International Endodontic Journal

doi:10.1111/j.1365-2591.2009.01602.x

Torsional behaviour of rotary NiTi ProTaper Universal instruments after multiple clinical use

E. P. Vieira[1], R. K. L. Nakagawa[1], V. T. L. Buono[2] & M. G. A. Bahia[1]

[1]Department of Restoration Dentistry, Faculty of Dentistry, Federal University of Minas Gerais, Belo Horizonte-MG, Brazil; and [2]Department of Metallurgical and Materials Engineering, Engineering School, Federal University of Minas Gerais, Belo Horizonte-MG, Brazil

Abstract

Vieira EP, Nakagawa RKL, Buono VTL, Bahia MGA. Torsional behaviour of rotary NiTi ProTaper Universal instruments after multiple clinical use. *International Endodontic Journal*, **42**, 947–953, 2009.

Aim To assess the influence of multiple clinical uses on the torsional behaviour of ProTaper Universal rotary NiTi instruments.

Methodology Root canal treatments were performed on patients using the ProTaper Universal rotary system to prepare canals. Ten sets of instruments were used by an experienced endodontist, each set being used in five molar teeth. After clinical use, S1, S2, F1 and F2 instruments were analysed for damage by optical and scanning electron microscopy. The used sets, along with a control group of 10 sets of new instruments, were then torsion tested based on the ISO 3630-1 specification. Data obtained were subjected to a one-way analysis of variance (ANOVA) with $\alpha = 0.05$.

Results The use of the ProTaper Universal rotary instruments by an experienced endodontist allowed for the cleaning and shaping of the root canal system of five molar teeth without fracture. The maximum torque for instruments S2, F1 and F2, and the angular deflection at fracture for instruments S2 and F1 were significantly lower following clinical use. The largest decrease in maximum torque was 18.6% ($P = 0.014$) for S2 instruments. The same maximum percent decrease was found for angular deflection at fracture for F1 instruments ($P = 0.009$).

Conclusions Torsional resistance and angular deflection of used instruments, as compared to that of new instruments, were reduced following clinical use.

Keywords: clinical use, endodontic instruments, nickel–titanium, ProTaper Universal, torsional resistance.

Received 21 January 2009; accepted 28 April 2009

Introduction

Reasons for the fracture of rotary NiTi instruments include variations in canal anatomy, such as merging, curving, re-curving, dilacerating or dividing canals (Ruddle 2002). In addition, other factors can affect the fracture resistance of endodontic instruments, such as size, taper, alloy composition, manufacturing methods, flexibility and rigidity, instrument shape and direction of rotation (Hilt *et al.* 2000). The cross-sectional profile also has a significant influence on the mechanical behaviour of NiTi instruments (Schäfer *et al.* 2003, Melo *et al.* 2008). The factors affecting the performance include the depth of the flute, the area of the inner core, the radial land and the peripheral ground surface (Gambarini 2005, Xu & Zheng 2006).

The fatigue life of a rotary endodontic instrument is related to the degree to which it is flexed when placed in a curved root canal, with greater flexures leading to a shorter fatigue life expectation (Pruett *et al.* 1997, Melo *et al.* 2002, Bahia & Buono 2005). Torsional failure occurs when the tip or another part of the instrument is locked in the canal, whilst the shaft continues to rotate. If the elastic limit of the metal is

Correspondence: Vicente T. L. Buono, Professor, Department of Metallurgical and Materials Engineering, Federal University of Minas Gerais, Rua Espírito Santo 35 room 206, 30160-030, Belo Horizonte, MG, Brazil (Tel.: +55 31 3409 1859; fax: +55 31 3409 1815; e-mail: vbuono@demet.ufmg.br).

exceeded, the instrument undergoes plastic deformation, which can be followed by fracture if the load is high enough (Blum *et al.* 1999, Gambarini 2000).

Peters *et al.* (2003) established that torque is correlated not only with apically exerted force, but also with preoperative canal volume. Hence, the preparation of narrow and constricted canals can subject rotary NiTi instruments to higher torsional loads and high-apically directed forces. The problem of fracture by torsional overload has been dealt with by determining the maximum torque at separation for each type of instrument and then using low-torque endodontic motors, which can be programmed in such a way as to avoid the application of torque values higher than that of each instrument can support without failing. Nevertheless, this approach does not take into account the fact that fatigue loads developed during curved root canal shaping may decrease the torsional resistance of endodontic instruments. This effect was studied by various authors (Yared *et al.* 2003, Ullmann & Peters 2005, Bahia *et al.* 2006), who reported a reduction in the maximum torque to failure for all instruments evaluated.

The reuse of rotary instruments of NiTi is a constant concern. The cumulative effects of multiple clinical uses on the incidence of fatigue, deformation and instrument separation have been analysed (Yared *et al.* 2000, Gambarini 2001, Fife *et al.* 2004, Bahia & Buono 2005), with the conclusion that their clinical reuse progressively reduced their resistance to fatigue. During canal preparation, especially in curved root canals in molar teeth, these instruments are submitted to a high degree of cyclic deformation that may consume a considerable amount of their fatigue life (Bahia & Buono 2005).

In a recent study, Vieira *et al.* (2008) observed that the flexural fatigue resistance of ProTaper instruments, used clinically by an experienced endodontist for the cleaning and shaping of five molars, was reduced up to 52% when compared with that of new instruments. The present work was undertaken to assess the influence of multiple clinical uses on the torsional behaviour of ProTaper Universal rotary NiTi instruments.

Material and methods

Twenty sets of ProTaper Universal instruments (Dentsply Maillefer, Ballaigues, Switzerland), type S1, S2, F1 and F2, totalling 88 files, were analysed. They were divided into two groups: (i) control group (CG), with 10 sets of new instruments tested in torsion until fracture to establish the mean values of maximum torque and angular deflection at fracture for each type of instrument and (ii) experimental group (EG), with 10 sets of instruments, each set used clinically by an endodontist with experience using the ProTaper Universal system in five molar teeth to shape between 15 and 20 root canals. The instruments of the EG were tested subsequently in torsion until fracture. The SX and F3 instruments used in the clinical procedures were not included in the study, since these instruments work only in the straight portion of the canals (SX) or in preparation of straight canals (F3).

Direct and angled radiographs of each tooth were obtained using a paralleling technique to evaluate anatomy, as well as to determine the canal radius and angle of curvature, as defined by Pruett *et al.* (1997), and its approximate length. The measurement of these parameters was performed by projecting the radiographic images using a profile projector (Mitutoyo, Tokyo, Japan) at 10 × magnification. The canal radius of curvature was measured along the outer canal wall.

After the orifices were located and the canal explored with sizes 10 and 15 stainless steel K-files (Dentsply Maillefer), cleaning and shaping of the canals were completed in accordance with a crowndown technique recommended by Ruddle (2005). Once a glide path had been created, the ProTaper Universal shaping instruments were used like a 'brush' to laterally and selectively cut dentine on the outstroke. The preparation was finished using the ProTaper Universal finishing instruments F1 and F2 in a 'nonbrushing' manner. The clinical protocol was followed with recapitulations until the working length, established at 0.5 mm of the canal patency length, could be reached by at least an F2 instrument, at which point shaping was considered complete.

A 5.25% sodium hypochlorite solution was used for irrigation and Rc-prep (Premier Dental Products, Norristown, PA, USA) was used as a lubricant. The rotational speed was 300 rpm, applied by an endodontic electric motor (Endo Plus, VK Driller, São Paulo, SP, Brazil), operating at a torque of 5 N·cm together with a hand piece of 16 : 1 reduction (W&H 975, Dentalwerk, Bürmoos, Austria).

After use in each patient, the instruments were washed, ultrasonically cleaned for 5 min in ethanol and steam autoclave sterilized. The S1, S2, F1 and F2 instruments of the EG were observed by optical microscopy (Mitutoyo TM, Tokyo, Japan), at 30 × magnification, to determine the presence of distortion, unwinding defects and macroscopic deformation. Before torsion testing, three sets of instruments were randomly selected and examined by scanning electron microscopy (SEM) (Jeol JSM 6360, Tokyo, Japan) to assess their surface characteristics.

Torsion testing was based on ISO 3630-1 specification, and using a torsion machine (Analógica, Belo Horizonte, MG, Brazil) was described in Bahia *et al.* (2006). The rotation speed was set clockwise to 2 rpm. The end of the shaft was clamped into a chuck connected to a reversible geared motor. Three millimetres of the instrument's tip was clamped in another chuck with brass jaws to prevent sliding. Continuous recording of torque and angular deflection, as well as measurements of the maximum torque and angular deflection to failure, was provided by a specifically designed computer program.

To determine the statistical significance of differences in the measured parameters amongst different groups, data obtained were subjected to a one-way analysis of variance (ANOVA). Significance was determined at the 95% confidence level.

Results

During the clinical part of the study, none of the instruments fractured or deformed permanently. The mean values (and standard deviations) of radius and angle of curvature characterizing the geometry of the root canals of the 50 molars instrumented with the 10 sets of files (five molars for each set) were 4.0 mm (1.7 mm) and 33.1° (11.1°), respectively.

The results of the torsion tests are summarized in Fig. 1, which shows mean values of the maximum torque and angular deflection at fracture of new instruments (CG) and of those previously used in the clinical practice (EG). As is common, torsional resistance increased as the diameter of the instruments increased, with the mean values of maximum torque appearing statistically different when instruments in the CG were compared one to another: S1–S2, S2–F1 and F1–F2. A similar tendency was observed for angular deflection at fracture in the CG, and statistically significant differences were found when comparing instruments S1 with S2, and F1 with F2, but not when comparing S2 with F2 instruments.

The mean values in Fig. 1 indicated that multiple clinical uses caused a reduction in maximum torque and angular deflection at fracture of ProTaper Universal instruments. Comparison between the values of maximum torque, measured for the same type of instruments from the Control and EGs, showed that this tendency was significant for instruments S2 (P = 0.014), F1 (P = 0.007) and F2 (P = 0.006), but not for S1 (P = 0.475). When a similar analysis was performed for angular deflection at fracture, statistically significant reduction in this parameter was found for S2 (P = 0.003) and F1 (P = 0.009) instruments, but not for S1 (P = 0.546) and F2 (P = 0.097).

After canal shaping, all instruments examined by SEM had microcracks and widening of machine grooves, as well as wear and blunting of the cutting edges. These surface characteristics were qualitatively similar in all three sets of randomly selected instruments of the EG. The SEM images shown in Fig. 2 illustrate typical microcracks found in used S2 instruments. The majority of the cracks were transverse to

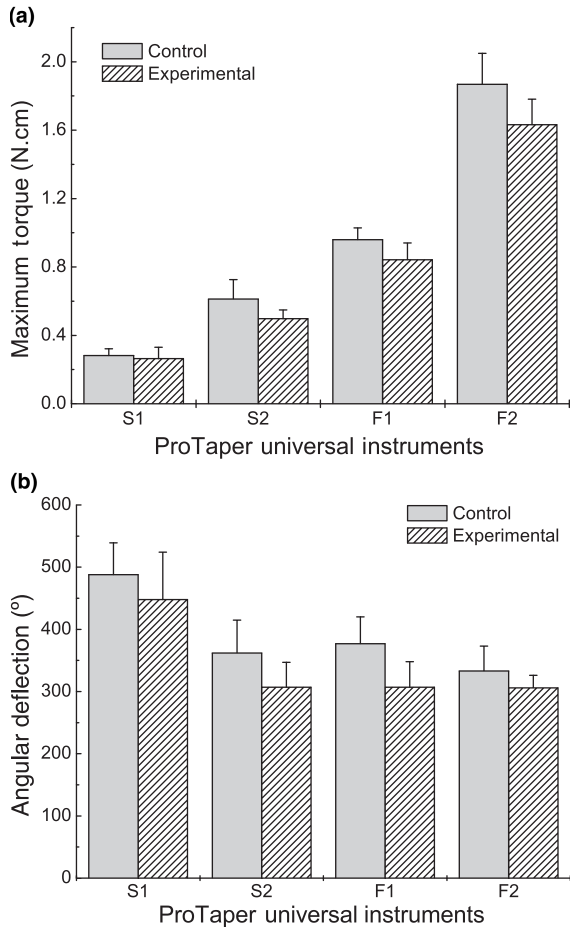

Figure 1 Mean values of maximum torque (a) and angular deflection at fracture (b) of ProTaper Universal instruments from the control and experimental groups. Error bars represent the standard deviations.

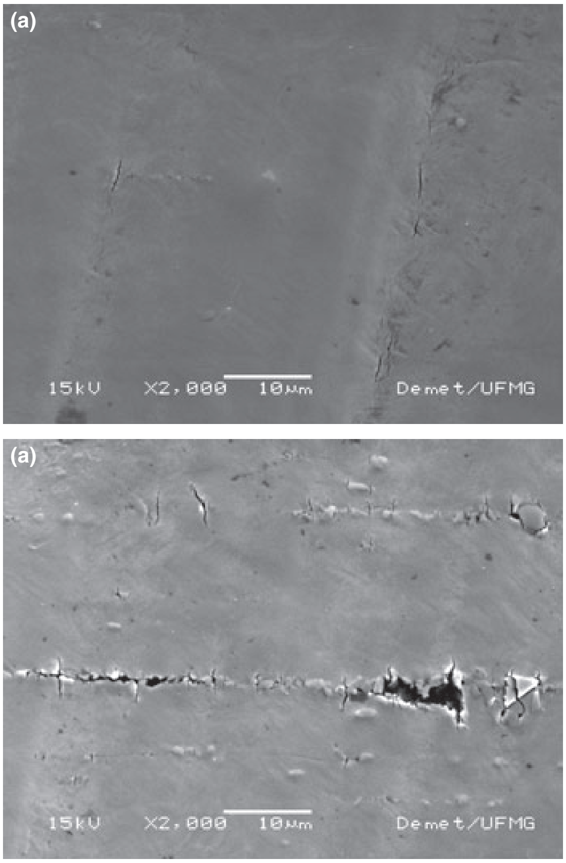

Figure 2 SEM images of the surface of an S2 ProTaper Universal instrument used for the cleaning and shaping of five molars showing (a) cracks transversal to the cutting edge and (b) longitudinal cracks.

the cutting edge (Fig. 2a), but longitudinal cracks, parallel to the long axis of the instrument, were also observed (Fig. 2b).

Discussion

The torsional behaviour of rotary NiTi endodontic instruments is affected by a variety of factors, such as size, taper, design, alloy chemical composition and thermomechanical processes applied during manufacturing (Kuhn & Jordan 2002, Bahia *et al.* 2005, Miyai *et al.* 2006). Nevertheless, there is a strong relationship between the maximum torque an instrument can withstand and its diameter (Peters & Barbakow 2002, Bahia & Buono 2005). It has also been suggested that the cross-sectional shape of instruments affects the stress distribution pattern as well as their torsional properties (Turpin *et al.* 2000, Berutti *et al.* 2003, Melo *et al.* 2008, Câmara *et al.* 2009, Kim *et al.* 2009). The results for the CG depicted in Fig. 1 are thus in agreement with the general observation that the maximum torque of endodontic instruments increases as instrument diameter becomes larger. On the other hand, measurements of angular deflection at fracture showed that this parameter does not correlate with instrument diameter in the same way (Gambarini 2001, Bahia *et al.* 2006). The results shown in Fig. 1 for new instruments confirm this observation.

In straight root canals, rotary endodontic instruments operate by cutting and removing organic tissue and debris, experiencing mostly frictional forces, which run in opposition to their torsional motion. However, when the instrument rotates inside a curved root canal, it is bent and thus submitted to tensile–compressive strain cycles in the region of the canal curvature, in addition to the torsional restraints. The strain levels attained by endodontic instruments during this cyclic loading depend on the root canal and instrument geometries, being concentrated at the portion of the instrument positioned in the maximum curvature region of the root canal (Bahia & Buono 2005, Cheung & Darvell 2007). These cyclic forms of stress cause flexural fatigue, involving crack nucleation and growth. The value of the tensile strain amplitude, ε_T, on the surface of an instrument of diameter D inserted into a canal of radius of curvature R can be estimated by the expression:

$$\varepsilon_T = \frac{D}{2R - D} \tag{1}$$

which is valid when the canal radius is measured at the outer canal wall (Bahia & Buono 2005), as was done in the present study. Alternatively, when R is measured at the canal central axis, this expression becomes (Cheung & Darvell 2007):

$$\varepsilon_T = \frac{D}{2R} \tag{2}$$

If the maximum amplitude is assumed to occur at 3 mm from the instrument tip, the region of the instrument subject to the maximum tensile strain amplitude is D_3. Table 1 shows the values of D_3 measured for ProTaper Universal instruments by Câmara *et al.* (2009) and the corresponding estimated values of ε_T, calculated using equation 1 for the average radius of curvature, 4.0 mm, of the root canals instrumented in the present study.

Cyclic flexural straining by the amounts shown in Table 1 would certainly cause damage to the

Table 1 Diameter of the ProTaper instruments at 3 mm from their tip, D_3, and corresponding maximum tensile amplitudes, ε_T, estimated for the average radius of curvature of 4.0 mm

Instrument	D_3 (mm)[a]	ε_T (%)
S1	0.29	3.8
S2	0.35	4.6
F1	0.42	5.5
F2	0.50	6.7

[a]Câmara *et al.* (2009).

instruments. The microcracks exemplified in Fig. 2 constitute evidence of this damage. The presence of longitudinal cracks, that is, cracks parallel to the long axis of the file, has previously been described (Peng *et al.* 2005, Tripi *et al.* 2006, Vieira *et al.* 2008), and is thought to reflect the direction of the stress on the surface of the instrument under torsional load. Similar cracking patterns have been observed on other rotary NiTi endodontic instruments subjected to cyclic torsional straining (Bahia *et al.* 2008). During this type of cyclic deformation, planes with a maximum shear stress are either perpendicular or parallel to the longitudinal axis, whilst the normal stress component on the slip plane is zero. Microscopic investigations have shown that microcracks nucleate in a slip band under cyclic torsion and then grow further in a direction perpendicular to the main stress. In a cylindrical bar, this direction makes an angle of 45° with the axis of the bar. Consequently, cracks in a round axle under cyclic torsion grow in the form of a spiral around its surface (Schijve 2001). The longitudinal appearance of the cracks observed in endodontic instruments is because of the fact that the instruments have helical shapes and that the cracks, being rather small in size, require large magnifications to be observed (Bahia *et al.* 2008).

When the torsional resistance of similar instruments belonging to CG and EG was compared, a tendency for this property to decrease with the clinical use in five molars was observed for all instruments analysed (Fig. 1). This tendency was statistically significant for S2, F1 and F2 instruments. Previous studies (Yared *et al.* 2003, Ullmann & Peters 2005, Bahia *et al.* 2006) reported that simulated clinical use lowered the mean values of maximum torque when compared with that of new instruments. Regarding the behaviour of angular deflection at fracture, Yared *et al.* (2003) and Ullmann & Peters (2005) found no statistically significant changes in this parameter between new instruments and those submitted to simulated clinical use. In the present study, angular deflection at fracture tended to decrease for the used instruments (Fig. 1b) and statistically significant decreases were found for S2 and F1 instruments. This result confirms previous findings on ProFile instruments submitted to simulated clinical use (Bahia *et al.* 2006). However, it is important to mention that angular deflection at fracture has little clinical significance, because at a typical rotational speed of 300 rpm, one complete revolution of a tip-locked instrument will occur in one-fifth of a second. Thus, differences in this parameter will not be perceived in clinical practice.

The reduction in maximum torque measured in the present study were, on average, 6%, 19%, 12% and 13% for S1, S2, F1 and F2 ProTaper Universal instruments, respectively. These results confirmed the role played by flexural fatigue in the torsional resistance of these instruments. However, in a previous work (Vieira *et al.* 2008) considerably higher values were found for the reduction of flexural fatigue life of ProTaper instruments clinically employed for the cleaning and shaping of five molars: 33%, 52%, 45% and 44% for S1, S2, F1 and F2 instruments, respectively. Taken together, these results indicated that the cumulative effects of multiple clinical uses on rotary NiTi endodontic instruments have a stronger influence on flexural fatigue behaviour than on their torsional resistance.

Although flexural fatigue appears to have a cumulative effect on rotary endodontic instruments, causing weakening over time, clinical studies have failed to demonstrate the extent of the cumulative effects of multiple clinical uses on the fatigue resistance of these instruments. For instance, Fife *et al.* (2004) did not observe statistically significant differences when the remaining fatigue life of ProTaper instruments used in two and four molars were compared, whilst Vieira *et al.* (2008) obtained a similar result after shaping of five and eight molars. Moreover, simulated clinical use of ProFile instruments up to one of two and three-fourth of their fatigue life (Bahia *et al.* 2006) and of ProTaper instruments up to 30%, 60% and 90% of their fatigue life (Ullmann & Peters 2005) did not significantly alter their torsional resistance when the prestrained instruments were compared. These results were interpreted as indicating that crack nucleation occurs early during flexural fatigue of NiTi rotary instruments, low-crack growth occupying a large fraction of their low-cycle fatigue life (Bahia & Buono 2005).

Conclusions

Torsional resistance of used instruments was reduced by average amounts varying from 6% to 19%, when compared with that of new instruments. Structural fatigue took place during the clinical use of the instruments and, in addition to the usual transversal cracks generate by flexural fatigue, longitudinal cracks were also observed on the surface of the used instruments. Comparisons with data on ProTaper instruments indicate that the cumulative effects of multiple clinical uses on rotary NiTi endodontic instruments have a stronger influence on flexural fatigue behaviour than on their torsional resistance.

Acknowledgements

This work was partially supported by Fundação de Amparo à Pesquisa do Estado de Minas Gerais – FAPEMIG, Belo Horizonte, MG, Brazil and Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq, Brasília, DF, Brazil.

References

Bahia MGA, Buono VTL (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.

Bahia MGA, Martins RC, Gonzalez BM, Buono VTL (2005) Physical and mechanical characterization and the influence of cyclic loading on the behaviour of nickel-titanium wires employed in the manufacture of rotary endodontic instruments. *International Endodontic Journal* **38**, 795–801.

Bahia MGA, Melo MCC, Buono VTL (2006) Influence of simulated clinical use on the torsional behavior of nickel–titanium rotary endodontic instruments. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **101**, 675–80.

Bahia MGA, Melo MCC, Buono VTL (2008) Influence of cyclic torsional loading on the failure of rotary nickel-titanium instruments. *International Endodontic Journal* **41**, 883–91.

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, Machtou P, Micallef JP (1999) Location of contact areas on rotary Profile instruments in relationship to the forces developed during mechanical preparation on extracted teeth. *International Endodontic Journal* **32**, 108–14.

Câmara AS, Martins RC, Viana ACD, Leonardo RT, Buono VTL, Bahia MGA (2009) Flexibility and torsional strength of ProTaper and ProTaper Universal rotary instruments assessed by mechanical tests. *Journal of Endodontics* **35**, 113–6.

Cheung GSP, Darvell BW (2007) Fatigue testing of a NiTi rotary instrument. Part 1: strain-life relationship. *International Endodontic Journal* **40**, 626–32.

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

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

Gambarini G (2001) Cyclic fatigue of ProFile rotary instruments after prolonged clinical use. *International Endodontic Journal* **34**, 386–9.

Gambarini G (2005) The K3 rotary nickel titanium instrument system. *Endodontic Topics* **10**, 179–82.

Hilt BR, Cunningham CJ, Shen C, Richards N (2000) Torsional properties of stainless steel and nickel–titanium files after multiple autoclave sterilizations. *Journal of Endodontics* **26**, 76–80.

Kim TO, Cheung GSP, Lee JM, Kim BM, Hur B, Kim HC (2009) Stress distribution of three NiTi rotary files under bending and torsional conditions using a mathematic analysis. *International Endodontic Journal* **42**, 14–21.

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

Melo MMC, Bahia MGA, Buono VTL (2002) Fatigue resistance of engine-driven rotary nickel–titanium endodontic instruments. *Journal of Endodontics* **28**, 765–9.

Melo MCC, Pereira ESJ, Viana ACD, Fonseca AMA, Buono VTL, Bahia MGA (2008) Dimensional characterization and mechanical behaviour of K3 rotary instruments. *International Endodontic Journal* **41**, 329–38.

Miyai K, Ebihara A, Hayashi y, Doi H, Suda h, Yoneyama T (2006) Influence of phase transformation on the torsional and bending properties of nickel-titanium rotary endodontic instruments. *International Endodontic Journal* **39**, 119–26.

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, Barbakow F (2002) Dynamic torque and apical forces of ProFile .04 rotary instruments during preparation of curved canals. *International Endodontic Journal* **35**, 379–89.

Peters OA, Peters CI, Schonenberger 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 (1997) Cyclic fatigue testing of nickel–titanium endodontic instruments. *Journal of Endodontics* **23**, 77–85.

Ruddle CJ (2002) Broken instrument removal. The endodontic challenge. *Dent Today* **21**, 70–2.

Ruddle CJ (2005) The ProTaper technique. Shaping the future of endodontics. In: Castellucci A, ed. *Endodontics, vol II*. Florence: IL Tridente, pp. 548–63.

Schäfer E, Dzepina A, Danesh G (2003) Bending properties of rotary nickel-titanium instruments. *Oral Surgery Oral Medicine Oral Pathology, Oral Radiology and Endodontics* **96**, 757–63.

Schijve J (2001) *Fatigue of Structures and Materials*. 1st edn. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Tripi TR, Bonaccorso A, Condorelli GG (2006) Cyclic fatigue of different nickel-titanium endodontic rotary instruments. *Oral Surgery Oral Medicine Oral Pathology, Oral Radiology and Endodontics* **102**, e106–14.

Turpin YL, Chagneau F, Vulcain JM (2000) Impact of two theoretical cross-sections on torsional and bending stress 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.

Vieira EP, França EC, Martins RC, Buono VTL, Bahia MGA (2008) Influence of multiple clinical use on fatigue resistance of ProTaper rotary nickel–titanium instruments. *International Endodontic Journal* **41**, 163–72.

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 (2000) Cyclic fatigue of Profile rotary instruments after clinical use. *International Endodontic Journal* **33**, 204–7.

Yared G, Kulkarni GK, Ghossayn F (2003) An in vitro study of the torsional properties of new and used K3 instruments. *International Endodontic Journal* **36**, 764–9.