
RaCe	1	6	8	6	0	0	5	8	6	2	0	3	7	9	2	1	14	23	21	4
P-values	<0.671					<0.670					<0.544					<0.416				

*Listed are the numbers of canal areas evaluated as scores 1–5 ($n = 24$ teeth per group). Three canal areas (coronal, middle and apical thirds) have been evaluated per tooth, thus resulting in a total of 72 canal areas per tooth. Because of two fractures of the ProTaper instruments, six canal areas could not be evaluated in this group. Because of three fractures of the RaCe files, nine canal areas could not be evaluated in this group. Score 1 indicates the best and score 5 the worst result.

and three canals enlarged with RaCe files. The mean changes of working length that occurred with the different instruments are listed in Table 4. The differences between the two instrument types were not statistically significant ($P = 0.724$).

The mean straightening of the curved canals is shown in Table 5. The use of RaCe files resulted in significantly less straightening (1.72°) during instrumentation ($P < 0.05$) compared to the ProTaper instruments (3.22°; Fig. 4).

Discussion

This two-part report is one of a series of investigations (Table 6) on different rotary nickel–titanium instruments with identical experimental conditions. One of the objectives of this investigation was to allow comparisons amongst different rotary systems.

Cleaning effectiveness

One of the most important objectives during root canal instrumentation is the removal of vital and/or necrotic pulp tissue, infected dentine and dentine debris in order to eliminate most of the microorganisms from the root canal system (European Society of Endodontology 1994, American Association of Endodontists 1998). The ability to achieve some of these objectives was examined *in vitro* in this investigation on severely curved root canals, involving ProTaper and RaCe rotary nickel–titanium instruments. To date, little information exists about the performance of these two instruments in terms of shaping ability in real teeth and their cleaning efficiency.

In this study, the cleaning efficiency of the different instruments was assessed using two criteria: debris and smear layer. Debris was defined as dentine chips, and residual vital or necrotic pulp tissue attached to the root canal wall, which in most cases is infected (Hülsmann *et al.* 1997). Thus, debris might prevent the efficient removal of microorganisms from the root canal system. Moreover, debris may occupy part of the root canal space and thus may also prevent complete obturation of the root canal (Wu *et al.* 2001). The smear layer is a surface film of a thickness of approximately 1–2 μm (American Association of Endodontists 1998). Smear layer, which is mainly inorganic, is produced when a canal is instrumented (Grandini *et al.* 2002); no smear layer is found on areas that are not instrumented (West *et al.* 1994). Although the influence of smear layer on outcome of the endodontic treatment is still controversial, it is considered to be desirable to remove the smear layer because of its potential deleterious effects (Lim *et al.* 2003). For example, the smear layer contains dentine particles, residual vital or necrotic pulp tissue, proteinic agglomerates, blood cells and might harbour microorganisms (West *et al.* 1994, Grandini *et al.* 2002). Thus, the smear layer might block the openings of the dentinal tubules and in this way impede penetration or diffusion of irrigants or antibacterial medicaments into the dentinal tubules (Bystrom & Sundqvist 1986, West *et al.* 1994). Moreover, the smear layer might compromise the complete sealing of the root canal (Petschelt *et al.* 1987, Saunders *et al.* 1992, Oksan *et al.* 1993, West *et al.* 1994).

Although the use of antibacterial irrigants is recommended in combination with chelating agents in order to remove debris as well as the inorganic/organic smear layer (West *et al.* 1994, Hülsmann *et al.* 1997, Gambarini 1999, Grandini *et al.* 2002, Lim *et al.* 2003), in the present study, sodium hypochlorite alone was used as an irrigant. This solution would appear the best available canal irrigant because of its antibacterial and organic tissue-dissolving properties (Spångberg *et al.* 1973, Turkun & Çengiz 1997), but it is not possible to remove the smear layer with NaOCl (Yamada *et al.* 1983, Grandini *et al.* 2002, Guerisoli *et al.* 2002, Lim *et al.* 2003). Nevertheless,

(a) (b) (c)

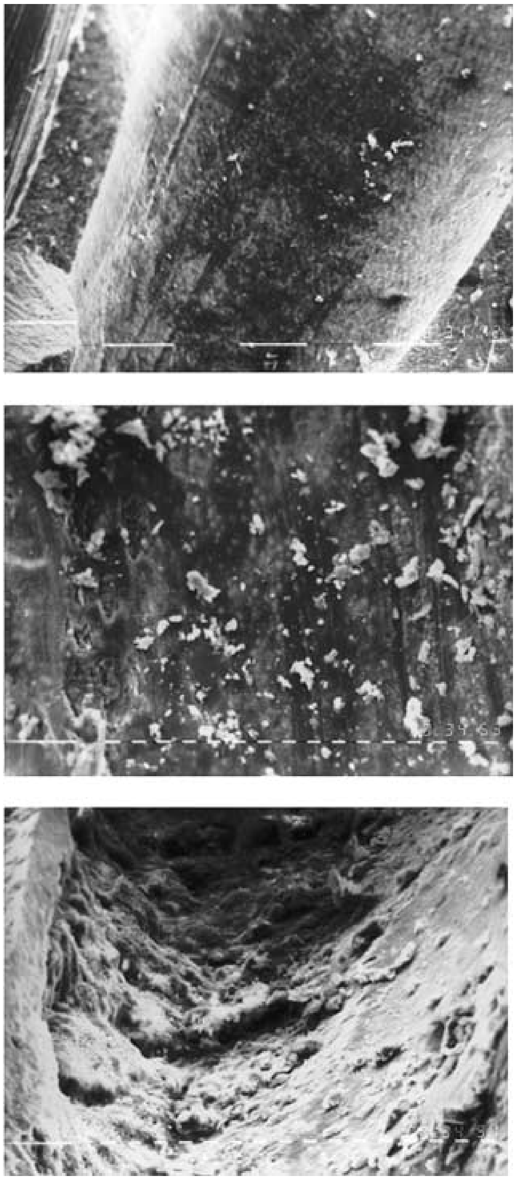


Figure 2 Canal wall after preparation with the two rotary nickel–titanium instruments. (a) Nearly clean canal wall with small agglomerations of debris particles in the middle portion of the canal prepared with ProTaper files (score 1, original magnification 160×). (b) Middle portion of the canal after enlargement with RaCe instruments (score 3, original magnification 320×). (c) Apical portion of the canal after instrumentation with ProTaper files: complete or nearly complete covering of the canal wall by debris after preparation (score 5, original magnification 640×).

(a) (b)

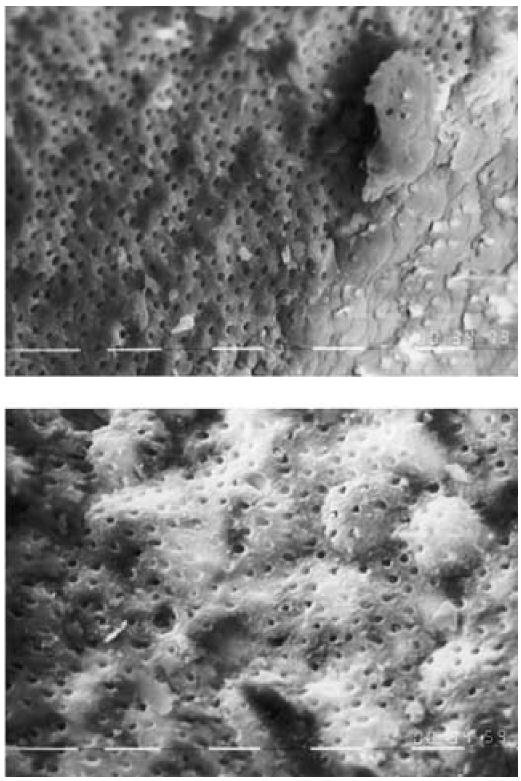


Figure 3 Canal wall after preparation with the two rotary nickel–titanium instruments: Small amounts of smear layer and some open dentinal tubules are visible (original magnification 1250×). (a) ProTaper: score 2; (b) RaCe: score 1.

Table 4 Mean preparation time (min) and SD and mean changes of working distance (mm) and SD with the two different instruments ($n = 24$ canals in each group)

Instrument	*n*	Preparation time (min)		Working distance (mm)	
		Mean	SD	Mean	SD
ProTaper	22*	6.48	0.97	−0.11	0.26
RaCe	21**	6.32	0.75	−0.06	0.17

*Because of two instrument fractures in this group.
**Because of three instrument fractures in this group.

Table 5 Mean degree of straightening of curved canals (°) and SD after canal preparation with the two different instruments ($n = 24$ canals in each group)

Instrument	*n*	Straightening (°)			
		Mean	SD	Minimum	Maximum
ProTaper	22*	3.22	2.64	0	9.5
RaCe	21**	1.72	1.74	0	5.6

*Because of two instrument fractures in this group.
**Because of three instrument fractures in this group.

considering the major objective of the present investigation (to compare the cleaning effectiveness of the two instrumentation techniques under identical conditions), a simple irrigation technique was used, avoiding any associations of different irrigation solutions. As it has been shown recently by several authors (Hülsmann *et al.* 2001, Grandini *et al.* 2002, Lim *et al.* 2003) that EDTA-containing chelating agents (e.g. RC-Prep, Premier, Philadelphia, USA, or Glyde File Prep, Dentsply Maillefer) may be partially responsible for effective cleaning of canal walls after instrumentation with rotary nickel–titanium instruments, it has to be taken into consideration that the cleaning efficiency of the two instruments evaluated in the present study might be further improved using a combination of NaOCl- and EDTA-containing chelating agent.

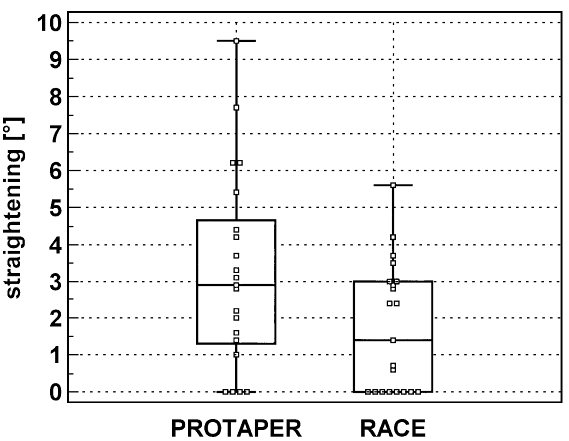


Figure 4 Straightening of the curved canals after preparation with the two different instruments ($n = 24$ canals in each group): combined box-and-whisker and dot plot; each dot represents a reading of the difference between canal curvature prior to and that after instrumentation.

In the present study, the cleaning efficacy of two instrumentation sequences was examined on the basis of a separate numerical evaluation scheme for debris and smear layer, by means of an SEM evaluation of the coronal, middle and apical portions of the canals (Haikel & Allemann 1988, Hülsmann *et al.* 1997). With both instrumentation techniques, partially uninstrumented areas with remaining debris were found in all canal sections. This finding has also been described by others (Bolanos & Jensen 1980, Hülsmann *et al.* 1997; 2003) and is consistent with two other investigations using micro computer tomography assessment of canal shapes (Peters *et al.* 2001, 2003). It has been reported that approximately 35% of the canal surface area was not prepared when different nickel–titanium preparation techniques were used (Peters *et al.* 2001), and that enlargement of wide canals using ProTaper files resulted in 43–49% uninstrumented canal walls (Peters *et al.* 2003). Moreover, the present results indicate that on average the apical third of the canals was less clean than the middle and coronal thirds regardless of the instrument used. This observation is also in agreement with other studies (Wu & Wesselink 1995, Hülsmann *et al.* 1997; 2001; 2003, Schäfer & Zapke 2000, Gambarini & Laszkiewicz 2002, Schäfer & Schlingemann 2003). Generally, these investigations underline the limited efficiency of all instruments tested in cleaning the apical part of the root canal and the importance of irrigation

Table 6 Comparison of the results obtained in previous studies under identical experimental conditions using different rotary nickel–titanium instruments

Instrument	Reference	Straightening (°)	Mean preparation time (min)	Mean score for debris	Mean score for smear layer	Mean loss of working length (mm)	Fracture rate (%) Related to the number of files used	Fracture rate (%) Related to the number of canals
ProFile	Schäfer & Zapke (2000)	3.10	n.e.	3.64	3.84	n.e.	0	0
FlexMaster	Schäfer & Lohmann (2002)	2.14	5.54	2.44	3.39	0.02	0	0
K3	Schäfer & Schlingemann (2003)	1.36	7.21	2.66	3.33	0.04	2.1	16.7
ProTaper	Present study	3.22	6.48	3.03	3.12	0.11	2.4	8.3
RaCe	Present study	1.72	6.32	2.33	3.22	0.06	3.6	12.5

n.e., not evaluated.

as crucial for sufficient disinfection of the root canal system (Hülsmann *et al.* 2003).

In general, the use of RaCe instruments resulted in significantly less remaining debris (Table 2) compared to canal shaping with ProTaper instruments ($P < 0.001$), whereas for smear layer no significant differences between these instruments occurred (Table 3; $P = 0.416$). A reason for this difference in the debris-removal capacity of the two instruments may be that the final apical preparation diameter in the ProTaper group was of size 30 (finishing file no. 3) and the final apical diameter in the RaCe group was of size 35, as already discussed in the first part of this report (Schäfer & Vlassis 2003). As most recently it has been shown that larger apical preparation sizes are necessary in many cases in order to contact as much of the circumference of the root canal as possible (Hülsmann *et al.* 2003), the difference in final apical preparation diameter should be kept in mind when interpreting the present results. Generally, the results of this present investigation are in agreement with the findings of several earlier studies on postpreparation canal cleanliness using different rotary nickel–titanium instruments (Hülsmann *et al.* 2001; 2003, Gambarini & Laszkiewicz 2002, Schäfer & Lohmann 2002, Schäfer & Schlingemann 2003). A comparison of the results obtained in previous studies under identical experimental conditions (Table 6) reveals that the RaCe instruments showed a relatively good cleaning ability. This is coincident with the report by Baumann *et al.* (2003).

A further comparison of the results for ProTaper and RaCe with those of recent studies investigating other rotary nickel–titanium instruments under identical conditions but with different operators (Table 6) elucidates that different rotary nickel–titanium instruments vary in their debris-removal efficiency, possibly because of their flute design (Gambarini 1999, Hülsmann *et al.* 2000). For instance, ProFile instruments have radial lands and this file design was less efficient in debris removal compared to rotary instruments having a positive rake angle (Table 6).

Shaping ability

Despite the variations in the morphology of natural teeth, several attempts have been made to ensure standardization of the experimental groups. Therefore, the teeth in both experimental groups were balanced with respect to the apical diameter of the root canal, and based on the initial radiograph, the teeth were also balanced with respect to the angle and the radius of canal curvature. To achieve this, a computerized digital image processing system was used to determine both the angle and the radius of curvature (Schäfer *et al.* 2002). The homogeneity of the two groups with respect to the defined constraints was examined using a *t*-test. According to the *P*-values obtained (Table 1), the groups were well balanced. The curvatures of all root canals ranged between 25° and 35°, and the radii ranged between 3.7 and 8.5 mm (Table 1). Thus, the curvatures of the human root canals were comparable to those of the simulated canals in resin blocks used in the first part of this two-part report (curvatures: 28° and 35°; radii: 6.5 and 7.5 mm), allowing a comparison of the results obtained in simulated and in human root canals (Schäfer & Vlassis 2003). Moreover, the apical canal diameters and the curvatures of the teeth used in the present study were comparable to the teeth used in previous investigations (Table 6), allowing comparisons amongst different rotary NiTi systems.

Concerning the ability of the two instruments tested to maintain original canal curvatures, better compliance with original canal shape was obtained using the RaCe system compared to ProFile instruments ($P < 0.05$; Fig. 4). In general, the results of the present study using extracted human teeth confirm the findings obtained in the first part of this two-part report after preparation of simulated canals (Schäfer & Vlassis 2003) in that the use of RaCe instruments resulted in significantly less canal transportation than did ProTaper. In simulated canals, RaCe instruments were significantly faster than ProTaper. Certainly, RaCe files needed less time to prepare the root canals of real teeth than did ProTaper, but this differences was not significant in contrast to the results obtained in simulated canals.

Interestingly, although the results for RaCe were comparable to those of recent investigations under identical experimental conditions (Table 6), the mean value for straightening of ProTaper files was greater than that for other rotary instruments. The reasons for this observation have already been discussed in the first part of this two-part report (Schäfer & Vlassis 2003).

Instrument failure

During the present study, two ProTaper and three RaCe instruments separated. Related to the total number of instruments used, a fracture rate of approximately 2.4% resulted for the ProTaper and 3.6% for the RaCe files, respectively. Related to the total number of real canals enlarged with these instruments, separation rates of approximately 8.3% (ProTaper) and 12.5% (RaCe) resulted. Summarizing these data and the findings obtained in the first part of this two-part report after preparation of simulated canals (Schäfer & Vlassis 2003) and comparing with previously published studies conducted under the same experimental conditions as used in the present investigation (Table 6), it was found that the separation rates of both files were lower compared to the fracture frequency of K3 files and nearly in the same range as that of other modern rotary instruments.

Conclusions

Within the parameters of this study, the use of RaCe files resulted in significantly less debris compared to canal preparation with ProTaper instruments, whereas in terms of smear layer, no statistically significant differences were apparent. RaCe files maintained the original curvature significantly better than ProTaper.

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