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Ex vivo study on root canal instrumentation of two rotary nickel–titanium systems in comparison to stainless steel hand instruments

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Abstract

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Aim To investigate instrumentation time, working safety and the shaping ability of two rotary nickel–titanium (NiTi) systems (Alpha System and ProTaper Universal) in comparison to stainless steel hand instruments.

Methodology A total of 45 mesial root canals of extracted human mandibular molars were selected. On the basis of the degree of curvature the matched teeth were allocated randomly into three groups of 15 teeth each. In group 1 root canals were prepared to size 30 using a standardized manual preparation technique; in group 2 and 3 rotary NiTi instruments were used following the manufacturers' instructions. Instrumentation time and procedural errors were recorded. With the aid of pre- and postoperative radiographs, apical straightening of the canal curvature was determined. Photographs of the coronal, middle and apical cross-sections of the pre- and postoperative canals were taken, and superimposed using a standard software. Based on these composite images the portion of uninstrumented canal walls was evaluated.

Results Active instrumentation time of the Alpha System was significantly reduced compared with ProTaper Universal and hand instrumentation ($P < 0.05$; ANOVA). No instrument fractures occurred in any of the groups. The Alpha System revealed significantly less apical straightening compared with the other instruments ($P < 0.05$; Mann–Whitney U test). In the apical cross-sections Alpha System resulted in significantly less uninstrumented canal walls compared with stainless steel files ($P < 0.05$; chi-squared test).

Conclusion Despite the demonstrated differences between the systems, an apical straightening effect could not be prevented; areas of uninstrumented root canal wall were left in all regions using the various systems.

Keywords: automated root canal preparation, NiTi instruments, root canal aberration, root canal shaping, working safety, working time.

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Introduction

The shaping ability of root canal instruments is often assessed in terms of the preservation of the original root canal curvature, and without creating iatrogenic events such as instrument fracture, external transportation, ledges, or perforations (Weine *et al.* 1975, 1976). Good canal shaping through mechanical instrumentation is generally considered essential because root canal shape may have an effect on the efficacy of chemical disinfection.

In the last decade, several rotary nickel–titanium (NiTi) instruments with different configurations and designs have been developed with the aim to reduce the preparation time and to simplify the preparation procedure. Many of these systems have been investigated with regard to their shaping and cleaning ability,

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handling safety, and working time (Guelzow *et al.* 2005, Schirrmeister *et al.* 2006, Sonntag *et al.* 2007). These studies have shown that NiTi instruments can effectively prepare continuously tapered and centred root canal forms exhibiting only minor deviations from the main axis of the root canal (Paqué *et al.* 2005, Schäfer *et al.* 2006, Sonntag *et al.* 2007). Moreover, investigations have demonstrated that the use of NiTi instruments decreased the prevalence and degree of root canal transportation compared with hand instruments (Schäfer & Lohmann 2002, Schäfer *et al.* 2004). Nevertheless, these effects could not be entirely eliminated, and statistically significant differences concerning the straightening effect between rotary NiTi instruments have been reported (Yun & Kim 2003, Yoshimine *et al.* 2005, Schäfer *et al.* 2006). In most studies the straightening effect has been analyzed radiographically in the bucco-lingual direction only (Guelzow *et al.* 2005, Paqué *et al.* 2005, Schäfer *et al.* 2006). Limited data exist about three-dimensional morphological changes during preparation.

Total postoperative cleanliness can only be evaluated histological or by using SEM techniques on longitudinal or horizontal sections of extracted teeth (Hülsmann *et al.* 2005). In addition, the pre- and post-instrumented root canal cross sections can be analyzed with respect to unprepared canal walls, thus allowing for conclusions regarding the mechanical cleaning ability. The available literature reveals that rotary NiTi instruments shape the coronal and middle third of the root canal effectively, and create a smooth surface profile (Foschi *et al.* 2004, Prati *et al.* 2004). It has been reported that the apical third is the critical area of the root canal, and remaining pulpal and inorganic debris have been detected (Foschi *et al.* 2004, Prati *et al.* 2004). Interestingly, stainless steel hand instruments revealed equal or even better results concerning cleaning effectiveness when compared with NiTi instruments (Schäfer & Lohmann 2002, Prati *et al.* 2004). Various studies reported untreated root canal wall areas after preparation using rotary NiTi instruments (Peters *et al.* 2001, 2003). Root canal cleanliness is also dependent on the size of the root canal instrument. The available literature has revealed that the use of larger apical instruments led to an advantageous cleaning effect compared with smaller apical files (Wu & Wesselink 1995, Bartha *et al.* 2006, Weiger *et al.* 2006). However, root canal preparation with large size instruments can weaken the root, and does increase the risk of apical transportation (Wu *et al.* 2003).

In 2005, a newly developed rotary NiTi system (Alpha System; Brasseler, Lemgo, Germany), and in 2006, an advanced rotary NiTi system (ProTaper Universal; Dentsply Maillefer, Ballaigues, Switzerland) were introduced into the market; only limited data exist on the performance of these systems.

The Alpha System consists of three different instrument sequences according to root canal anatomy (small, average and large canals). The basic set consists of five instruments with descending tapers ranging from 10% to 2%, and sizes from 20 to 35. The instruments are provided with a titanium nitride coating, have a five-edged (pentagon) cross-section as well as a noncutting safety tip. For coronal flaring, an instrument with an increased taper, a square cross-section (kite-shaped) and large chip spaces is available (AF10; access reamer).

ProTaper Universal represents an advancement of ProTaper, which has been previously investigated in several studies (Calberson *et al.* 2004, Guelzow *et al.* 2005, Paqué *et al.* 2005, Sonntag *et al.* 2007). The basic sequence of ProTaper Universal exhibits an advanced flute design that combines multiple tapers within the shaft, a convex triangular cross-sectional design, blades close to the noncutting pilot tip as well as an increasing chip space (space for the accumulation of debris) from tip to shaft. A new design feature of ProTaper Universal NiTi system comprises the more rounded tips of the finishing files with the aim to increase the working safety as well as to improve shaping ability. Furthermore, the cross-section design has been modified. The convex lateral surfaces of F3 to F5 are machined to increase its inherent flexibility.

The aim of the present study was to investigate the instrumentation time, the working safety and the shaping ability in extracted mandibular molar teeth with curved root canals using the rotary NiTi systems Alpha System and ProTaper Universal in comparison to stainless steel hand instruments. A modified muffle system was used to enable evaluation both in the bucco-lingual and in the mesio-distal direction. The hypothesis was that the parameters instrumentation time, working safety and shaping ability would be influenced by the instrumentation technique.

Materials and methods

Selection of teeth and experimental set-up

A total of 45 human mandibular molars (extracted for periodontal reasons) with intact crowns and curved mesial roots were selected. The study protocol conformed to the principles outlined in the Central German Ethics Committee's statement (Zentrale Ethikkommission 2007) focusing on the use of human body material in medical research. Only teeth with completed root formation, intact root apices, and without visible apical resorption were included. Coronal access was achieved using diamond burs, and the mesial root canals were controlled for apical patency with a size 10 reamer (VDW, Munich, Germany).

For evaluation of the several parameters a modification of the muffle-block, as previously described by Bramante *et al.* (1987), Campos & del Rio (1990) and Hülsmann *et al.* (1999) was used. A muffle-block was constructed, which allows removal and exact repositioning of the complete specimen or sectioned parts of the latter (Fig. 1). Using this modified muffle, the exposure of radiographs under reproducible conditions in two directions (bucco-lingual and mesio-distal) was guaranteed to take radiographs before, during and after root canal preparation.

The muffle consisted of a ground section, four lateral walls and a cover with eight vertical screws. The holder for the radiographic sensor (fabricated from clear epoxy resin) could be adjusted at the ground section of the muffle, and the positioner for the X-ray tube could be fixed at the outside of the ground part of the muffle (Fig. 1).

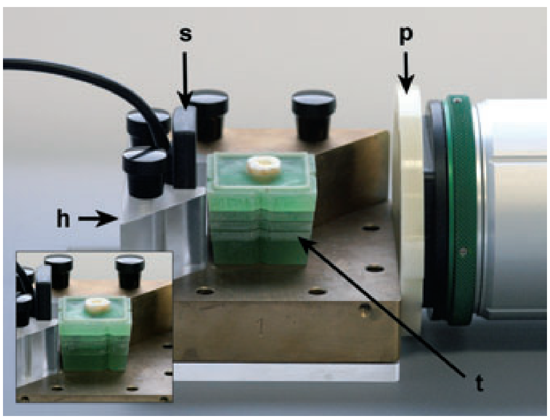

Figure 1 Insight into the modified muffle system with fixed positioner for the X-ray tube (p) and inserted sectioned parts of specimen (t), mounted for radiographic evaluation in vestibulo-oral direction. The holder (h) bearing the slot for the radiographic sensor (s) is adjusted at the ground section of the muffle. The inserted small photograph reveals the tooth specimen rotated at an angle of 90° to enable radiographic evaluation in mesio-distal direction (for presentation, front and side sections of the muffle-block have been removed).

Specimen preparation

The teeth were embedded into the muffle-block with acrylic resin (Technovit 4071; Heraeus Kulzer, Hanau, Germany), and shortened coronally to a length of 19 mm. Subsequently, specimens were sectioned horizontally at 3, 6, and 9 mm from the apex (Sägemikrotom Leitz 1600; Leica Microsystem, Wetzlar, Germany). The horizontal segments were remounted into the muffle, and loss of material (300 μm, because of the thickness of the saw blade as well as the interslice thickness) was compensated using metal disks of the corresponding height (300 μm).

An initial size 10 root canal instrument was inserted into the curved root canal. Standardized radiographs were taken prior to the instrumentation in a bucco-lingual as well as in a mesio-distal direction with a digital radiographic system (Planmeca intra; Planmeca, Hamburg, Germany), operating at 70 kV and 7 mA. Thus, the straightening of the instrumented root canals could be evaluated from two directions to describe the three-dimensional morphological changes during preparation.

Root canal curvatures were measured according to a modified method (Hülsmann & Stryga 1993) using the software AxioVision (Carl Zeiss MicroImaging; Jena, Germany). The specimens were divided into three groups according to the root canal curvature (<25°, 25°–35°, and >35°). On the basis of the degree of the bucco-lingual curvature the teeth were randomized equally into three groups of 15 teeth each (stratified random sampling); thus, groups that were equal on the matching variable were created.

With the aim to analyze the shaping ability and to draw conclusions regarding the mechanical cleaning ability of the systems photographs of the preoperative coronal, middle, and apical cross-sections of the root canals were taken using a stereo microscope (Stemi SV11; Carl Zeiss, Oberkochen, Germany) including a video camera attachment (JVC TK 1070E; Carl Zeiss) at 70× magnification.

Instruments and preparation technique

According to the manufacturers' instructions all root canals were initially prepared using a size 10 reamer followed by a size 15 reamer. Alpha System files were set into permanent rotation with a 4-level torque limit setting ENDOadvance handpiece (KaVo; Biberach, Germany), powered by an electric motor (MF-Perfecta; W&H, Buermoos, Austria), and using a working speed

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

System	Sequence
Alpha System (Brasseler, Lemgo, Germany; five instruments)	Average canals (as indicated by the manufacturer) AF10.045 – 10% taper, size 45 (canal orifice) AF06.025 – 6% taper, size 25 (crown down to the curvature) AF04.025 – 4% taper, size 25 (crown down to the curvature) AF02.025 – 2% taper, size 25 (WL) AF02.030 – 2% taper, size 30 (WL)
ProTaper Universal (Dentsply Maillefer, Ballaigues, Switzerland; seven instruments)	S1 file (shaping file 1) - 2–11% taper, size 17 (canal orifice) SX (auxiliary shaper file) - 3–19% taper, size 19 (canal orifice) S1 (shaping file 1) - 2–11% taper, size 17 (WL) S2 (shaping file 2) - 4–11.5% taper, size 20 (WL) F1 (finishing file 1) - 7–5.5% taper, size 20 (WL) F2 (finishing file 2) - 8–5.5% taper, size 25 (WL) F3 (finishing file 3) - 9–5.5% taper, size 30 (WL)
Stainless steel instruments (Vereinigte Dentalwerke, Germany; eight instruments)	Reamer - 2% taper, size 15 (WL) Hedström file - 2% taper, size 15 (WL) Reamer - 2% taper, size 20 (WL) Hedström file - 2% taper, size 20 (WL) Reamer - 2% taper, size 25 (WL) Hedström file - 2% taper, size 25 (WL) Reamer - 2% taper, size 30 (WL) Hedström file - 2% taper, size 30 (WL)

of 250 rpm (500 rpm for AF10). ProTaper Universal instruments were set into permanent rotation with a 4 : 1 reduction handpiece (WD-66 EM; W&H, Buermoos) powered by a low torque-limited electric motor (Endo IT control motor; VDW), and a working speed of 300 rpm was used. Instrumental sequences followed the manufacturers' instructions (see Table 1). The instruments were kept rotating inside the root canal until they reached the working length and the instruments designed for crown down technique (AF10.045, AF06.025, AF04.025) were left in the root canal for a short period of time (5–8 s). The manual preparation technique was performed using stainless steel K-Reamers (VDW) as well as Hedström files (VDW). All root canals were preflared in the coronal section with number 1 through three Gates Glidden burs. The K-Reamers were used in a reaming motion and manipulated in a clockwise rotation of about 90–120° with a very light inward force until the file reached the full working distance, followed by a straight outward pull (turn-and-pull motion). Hedström files were used additionally with a withdrawing filing motion only. All instruments were pre-curved. No step-back method of instrument manipulation was used with the hand instruments.

The individual working length for all specimens was obtained by measuring the length of the initial instrument (size 10; VDW) at the apical foramen subtracting 1 mm. All files were used to instrument only one canal and coated with a lubricant containing EDTA (FileCare; VDW) before use. The root canals of all teeth were instrumented up to size 30. After each instrument, the root canal was irrigated with 2 mL of 1% NaOCl solution using a syringe and a 28-gauge needle. All canals were instrumented and analyzed by the same experienced operator.

Assessment of root canal preparation

Instrumentation time

The active time for root canal instrumentation was recorded using a digital stopwatch (http://www.jumk.de/stoppuhr; Internetservice Kummer + Oster, Buchenberg, Germany). Time for instrument changes as well as irrigation times were not considered.

Working safety

The number of fractured instruments during instrumentation was documented.

Shaping ability

The assessment of the apical straightening effect for each system was carried out after preparation up to sizes 25 and 30, respectively. Radiographs were taken with a size 25 and 30 instrument from both directions

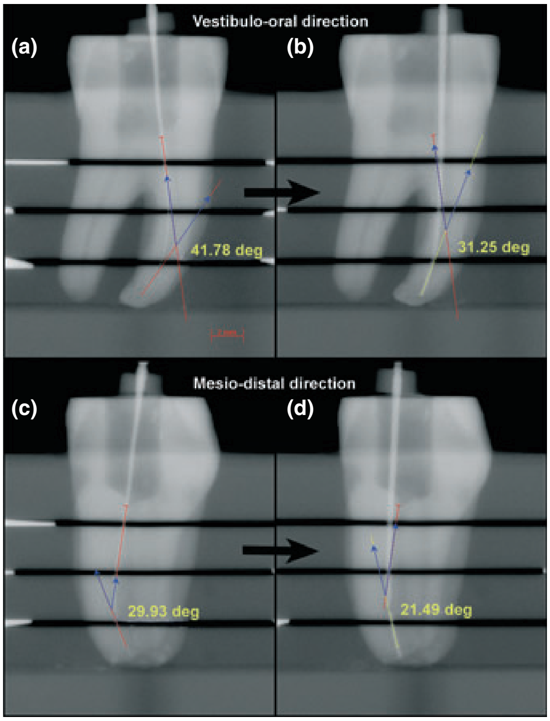

Figure 2 Representative example of a series of radiographs taken in vestibulo-oral (a) and mesio-distal direction before (c) and after preparation up to ISO size 30 (b, d). The root canal curvature was measured prior to instrumentation with the initial instrument inserted (reamer ISO size 10) (a, c). Based on the radiographs taken after preparation up to ISO size 30 (b, d), canal curvature could be measured and apical straightening could be determined.

(bucco-lingual and mesio-distal) (Fig. 2). Based on the canal curvatures assessed pre- and postoperatively, the apical root canal straightening was determined as the difference between apical root canal curvatures before and after instrumentation using instruments of size 25 and 30, respectively.

In the coronal, middle and apical cross-sections of the root canal the portion of uninstrumented canal walls was evaluated. After root canal preparation postoperative photographs of the cross sections were taken. Pre- and postoperative photographs were superimposed using reference marks (Fig. 3) (Corel Draw; Corel Corporation, Unterschleißheim, Germany).

On the basis of these images the distance of contact between the pre- and postoperative root canal walls was measured, and the portion of uninstrumented root canal walls was determined (Fig. 3). According to the results, specimens were divided into four groups:

Group 1: 0–25% contact between pre- and postoperative cross-section/root canal wall.
Group 2: >25% contact between pre- and postoperative cross-section/root canal wall.
Group 3: >50% contact between pre- and postoperative cross-section/root canal wall.
Group 4: >75% contact between pre- and postoperative cross-section/root canal wall.

Statistical analyses

The statistical analysis was conducted using one-way ANOVA with *post hoc* Tukey B tests for the active

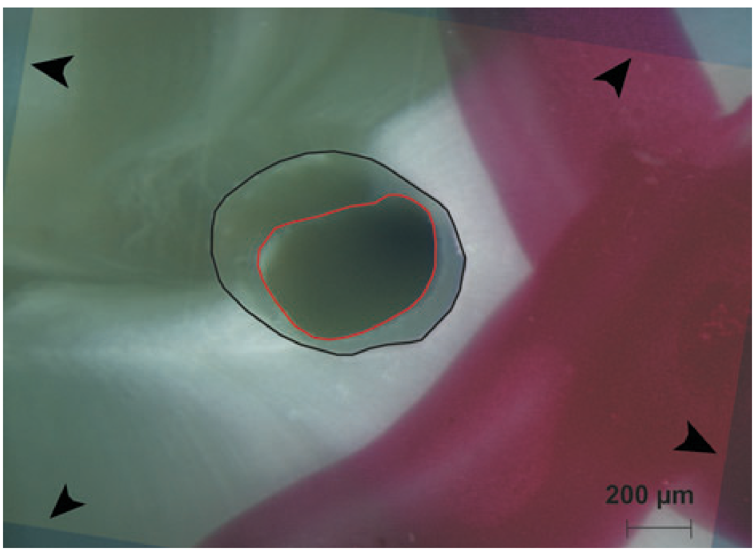

Figure 3 Representative superimposition of the pre- and postoperative photographs of the root canal cross-sections using reference marks (apical area). The bolts demonstrate the edge of the half-transparent superimposed photograph of the instrumented canal. The coloured lines show the traced root canal outlines (red = initial outline; black = outline after root canal preparation). Note that all root canal walls were instrumented in this specimen.

instrumentation time, and Kruskall–Wallis test followed by pairwise comparisons using Mann–Whitney *U* tests for the straightening effect. The Wilcoxon test for paired samples was used for comparisons of both directions (bucco-lingual and mesio-distal) regarding the degree of straightening. The percentages of uninstrumented root canal walls were compared using chi-squared test (exact test was used). The level of significance was set at $\alpha = 0.05$ (without adjusting for the respective comparisons, as the described proceeding is equivalent to the closed test procedure for the particular case of three study groups). All statistical analyses were performed using SPSS version 15.0 software (SPSS; Chicago, IL, USA).

Results

Working time

The active time for root canal instrumentation (Table 2) was affected significantly by the systems used ($P < 0.0005$; ANOVA). The Alpha System required significantly less time compared with the other systems ($P < 0.05$; Tukey B), whereas ProTaper Universal revealed a significantly reduced instrumentation time compared with the manual technique ($P < 0.05$; Tukey B).

Working safety

During the preparation of the curved root canals, no fractures of any of the used instruments (stainless steel files as well as the NiTi instruments) could be observed.

Shaping ability

The apical straightening of the curved root canals was significantly affected by the instrumentation system (Kruskall–Wallis). Results and *P*-values (for comparisons of all techniques, and with regard to the respective preparations sizes) are summarized in Table 3. In general, straightening was more pronounced with size 30 instruments compared with size 25; differences amongst the groups were increased (as indicated by the *P*-values) after use of size 30 instruments. In both directions (bucco-lingual and mesio-distal), the use of stainless steel instruments resulted in significantly increased ($P < 0.05$; Wilcoxon) straightening if compared with Alpha files; differences between ProTaper Universal and the manual technique were not significant. No statistically significant differences between the two directions regarding the degree of straightening could be observed.

Table 2 Mean active preparation time (in s) and standard deviation (SD)

System	Mean	SD
Alpha System[a]	103.2	13.5
ProTaper Universal[b]	150.7	18.9
Manual technique[c]	238.3	35.1

[a,b,c]Means with differing superscript letters indicate significant differences at $\alpha = 0.05$.

The analysis of the pre- and postoperative cross-sections revealed that all systems used left uninstrumented root canal walls in all regions. For the coronal and middle cross-sections no differences between the systems were found with respect to uninstrumented root canal walls ($P > 0.05$; Kruskal–Wallis). The portion of uninstrumented root canal walls in the apical cross-sections was significantly affected by the instrumentation system ($P = 0.004$; chi-squared test); the results are summarized in Table 4. Instrumentation using the Alpha System resulted in significantly less unprepared root canal walls compared with the manual technique ($P = 0.001$; chi-squared test). Comparison between ProTaper Universal and stainless steel files did not reveal any significant differences ($P = 0.153$; chi-squared test). ProTaper Universal left more unprepared root canal walls compared with Alpha System; however, this statistical difference was only weakly significant ($P = 0.043$; chi-squared test).

Discussion

The aim of the present investigation was to compare the shaping ability of two recently introduced rotary NiTi instruments in contrast to a manual technique using stainless steel instruments. The results revealed significant differences between the used systems with respect to their shaping ability as well as regarding the working time. Thus, the hypothesis of the present study concerning the differences between the systems regarding the evaluated parameters could not be rejected.

Study design

Previous investigations that focused on the shaping ability of NiTi instruments used either simulated root canals (Yun & Kim 2003, Yoshimine *et al.* 2005, Schirrmeister *et al.* 2006) or extracted human teeth (Paqué *et al.* 2005, Schäfer *et al.* 2006). Simulated root

Table 3 Mean values (including standard deviations as well as minimum and maximum values) of apical straightening in both directions (in degrees)

	Straightening of *vestibulo-oral* direction (in degrees)							
	ISO size 25				ISO size 30			
System	Mean	SD	Min	Max	Mean	SD	Min	Max
Alpha System	0.6[a]	0.5	0.0	1.4	1.4[a]	1.0	0.2	3.8
ProTaper Universal	2.7[a,b]	2.8	0.0	9.2	4.3[b]	3.4	0.1	12.5
Manual technique	2.9[b]	3.0	0.1	9.4	4.4[b]	3.7	0.5	13.2
P-value (Kruskal-Wallis)	0.043				0.012			
	Straightening of *mesio-distal* direction (in degrees)							
	ISO size 25				ISO size 30			
System	Mean	SD	Min	Max	Mean	SD	Min	Max
Alpha System	1.7[a]	1.6	0.0	6.4	2.4[a]	1.9	0.1	7.0
ProTaper Universal	3.4[b]	2.2	0.0	7.7	4.4[b]	2.1	0.2	7.8
Manual technique	3.5[b]	2.9	0.1	11.7	4.7[b]	3.8	0.8	16.4
P-value (Kruskal-Wallis)	0.028				0.019			

[a,b,c]Significant differences ($P < 0.05$) according to comparisons using Mann–Whitney *U* test are indicated by different superscript letters.

Table 4 Portion of uninstrumented area between superimposed pre- and postoperative root canal walls in the apical region when viewed in cross-sections

		Contact between pre- and postoperative cross-section (%)			
System		0–25%	>25%	>50%	>75%
Alpha System	Number	14	1	0	0
	percentage	93.3%	6.7%	0.0%	0.0%
ProTaper Universal	Number	8	5	2	0
	percentage	53.3%	33.3%	13.3%	0.0%
Manual technique	Number	3	10	1	1
	percentage	20.0%	66.6%	6.7%	6.7%

canals using pre-fabricated resin blocks allow for standardization of degree, location and radius of root canal curvature in three dimensions as well as the root canal length (Peters 2004, Hülsmann *et al.* 2005). However, the hardness and abrasion behaviour of acrylic resin and root dentine is not identical, and consequently does not reflect the action of the instruments in root canals of real teeth (Peters 2004, Hülsmann *et al.* 2005). Therefore, using extracted human teeth reflects the clinical situation more adequately. Nevertheless, large variations concerning root canal morphology and dentine hardness complicate standardization of groups (Hülsmann *et al.* 1999).

Similar apical preparation diameters are required for the comparison of the shaping and cleaning ability of different root canal instruments. Thus, in all investigated groups of the present investigation, the final apical preparation diameter was size 30. Moreover, to reduce the wide range of variations in three-dimensional root canal configuration the present study used mesial root canals of first and second mandibular molars. These teeth reveal root canal curvatures in most cases. Consequently, the measured degrees of the root canal curvature were categorized into three groups according to a modified method described by Schneider (Schneider 1971); this matched-group design allowed for minimization of high variations in the degree of curvature between the groups.

To evaluate the quality of root canal preparation a study design is desirable that allows for standardization and facilitates simulation of the clinical situation. Additionally, all relevant parameters should be recorded. Root canal morphology and the effect of instrumentation have been studied via numerous techniques (Campos & del Rio 1990, Hülsmann *et al.* 1999).

A method has been introduced (Bramante *et al.* 1987) and modified (Campos & del Rio 1990, Hülsmann *et al.* 1999) in which root canals can be analyzed before and after instrumentation using extracted teeth. Previously published literature has described the varying configurations of the used muffle-blocks (Campos & del Rio 1990, Hülsmann *et al.* 1999). Various elements, horizontal and vertical grooves in the walls of the muffle-blocks have been designed and integrated to guarantee the exact reposition of the specimen. In the present investigation a muffle-block was constructed to evaluate simultaneously both mechanical cleaning and shaping ability under reproducible conditions. The elements were designed to facilitate removal and exact repositioning of the complete specimen or sectioned parts of the latter. On the basis of the tapered internal space, integrated positioning devices as well as a cover, the exact and nonrelocatable vertical and horizontal position of the specimen was guaranteed.

After sectioning of the embedded teeth horizontally, the specimens were remounted into the muffle for instrumentation. The loss of material was predictable because of the use of the saw microtome, and could be compensated using spacers (metal disks) of the same height. The configuration of the used muffle system allowed for evaluation of the root canal cross-section prior, during and after instrumentation without changing the three-dimensional morphology of root canal. A further important improvement was the ability to evaluate the parameter '*straightening* of curved root canals' in two directions (bucco-lingual and mesio-distal) with the aim to describe the three-dimensional morphological changes during preparation. This parameter refers to the maintenance of the original shape of curved root canals, and provides information about the direction of removed material.

Shaping ability

This study showed that root canal preparation using stainless steel instruments as well as NiTi systems results in a pronounced apical straightening effect in the bucco-lingual as well as in the mesio-distal plane. No differences were found between the two directions regarding the degree of root canal transportation. Various investigations demonstrated that the use of NiTi instruments decreased the prevalence and degree of root canal transportation compared with stainless steel hand instruments (Schäfer & Lohmann 2002, Schäfer *et al.* 2004). However, other studies reported no differences between rotary NiTi systems and stainless steel hand instruments regarding root canal transportation (Guelzow *et al.* 2005, Hartmann *et al.* 2007). These divergent outcomes might be explained by differences in methodologies, methods of assessment, instruments and preparation techniques.

A further aspect is the design of an instrument that might influence the shaping ability. Stainless steel files are relatively stiff that will increase with larger instrument size and causes high lateral forces in curved root canals (Bergmans *et al.* 2001, Schäfer & Tepel 2001). The rigidity of an instrument could be responsible for straightening of and aberration from the root canal (including ledges, zipping and perforations), along with leaving significant portions of the root canal wall uninstrumented (Peters *et al.* 2003, Calberson *et al.* 2004). It has been assumed that NiTi instruments could improve shaping ability and minimize any aberrations during root canal preparation (Paqué *et al.* 2005, Yoshimine *et al.* 2005, Schirrmeister *et al.* 2006, Sonntag *et al.* 2007). However, these effects could not be entirely eliminated, and differences amongst rotary NiTi instruments have been demonstrated (Yun & Kim 2003, Yoshimine *et al.* 2005, Schäfer *et al.* 2006). With regard to the reported outcomes, it has to be stressed that different rake angles of instruments should reveal varying cutting efficacies; indeed, most rotary files have negative rake angles with a predominantly scraping motion. In general, the shaping ability of root canal instruments is a complex interrelationship of various parameters such as cross-sectional design, chip removal capacity, helical and rake angle, metallurgical properties and surface treatment of the instrument (Schäfer 1999, Schäfer & Oitzinger 2008).

The more rounded tip of the finishing files in the ProTaper Universal sequence has been developed to increase the working safety as well as to improve the shaping ability. Furthermore, the cross-section design has been modified to increase its inherent flexibility. Obviously, the advanced design features of the ProTaper Universal system revealed similar results compared with previous studies evaluating the classic ProTaper files (Peters *et al.* 2003, Calberson *et al.* 2004, Sonntag *et al.* 2007).

This study found a significantly pronounced apical straightening effect in both directions using ProTaper Universal compared to Alpha System. The different instrument designs of these NiTi systems (i.e. progressive versus constant taper) could have influenced the observed outcomes. Previously published studies demonstrated relationships between bending moment and cross-section, file size as well as taper of an instrument (Schäfer & Tepel 2001, Schäfer *et al.* 2003). The ProTaper Universal files have multiple and increased tapers within the shaft compared with the Alpha files presenting a less and constant taper. The apical transportation towards the outer aspects of the root canal could have been affected by the variable tapers along the cutting surface of the ProTaper Universal files (up to 11% at the tip) compared with the moderately tapered (2%) Alpha System instruments. An increasing taper is associated with increased cross-section areas and, accordingly, with decreased flexibility of the files that could cause straightening and root canal aberration during preparation (Bergmans *et al.* 2001). The decreasing taper sequence of the finishing files enhance the strength of the instruments, but increase the stiffness of their tips (i.e. ProTaper Universal size 30 is 9%, size 20 is 7%), thus resulting in high lateral forces.

Previously published data about classic ProTaper files showed similar results compared with the present investigation and demonstrated varying degrees of root canal straightening and transportation (Peters *et al.* 2003, Yoshimine *et al.* 2005). These tended at the midpoint of the curvature towards the inner aspects and apically towards the outer aspects of the root canal (Calberson *et al.* 2004, Sonntag *et al.* 2007). An investigation comparing three rotary NiTi instruments has demonstrated a tendency to ledge or zip formation at the end-point of preparation using ProTaper compared with RaCe and K3 (Yoshimine *et al.* 2005). The RaCe and K3 groups showed favourable results, and the prepared root canals displayed a smooth shift to the original root canals at the end point. The authors recommended that more flexible instruments, like K3 and RaCe, should be used in the apical preparation of curved root canals (Yoshimine *et al.* 2005). Comparisons amongst different rotary NiTi systems instruments revealed more root canal straightening after use of ProTaper compared to Mtwo, K3, ProFile, GT Rotary, and Quantec (Yun & Kim 2003, Sonntag *et al.* 2007). In contrast to these observations, other investigations found no statistical differences in root canal transportation using ProTaper compared with other rotary NiTi instruments after preparation of up to size 30 (Guelzow *et al.* 2005, Paqué *et al.* 2005).

The rotary NiTi Alpha System files provided a centred apical preparation and maintained the original shape of the curved root canals with only minor deviation from the main axis. The files are characterized by a pentagon-type cross-sectional design resulting in only slightly positive cutting angles and a comparable low chip space (Schäfer & Oitzinger 2008). The reduced root canal transportation could be explained by the high flexibility of these instruments because of their minor and constant taper along the cutting surface. This superior flexibility reduces the risk of root canal transportation during the enlargement of curved root canals (Schäfer *et al.* 2003).

Furthermore, it has been shown that the cross-sectional design as well as cross-sectional areas mainly influenced bending properties of instruments (Schäfer & Tepel 2001, Schäfer *et al.* 2003). It has been reported that for identical working diameters, the area of a triple-helix cross-section was found to be approximately 30% greater than that of triple-U file (Turpin *et al.* 2000). Because of the more massive structure of a triple helix file, this instrument was found to be less flexible than the triple-U instrument (Turpin *et al.* 2000). The Alpha files used in the present study had a pentagon-type cross-section. It might be speculated that this form of cross-section results in a high core diameter and a high cross-sectional area compared with other forms (i.e. triangular, square cross-section), and, consequently, in reduced flexibility. Furthermore, the small chip space could lead to apical blockage caused by insufficient transportation of debris towards the orifice (Bergmans *et al.* 2001). Alpha system files are the only known rotary NiTi systems with a pentagon cross-sectional design, and no published literature exists about this design feature up to now.

Obviously, in the case of comparison between Alpha System and ProTaper Universal the taper had a greater influence on the flexibility than the cross sectional design. Under the conditions of the present study the use of the rotary NiTi Alpha System files resulted in minimal apical root canal transportation. However, the influence of the individual geometric characteristics of the instruments on the cleaning and shaping ability remains speculative.

It is well known that the surface hardness of NiTi instruments is lower than that of stainless steel instruments (Brockhurst & Hsu 1998, Schäfer & Oitzinger 2008). Consequently, the cutting efficiency should be less compared with most stainless steel instruments (Brockhurst & Hsu 1998). With the aim to improve the surface hardness (and thereby increasing the shaping efficiency of NiTi instruments) several surface engineering techniques have been used, i.e. physical vapour deposition (PVD) techniques. Recent studies have shown that the PVD technique is suitable to significantly increase the cutting efficiency of NiTi instruments (Schäfer 2002). However, those findings did not corroborate the observation of a previously published study comparing the cutting efficiency of different NiTi systems (Schäfer & Oitzinger 2008); here, the results revealed no significant influence of the PVD coating surface on the cutting efficiency, and the Alpha System files showed a significantly lower cutting efficiency compared with Mtwo, RaCe, and Flexmaster (Schäfer & Oitzinger 2008). Thus, the influence of the PVD coating on the cutting efficacy of NiTi instruments with different cross-sectional design remains unclear.

Unprepared root canal wall areas

The comparison of the pre- and postoperative photographs of root canal cross-sections enables conclusions on shaping ability as well as mechanical cleaning ability. The prepared root canal should include the original root canal dimensions, and no unprepared areas should remain (compare Fig. 3). In the present investigation analysis of the pre- and postoperative cross-sections showed that the manual technique using stainless steel instruments as well as the rotary NiTi systems left uninstrumented root canal walls in all regions. While the coronal and middle cross-sections demonstrated sufficient shaping outcomes with only minor untreated areas, the percentage of uninstrumented root canal walls in the apical cross-section was significantly affected by the instrumentation system. Following preparation using the Alpha System the specimens showed the lowest percentage of unprepared root canal outlines compared with the manual technique using stainless steel instruments and the ProTaper Universal that ranged between the two previous groups.

These findings corroborate the results of previous studies. It has been reported that in the apical part of the root canal amounts of remaining pulpal and inorganic debris could be detected after using rotary NiTi instruments (Foschi *et al.* 2004, Prati *et al.* 2004). Furthermore, results indicated large untreated areas of the root canal walls (Peters *et al.* 2001, 2003). These areas tended to be on the convex curvature at mid-root and the concave side of the curvature more apically (Peters *et al.* 2003). Evaluation of the original ProTaper resulted in untouched areas ranging from 43% to 49% (Peters *et al.* 2003).

The superior shaping efficiency of the Alpha System could be attributed to the high elasticity characteristics of the instruments that resulted in minor root canal transportation during root canal preparation. Consequently, the files remove dentine uniformly on the outer and inner side of the root canal and only minor areas remain untouched. However, further studies should evaluate whether the preparation of wide root canals using the less tapered Alpha files will result in sufficient cleanliness.

Nevertheless, the clinical significance of the parameter '*prepared surface*' is not yet clarified. However, when considering the fact that viable microbes may penetrate deep into the dentinal tubules and may persist during root canal treatment (Chuste-Guillot *et al.* 2006), the need of an efficient irrigation (in addition to the shaping regime) to clean the root canals effectively is clearly highlighted.

Instrumentation time

The evaluation of the parameter '*working time*' should demonstrate the efficacy of a system and its clinical suitability. Studies that investigated the working time of various NiTi systems used the latter in different treatment sequences and changing number of files. Notwithstanding, working time depends on preparation technique and operator experience.

Some investigations evaluated working time as the active instrumentation time (summation of time taken for files to work inside the root canal) (Paqué *et al.* 2005). Other studies measured the working time including the active instrumentation time as well as the time for changing instruments and irrigation, thus resulting in considerably higher values (Schirrmeister *et al.* 2006). Evaluations of manual techniques and rotary NiTi instruments have demonstrated huge variations of working time, and cannot provide recommendations for one of the two techniques (Schäfer *et al.* 2004, Guelzow *et al.* 2005, Schirrmeister *et al.* 2006). The present investigation observed shorter working times for NiTi preparation compared with the manual instrumentation. The results indicate that the ProTaper Universal system required more time to prepare a root canal than the Alpha System.

These results may be explained by the varying number of instruments. In the present investigation, root canal preparation was performed using eight stainless steel files for the manual technique, and seven files for ProTaper Universal. The five Alpha System files exhibited the lowest number of required instruments for root canal enlargement.

Working safety

The reasons for fractures of rotary NiTi instruments are multifactorial, and complications can be attributed to instrument design, manufacturing process, canal configuration, applied force during instrumentation, preparation technique, operator's skills and experience as well as the number of application inside the root canal (Parashos & Messer 2006). In the present investigation no fractures of the stainless steel files as well as the NiTi instruments could be observed. All instruments were used to instrument only one single root canal. It should be emphasized that the regimen used was owing to the objectives (to compare the cleaning and shaping ability of different systems). Thus, this procedure does not adequately reflect the clinical situation, and the clinical relevance concerning the working safety should be interpreted with caution.

Conclusion

Within the limitations of the present *ex vivo* study, the experimental results suggest that none of the rotary NiTi systems used was able to impede an apical straightening effect during root canal preparation; uninstrumented root canal wall areas were left in all regions with all systems.

Few statistically significant differences amongst the three instrumentation techniques could be revealed. Instrumentation of curved root canals to ISO size 30 using instruments with greater taper (Pro Taper Universal F2, F3) and stiffer instruments (Pro Taper Universal F3, stainless steel file of size 30) seemed to result in increased root canal transportation and in a higher portion of unprepared root canal walls compared with flexible NiTi instruments (Alpha 02/30) that maintained the curvature of the root canal.

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