Defects in ProTaper S1 instruments after clinical use: fractographic examination

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

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

Abstract

Cheung GSP, Peng B, Bian Z, Shen Y, Darvell BW. Defects in ProTaper S1 instruments after clinical use: fractographic examination. *International Endodontic Journal*, **38**, 802–809, 2005.

Aim To investigate the mode of failure of a brand of nickel-titanium instruments separated during clinical use, by detailed examination of the fracture surface.

Methodology A total of 122 ProTaper S1 instruments were discarded from an endodontic clinic at a stomatological school in China over a period of 17 months; 28 had fractured. These fractured instruments were ultrasonically cleaned, autoclaved and then examined under a scanning electron microscope. From the lateral view the fracture was classified into 'torsional' or 'flexural'. The specimens were then re-mounted and the presence of characteristics of shear failure and fatigue striations was recorded under high-power view of the fracture surface. The difference in the mean lengths of fractured segment between the shear and fatigue groups was compared using Student's *t*-test.

Results Twenty-seven separated instruments were available for analysis. Under low-power magnification, only two fell into the category of 'torsional' failure when examined laterally; the others appeared to be 'flexural'. Close examination of the fracture surface revealed the presence of fatigue striations in 18 specimens. Nine instruments (including the two putative 'torsional' failures above) fell into the shear fracture group, in which fatigue striations were absent or characteristics of shear failure of the material were found. The mean length of fractured segments resulting from fatigue failure (4.3 ± 1.9 mm) was significantly greater than that for shear failure (2.5 ± 0.8 mm) ($P < 0.001$, two-sample *t*-test).

Conclusions Examination of the fracture surface at high magnification is essential to reveal features that may indicate the possible origin of cracks and the mode of material failure. Macroscopic or lateral examination of separated instruments would fail to reveal the true mechanism of failure. Fatigue seems to be an important reason for the separation of rotary instruments during clinical use.

Keywords: fatigue, fracture, nickel-titanium, rotary instrument, shear.

Received 22 March 2005; accepted 13 June 2005

Introduction

The introduction of nickel-titanium (NiTi) endodontic instruments has transformed root canal preparation. The use of NiTi rotary instruments generally can minimize undesirable complications often encountered during hand instrumentation of curved root canals (Glosson *et al.* 1995). Instruments made of this alloy not only have a high resistance to corrosion and excellent biocompatibility, but also a special mechanical property known as 'superelasticity' (Otsuka & Wayman 1998). Superelasticity is associated with the occurrence of a phase transformation of the alloy upon application of stress above a critical level, which takes place when the ambient temperature is above the

Correspondence: Dr Y. Shen, Key Lab for Oral Biomedical Engineering of the Ministry of Education Department of Operative Dentistry and Endodontics, School of Stomatology, Wuhan University, 65 Luoyu Road, Wuhan, China (Tel.: +86 2787 161981; fax: +86 2787 873260; e-mail: yashen36@hotmail.com).

so-called austenite-finish temperature of the material. This stress-induced martensitic transformation reverses spontaneously upon release of the stress; the material then returns to its original shape and size (Saburi 1998). This special property manifests as an enhanced elasticity of the NiTi alloy, allowing the material to recover after large strains (or distortion). Thus, NiTi instruments appear highly flexible and elastic, hence the possibility of use in a continuous rotary fashion, even in a curved canal. On the other hand, separation (fracture) of NiTi instruments can still occur as a result of: (i) rotational bending, i.e. due to fatigue or (ii) shear fracture, usually when the instrument tip is stalled (jammed) but the handpiece continues to rotate.

Numerous factors have been implicated in the separation of NiTi endodontic instruments, amongst which are operator proficiency (Yared & Kulkarni 2002, Sonntag *et al.* 2003, Parashos *et al.* 2004), method of use (Blum *et al.* 1999, Regan *et al.* 2000), rotational speed (or better rotation rate) (Daugherty *et al.* 2001, Martín *et al.* 2003), anatomic configuration of the canals (Martín *et al.* 2003, Peters *et al.* 2003), design of the instrument (Berutti *et al.* 2003), and number of sterilization cycles (Silvaggio & Hicks 1997). Whilst these studies have investigated the influence of such factors on the chance of instrument separation, an evaluation of the true mode of failure seems to be lacking. Some studies have examined the fracture characteristics under controlled laboratory conditions (Pruett *et al.* 1997, Haïkel *et al.* 1999, Li *et al.* 2002), but that probably did not reproduce the complex clinical situation affecting the stresses and strains imposed on the instrument and hence the true reason for its fracture. Whilst some authors have indicated that both torsional and cyclic flexural loads are important in causing instrument separation in use (Gambarini 2001, Ullmann & Peters 2005), the mechanism of failure has not been determined. The purpose of this study, therefore, was to determine the mode of material failure of one brand of NiTi rotary instrument separated during clinical use with a view to identifying the fracture mechanism.

Materials and methods

The collection of clinically-used NiTi instruments (ProTaper; Dentsply Maillefer, Ballaigues, Switzerland) has been described earlier (Peng *et al.* 2005). In short, all instruments of the one brand discarded from an endodontic clinic over a 17-month period from January 2003 to May 2004 were collected. In that clinic, each such instrument was limited to a maximum number of uses according to the tooth being treated: four molars, 20 premolars, or 50 incisors and canines. Instruments would also be discarded after a single use in very complex, severely curved or calcified canals. Of the 325 ProTaper instruments collected, 122 were S1 instruments; 28 of them (23%) had fractured (Table 1). They were autoclaved and then ultrasonically cleaned in absolute alcohol for approximately 90 s prior to examination under the scanning electron microscope (SEM) (Sirion-FEG; Philips, Eindhoven, the Netherlands). At ×25 magnification, in lateral view, each fractured file was classified by one examiner (YS) into either 'torsional' (associated with unwinding deformation) or 'flexural' failure according to the description by Sattapan *et al.* (2000). The specimens were then re-mounted and secondary SEM images of the fracture surface were obtained at high magnifications at an accelerating voltage of 25 kV and 100 nA beam current. Two examiners (GC, YS) jointly examined the fractographic images. The presence of 'fatigue

Table 1 Summary statistics of the sample

	No.	Location from tip[a] (mm)	Teeth in which separation occurred		
			Anterior	Premolar	Molar
All separated S1 files	28	3.7 ± 1.8	1	10	17
Longitudinal view (×25)					
Torsional	2	3.5,4.0	0	1	1
Flexural	25	3.7 ± 1.9	1	9	15
Fractographic examination (×1000 or above)[b]					
Shear failure	9	2.5 ± 0.8	0	3	6
With fatigue striations	18	4.3 ± 1.9	1	7	10

[a]One specimen was lost during processing and the average length was calculated from the remaining 27 specimens. Mean values (±SD) were given for groups with $n > 3$.
[b]Significant difference in the mean length of fractured segment between the shear and fatigue groups (two-sample *t*-test, $t = 6.5185$, $P < 0.001$).

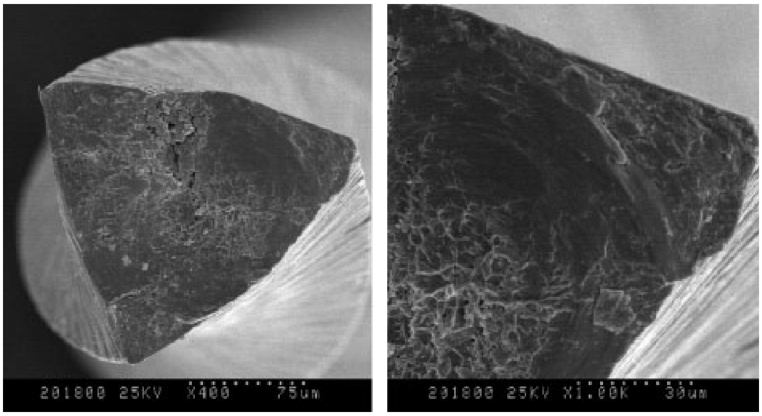

Figure 1 (Left) Fracture surface of a separated S1 file showing shear failure of the material; note presence of circular abrasion marks and absence of fatigue striations on high-power view (right).

striations' or 'beach marks', which are characteristic of fatigue failure of all metallic materials (ASM International 1987), was noted. The mode of failure was then categorized as either 'fatigue' or 'shear'. The latter showed concentric rubbing or abrasion marks (from contact of the fracture surfaces), absence of fatigue striations and areas of skewed dimples on the fracture surface (Kocańda 1978). The distance between the broken end and the handle was measured to calculate the length of the fractured segment for each instrument. The difference in the mean length of fractured segment between the shear and fatigue groups was compared using Student's *t*-test.

Results

Of the 28 fractured S1 instruments collected, one instrument was lost during processing, leaving 27 available for analysis. Two (7%) fell into the category of 'torsional' failure under low-power examination; the others appeared to be 'flexural' (Table 1). At high magnification of the fracture surface, both 'torsional failure' cases above and a further seven (i.e. nine, 33%) showed features of shear failure (Fig. 1). Fatigue striations (Fig. 2) were found on 18 specimens, indicating that true fatigue failure had occurred (Fig. 3). High-power photomicrographs near the centre of the fracture surface showed the presence of irregular or skewed dimples in areas that were not affected by fatigue striations or abrasion marks (Fig. 4). The number of discrepancies between the lateral and fractographic deductions was high; 26% of observations ($n = 7$) did not agree, all falling in the macroscopic 'flexural' group (Table 2).

Few specimens showed the presence of cracks that did not communicate with the periphery, i.e. the exterior surface of the instrument; this was classified as fatigue failure because of the presence of fatigue striations near the centre of the cross section (Fig. 5). The mean length of the fractured segments due to shear failure was 2.5 ± 0.8 mm, whilst that for fatigue failure was 4.3 ± 1.9 mm (Table 1). The difference was statistically significant (two-sample *t*-test, $P < 0.001$).

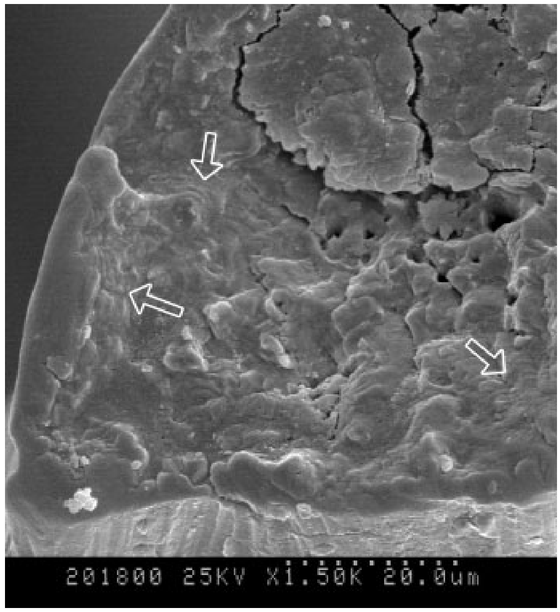

Figure 2 Clusters of fatigue striations on fracture surface of instrument (arrows).

Discussion

There are four recognized modes of fracture in solid metal: (i) cleavage, (ii) dimple rupture, (iii) fatigue and

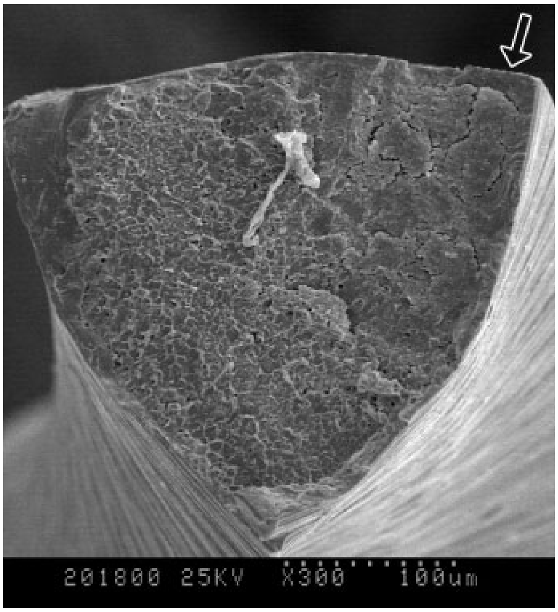

Figure 3 Fracture surface showing crack initiation at the periphery of the instrument (arrow).

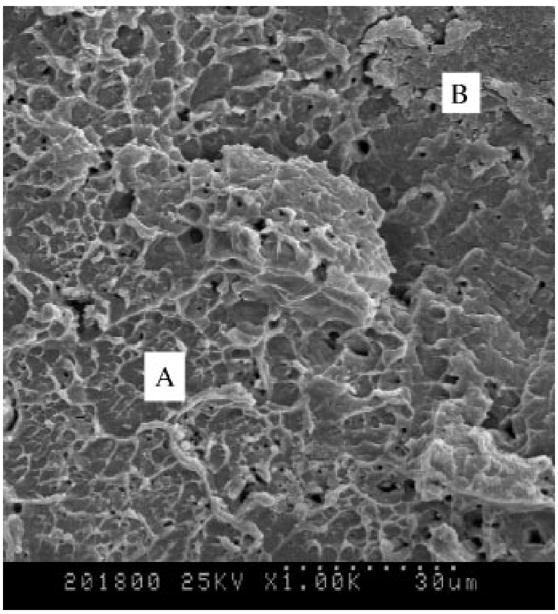

Figure 4 Central portion of specimen in Fig. 3 showing skewed dimples (A) on the fracture surface at areas not involved in fatigue-crack propagation (cf. upper right corner of the field, B).

(iv) decohesion (Collins 1993). Cleavage refers to the cracking of a crystalline solid along slip planes. Dimple rupture is the typical fractographic appearance of ductile failure; under (tensile or shear) load internal voids (due to inclusions, microporosities, precipitates or other microstructural heterogeneities) grow in size until the remaining material in between these 'holes' fails because of overload (ASM International 1987). Fatigue is a form of transgranular fracture where the grain boundaries have little effect on the direction of crack propagation (Schijve 2001). Decohesion is the rupture of a material along grain boundaries, usually under the influence of environmental factors, such as hydrogen embrittlement or attack by corrosive agents (ASM International 1987). Once a crack is formed, its propagation is related to the stress field at the crack tip: tension tends to pull the material apart, compression pushes the structure of the material together, and shear causes one part of the material to slide over another (Ewalds & Wanhill 1989). In the case of fatigue, microcracks are first formed on the surface of a material, especially where there are surface flaws or irregularities that will serve as stress-raisers, i.e. where stress concentration occurs (Schijve 2001). The machining grooves (scratches) left on the surface of instrument after the manufacturing process are such 'initiators' of microcracks. Once initiated, fatigue-cracks propagate in each and every load cycle until the remaining intact material is unable to sustain the same load and thus fails. Various microscopic marks left by the propagating crack front are observable on the fracture surfaces. In the case of rotational bending, the direction of maximum tension at any one point on the skin of the material changes in a sine function-like manner. Thus, the orientation of fatigue striations often is neither regular nor uniformly oriented (see also Figs 3 and 4 in Li *et al.* 2002). Clusters of striations may be found, instead of regular markings seen on specimens subjected to uniform, cyclic tensile loads (Kocańda 1978).

Table 2 Fracture modes of ProTaper S1 instrument as determined by lateral and fractographic examinations

	Lateral view	Fractographic
'Torsional' or shear	2	9[a]
'Flexural' or fatigue	25	18

[a]Seven shear failures were initially classified as 'flexural' in lateral view.

In the endodontic context, many studies of the mode of separation have been carried out on the 'longitudinal' or, more accurately, lateral view of the instrument under magnifying loupes (Gabel *et al.* 1999, Daugherty *et al.* 2001), under an operating

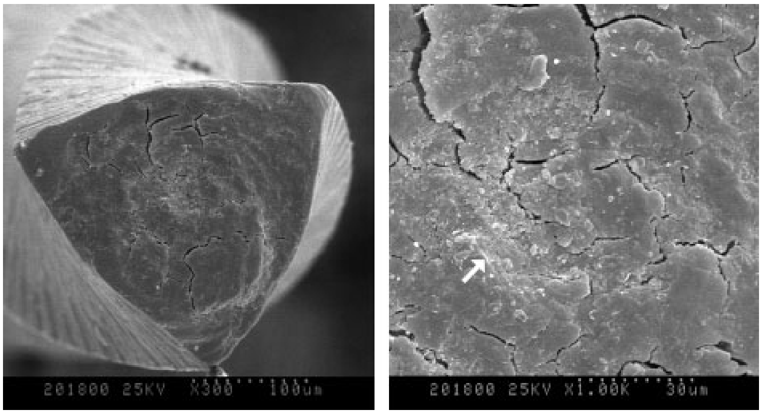

Figure 5 (Left) Fracture surface showing cracks in the central portion that did not extend to the surface of the instrument. (Right) Presence of fatigue striations (arrow) under high-power examination.

microscope (Tygesen *et al.* 2001, Arens *et al.* 2003), or at low power under SEM (Sattapan *et al.* 2000). Using this method of evaluation, the great majority (93%) of instruments in the current study appeared to have failed because of 'flexural fatigue'. In comparison, Sattapan *et al.* (2000) reported some 56% of 'torsional' and 44% of 'flexural' failures for Quantec instruments, whilst Arens *et al.* (2003) reported that some 15% of ProFile 0.04 taper instruments were either distorted without failure or had fractured after a single clinical use. However, whilst such examination in lateral view allows the detection of plastic deformation in the separated instrument, it fails to indicate the actual mechanism involved in the fracture process. Fractographic examination aims to identify features on the fracture surface that would indicate the origin and (direction of) propagation of the crack(s) leading to material failure (ASM International 1987). For instance, fatigue striations on the fracture surface left by the incremental progression of a crack are unique to fatigue, and these can only be observed on the fracture surface of a material, not in lateral view. In the present study, two-thirds of the separated instruments were determined to have failed because of fatigue because fatigue striations could be identified on the fracture surface; no macroscopic deformation was discernible. However, the converse was not always true. Seven of the 25 files that were initially categorized as suffering 'flexural' failure from low-power examination carried features of shear fracture. This underlines the importance of detailed examination of the fracture surface in the analysis of instrument separation.

Fatigue failure often occurs at the point of maximum curvature (Pruett *et al.* 1997), where the strain is highest. The surface strain may be estimated as the ratio of the radius of the instrument (assuming it to be of circular cross section) to the radius of curvature. Thus, sections of a larger diameter, i.e. farther from the instrument tip, are more susceptible to fatigue fracture than smaller sections when rotating with the same curvature. This may explain the general difference in the lengths of the fractured segments for shear and fatigue failures.

In the fatigue process, progression of a crack effectively reduces the area of intact material at that cross section. When the stress acting on the remaining material exceeds its ultimate strength (as the engineering stress is inversely proportional to the cross-sectional area in the case of monotonic load) at the next load cycle, the alloy fails in a ductile manner, producing a dimple configuration. The dimples observed in the present study were skewed and not equiaxed (the latter being typical of tensile overload) because of the presence of a torsional (shear) load. The ductile failure applies to the last stage of the fatigue phenomenon – areas involved in crack propagation generally do not reveal the dimple appearance. There are times where features left by the propagating fatigue-cracks may be modified, or even masked, by one or a combination of two mechanisms. First, during rotational bending under a simultaneous compressive load (e.g. pushing on a rotating instrument in a curved root canal), surfaces on either side of a crack may contact and slide over each other during the compressive part of the cycle, leading to abrasion and abolition of the surface topography (ASM International 1987). Thus, depending on the method of use by individual operators, the present study might have underestimated the frequency of fatigue failure. Another possibility is the influence of a corrosive agent such as hypochlorite used in root canal treatment. Surface features could become masked by corrosion products, which might worsen after autoclaving. Further work is necessary to determine whether corrosive agents might play a role in the separation of NiTi rotary instruments in the clinical environment. Electropolishing and ion implantation have been reported to result in a surface more 'resistant' to wear (Rapisarda *et al.* 2001) and corrosive attack (Cissé *et al.* 2002). Some commercially available NiTi rotary instruments are electropolished (FKG Dentaire 2005).

Fatigue failure accounted for the majority of broken instruments in the present study, which might be explained as follows. First, fatigue-crack growth rates in NiTi alloys have been reported to be significantly greater than in other metals of similar strength (Dauskardt *et al.* 1989). Thus, once a microcrack is initiated, it can quickly propagate to cause catastrophic failure. This seems to agree with the general impression that ProTaper instruments fail without much warning during clinical use (Ankrum *et al.* 2004). Secondly, increasing the strain rate (i.e. rotation rate in the case of rotational bending) generates increased crystallographic slip because there is little time for stress relaxation and stress-induced martensitic transformation to occur (Lin *et al.* 1996). Thus, compared with using an instrument by hand, there is a greater chance for failure in an apparently 'brittle' manner for engine-driven instruments. The machining scratches on the instrument surface would act as stress raisers or even crack-like features that may become origins of fatigue-cracks; a smooth surface is less prone to fatigue failure (Schijve 2001).

It appears peculiar that in a minority of specimens some cracks seemed to have originated near the centre and extended towards the periphery of the instrument (Fig. 5). This is contrary to the classic fatigue phenomenon where microcracks begin on the surface and propagate inwards (Ewalds & Wanhill 1989, Schijve 2001). Commercial NiTi alloy is polycrystalline; the first grain to undergo the stress-induced martensitic transformation is the one subject to the highest resolved tensile stress (Hosogi *et al.* 2002). The adjacent grain boundary, therefore, may become an area of high stress concentration. This earliest-transformed martensite grain (being subjected to the greatest stress) and its adjoining grain boundaries have been proposed as possible initial sites of crack formation, giving rise to 'microscopic cracks penetrating axially around some columnar blocks of material' (Hosogi *et al.* 2002). Further studies are required to determine the source and site of crack initiation in NiTi instruments.

NiTi instruments tested by means of rotational bending have generally been reported to have a fatigue life of only hundreds to thousands of revolutions (Pruett *et al.* 1997, Gambarini 2001, Li *et al.* 2002, Ullmann & Peters 2005). Such limited number of rotations is not typical of high-cycle fatigue failure (that is of the order of 10^4–10^7 cycles or more, with the peak stress below the yield point) (Collins 1993). Hence, most NiTi instruments have failed as a result of low-cycle fatigue (LCF) where the material is subject to a high service load (exceeding the yield point) and hence only able to survive a relatively small number of cycles. Local plastic deformation is a prominent feature in LCF (although it escapes low-power examination) and, fractographically, fatigue striations become less prominent and irregular compared with those found in high-cycle fatigue (Kocańda 1978, Schijve 2001). This may explain the patchy, irregularly oriented striations observed in this study. To date, whilst torque-limited electric motors seem to have provided an effective means to reduce the chance of shear failure (Gambarini 2000 & 2001), there is no good measure yet to limit the influence of fatigue-crack propagation in rotary NiTi instruments. It seems that the best recommendation is to discard them after a certain period of use, but the exact time cannot be estimated from the data of this study. The usage period would be expected to vary widely depending on the design, size, magnitude of the stress and strain on the instrument, and clinical factors such as the dimension and curvature of the canal, and accessibility. The radius of curvature, which determines the stress field, is a more important factor in work hardening, and hence susceptibility of the instrument to fracture, than the number of root canals treated (Kuhn & Jordan 2002). Thus, correct assessment of root canal curvature cannot be overemphasized. In the case of an abruptly curved canal, discarding the instrument after a single use may be the safest advice.

Conclusions

Macroscopic or lateral view examination of a separated instrument fails to indicate accurately the mode of material failure. Detailed examination of the fracture surface is essential to reveal the topographic features that may suggest the underlying mechanism of failure. Material fatigue appears to be an important reason for the separation of rotary instruments during clinical use.

Acknowledgements

The authors would like to thank Prof. Ren-hui Wang and Prof. Jia-nian Gui of the Center for Electron Microscopy of Wuhan University for their advice and technical guidance. This research was supported in part by the National Key Technologies R&D Programme of the Tenth Five-Year Plan of the Ministry of Science and Technology, China (grant no. 2004BA720A23).

References

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

Arens FC, Hoen MM, Steiman HR, Dietz GC Jr (2003) Evaluation of single-use rotary nickel titanium instruments. *Journal of Endodontics* **29**, 664–6.

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

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.

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.

Cissé O, Savadogo O, Wu M, Yahia LH (2002) Effect of surface treatment of NiTi alloy on its corrosion behaviour in Hank's solution. *Journal of Biomedical Materials Research* **61**, 339–45.

Collins JA (1993) *Failure of Materials in Mechanical Design: Analysis, Prediction, Prevention*, 2nd edn. New York, NY: John Wiley & Sons, pp. 1–644.

Daugherty DW, Gound TG, Comer TL (2001) Comparison of fracture rate, deformation rate, and efficiency between rotary endodontic instruments driven at 150 rpm and 350 rpm. *Journal of Endodontics* **27**, 93–5.

Dauskardt RH, Duerig TW, Ritchie RO (1989) Effect of in situ phase transformation on fatigue-crack propagation in Ti-Ni shape memory alloy. In: *Proceedings of Materials Research Society International Meeting on Advanced Materials*, Vol. 9. Pittsburgh, PA: Materials Research Society, pp. 243–9.

Ewalds HL, Wanhill RJH (1989) *Fracture Mechanics*, Part V. London, UK: Edward Arnold, pp. 226–98.

FKG Dentaire (2005) *Race NiTi instruments & SMD*. http://www.fkg.ch/pdf/FKG-Datasheet-Race-AN.pdf [accessed on 2 February 2005].

Gabel WP, Hoen M, Steiman HR, Pink FE, Dietz R (1999) Effect of rotational speed on nickel titanium file distortion. *Journal of Endodontics* **25**, 752–4.

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

Gambarini G (2001) Cyclic fatigue of nickel titanium rotary instruments after clinical use with low- and high-torque endodontic motors. *Journal of Endodontics* **27**, 772–4.

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.

Hosogi M, Okabe N, Sakuma T, Keiksuke O (2002) Effect of cold-working ratio on superelastic cyclic behaviour and fatigue life in Ti-41.7 Ni-8.5 Cu (at %) shape-memory alloy wire. *Materials Science Forum* **394–395**, 257–60.

Kocańda S (1978) *Fatigue Failure of Metals. Chapter 5: Fatigue Fractures*. Alphen aan den Rijn, the Netherlands: Sijthoff & Noordhoff, pp. 269–355.

Kuhn G, Jordan L (2002) Fatigue and mechanical properties of nickel titanium endodontic instruments. *Journal of Endodontics* **28**, 716–20.

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.

Lin PH, Tobushi H, Tanaka K, Hattori T, Ikai A (1996) Influence of strain rate on deformation properties of TiNi shape memory alloy. *JSME International Journal Series A* **39**, 117–23.

Martín B, Zelada G, Varela P et al. (2003) Factors influencing the fracture of nickel-titanium rotary instruments. *International Endodontic Journal* **36**, 262–6.

Otsuka K, Wayman CM (eds) (1998) Mechanism of shape memory effect and superelasticity. In: *Shape Memory Materials*. Cambridge, UK: Cambridge University Press, pp. 27–48.

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

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 (2003) ProTaper rotary root canal preparation: assessment of torque and force in relation to canal anatomy. *International Endodontic Journal* **36**, 93–9.

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

Rapisarda E, Bonaccorso A, Tripi TR, Condorelli GG, Torrisi L (2001) Wear of nickel-titanium endodontic instruments evaluated by scanning electron microscopy: effect of ion implantation. *Journal of Endodontics* **27**, 588–92.

Regan JD, Sherriff M, Meredith N, Gulabivala K (2000) A survey of interfacial forces used during filing of root canals. *Endodontics and Dental Traumatology* **16**, 101–6.

Saburi T (1998) Ti-Ni shape memory alloys. In: Otsuka K, Wayman CM, eds. *Shape Memory Materials*. Cambridge, UK: Cambridge University Press, pp. 49–96.

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

Schijve J (2001) *Fatigue of Structures and Materials*. Dordrecht, The Netherlands: Kluwer Academic, pp. 1–507.

Silvaggio J, Hicks ML (1997) Effect of heat sterilization on the torsional properties of rotary nickel-titanium endodontic files. *Journal of Endodontics* **23**, 731–4.

Sonntag D, Delschen S, Stachniss V (2003) Root-canal shaping with manual and rotary Ni-Ti files performed by students. *International Endodontic Journal* **36**, 715–23.

Tygesen YA, Steiman HR, Ciavarro C (2001) Comparison of distortion and separation utilizing ProFile and Pow-R nickel-titanium rotary files. *Journal of Endodontics* **27**, 762–4.

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.

Yared GM, Kulkarni GK (2002) Failure of ProFile Ni-Ti instruments used by an inexperienced operator under access limitations. *International Endodontic Journal* **35**, 536–41.