doi:10.1111/j.1365-2591.2006.01200.x

Comparison of defects in ProTaper hand-operated and engine-driven instruments after clinical use

G. S. P. Cheung[1], Z. Bian[2], Y. Shen[2], B. Peng[2] & B. W. Darvell[1]

[1]Department of Endodontics, Faculty of Dentistry, The University of Hong Kong, Hong Kong; and [2]Laboratory for Oral Biomedical Engineering of the Ministry of Education, School of Stomatology, Wuhan University, Wuhan, China

Abstract

Cheung GSP, Bian Z, Shen Y, Peng B, Darvell BW. Comparison of defects in ProTaper hand-operated and engine-driven instruments after clinical use. *International Endodontic Journal*, **40**, 169–178, 2007.

Aim To compare the type of defects and mode of material failure of engine-driven and hand-operated ProTaper instruments after clinical use.

Methodology A total of 401 hand-operated and 325 engine-driven ProTaper instruments were discarded from an endodontic clinic over 17 months. Those that had fractured were examined for plastic deformation in lateral view and remounted for fractographical examination in scanning electron microscope. The mode of fracture was classified as 'fatigue' or 'shear' failure. The lengths of fractured segments in both instruments were recorded. Any distortion in hand instrument was noted. Data were analysed using chi-square, Fisher's exact or Student's *t*-test, where appropriate.

Results Approximately 14% of all discarded hand-operated instruments and 14% of engine-driven instruments were fractured. About 62% of hand instruments failed because of shear fracture, compared with approximately 66% of engine-driven instruments as a result of fatigue ($P < 0.05$). Approximately 16% of hand instruments were affected by shear, and either remained intact or was fractured, compared with 5% of engine-driven instruments ($P < 0.05$). The length of the broken fragment was significantly shorter in hand versus engine-driven group ($P < 0.05$). Approximately 7% of hand instruments were discarded intact but distorted (rarely for engine-driven instruments); all were in the form of unscrewing of the flutes. The location of defects in hand Finishing instruments was significantly closer to the tip than that for Shaping instruments ($P < 0.05$).

Conclusions Under the conditions of this study (possibly high usage), the failure mode of ProTaper engine-driven and hand-operated instruments appeared to be different, with shear failure being more prevalent in the latter.

Keywords: fatigue, fracture, nickel–titanium, ProTaper, rotary instrument, shear.

Received 12 May 2006; accepted 3 August 2006

Introduction

Root canal instrumentation should provide a tapered canal form with adequate shape to allow effective irrigation and filling (Schilder & Yee 1984). Realizing this objective in fine, curved root canals is often difficult with the use of traditional stainless steel instruments as they are stiff and tend to create aberrations such as ledges, zips and perforations. Over the years, modified instrumentation techniques and new, flexible instruments have been introduced to prevent or minimize these errors. Nowadays, nickel–titanium (NiTi) instruments play an important role in root canal preparation. Because of the pseudoelasticity of NiTi alloy, it has been possible to use such instruments in a continuously rotating motion in a low-speed handpiece (Glosson *et al.* 1995, Knowles *et al.* 1996, Bergmans *et al.* 2001). However, NiTi rotary instruments may undergo

Correspondence: Dr Ya Shen and Dr Bin Peng, Laboratory for Oral Biomedical Engineering of the Ministry of Education, School of Stomatology, Wuhan University, Wuhan, China (Tel.: +86 2787 164323; fax: +86 2787 873260; e-mail: yashen36@hotmail.com).

unexpected fracture without any visible warning in the form of permanent plastic deformation (Sattapan *et al.* 2000, Peng *et al.* 2005, Shen *et al.* 2006).

The original ProTaper system (Dentsply Maillefer, Ballaigues, Switzerland) consisted of three 'Shaping' files (Sx, S1 and S2) and three 'Finishing' files (F1, F2 and F3). They have varying taper over the length of the shaft and a triangular cross-sectional shape with convex sides. There was no 'radial land', supposedly, making these instruments perform a 'cutting' rather than a 'planing' action (Ruddle 2001). The ProTaper system is also available as a hand-operated instrument, which was recommended to be used in a reaming or a modified 'balance force' motion (Tseng 2004).

The mechanical stresses acting on a hand-operated instrument can be different from that on an engine-driven instrument. Whilst the NiTi engine-driven instruments operate in continuous rotation and thus are subjected mainly to unidirectional torque, hand-operated ProTaper instruments are used in a repeated clockwise-then-anticlockwise motion. The effect of such usage method on NiTi instruments has not been studied. Also, there are few reports of studies of instrument fracture based on fractographical analysis, especially for hand-operated NiTi instruments. The purpose of this study, therefore, was to compare the type of defects and mode of failure of a manually operated NiTi instrument and an engine-driven instrument of the same design after routine clinical use.

Materials and methods

The ProTaper system (Dentsply Maillefer) has been adopted for use at an endodontic clinic of the Stomatological School and Hospital of the Wuhan University, China. The engine-driven version has been in use since January 2003 and the hand version since January 2004. Four dentists, all having been trained in the use of the two systems, were the operators. They had not been told to use one system or another, although ProTaper engine-driven instruments had been used exclusively prior to the introduction of the hand-operated version. The instruments were operated according to the manufacturer's instructions. Each ProTaper hand or engine instrument was limited for use in a particular tooth type up to a maximum number: four molars, 20 premolars or 50 incisors and canines until distortion was noticed. Instruments would also be discarded after a single use in very complex canals. According to the records of the clinic, 564 ProTaper engine-driven instruments were issued, of which 325 (58%) were discarded after normal clinical use from January 2003 to May 2004, whereas 401 out of 572 ProTaper hand instruments (70%) were discarded from January 2004 to May 2005 (Table 1).

Instrumentation technique

All root canals were prepared using a crown-down approach (Ruddle 2002). After access cavity preparation, canals were negotiated with a size 10 and then a size 15 K-file to the estimated working length (EWL) before using the ProTaper instruments. The S1 file was used in the canal to just short of EWL or where resistance was met. Next, the Sx instrument was used to about the same length. Then, after the working length (WL) had been determined at 0.5 mm from the apical foramen using an electronic apex locator (Root ZX; J. Morita, Kyoto, Japan) and confirmed with a periapical radiograph, the S1, S2 and F1 files, in turn, were used to WL. Generally, the preparation was completed with either the F1 or F2 instrument. The apical dimension of the canal was gauged with a size 25, then size 30 K-files; further enlargement with the F3 was carried out only when necessary. The preparation technique using this system of engine file has been described previously (Peng *et al.* 2005). For the hand-operated instrument, the method of use was based on the 'Balanced Force Technique' (Roane *et al.* 1985) in a modified manner: the instrument was first pushed apically until it stopped advancing in the canal, rotated clockwise for one-half to three-quarter turn to engage the canal wall, and then rotated a half turn anticlockwise. The file was then withdrawn from the canal, its flutes cleaned and the process was repeated until the desired length was reached. The instruments were ultrasonically cleaned and sterilized in an autoclave (20 min at 120 °C) before use on another patient. Canals were irrigated with 1% sodium hypochlorite and patency was confirmed after every instrument. All canals were filled with warm vertical or cold lateral compaction of gutta-percha in the same or a subsequent visit.

Collection and examination of discarded instruments

After each use, the instruments were wiped with a piece of gauze soaked with isopropyl alcohol and inspected at ×2.5 magnification for signs of distortion or fracture. When any defect was noticed, the file was discarded regardless of the number of previous uses. Instruments would also be discarded after a single use

Table 1 Number of instruments collected in this study (% of total no. instruments)

Group	No. instruments	Defect free	Number showing defect or breakage: Intact but unwound	Fractured[a]	Defect caused by shear, i.e. unwound + shear failure
ProTaper Hand (PT-Hand)					
Shaping files	231	178 (77)	19 (8)	34 (15)	41 (18)
Finishing files	170	137 (81)	9 (5)	24 (14)	23 (14)
Subtotal	401	315 (79)	28 (7)	58 (14)	64 (16)
ProTaper Engine (PT-Engine)					
Shaping files	261[b]	217 (83)	1 (0.4)	42 (16)	16 (6)
Finishing files	64	62 (97)	0	2 (3)	0
Subtotal	325	279 (86)	1 (0.3)	44 (14)	16 (5)

[a]Including both fatigue and shear failures.
[b]Excluding one S1 engine-file that was lost during processing.

in a very complex, severely curved or calcified canal. The collected specimens were ultrasonically cleaned and autoclaved prior to examination in the laboratory. Any defects in hand instruments was noted, and the location determined by measuring the length between the instrument tip and the beginning, as well as the end, of the unwound region (Fig. 1) using a travelling microscope, at a precision of 0.01 mm (Model VRZ-XY; Leitz, Wetzlar, Germany). Of all discarded instruments, some 14% (58/401) of hand, and 14% (44/325) of engine-driven instruments had fractured; their remains were cleaned in an ultrasonic bath of absolute alcohol for 90 s and first examined, in lateral view (Fig. 2), in a scanning electron microscope (Sirion-FEG; Phillips, Eindhoven, The Netherlands). The presence of plastic deformation adjacent to the fractured surface was noted, according to the description by Sattapan *et al.* (2000). The specimen was retrieved, and the distance between the fracture point and the handle was measured to estimate the length of the fractured segment. Then, part of the instrument was sectioned and mounted on the microscope stage, with the fracture end facing upward, for fractographical examination. The mode of fracture was classified as 'fatigue' or 'shear', as described by Cheung *et al.* (2005). Data were analysed using chi-square, Fisher's exact or Student's *t*-test, as appropriate.

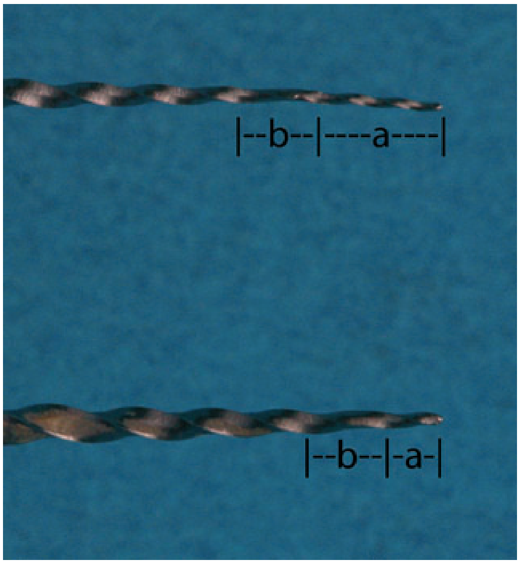

Figure 1 Photograph of unwinding of flutes in a Shaping (upper) and a Finishing (lower) file; measurement 'a', the length of start from tip and 'b', the length of the unwound region.

Results

Of the 401 hand-operated instruments collected, 86 (21%) were defective; 28 (7%) were intact and 58 (14%) were fractured in use (Table 1). Fifty-three Shaping files (23% of all discarded Shaping files) and 33 Finishing files (19%) were either distorted or fractured; the difference was not significant between the two instrument categories for this hand instrument (Table 1).

The results for ProTaper engine-driven instruments have been partially reported before (Shen *et al.* 2006). The proportion of the hand instruments affected by shear, either intact or broken, was 16% (64/401), which was significantly greater than for engine-driven instruments (5%; 16/325) (chi-square, $P < 0.05$)

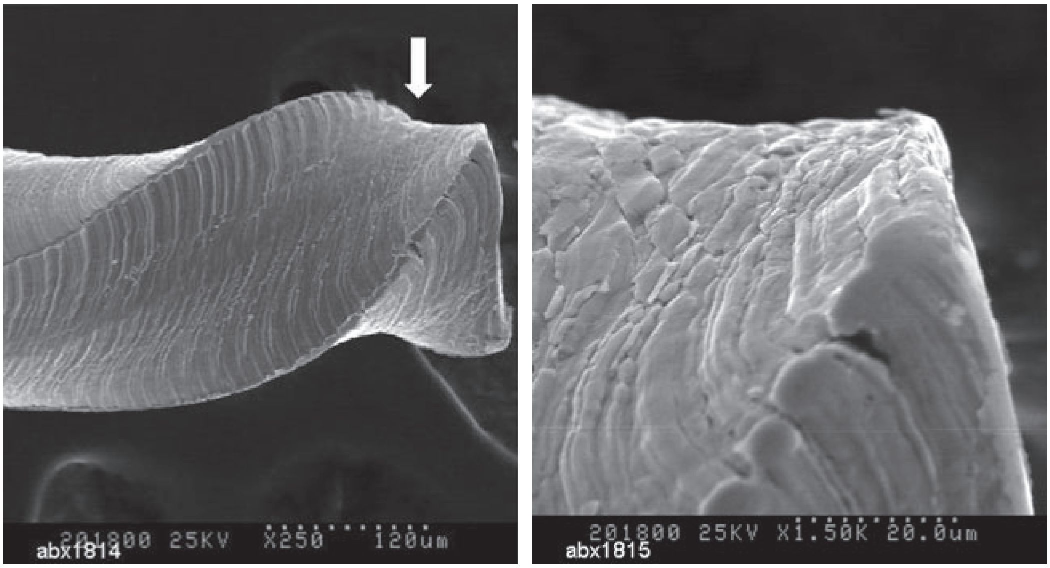

Figure 2 Lateral-view scanning electron micrograph of a broken PT-Hand file showing shear failure of the material (arrow) (left); note presence of plastic deformation (right).

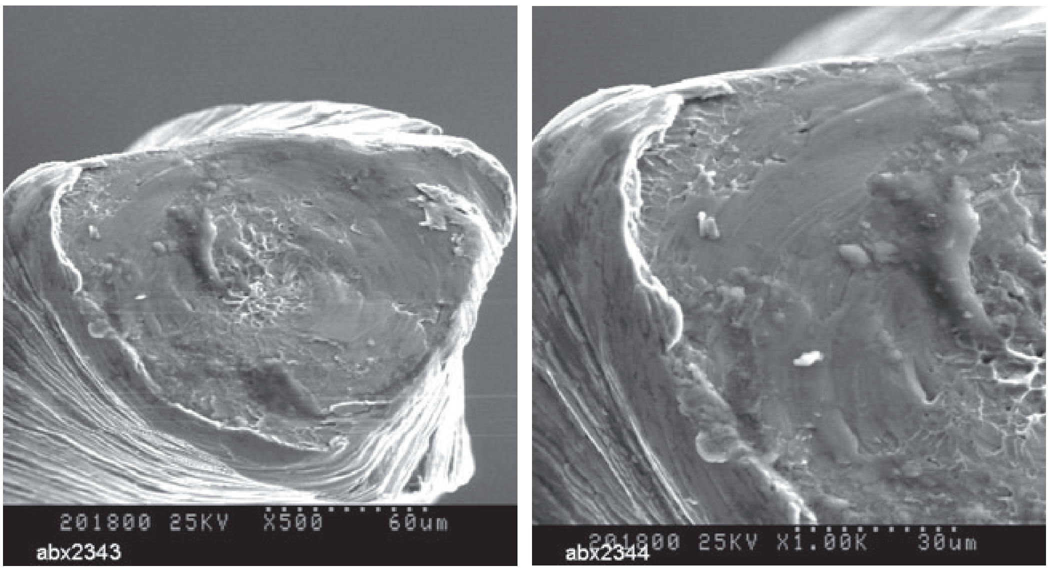

Figure 3 Fracture surface of the specimen in Fig. 2 showing topographical features of shear failure with concentric abrasion marks encircling an area of microscopic dimples (ductile rupture) near the centre of the cross-section (left); note an absence of fatigue striations in high-power on the presence of microscope dimples at the centre and near the cutting edge (right).

(Table 1). Amongst all broken instruments, significantly fewer hand instruments had no plastic deformation, in lateral view at low power, adjacent to the fracture site than for the engine-driven instruments (Fisher's exact test, $P < 0.05$) (Table 2). Fractographically, almost half of the fractured ProTaper hand instruments had concentric abrasion marks encircling a central region with microscopical dimples, indicative of shear fracture of the material (Fig. 3); some 34% (15/44) of the engine-driven instruments showed this. Many of those shear-fractured instruments also showed the presence of cracks running in an axial direction, i.e. perpendicular to the machining grooves (machine-tool scratch marks) in the flute on lateral-view examination

Table 2 Results of scanning electron microscope examination of the broken files (% of no. fractured)

Group	Total no. discarded	Number fractured	Lateral view[a] 'Torsional' defect	Not deformed	Fractographical examination[b] Shear failure	Fatigue failure
PT-Hand	401	58	11 (19)	47 (81)	36 (62)	22 (38)
PT-Engine	325	44	2 (5)	42 (95)	15 (33)	29 (67)

Results of Fisher's exact test for [a]lateral-view data, $P = 0.0372$ and [b]fractographical data, $P = 0.0090$.

(Fig. 4). Microscopical fatigue-striations were found in some 66% of engine-driven instrument (Fig. 5), whereas only 38% of hand-operated instruments showed such sign of material fatigue; the difference was statistically significant (Fisher's exact test, $P < 0.05$) (Table 2). However, a majority (81–95%) of the fractured instruments did not show any distortion or unwinding of flutes adjacent to the break. There was no difference in the fragment length for each mode of fracture, i.e. shear or fatigue, between the hand and engine-driven instruments (two-sample *t*-test, $P > 0.05$), whilst the overall mean length of the broken fragment was significantly shorter for ProTaper hand than the ProTaper engine-driven group ($P < 0.05$) (Table 3). The broken fragment caused by shear failure was significantly shorter than that for fatigue failure ($P < 0.05$) (Table 3).

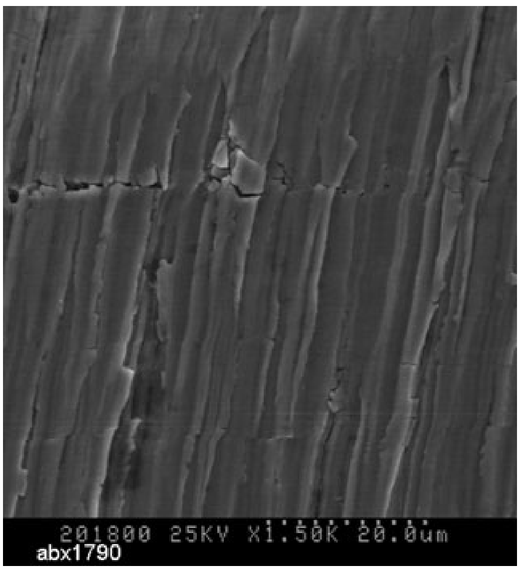

Figure 4 Lateral-view scanning electron micrograph of a separated hand-operated instrument showing cracking along the axis of the instrument (running horizontally on the photograph), which direction was near-perpendicular to the machining grooves in the flute.

For those intact but distorted hand instruments all defects were in the form of unwinding (or unscrewing) of the flutes, with Shaping instruments tending to be more often affected than Finishing instruments, although this difference was not statistically significant (Fisher's exact test, $P > 0.05$) (Table 1). The location of (the beginning of) defects in hand Shaping files was significantly farther from the tip than for hand Finishing instruments (two-sample *t*-test, $P < 0.05$), whereas the length of the unwound region was similar in both (Table 4).

Discussion

The maximum number of (re-)uses for the instruments used in this study appear high. The guideline used was a compromise between the number, potential size and curvature of root canal(s) in each tooth, and the cost of instruments and authors recognized the possibility of having overused the instruments. Patiño *et al.* (2005) reported that instruments used more than eight times (in canals with mean curvatures of about 40 degrees) fractured more frequently than those used sparingly. The study set a maximum usage in four molars, i.e. about 12–16 canals. Despite the (seemingly high) number, it was unlikely that all these canals had the same degree of (severe) curvature as in the study of Patiño *et al.* (2005); the canal curvature in premolars or anterior teeth is even less severe than that. A safety net was also provided by allowing disposal of the instrument after (a single) use in a complex or severely curved canal.

Root canal instruments are subjected to various stresses during clinical use. Both the instrument design and instrumentation technique can influence the magnitude of stress concentration and likelihood of instrument fracture (Blum *et al.* 1999, Berutti *et al.* 2003, Xu & Zheng 2006). Recent studies have indicated that the complexity of canal anatomy and its initial diameter are important factors contributing to fracture of NiTi rotary instruments (Peters *et al.*

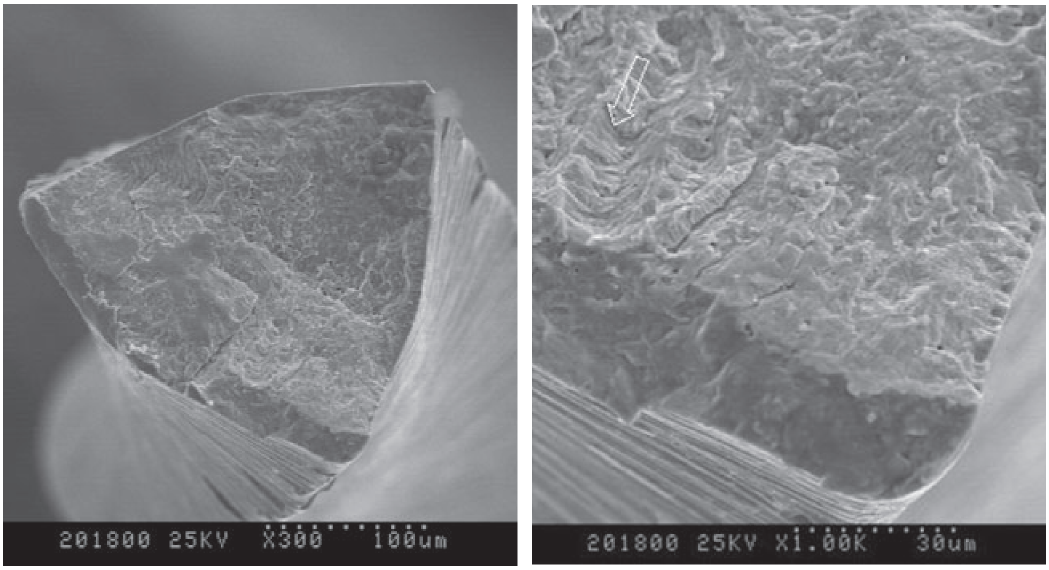

Figure 5 Fracture surface (left) of a separated engine-driven file showing clusters of fatigue striations (arrow) under high magnification (right).

Table 3 Mean length of the broken fragment for the hand and engine-driven instruments (lengths are given as mean ± SD)

	Shear failure		Fatigue failure		Overall	
Group	n	Length per mm	n	Length per mm	n	Length per mm
[a]PT-Hand	36	2.4 ± 1.0	22	3.7 ± 0.6	58	2.9 ± 1.0
[a]PT-Engine	15	2.5 ± 1.1	29	4.1 ± 1.6	44	3.6 ± 1.6
Results of testing between Hand and Engine groups	$t = -0.3161$, $P = 0.7533$		$t = -1.237$, $P = 0.2239$		$t = -2.549$, $P = 0.0131$	

[a]Examination for difference in mean fragment length between shear and fatigue failures in either the Hand or Engine group were (two-sample t-test) (i) Hand group: $t = -6.188$, $P < 0.0001$ and (ii) Engine group: $t = -3.463$, $P = 0.0012$.

Table 4 Location of unwinding defects in intact, discarded PT-Hand instruments (lengths are given as mean ± SD)

Instrument	No. (% of total discarded)	Start from tip, a per mm	Length of the unwound region, b per mm
Shaping files	19 (8)	3.0 ± 0.7	2.9 ± 0.9
Finishing files	9 (5)	2.4 ± 0.4	3.7 ± 1.4
Result of t-test between the two file categories	–	$t = 2.379$, $P = 0.0250$	$t = -1.833$, $P = 0.0783$

Refer to Fig. 1 for distances a and b.

2003a), hence the emphasis for the need for coronal enlargement prior to the use of engine-driven instruments at WL (Roland *et al.* 2002, Peters *et al.* 2003b). In the ProTaper system, the Shaping instruments are designed for coronal enlargement and mid-root preparation when most dentine removal is carried out. Once this is achieved, the Finishing instruments are then used, to prepare the apical few millimetres of the canal. Hence, it is not surprising that a greater amount of Shaping instruments was discarded either undistorted or fractured, which is in agreement with previous studies of the same brand of instrument (Fife *et al.* 2004, Shen *et al.* 2006). Also for the same reason, binding of the instrument in the canal is likely to occur closer to the tip of a Finishing rather than a Shaping instrument, explaining the difference in location of the distorted region for these two (hand-operated) instruments. The fractured fragment, as a result of shear fracture, was also shorter than that caused by material fatigue in both hand-operated and engine-driven instruments.

The tip diameter of the S1 instrument is 0.19 mm and S2 is 0.2 mm. Both S1 and S2 have an increasing taper over the working part, from 2% at D_1 to 11% at D_{14} for S1, and 4% on D_1 to 11.5% at D_{14} for S2. Thus, Shaping instruments exhibit a greater flexibility near their tip than in the middle portion where the taper, and hence the diameter, becomes greater. On the other hand, the Finishing instruments have a relatively large taper in the first 3 mm (compared with the body of the instrument) from D_0 to D_3: 7% for F1, 8% for F2 and 9% for F3. The diameter at the apical few millimetres of the instrument is greater than that of a Shaping instrument, making the Finishing instruments stronger with respect to monotonic load, especially in situation where the first 3 mm of the instrument was clamped for testing of ultimate strength (Yun & Kim 2003, Ullmann & Peters 2005). On the other hand, instruments of a smaller dimension were generally more resistant to cyclic fatigue than larger ones (Pruett *et al.* 1997, Haïkel *et al.* 1999, Fife *et al.* 2004). That may explain the greater amount of defects caused by torsion, i.e. manifesting either as unwinding of flutes or shear failure, observed in Shaping (hand, 18%; engine, 6%) rather than Finishing instruments (hand, 14%; engine, 0%).

Whilst NiTi rotary (engine-driven) instruments may facilitate root canal preparation with little canal transportation (Bergmans *et al.* 2001, Ruddle 2002), there is a concern that there has been unexpected fracture during use. Fracture of NiTi rotary instruments can occur even after detailed tuition for their use (Barbakow & Lutz 1997). Mechanically, an instrument will fail if an applied force exceeds its ultimate strength. Fracture can also result from material fatigue whereby the instrument is subjected to alternating stresses below the yield point of the material (Suresh 1998). The ProTaper hand instruments were introduced by the manufacturer to supplement, or to substitute for, their engine-driven counterpart. The results showed that the incidence of fatigue failure was reduced, possibly because of the low rate of rotation the instruments were operated by hand, and that the number of load cycles is the main determinant of fatigue life (Suresh 1998). Indeed, significantly greater numbers of ProTaper hand instruments suffered from shear damage (intact or broken) than for the engine driven.

There have been two methods described in the endodontic literature to identify the mode of instrument separation. One is lateral-view examination (Sattapan *et al.* 2000, Shen *et al.* 2006), but that fails to indicate the actual mechanism involved in the fracture process (Cheung *et al.* 2005). The other is a detailed, systematic (so-called 'fractographical') examination of the topographical features of the fracture surface to reveal the failure history of the part (Cheung *et al.* 2005, Spanaki-Voreadi *et al.* 2006). In the present study, some common fractographical features were observed in both groups of instrument: (1) A region of microscopic dimples, indicative of ductile failure during the last stage of rapid crack propagation (i.e. catastrophic failure caused by simple overload at the last load cycle), was present. (2) In the case of fatigue failure, the presence of clusters of short, near-parallel striation marks (so-called fatigue striations) (Li *et al.* 2002, Cheung *et al.* 2005). Fatigue striations are 'pathognomonic' of material fatigue, even though other features may also be present (ASM International 1987, Hull 1999). (3) In the case of shear fracture, circular abrasion marks on the fracture surface surrounding a (central) region of microscopical dimples would be observed, with the combine of abrasion marks through contact and sliding over of the surfaces on either side of a crack in mode II and III crack opening (Hull 1999). It might be possible that some fatigue striations could have been abolished through such contact of the opposing surfaces, but careful, systematical examination of the fracture surface (at high power) should reveal the actual mechanism.

Clinically, instruments used in curved root canals are subjected to both bending and shear stresses simultaneously; the magnitude of each varying with the manner of use. The influence of torsional load and cyclic fatigue on instrument separation may depend on canal curvature (Pruett *et al.* 1997, Bahia & Buono 2005), instrument cross-sectional design and the stress distribution in the instrument (Turpin *et al.* 2000, Berutti *et al.* 2003, Xu & Zheng 2006). In general, whilst rotational-bending can lead to material fatigue, excessive monotonic torsional stress would be the main cause of shear-fracture of the instrument. Excessive torsion may occur either caused by friction, such as the case of extensive contact between the instrument and canal walls (so-called 'taper locking') (Blum *et al.* 1999, Yared *et al.* 2002), or where the handpiece continues to rotate whilst the tip of the instrument is bound (jammed) in the canal (Gambarini 2000, Roland *et al.* 2002). When the shear stress rises beyond the yield point of the material the instrument undergoes plastic deformation and ultimately fails producing the characteristic concentric marks on the fracture surface (Hull 1999).

The results of the present study indicate that shear failure predominated in the hand instruments, whereas a majority of the engine-driven instruments of the same brand (i.e. design) failed because of fatigue. When the hand instruments are completed using the modified 'balanced force' movement, the instrument is subjected to rotational shear in alternating directions. The instrument begins to rotate when the moment of force is sufficient to overcome the static friction and the work done to cut away dentine from the root canal wall. Once the cutting action begins, the torque decreases (Blum *et al.* 1999). Static friction is always greater than kinetic friction (Blatt 1992). Thus, with the rotary (engine-driven) technique, where the NiTi instruments are rotating before insertion into the canal, an engine-driven instrument only has (apart from other work done, e.g. cutting dentine) to overcome the kinetic friction, the stress of which would be lower than that (i.e. static friction) developed in hand-operated instruments. The axial crack pattern found on the surface of hand instruments was seldom observed in the engine-driven instruments in this study. The crack direction may be related to the resolved direction of stress on the surface of the body when an object of a circular cross-section is subject to torsion (Gere 2001). Similar patterns of cracks have also been reported elsewhere (Alapati *et al.* 2005). Further work is required to examine the mechanical behaviour of the instruments used under the two forms of movement, possibly by finite-element analysis.

Engine-driven NiTi instruments are used typically at a rotation rate of 150–350 rpm. Thus, the material is subjected to repeated tension-compression cycles if operated in a curved canal (Turpin *et al.* 2000, Kuhn *et al.* 2001). The chance for fatigue failure would be much greater in engine-driven instruments than in hand-operated instruments (which only rotate at a low rate), because the number of strain cycles is the main determinant of the fatigue life of a material (Suresh 1998). Instrument fracture is a complex, multifactorial clinical problem; the operator and root canal anatomy might be more influential than the instruments *per se* on the fracture rate (Parashos *et al.* 2004, Spanaki-Voreadi *et al.* 2006). Whilst there seems to be few warning signs prior to fracture of ProTaper engine-driven instruments (Ankrum *et al.* 2004, Shen *et al.* 2006), approximately one-fifth (11/58) of fractured, hand-operated instruments had evidence of unwinding of flutes on (low-power) lateral-view examination. Indeed, a number (approximately 7%) of ProTaper hand instruments were discarded intact, but unwound, which was rarely the case in the engine-driven counterpart. Given that more of the hand instruments showed plastic deformation before breakage, it would appear to be essential that instruments are examined, preferably under the operating microscope, prior to use to try to identify damaged examples.

Conclusions

Under the conditions of this study, a majority of defects found in hand-operated ProTaper instruments was in the form of plastic deformation (unwinding of flutes) or shear failure. The fracture rate of this hand instrument was 14%, of which 38% were caused by fatigue; the figures for the engine-driven instrument of the same brand were 14% and 67% respectively. The fracture mode of engine-driven and hand-operated instruments appeared to be different, with shear failure being more prevalent in the latter. It seems that unwinding of flutes may be discernible in NiTi hand instruments before breakage, suggesting that they should be examined for such plastic deformation prior to use in the canal.

Acknowledgement

This research was supported, in part, by the National Key Technologies R&D Program of the Tenth Five-Year Plan of the Ministry of Science and Technology, China (grant no. 2004BA720A23).

References

Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS (2005) SEM observations of nickel-titanium rotary endodontic instruments that fractured during clinical use. *Journal of Endodontics* **31**, 40–3.

Ankrum MT, Hartwell GR, Truitt JE (2004) K3 Endo, ProTaper, and ProFile systems: breakage and distortion in severely curved roots of molars. *Journal of Endodontics* **30**, 234–7.

ASM International (1987) *ASM Handbook. vol. 12: Fractography*. Materials Park, OH: The Materials Information Society, pp. 12–165.

Bahia MG, Buono VT (2005) Decrease in the fatigue resistance of nickel-titanium rotary instruments after clinical use in curved root canals. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **100**, 249–55.

Barbakow F, Lutz F (1997) The 'Lightspeed' preparation technique evaluated by Swiss clinicians after attending continuing education courses. *International Endodontic Journal* **30**, 46–50.

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

Berutti E, Chiandussi G, Gaviglio I, Ibba A (2003) Comparative analysis of torsional and bending stresses in two mathematical models of nickel-titanium rotary instruments: ProTaper versus ProFile. *Journal of Endodontics* **29**, 15–9.

Blatt FJ (1992) *Modern Physics*. New York, NY: McGraw-Hill.

Blum JY, Cohen A, Machtou P, Micallef JP (1999) Analysis of forces developed during mechanical preparation of extracted teeth using ProFile NiTi rotary instruments. *International Endodontic Journal* **32**, 24–31.

Cheung GSP, Peng B, Shen Y, Bian Z, Darvell BW (2005) Defects in ProTaper S1 instruments after clinical use: fractographic examination. *International Endodontic Journal* **38**, 802–9.

Fife D, Gambarini G, Britto LL (2004) Cyclic fatigue testing of ProTaper NiTi rotary instruments after clinical use. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **97**, 251–6.

Gambarini G (2000) Rationale for the use of low-torque endodontic motors in root canal instrumentation. *Endodontics and Dental Traumatology* **16**, 95–100.

Gere JM (2001) *Mechanics of Materials*, 5th edn. Pacific Grove, CA: Brooks/Cole, pp. 187–270.

Glosson CR, Haller RH, Dove SB, del Rio CE (1995) A comparison of root canal preparations using Ni-Ti hand, Ni-Ti engine-driven and K-Flex endodontic instruments. *Journal of Endodontics* **21**, 146–51.

Haïkel Y, Serfaty R, Bateman G, Senger B, Allemann C (1999) Dynamic and cyclic fatigue of engine-driven rotary nickel-titanium endodontic instruments. *Journal of Endodontics* **25**, 434–40.

Hull D (1999) *Fractography: Observing, Measuring and Interpreting Fracture Surface Topography*. Cambridge, UK: Cambridge University Press.

Knowles KI, Ibarrola JL, Christiansen RK (1996) Assessing apical deformation and transportation following the use of LightSpeed root-canal instruments. *International Endodontic Journal* **29**, 113–7.

Kuhn G, Tavernier B, Jordan L (2001) Influence of structure on nickel-titanium endodontic instruments failure. *Journal of Endodontics* **27**, 516–20.

Li UM, Lee BS, Shih CT, Lan WH, Lin CP (2002) Cyclic fatigue of endodontic nickel-titanium rotary instruments: static and dynamic tests. *Journal of Endodontics* **28**, 448–51.

Parashos P, Gordon I, Messer H (2004) Factors influencing defects of rotary nickel-titanium endodontic instruments after clinical use. *Journal of Endodontics* **30**, 722–5.

Patiño PV, Biedma BM, Liébana CR, Cantatore G, Bahillo JG (2005) The influence of a manual glide-path on the separation rate of NiTi rotary instruments. *Journal of Endodontics* **31**, 114–6.

Peng B, Shen Y, Cheung GSP, Xia TJ (2005) Defects in ProTaper S1 instruments after clinical use: longitudinal examination. *International Endodontic Journal* **38**, 550–7.

Peters OA, Peters CI, Schönenberger K, Barbakow F (2003a) ProTaper rotary root canal preparation: assessment of torque and force in relation to canal anatomy. *International Endodontic Journal* **36**, 93–9.

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

Pruett JP, Clement DJ, Carnes DL (1997) Cyclic fatigue testing of nickel-titanium endodontic instruments. *Journal of Endodontics* **23**, 77–85.

Roane JB, Sabala CL, Duncanson MG Jr. (1985) The 'balance force' concept for instrumentation of curved canals. *Journal of Endodontics* **11**, 203–11.

Roland DD, Andelin WE, Browning DF, Hsu GH, Torabinejad M (2002) The effect of preflaring on the rates of separation for 0.04 taper nickel titanium rotary instruments. *Journal of Endodontics* **28**, 543–5.

Ruddle CJ (2001) The ProTaper endodontic system: geometries, features and guidelines for use. *Dentistry Today* **20**, 60–7.

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

Sattapan B, Nervo GJ, Palamara JEA, Messer HH (2000) Defects in rotary nickel-titanium files after clinical use. *Journal of Endodontics* **26**, 161–5.

Schilder H, Yee FS (1984) Canal debridement and disinfection. In: Cohen S, Burns RC, eds. *Pathways of the Pulp*, 3rd edn. St. Louis, MO: Mosby, pp. 175.

Shen Y, Cheung GS, Bian Z, Pang B (2006) Comparison of defects in ProFile and ProTaper systems after clinical use. *Journal of Endodontics* **32**, 61–5.

Spanaki-Voreadi AP, Kerezoudis NP, Zinelis S (2006) Failure mechanism of ProTaper NiTi rotary instruments during clinical use: fractographic analysis. *International Endodontic Journal* **39**, 171–8.

Suresh S (1998) *Fatigue of Materials*, 2nd edn. Cambridge, UK: Cambridge University Press, pp. 256–80.

Tseng PSK (2004) Root canal preparation with hand ProTapers. In: Wei SHY, ed. *Contemporary Endodontics 2004*, Hong Kong, China: Dentsply Asia, pp. 14–6.

Turpin YL, Chagneau F, Vulcain JM (2000) Impact of two theoretical cross-sections on torsional and bending stresses of nickel-titanium root canal instrument models. *Journal of Endodontics* **26**, 414–7.

Ullmann CJ, Peters OA (2005) Effect of cyclic fatigue on static fracture loads in ProTaper nickel-titanium rotary instruments. *Journal of Endodontics* **31**, 183–6.

Xu X, Zheng Y (2006) Comparative study of torsional and bending properties for six models of nickel-titanium root canal instruments with different cross-sections. *Journal of Endodontics* **32**, 372–5.

Yared GM, Bou Dagher FE, Machtou P, Kulkarni GK (2002) Influence of rotational speed, torque and operator proficiency on failure of Greater Taper files. *International Endodontic Journal* **35**, 7–12.

Yun H, Kim SK (2003) A comparison of the shaping abilities of 4 nickel-titanium rotary instruments in simulated root canals. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics* **95**, 228–33.

