Comparative study of six rotary nickel–titanium systems and hand instrumentation for root canal preparation

A. Guelzow[1], O. Stamm[1], P. Martus[2] & A. M. Kielbassa[1]

[1]Department of Operative Dentistry and Periodontology, University School of Dental Medicine, Campus Benjamin Franklin, Berlin, Germany; and [2]Department of Medical Informatics, Biometry, and Epidemiology, Campus Mitte; Charité – Universitätsmedizin Berlin, Berlin, Germany

Abstract

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Aim To compare *ex vivo* various parameters of root canal preparation using a manual technique and six different rotary nickel–titanium (Ni–Ti) instruments (FlexMaster, System GT, HERO 642, K3, ProTaper, and RaCe).

Methodology A total of 147 extracted mandibular molars were devided into seven groups ($n = 21$) with equal mean mesio-buccal root canal curvatures (up to 70°), and embedded in a muffle system. All root canals were prepared to size 30 using a crown-down preparation technique for the rotary nickel–titanium instruments and a standardized preparation (using reamers and Hedströem files) for the manual technique. Length modifications and straightening were determined by standardized radiography and a computer-aided difference measurement for every instrument system. Post-operative cross-sections were evaluated by light-microscopic investigation and photographic documentation. Procedural errors, working time and time for instrumentation were recorded. The data were analysed statistically using the Kruskal–Wallis test and the Mann–Whitney *U*-test.

Results No significant differences were detected between the rotary Ni–Ti instruments for alteration of working length. All Ni–Ti systems maintained the original curvature well, with minor mean degrees of straightening ranging from 0.45° (System GT) to 1.17° (ProTaper). ProTaper had the lowest numbers of irregular post-operative root canal diameters; the results were comparable between the other systems. Instrument fractures occurred with ProTaper in three root canals, whilst preparation with System GT, HERO 642, K3 and the manual technique resulted in one fracture each. Ni–Ti instruments prepared canals more rapidly than the manual technique. The shortest time for instrumentation was achieved with System GT (11.7 s).

Conclusions Under the conditions of this *ex vivo* study all Ni–Ti systems maintained the canal curvature, were associated with few instrument fractures and were more rapid than a standardized manual technique. ProTaper instruments created more regular canal diameters.

Keywords: automated root canal preparation, canal aberration, Ni–Ti instruments, root canal diameter, working length, working safety, working time.

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Correspondence: Andrej M. Kielbassa, Poliklinik für Zahnerhaltungskunde und Parodontologie, Universitätsklinik für Zahn-, Mund- und Kieferheilkunde, Campus Benjamin Franklin, Charité – Universitätsmedizin Berlin, Aßmannshauser Straße 4-6, D-14197 Berlin, Germany (Tel.: +49-30-84 45 63 03; fax: +49-30-84 45 62 04; e-mail: andrej.kielbassa @charite.de).

Introduction

One of the main objectives of root canal preparation is to shape and clean the root canal system effectively whilst maintaining the original configuration without creating any iatrogenic events such as instrument fracture, external transportation, ledge, or perforation

(Ruddle 2002). However, in particular when used in severely curved canals, traditional stainless steel instruments often fail to achieve the tapered root canal shapes needed for adequate cleaning and filling (Briseño & Sonnabend 1991, Al-Omari *et al.* 1992, Schäfer *et al.* 1995).

During the last decade, several new nickel–titanium (Ni–Ti) instruments for rotary endodontic treatment have extended the endodontic armamentarium. Even though the working safety of rotary instruments has been discussed in different ways, several investigations have shown the ability of some new rotary Ni–Ti systems to maintain the original root canal curvature well (Versümer *et al.* 2002, Hülsmann *et al.* 2003, Paqué *et al.* 2005). In order to improve working safety, shorten preparation time and create a continuously tapered, conical flare of preparations advanced instrument designs with noncutting tips, radial lands, different cross-sections, superior resistance to torsional fracture and varying tapers have been developed (Thompson 2000). There are several series of investigations that have focused on different Ni–Ti systems using an identical design (Thompson & Dummer 2000b, Schäfer & Vlassis 2004, Paqué *et al.* 2005). Unfortunately, most studies available in the literature focus only on the comparison between two instrument types; moreover, in many cases these investigations have been performed by different operators. In general, information on the various aspects of *several* different systems is rare.

Thus, the purpose of the present study was to evaluate several parameters of root canal preparation using FlexMaster (Vereinigte Dentalwerke, Munich, Germany), System GT Rotary Files (Dentsply Maillefer, Ballaigues, Switzerland), HERO 642 (MicroMéga, Besançon, France), K3 (sds Kerr Sybron Dental Specialties, Orange, CA, USA), ProTaper (Dentsply Maillefer, Baillaigues, Switzerland), and RaCe (FKG Dentaire SA, La Chaux-de-Fonds, Switzerland) Ni–Ti instruments as well as a manual technique. This study focused on alteration of the working length, straightening of curved root canals, post-operative root canal diameter, procedural incidents, and working time.

Materials and methods

For evaluation of the preparation form (cross-sectional, alteration of working length and straightening) a modified Bramante muffle system was used (Bramante *et al.* 1987, Hülsmann *et al.* 1999). The muffle consisted of a U-formed middle section and two lateral walls that were assembled with three screws, as described previously by Hülsmann *et al.* (1999). In order to reposition the complete tooth block exactly, grooves were integrated in the wall of the muffle block.

A radiographic platform could be adjusted to the outsides of the middle part of the muffle (Southard *et al.* 1987, Sydney *et al.* 1991). This allowed the exposure of radiographs under reproducible conditions and geometric standards so that pre- and post-operative views could be evaluated. A total of 147 human mandibular molars that had been extracted for periodontal reasons in elderly patients were selected. The teeth had completed root formation (without multiple root curvatures), narrow canals (due to the age of the patients), and were without visible apical resorption. All pulp chambers were coronally accessed and the root canals tested to ensure apical patency of the mesial root canals; a size 10 reamer was inserted until its tip could be visualized at the apical foramen.

The molars were shortened coronally to a length of 17 mm and embedded into the mould with acrylic resin. The working length was established 1 mm short of the canal length. After insertion of a size 15 reamer root canal curvatures were measured from standardized pre-operative radiographs according to Schneider (1971), using Ultraspeed films (Eastman Kodak Company, Rochester, NY, USA) and a Heliodent 70 X-ray machine (Siemens, Bensheim, Germany) operating at 70 kV and 7 mA. In order to emphasize the morphology of each different canal, silver points were inserted in all teeth both before preparation with the different systems and after every instrument reaching the full working length. For homogenous distribution of the differently curved root canals within the groups, teeth with varying degrees of curvature (<10°, <25°, and >25°) were equally allocated into seven identical groups of 21 teeth each.

Instruments and preparation techniques

Rotary Ni–Ti instruments

The instruments of the FlexMaster system show a convex cross-section without radial lands and three cutting edges with a negative cutting angle. The tip of these instruments is noncutting. The manufacturer recommends a working speed of 150–300 rpm and the use of a low-torque motor.

System GT instruments have radial lands with U-shape and a noncutting tip. The recommended working speed is 150–300 rpm.

Table 1 Total number of instruments used, sequence of preparation, and working length (WL)

System:	FlexMaster (seven instruments)	System GT (four instruments)	Hero 642 (six instruments)
Sequence:	6% taper, size 20 (WL 8 mm)	10% taper, size 30 (WL 6 mm)	6% taper, size 20 (WL 8 mm)
	4% taper, size 30 (WL 10 mm)	8% taper, size 30 (WL 9 mm)	4% taper, size 20 (WL 14 mm)
	4% taper, size 25 (WL 12 mm)	6% taper, size 30 (WL 12 mm)	2% taper, size 20 (WL 16 mm)
	4% taper, size 20 (WL 14 mm)	4% taper, size 30 (WL 16 mm)	4% taper, size 25 (WL 14 mm)
	2% taper, size 20 (WL 16 mm)		2% taper, size 25 (WL 16 mm)
	2% taper, size 25 (WL 16 mm)		2% taper, size 30 (WL 16 mm)
	2% taper, size 30 (WL 16 mm)		
System:	K3 (nine instruments)	ProTaper (seven instruments)	RaCe (nine instruments)
Sequence:	Orifice Opener 10 (WL 6 mm)	S1 file (shaping file no. 1) (WL 8 mm)	crown down 10% (WL 6 mm)
	Orifice Opener 8 (WL 7 mm)	SX (auxiliary shaping file) (WL 10 mm)	crown down 8% (WL 8 mm)
	4% taper, size 40 (WL 8 mm)	S1 file (WL 12 mm)	crown down 6% (WL 10 mm)
	4% taper, size 35 (WL 10 mm)	S2 file (shaping file no. 2) (WL 14 mm)	crown down 4% (WL 12 mm)
	4% taper, size 30 (WL 12 mm)	F1 file (finishing file no. 1) (WL 16 mm)	crown down 2% (WL 14 mm)
	4% taper, size 25 (WL 14 mm)	F2 file (finishing file no. 2) (WL 16 mm)	2% taper, size 15 (WL 16 mm)
	4% taper, size 20 (WL 16 mm)	F3 file (finishing file no. 3) (WL 16 mm)	2% taper, size 20 (WL 16 mm)
	4% taper, size 25 (WL 16 mm)		2% taper, size 25 (WL 16 mm)
	4% taper, size 30 (WL 16 mm)		2% taper, size 30 (WL 16 mm)

HERO 642 instruments have a noncutting tip, a negative cutting angle, and a triangular cross-section with three cutting edges are characteristic. The recommended working speed is between 300 and 600 rpm.

The K3 endo instrument is reported to have a slightly positive rake angle in combination with a so-called radial land relief and an asymmetrical cross-sectional design. The working speed for this system having a noncutting tip is between 200 and 300 rpm.

ProTaper instruments have a convex triangular cross-sectional design, a noncutting safety tip and a flute design that combines multiple tapers within the shaft. The manufacturer recommends a working speed of 250–350 rpm.

The RaCe instruments have a triangular cross-sectional design with alternating sharp cutting edges. The recommended working speed is 300–600 rpm.

All Ni–Ti rotary instruments were set into a permanent rotation with a 4:1 reduction handpiece powered by a torque-limited electric motor (300–600 rpm). The Endo IT control motor (Vereinigte Dentalwerke, VDW) was used for FlexMaster, System GT, HERO 642 and ProTaper. Preparation with K3 was performed by a torque-controlled motor (TCM IV; Nouvag, Goldach, Switzerland). A conventional reduction handpiece with regulated 600 rpm was used for preparation with RaCe. The sequences used in the present study were following the manufacturers' instructions for each system, and are given in Table 1. With all teeth used, the described uniform protocol (with a final preparation to size 30) was followed.

The manual technique

The preparation involved stainless steel K-Reamers (Vereinigte Dentalwerke, VDW) manipulated in a clockwise rotation of about 90–120° with a very light inward force until the instruments reached the full working distance, followed by a straight outward pull (turn-and-pull motion). Hedströem files (Vereinigte Dentalwerke, VDW) were used additionally with a withdrawing filing motion only. Files were precurved and anticurvature directing of the stroke was used. Patency was confirmed with a size 15 file after each sequence. All instruments were used only once per canal and then discarded. A step-back method was not applied.

All canals were sequentially prepared from size 15 up to 30. The working length was 16 mm for each instrument. Furthermore, in all groups, irrigation was performed with 2 mL NaOCl (2%) after each instrument size. Since the manufacturers' recommendations regarding the use of chelating agents were not consistent, EDTA containing preparations were not used in the present study. Thus, standardized conditions could be established for each system used. Only new instruments were used for the preparation of each canal, and care was taken to mimic the clinical situation by gaining access to the root canals only from the mesial direction with all systems used. Preparation with the different instruments was performed by the same operator (A.G.) after substantial training with the systems.

Assessment of root canal preparation

First, the mesio-buccal root canal was instrumented in the unsectioned teeth. Alterations of working length as well as maintenance of root canal curvature were evaluated at this time. The frequencies of length modifications and straightening were determined by standardized radiography and a computer-aided difference measurement for every instrument. All radiographs were scanned and saved as jpg-files. Subsequently, the digitized X-rays were analysed using dedicated software (SIDEXIS 5.5/5.5x; Sirona Dental Systems, Bensheim, Germany). In this way determination of measurement, distance as well as ratio of size of the X-rays could be completed, in order to analyse alteration of working length and straightening of the curved root canals. The lengths of the root canals were measured by setting reference points within the operating program. After calibration of working length, the distance to the radiological apex was determined. For the parameter of straightening the pre- and post-operative angles were measured and compared (Fig. 1).

When preparation of the canals was completed, the teeth were sectioned horizontally at 3, 6, and 9 mm from the apex. Subsequently, the post-operative cross-sections were evaluated by light-microscopic investigation (×50) and photographic documentation. According to Loushine *et al.* (1989), the cross-sections were classified as round, oval or irregular.

Statistical analysis

Overall comparisons of quantitative variables (degree of curvature, working length, straightening of curved root canals, working time, time for changing the instruments) between the seven groups were completed using the Kruskal–Wallis test. Pairwise comparisons amongst instruments and between instruments and manual technique were computed using the Mann–Whitney *U* test, and were corrected for multiple testing (Bonferroni correction; factor 15 and factor 21, respectively). The data on fractures and the post-operative cross-sections were analysed descriptively only. The significance level was set at $P < 0.05$ (two-sided). All analyses were performed using SPSS WIN (release 12.0; SPSS, Munich, Germany).

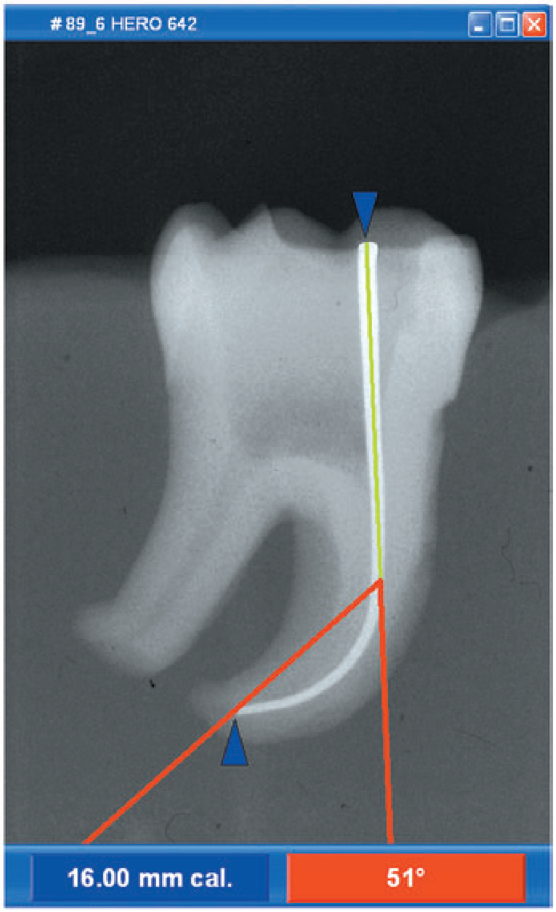

Figure 1 Representative radiograph depicting the computer-aided evaluation of length measurement and evaluation of pre- and post-operative curvature.

Results

Degree of pre-operative curvature

The mean degree of pre-operative angles varied from 16.6° (manual technique) to 21.7° (K3 group). No significant differences were found between the groups ($P = 0.92$, Kruskal–Wallis; $P > 0.05$ for all pairwise comparisons before Bonferroni correction; see Table 2).

Alteration of working length

None of the canals became blocked with dentine debris, whereas both loss of working length and prolongation of working distance were found in several canals. The alterations of working length that occurred when working with the different instruments are listed in

Table 2 Distribution of pre-operative angles in degrees

System	*n*	Mean	SD	Q3 (75%)	Q2 (median)	Q1 (25%)
FlexMaster	21	20.5	15.9	37	19	4
System GT	21	20.2	16.1	38.5	18	3.5
HERO 642	21	20.4	17.1	36	19	3.5
K3	21	21.7	19.3	37	19	3
ProTaper	21	21.2	18.7	31	19	3.5
RaCe	21	20.7	20.1	35.5	17	3
Manual technique	21	16.6	13.7	28.5	17	2

Table 3 Alteration of working length including lengthening as well as loss (in mm)

System	*n*	Mean	SD	Q3 (75%)	Q2 (Median)	Q1 (25%)
FlexMaster	21	0.0	0.6	0.5	0.3	−0.4
System GT	20	0.2	0.4	0.4	0.1	0.0
HERO 642	20	0.6	0.5	0.2	0.0	−0.1
K3	20	0.1	0.4	0.4	0.3	0.0
ProTaper	18	0.3	0.3	0.6	0.2	0.0
RaCe	21	0.3	0.3	0.5	0.3	0.0
Manual technique	20	0.0	0.5	0.4	0.0	−0.4

Table 3 (due to instrument fractures, the number of canals was not always 21 in the different groups). There were no significant differences concerning the lengthening between the different groups ($P = 0.26$, Kruskal–Wallis). The differences between RaCe and the manual technique as well as between ProTaper and the manual technique were not statistically significant (raw $P = 0.024$ and 0.035, respectively; $P > 0.05$ after Bonferroni correction).

Straightening

The results of straightening are summarized in Table 4. The overall comparison was not significant ($P = 0.12$, Kruskal–Wallis). With the exception of the comparison between System GT and ProTaper ($P = 0.002$; $P = 0.042$ after Bonferroni correction), as well as HERO 642 and ProTaper ($P = 0.012$; not significant after Bonferroni correction) the differences were not statistically significant ($P > 0.05$).

Post-operative root canal diameter

The results concerning post-operative cross-sections of the root canals are given in Table 5. The diameters of the root canals were classified as round, oval, and irregular. ProTaper ($n = 18$) achieved the lowest numbers of irregular cross-sections in the apical, middle and coronal third.

Procedural errors

All fractures occurred at the tip region of the instruments when working in the apical regions of the root canals. During preparation one System GT (size 30, curvature: 38°), one HERO 642 (size 30, curvature: 36°), one K3 (size 25, curvature: 13°), and three ProTaper (two S2 and one S1, curvatures: 5°, 20°, and 27°) instruments fractured. In the group of the manual technique one instrument (K-Reamer size 30, curvature 20°) was fractured.

Table 4 Evaluation of root canal straightening in degrees

System	*n*	Mean	SD	Q3 (75%)	Q2 (Median)	Q1 (25%)
FlexMaster	21	0.9	0.9	2.0	1.0	0.0
System GT[a]	20	0.5	0.7	1.0	0.0	0.0
HERO 642	20	0.6	0.7	1.0	0.5	0.0
K3	20	0.9	1.0	1.8	1.0	0.0
ProTaper[a]	18	1.2	0.6	2.0	1.0	1.0
RaCe	21	0.7	0.9	1.5	0.0	0.0
Manual technique	20	0.7	0.9	1.8	0.5	0.0

[a]Significant differences between the groups.

Table 5 Distribution of canal forms in the apical, middle, or coronal aspects of the of cross-sectioned canals

System	*n*	Round	Apical Oval	Irregular (n-a)[a]	Round	Middle Oval	Irregular (n-a)[a]	Round	Coronal Oval	Irregular (n-a)[a]
FlexMaster	21	6	6	9	6	6	9	8	5	8
System GT	20	5	7	8	5	8	7	6	7	7
HERO 642	20	5	8	7	3	10	7	7	9	4
K3	20	7	4	9	6	5	9	5	8	7
ProTaper	18	4	11	3	7	10	1	11	5	2
RaCe	21	5	10	6	3	11	7	3	11	7
Manual technique	20	5	11	4	6	11	3	7	9	4

[a]Nonacceptable, irregular canal form (because of noninstrumentation).

Working time

With the rotary instruments, the mean preparation time ranged from 93.5 s (System GT) to 207.6 s (RaCe). Mean preparation time with the manual technique was 1179.8 s. The overall comparison was significant ($P < 0.0005$, Kruskal–Wallis). Three groups of instruments could be identified: compared with K3, both Flex Master and System GT had significantly smaller values. K3 had significantly smaller values than Hero 642, RaCe, and ProTaper. All Ni–Ti instruments had significantly smaller values than the manual technique (all pairwise comparisons were significant after Bonferroni correction). The results for working time are given in Table 6.

Time for changing instruments

The mean time for changing the instruments ranged from 11.7 s (System GT) to 47.1 s (K3). Between FlexMaster and ProTaper no significant differences were found ($P > 0.05$). All other comparisons between the systems revealed statistically significant differences ($P < 0.05$ after Bonferroni correction), with increasing values in the sequences of System GT, Hero 642, (Flex Master, ProTaper), RaCe, and K3 (Table 7).

Discussion

To date, the majority of the available papers on automated root canal preparations have focused on few systems; therefore, conclusions are difficult to draw, since comparability of the varying study designs is limited (different operators involved, different length of root canals, different working diameter of final preparation). Due to the shortcomings of acrylic resin blocks (hardness, abrasion behaviour), the use of natural teeth has an advantage when assessing preparation techniques and new endodontic instruments. On the other hand, large variations concerning root canal morphology and dentine hardness have to be overcome by highly standardized preparation and evaluation procedures as well as by a sufficiently large number of specimens when using natural teeth.

In the present study, all root canals were uniformly prepared to size 30; this was because of the instrument diameters limited by the greatest file of the ProTaper system. Thus, the standardized assay arrangement used here allowed the evaluation of comparative measurements between six different rotary Ni–Ti systems and the standardized manual technique (Ingle 1961, Kerekes & Tronstad 1979), a method which is widely used in more or less modified forms in general practice (Schwarze *et al.* 1999, Slaus & Bottenberg 2002, Parashos & Messer 2004). For standardization all teeth

Table 6 Time to complete root canal preparation (s)

System	*n*	Mean	SD	Q3 (75%)	Q2 (median)	Q1 (25%)
FlexMaster[A]	21	102.9	46.3	114.3	89.5	70.3
System GT[A]	20	93.5	34.0	117.2	90.1	63.4
HERO 642[B]	20	186.1	92.0	234.6	166.1	118.7
K3[C]	20	114.2	40.8	147.4	107.4	81.5
ProTaper[B]	18	152.0	46.8	179.8	147.4	113.3
RaCe[B]	21	207.6	223.9	202.7	182.0	112.4
Manual technique[D]	20	1179.8	536.6	1598.3	1000.7	716.9

[A,B]Means with the same letters are not significantly different.

Table 7 Time for changing instruments (s)

System	*n*	Mean	SD	Q3 (75%)	Q2 (median)	Q1 (25%)
FlexMaster[A]	21	32.9	4.6	36.4	32.8	29.4
System GT	20	11.7	1.1	12.7	11.6	10.8
HERO 642	20	20.2	4.8	23.7	21.1	16.5
K3	20	47.1	3.2	48.9	47.1	44.7
ProTaper[A]	18	33.0	2.6	34.5	32.5	31.7
RaCe	21	43.1	3.5	45.3	43.6	39.4
Manual technique	20	–	–	–	–	–

[A]Means with the same letters are not significantly different.

were shortened to a length of 17 mm; thus, several parameters usually found in the *in vivo* situation (e.g. complicated access to cavity, greater length of root canals, young versus old teeth with narrowed canals) could not be simulated. Moreover, the speed variability of the different systems has not been evaluated, and although the manufacturers' recommendations have been followed, the results do not allow conclusions concerning the differences of the various systems (e.g. handpiece, motor, torque).

Alteration of working length

In the present investigation the only statistically significant differences were found between RaCe and the manual technique and ProTaper and the manual technique ($P < 0.05$). This finding is in agreement with observations of other investigators who observed only small mean changes in working distance occurring with rotary Ni–Ti instruments (Thompson & Dummer 2000a, Schäfer & Vlassis 2004). A number of reasons have been discussed to explain possible reasons for alteration of the working distance. Thompson & Dummer (2000a) reported that these changes may probably be due to a minor canal straightening during canal enlargement or lack of length control by the operator. From a clinical point of view it seems questionable whether these comparably small changes of the working length have any relevance.

Straightening of curved root canals

The straightening of curved root canals represents a central problem during root canal preparation. Several studies confirmed that elbow-zip formations occurred in 4.5–100% of the specimens (Dummer *et al.* 1989, Nagy *et al.* 1997). In order to reduce canal aberrations new Ni–Ti instruments have been developed such as the systems investigated in the present study. Because of the greater flexibility of these instruments a superior ability to maintain curvature even in severely curved root canals has been described (Short *et al.* 1997, Pettiette *et al.* 1999). Maintaining the original canal as far as possible is a pre-requisite during preparation; thus, iatrogenic complications arising from cleaning and shaping can be avoided. However, minor procedural errors in the canal wall occur subtly, and a tolerable extent of transportation of canal or foramen has not been evaluated so far, even if a previously published study compiling data on older automated systems stated that straightening of the canal should not be tolerable, if values between 5° and 7.7° are reached (Hülsmann 2000).

In the present evaluation all rotary Ni–Ti systems as well as the manual technique achieved good results regarding the evaluation of canal aberrations, even in more severely curved canals. The mean difference between the pre- and post-operative angle was between 0.5° and 1.2° for all groups, with a minor canal transportation toward the outer aspect of the curvature in the apical region. This was comparable with previous papers (Hülsmann 2000, Park 2001, Schäfer 2001, Schäfer & Lohmann 2002, Paqué *et al.* 2005). Overall, the minor straightening observed in the present study suggests that automated root canal preparation up to size 30 is possible even in more severely curved root canals, when the operator is experienced. Even preparation with stainless steel hand instruments (reamers and Hedströem files) resulted in only minor aberration; transportation was comparable with other investigations (Kosa *et al.* 1999).

Post-operative root canal diameter

One of the most important requirements of root canal preparation is the complete preparation of the canal. The evaluation of the post-operative cross-sectional area of canals can be used to score shaping ability, since this aspect varies amongst different instruments and techniques (Yun & Kim 2003, Paqué *et al.* 2005).

Comparing the apical to the coronal region, the present study revealed only minor changes concerning the amount of irregular canal forms, and it can be assumed that this was consistent, even for the noninvestigated regions. Previous investigations substantiated the good results of rotary Ni–Ti instruments since they remain centered in prepared canals (Glosson *et al.* 1995, Barbakow & Lutz 1997, Short *et al.* 1997). However, it should be kept in mind that previous work has emphasized that some 35% (or even more) of the root canal's surface will be left un-instrumented, even when using rotary Ni–Ti systems (Peters *et al.* 2001, Bergmans *et al.* 2003).

According to these findings, in the majority of specimens of the present study, round or oval cross-sections were found without any differences between the rotary systems and the manual technique. These results are comparable with a study by Tucker *et al.* (1997), who reported no differences between the rotary systems and the manual technique in terms of root canal diameter. Nevertheless, the present investigation showed that the ProTaper system achieved clearly better results in comparison with the other systems, which is in agreement with other investigations (Yun & Kim 2003, Paqué *et al.* 2005). Additionally, the constantly tapered FlexMaster and K3 files (as well as System GT and HERO 642) showed the greatest amounts of irregular post-operative cross-sections, although this seems to contradict previous findings (Bergmans *et al.* 2003).

However, it should be stressed that the final preparation size in the present study was 30, and thus was comparably small when compared with the results of previous studies (Hülsmann *et al.* 2001, 2003). From recent work it can be concluded that with greater instrument size the amount of instrumented canal walls will increase (Versümer *et al.* 2002). It has been speculated that a preparation size larger than 40 could be advantageous, because of a higher probability to contact most parts of the root canal's circumference (Hülsmann *et al.* 2003).

Procedural errors

Previous studies reported high numbers of instrument fractures for Ni–Ti instruments, indicating that they may be more susceptible to failure than conventional stainless steel instruments (Kavanagh & Lumley 1998, Baumann & Roth 1999). The present study emphasized that there was no difference between the manual technique and Ni–Ti instruments concerning their working safety, at least when working with instrument sizes up to 30. The only exception was ProTaper with three fractures, whilst with some other systems only one fracture occurred. The relatively high incidence of instrument fractures with the ProTaper series may be related to the convex triangular cross-sectional design which results in a larger core of the instruments and increasing inflexibility, even when used with the crown–down technique. However, in the present investigation most of the instrument fractures occurred with instrument sizes 30. These results are in accordance to a previous study where the incidence of fractures was enhanced with increasing size of the files, and with most fractures occurring with size 30 and 35 files (Baumann & Roth 1999, Versümer *et al.* 2002).

Working time

System GT, FlexMaster and K3 instruments prepared canals in approximately the same time, although the number of instruments was different. These three systems were significantly faster than ProTaper, HERO 642 and RaCe. Nevertheless, the present investigation demonstrated that root canal preparation was less time consuming when using rotary Ni-Ti instruments compared with a manual technique. This is in agreement with the findings of a previous study (Schäfer & Lohmann 2002).

Time for changing the instruments

The present investigation showed that time for changing the instruments is substantial and will vary between systems.

Conclusions

It should be kept in mind that the clinical outcome of endodontic treatment is significantly affected by preoperative diagnoses but not by the specific choice of an instrumentation system (Peters *et al.* 2004). The results of the present study suggest that all systems evaluated *ex vivo* respected the original root canal curvature, were safe to use, and saved time with respect to the manual technique.

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