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Journal

International Endodontic Journal, 36(12)

ISSN

0143-2885

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Publication Date

2003-12-01

Peer reviewed

Root-canal preparation with FlexMaster: asessment of torque and force in relation to canal anatomy

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Abstract

Hübscher W, Barbakow F, Peters OA. Root-canal preparation with FlexMaster: assessment of torque and force in relation to canal anatomy. *International Endodontic Journal*, **36**, 000–000, 2003.

Aim To investigate physical parameters of FlexMaster nickel-titanium instruments while preparing curved canals in maxillary molars *in vitro*.

Methodology A torque-testing platform was used to prepare root canals in 11 extracted human maxillary molars with FlexMaster rotary instruments. Peak torque and force was registered along with numbers of rotations required to shape the canals. Canals were divided into 'wide' and 'constricted' groups depending on canal volumes assessed by microcomputed tomography. Resistance to cyclic fatigue was also tested. Mean scores for each instrument type were calculated and statistically compared using ANOVA and Scheffé post hoc tests.

Results Mean torque varied between 0.1 ± 0.1 and 0.8 ± 0.5 N cm while mean force ranged from 4.2 ± 2.0 to 7.3 ± 3.5 N. Mean numbers of rotations totalled up to 18. All three variables registered showed weak correlations to preoperative canal volumes ($P < 0.01$) and differed significantly between 'wide' and 'constricted' canals ($P < 0.001$). Numbers of rotations to fracture in a cyclic fatigue test were between 348 and 1362.

Conclusion FlexMaster instruments generated low torque scores and were highly resistant to cyclic fatigue, whilst three instruments fractured in extremely narrow canals. Consequently, more research is required to limit fracture incidence and to optimize instrumentation guidelines.

Keywords: cyclic fatigue, FlexMaster, force, torque.

Received 14 April 2003; accepted 15 August 2003

Introduction

There is increasing evidence from *in vitro* and *in vivo* studies that nickel-titanium (NiTi) instruments produce better prepared root canals than stainless steel files. However, there appears to be a higher risk of instrument
[Q1] separation (Barbakow & Lutz 1997). Reasons for separation of rotary NiTi Instruments include variations in canal anatomy (Ruddle 2002) and problems in handling (Barbakow *et al*. 1997). More specifically, retrospective analysis of discarded NiTi instruments indicated two distinct fracture mechanisms, namely torsional and flexural fractures (Sattapan *et al*. 2000).

Whilst both these mechanisms are likely to contribute to instrument separation, a combination of both factors is likely to occur clinically. These so-called hybrid forces consist of locking the instrument tip into small canal areas, while subjecting the instrument to cyclic fatigue because of rotation in a curved canal. To avoid build-up of fatigue, newer instrument systems such as FlexMaster (VDW, Munich, Germany) incorporate rotary files with .02 taper in addition to the greater tapers (.04 and .06). Other suggestions in that regard include limiting the use of rotary instruments while shaping root canals to between 10 or 20 s and not to remain in a canal once a certain working length has been reached (Ruddle 2002). Another method addressing torsional fractures is to construct cross-sectional geometries without radial lands, thereby increasing cutting efficiency and consequently reducing contact areas and torsional loads

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Edi.: Moumita, Prod. Cont.: Dharmesh

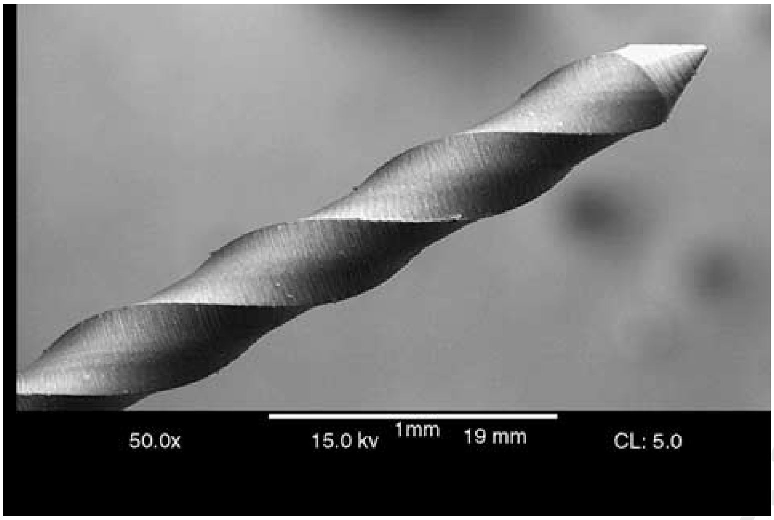

Figure 1 Scanning electron micrograph of a FlexMaster instrument size 40 taper .02, detailing the instrument tip and the nonlanded cross-section (original magnification ×150).

(Blum *et al.* 1999), for example in ProTaper (Dentsply Maillefer, Ballaigues, Switzerland) or FlexMaster instruments (Fig. 1).

There are difficulties in objectively analysing torsional loads and other physical parameters during preparation of curved canals because of complicated underlying engineering principles (Peters & Barbakow 2002, Peters *et al.* 2003). Indeed, few reports have appeared detailing torque and force during rotary preparation under these conditions.

Therefore, the aim of this study as a part of an ongoing project was to investigate torque and force generated by FlexMaster instruments when curved canals in extracted maxillary molars were prepared. The effects of canal anatomy on physical parameters as well as cyclic fatigue behaviour were also tested.

Materials and methods

Construction of torque-testing platform

A specific testing platform was used for the experiments, which is described in detail elsewhere (Peters & Barbakow 2002). In brief, specimens are secured into a rigid holder attached to a strain gauge, which is in turn connected to a preamplifier (A&D 30, Orientec, Tokyo, Japan). The holder is constructed in a way to allow lateral movement to adjust for various canal orifice positions.

A torque sensor (MTTRA 2, with amplifier Microtest, both Microtec Systems, Villingen, Germany) and a motor (Type ZSS, Phytron, Gröbenzell, Germany) are mounted on a stable metal platform (Fig. 2), which moves along a low-friction guide rail for a width of approximately

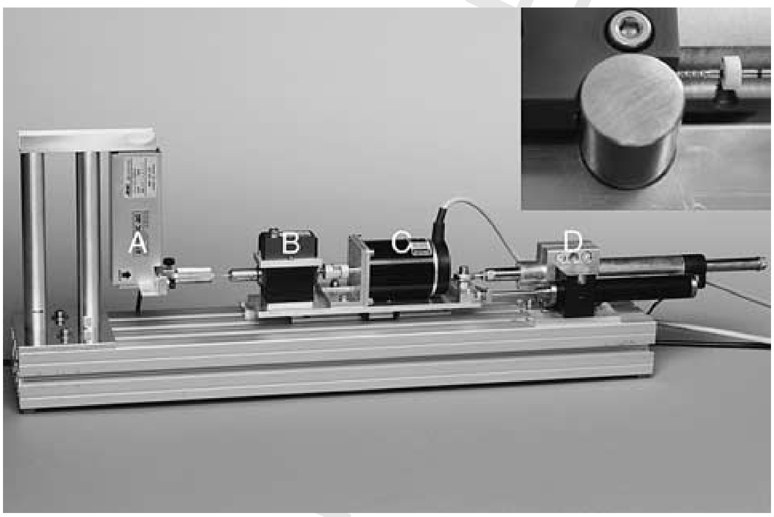

Figure 2 Construction of the torque-testing device showing major components: (A) force gauge, (B) torque sensor, (C) motor and (D) linear drive. Insert shows artificial canal used for cyclic fatigue testing.

5 cm. A linear potentiometer (Lp-100, Midori, Osaka, Japan) is attached to the sliding platform to record linear movements.

Data for torque, force and insertion depth were acquired from the sensors via three analogue channels using a 12-bit interface (PCI-MIO-16XE, National Instruments, Austin, TX, USA) and the ENDOTEST software package, which was specifically written for that purpose. Sensors were calibrated regularly using precision-made levers and a set of brass weights of 1–400 g, according to the guidelines listed by the respective manufacturers. Variables recorded during each measurement were registered as N cm, N and mm, respectively, for torque, force and distance of canal preparation and were stored for subsequent off-line analyses.

In this study, manual feed was used to prepare canals in extracted human maxillary molars, and data were recorded at a sampling rate of 100 Hz. In addition to torque and force, the numbers of rotations were counted under the condition that torque exceeded a preset threshold of 0.01 N cm. This threshold was determined from preliminary experiments in order to exclude noise and count only rotations when the canal walls were actually contacted by the rotating instrument.

Preparation of specimens

Eleven three-rooted maxillary molars were selected from a pool of extracted teeth and stored in 0.1% thymol solution until used. These specimens were mounted
[Q2] on SEM stubs (014001-T, Balzers Union AG, Balzers, Liechtenstein) and then scanned, before and after preparation in a microcomputed tomography system (μCT-20, Scanco Medical, Bassersdorf, Switzerland) at 36 μm resolution to metrically determine canal morphology using previously established criteria (Peters *et al.* 2000).

Canal orifices were enlarged with Gates–Glidden burs (insertion depth 3 mm, nos. 3 and 2; Dentsply Maillefer), and pulp chambers were irrigated with 5 mL of tap water. Working lengths were then set by subtracting 1 mm from the lengths of size 010 K-Flexofiles (Dentsply Maillefer) when their tips were just visible at the main apical foramina. Digital radiographs (Digora, Soredex, Helsinki, Finland) were also taken of each canal to verify file position and canal anatomy. Canal preparations with rotary instruments began once a size 015 K-Flexofile had reached working length, using Glyde (Dentsply Maillefer) as the lubricant.

Subsequent canal preparation using FlexMaster instruments differed slightly from the manufacturer's instructions: generally, the sequence indicated for large canals was used initially and, on encountering resistance, modified for smaller canals. In detail, the instruments used were:

- .06 taper size 30 in the coronal third;
- .06 taper size 25 and size 20 in the middle third and
- .06 taper size 20;
- .04 taper size 30, size 25 and 30; as well as
- .02 taper size 25, 30, 35, 40 and 45 in the apical third.

The rationale for the small adaptation in instrument sequence was that only a limited number of teeth were used in the present study. These teeth were statistically similar with respect to canal volumes and surface areas, as determined by μCT analysis. Therefore, similar sequences could be used in most cases and statistically useful data could be generated, whilst clinical cases should be judged and instrument sequences should be varied, on an individual anatomy-related basis.

Mesiobuccal (mb) and distobuccal (db) canals were then prepared to an apical size 40 while palatal (p) canals were shaped to a size 45. Tap water served as the irrigant after each instrument delivered by means of a gauge 27 needle, allowing for adequate back-flow. After preparing one specimen (three canals), each set of FlexMaster instruments was discarded and replaced by a new set.

Rotational speed was preset to 240 r.p.m. using the ENDOTEST software, and canals were shaped by a student (W.H.) with clinical expertise in rotary techniques. This student had undergone an extensive training period with the torque-testing device shaping canals in plastic blocks and extracted teeth. The training was aided by specific instructions on the use of FlexMaster instruments, utilizing information material supplied by the manufacturer, and ensured sufficient operator proficiency.

Cyclic fatigue analysis

The testing platform was fitted with an attachment that allowed the file to rotate freely around a curve of 90° with a radius of 5 mm (insert in Fig. 2; Haikel *et al.* 1999, Peters & Barbakow 2002). The time required to fracture an instrument was registered to the nearest 0.1 s, and the number of rotations was calculated.

Statistics

A total of 33 root canals in 11 maxillary molars were analysed during shaping procedures. Maximum torques and forces as well as numbers of rotations were calculated for the five tested instruments and were expressed as means ± SD. When appropriate, Pearson correlation coefficients were calculated to determine relationships between canal anatomy and physical parameters. Furthermore, based on an overall median canal volume of 2.33 mm^3, all 33 canals of the current sample were divided into 'wide' (mean volume: 4.67 ± 1.97 mm^3) and 'constricted' (mean volume: 1.17 ± 0.55 mm^3) groups.

The data were normally distributed and allowed means in subgroups to be statistically contrasted using one- and two-way ANOVAs with Scheffé tests for post hoc comparisons. A level of $P < 0.05$ was considered significant.

Results

A total of 245 records were produced while preparing 11 root canals in maxillary molars *in vitro*. The results showed a distinct relationship between torque, force and instrument insertion depth. FlexMaster instruments were inserted into root canals in an oscillating manner, as suggested by the manufacturer. Each oscillation produced paralleling increases in apically directed force and torque; however, there was only a weak positive correlation between applied force and generated torque ($r = 0.35$, $P < 0.01$). Three FlexMaster instruments fractured during 245 individual canal-shaping procedures, one instrument size 20, .04 taper and 2 instruments size 20, .06 taper. Figure 3 illustrates an example of an instrument insertion that ended with separation. Torque, force and preparation time during this run are in the same range that was used in previous shaping sequences.

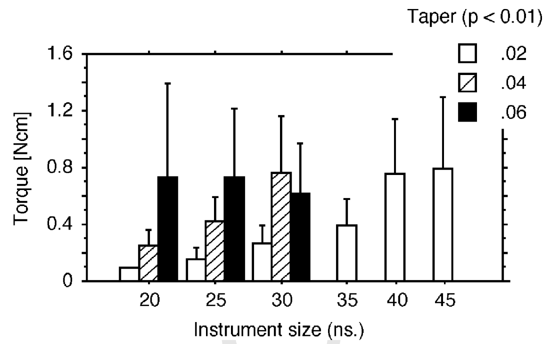

Figure 4 Torsional loads of various FlexMaster instruments during shaping of curved canals ($n = 11$–31, depending on instrument size). Differences analysed by ANOVA (ns, not significant).

Torques

Peak torque scores for various FlexMaster instruments ranged from 0.03 to 3.25 N cm, with the lowest and highest mean scores generated by size 20 instruments with .02 and .06 taper, respectively. Mean torque scores varied significantly between the 12 tested FlexMaster instruments ($P < 0.01$, Fig. 4), with smaller and less tapered instruments generating the lowest torsional loads (0.1 ± 0.1 and 0.8 ± 0.5 N cm, respectively). No significantly different loads were recorded while preparing various root-canal types (mb, db and p). However, there was a significant difference between torque scores with respect to preoperative canal volumes, as calculated from µCT data, with higher torque scores generated in the 'constricted' root canals (Table 1).

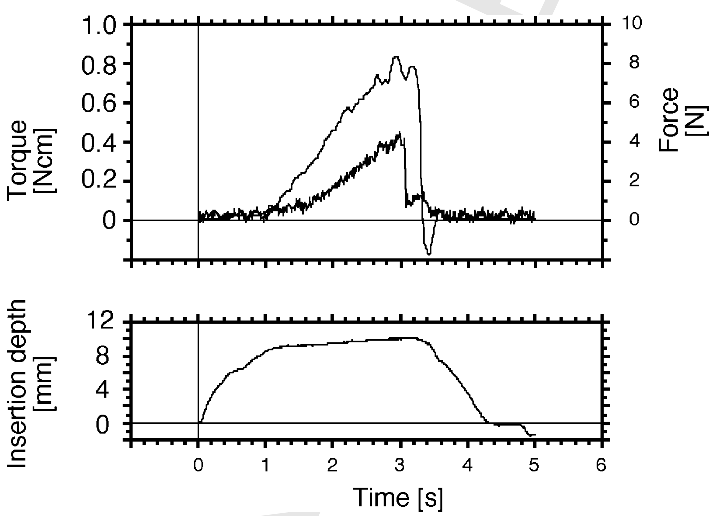

Figure 3 Typical data registration while fracturing a FlexMaster instrument. Torque denoted by solid line, force by fine line. Note scales for torque and force.

Table 1 Mean torque scores (±SD), grouped for wide and constricted root canals (n = number of runs)

	Wide canals (n = 136)	Constricted canals (n = 107)
Torque (N cm)	0.47 ± 0.41	0.69 ± 0.43
Range (N cm)	0.05–3.25	0.03–1.87

Means significantly different, $P < 0.001$.

Forces

Individual apically directed forces ranged between 0.2 and 15.2 N, with the lowest and highest mean scores again generated by size 20 instruments with .02 and .06 taper, respectively. Mean forces did not vary significantly between instrument sizes (ANOVA, Fig. 5) and ranged between 4.2 and 7.3 N. Furthermore, there were no relevant differences in apically directed forces when data were grouped for root types. Conversely, there was a significant difference between force scores with respect to preoperative canal volumes, as calculated from μCT data, with higher forces generated in 'constricted' root canals (Table 2).

Numbers of rotations

Cutting rotations of the respective instruments were counted under the condition that torque exceeded a pre-

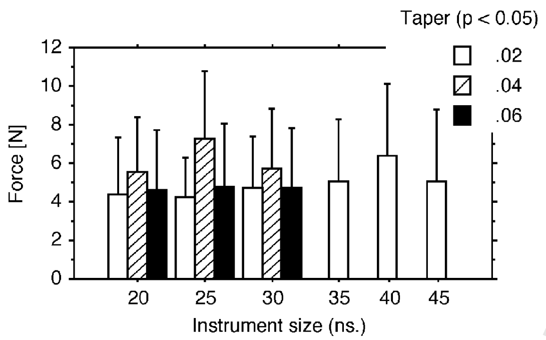

Figure 5 Apically directed forces of various FlexMaster instruments during shaping of curved canals (n = 1–31, depending on instrument size). Differences analysed by ANOVA (ns, not significant).

Table 2 Mean apically directed forces (±SD), grouped for wide and constricted root canals (n = number of runs)

	Wide canals (n = 136)	Constricted canals (n = 107)
Force (N)	4.5 ± 3.1	6.5 ± 3.1
Range (N)	0.1–15.2	1.2–14.7

Means significantly different, $P < 0.001$.

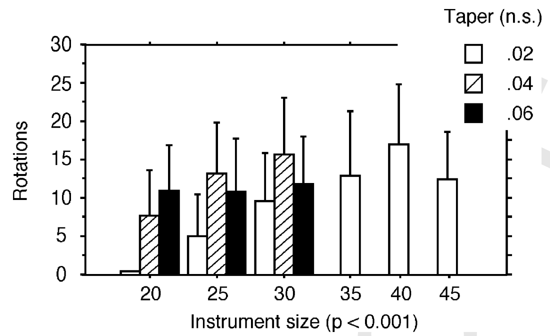

Figure 6 Numbers of rotations of various FlexMaster instruments during shaping of curved canals (n = 11–31, depending on instrument size). Rotations counted when torque exceeded threshold of 0.01 N cm (see Materials and methods). Differences analysed by ANOVA (ns, not significant).

Table 3 Mean numbers of working rotations* (±SD), grouped for wide and constricted root canals (n = number of runs)

	Wide canals (n = 136)	Constricted canals (n = 107)
Rotations	10.5 ± 7.5	14.8 ± 7.2
Range	0–31.0	0–30.5

Means significantly different, $P < 0.001$.
*Torque threshold, 0.01 N cm.

set threshold. Overall, mean numbers of rotations for various FlexMaster instrument sizes differed significantly (Fig. 6) and ranged between 5 and 18. Larger instrument sizes with a .02 taper, which were used for apical enlargement, yielded higher numbers of rotations than smaller ones. Again, preparation of 'constricted' and 'wide' canals resulted in significantly different numbers of rotations (Table 3).

Correlation of physical parameters with canal anatomy

All three instrument separations occurred in canals that had very small preoperative canal volumes (<0.5 mm^3) and canal diameters at the point of fracture between 0.15 and 0.18 mm. However, only weak correlations were found between preoperative canal volumes and the tested parameters of torque, force and rotations.

Cyclic fatigue

Finally, resistance of FlexMaster instruments to cyclic fatigue is detailed in Fig. 7. Overall, numbers of rotations to fracture ranged between 348 (size 30, .06) and 1362

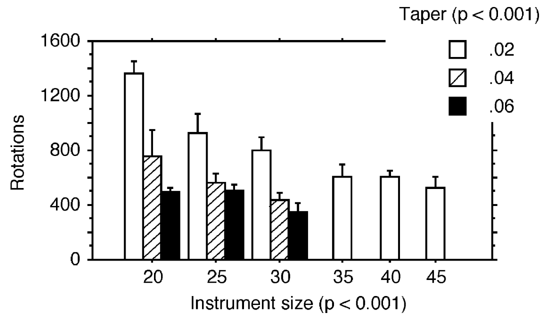

Figure 7 Numbers of rotation to fracture for various FlexMaster instruments rotating in simulated curved canals ($n = 6$). Differences analysed by ANOVA.

(size 20, .02), These figures decreased significantly with increasing instrument size and taper (Fig. 7). However, a size 45 instrument with taper .02 showed similar fatigue resistance as a size 25 taper .04 instrument.

Discussion

There is accumulating evidence suggesting that rotary nickel-titanium instruments facilitate root-canal preparation with minimal or no canal transportation (Peters *et al.* 2001). However, instrument separation might occur more frequently with rotary systems than with conventional hand instruments (Yared *et al.* 2002).

Consequently, physical parameters governing the fracture mechanisms of rotary endodontic instruments are of considerable interest. Two distinct fracture mechanisms, i.e. torsional fracture and flexural fracture have been outlined previously by Sattapan *et al.* (2000). Torsional fractures occur when the apical portion of a rotating instrument is forced into narrow root canals. Friction increases at this point, high torque is required to rotate the instrument and the fragile instrument tip is subjected to excessive torque (Blum *et al.* 1999, Peters *et al.* 2003). This effect has been described as 'taper lock' because it might occur with similarly tapered instruments of varying tip diameters rather than with variably tapered instruments (Yared *et al.* 2002). Consequently, the instrumentation sequence suggested for FlexMaster (Fig. 1) embodies three different tapers used during the crown-down phase of the preparation.

In vitro studies have indicated that tapered rotary NiTi instruments have a predefined fatigue life and are able to withstand between 250 and 500 rotations in simulated metal canals with 90° curvatures and 5 mm radii (Peters & Barbakow 2002). Instrument cross-sectional diameter will increase with size and taper, which will in turn negatively impact on fatigue resistance. Therefore, rotary instruments with .02 tapers were recently added to existing systems or incorporated in newer ones in order to increase fatigue life spans.

Clinical ability is also an important factor related to instrument separation (Yared *et al.* 2002), and consequently, electric motors and handpieces have been developed to simplify the use of NiTi rotary instruments. Although some of these handpieces are equipped with torque-limiting systems, operators will use varying amounts of apically directed force and speed of insertion. Furthermore, times required to prepare canals of various anatomy must differ greatly, and consequently, the risk of fatigue fracture will vary. Finally, recent research has demonstrated that operator proficiency is an important factor in relation to instrument separation (Yared *et al.* 2002). However, the torque-testing device used in the present study requires a training period. During that period, and with the aid of specific information material, the operator in the present study, an undergraduate student, learned to use FlexMaster instruments with adequate torque and force.

While the problem of cyclic fatigue of NiTi instruments has been described in several studies under varying *in vitro* situations, little is known about the torque and force generated by these instruments during root-canal preparation. In the current study, FlexMaster instruments were used to shape canals in extracted maxillary molars whose internal morphology had previously been assessed using microcomputed tomography (Peters *et al.* 2000). The specimens were shaped in a torque-testing platform (Fig. 2), that had been used previously to test GT rotary (Peters *et al.* 2002), ProFile .04 (Peters & Barbakow 2002) and ProTaper instruments (Peters *et al.* 2003).

Overall, mean maximum peak torque scores were 0.6 N cm, and this result was lower than that for other instruments tested with the same system. For example, in previous reports on ProTaper (Peters *et al.* 2003), mean torque scores for shaping and finishing instruments ranged from 0.8 to 2.2 N cm. In contrast to the results in that study, torsional loads for FlexMaster were not closely related to preoperative canal anatomy. A possible explanation could be the crown-down sequence utilized in the present study that might have decreased contact areas for individual instruments. Furthermore, up to 11 FlexMaster instruments were utilized in any one canal in this study, while only 4–5 ProTaper instruments may have been used, thus increasing the strain on individual ProTaper instruments. However, the three separations in the present study all occurred in extremely small canals at forces and torques that did not lead to fracture in other canals. It appears that the canal diameters were smaller than those of the size 20 instrument tip; the tip became active and was overloaded. Therefore, we recommend, as a guideline, to enlarge canals to a size 020 K-File prior to the use of FlexMaster instruments at working length.

Whilst forces in excess of 10 N were seen occasionally, mean apically directed forces amounted to 5.4 N. Interestingly, the operator in the present study was not as experienced clinically as that in previous reports but used forces similar to those used by other operators in
[Q3] previous studies (Peters & Barbakow 2002, Peters *et al.* 2003). It has been demonstrated that operator proficiency is a relevant variable with regard to instrument separation (Yared *et al.* 2002).

In the current study, the numbers of rotations during simulated shaping of root canals were also counted in order to address cyclic fatigue. Significantly higher numbers of rotations were counted for instruments size 40 and 45, taper .02 during shaping of the apical stop, compared with the smaller instruments used in the crown-down segment. However, mean scores were below 20 in all cases whilst numbers of rotation to fracture were well above 400 in an artificial metal canal with a 90° curvature. These results are similar to those in earlier studies (Haikel *et al.* 1999), with the exception that .02 taper FlexMaster instruments showed higher resistance to fatigue than previously tested instruments.

Sattapan *et al.* (2000) speculated that fatigue fracture might play a major role in Quantec instruments, but others have reported that cyclic fatigue was a minor factor for ProFile instruments when used correctly and discarded regularly (Yared *et al.* 2001). Apparently, the instruments' cross-sectional geometry does play an important role in cyclic fatigue as well as resistance to torque (Turpin *et al.* 2000). Hence, FlexMaster incorporates a cross-sectional design that has sharp cutting edges and a set contains .02 taper instruments. Both modifications seem to contribute to low torsional loads and extended cyclic fatigue life.

However, torsional and flexural fractures are not mutually exclusive categories, and cyclic fatigue simulation using metal canals cannot closely resemble clinical conditions because only minimal friction occurs between the rotating instrument and the holding device. Cyclic fatigue might occur differently if instruments are subjected to apically directed force and rotate in curved canals, as expected in clinical use (Gambarini 2001). This might have occurred in the three canals with instrument separation. Clinically, supra-threshold torque does occur for a limited time period only (Peters & Barbakow 2002), and it might be more appropriate to calculate the product of torque and time in order to assess the amount of stress the instruments have been subjected to. This question will be addressed in further studies.

Conclusions

FlexMaster instruments generated lower torque scores than those described previously for other rotary instruments. There were weak positive correlations between canal geometry and physical parameters during shaping. FlexMaster instruments were highly resistant to cyclic fatigue, whilst three instruments unexpectedly fractured in extremely narrow canals. Consequently, more research is required to limit fracture incidence and to optimize hybrid instrumentation guidelines.

Acknowledgements

The authors are indebted to Mr Stefan Kappeler for valuable help during the course of the experiments. The project was supported by grant no. 195 from the Swiss Dental Society SSO and was presented in a preliminary form at the 10th Biennial Session of the ESE in Munich, October 2001.

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