doi:10.1111/j.1365-2591.2008.01481.x

Stress distribution of three NiTi rotary files under bending and torsional conditions using a mathematic analysis

T. O. Kim[1], G. S. P. Cheung[2], J. M. Lee[3], B. M. Kim[3], B. Hur[1] & H. C. Kim[1]

[1]Department of Conservative Dentistry, School of Dentistry, Pusan National University, Busan, Korea; [2]Area of Endodontics, Faculty of Dentistry, The University of Hong Kong, Hong Kong; and [3]Division of Precision Manufacturing Systems, Pusan National University, Busan, Korea

Abstract

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

Aim To compare and evaluate the stress distribution of three NiTi instruments of various cross-sectional configurations under bending or torsional condition using a finite-element analysis model.

Methodology Three NiTi files (ProFile, ProTaper and ProTaper Universal) were scanned using Micro-CT to produce a three-dimensional digital model. The behaviour of the instrument under bending or torsional loads was analysed mathematically in software (ABAQUS V6.5-1), taking into consideration the nonlinear mechanical characteristic of NiTi material.

Results ProFile showed the greatest flexibility, followed by ProTaper Universal and ProTaper. The highest stress was observed at the surface near the cutting edge and the base of (opposing) flutes during cantilever bending. Concentration of stresses was observed at the bottom of the flutes in ProFile and ProTaper Universal instruments in torsion. The stress was more evenly distributed over the surface of ProTaper initially, which then concentrated at the middle of the convex sides when the amount of angular deflection was increased.

Conclusion Incorporating a U-shaped groove in the middle of each side of the convex-triangular design lowers the flexural rigidity of the origin ProTaper design. Bending leads to the highest surface stress at or near the cutting edge of the instrument. Stress concentration occurs at the bottom of the flute when the instrument is subjected to torsion.

Keywords: bending, cross-sectional geometry, finite-element analysis, NiTi rotary file, stress distribution, torsion.

Received 19 March 2008; accepted 16 August 2008

Introduction

Root canal instruments manufactured with nickel–titanium (NiTi) have been developed in an attempt to overcome the rigidity of instruments made from stainless steel alloys (Walia *et al.* 1988). NiTi instruments possess a lower modulus of elasticity and a superior resistance to torsional fracture, compared with stainless steel instruments of similar size (Walia *et al.* 1988, Schäfer *et al.* 2003). The NiTi rotary instruments allow root canal preparation to be accomplished more expeditiously than hand instruments; a well-centred, tapered root canal form with minimal risk of transporting the original canal centre is often achieved (Glosson *et al.* 1995, Garip & Gunday 2001, Schäfer 2001, Chen & Messer 2002, Lee *et al.* 2003, Schäfer *et al.* 2004).

To date, many NiTi rotary systems have been introduced to the market. Most brands, e.g. ProFile (Dentsply Maillefer, Ballaigues, Switzerland), K3 (SybronEndo, Orange, CA, USA), Mtwo (VDW, Munich, Germany) and Hero Shaper (Micro-Mega, Besançon,

Correspondence: Dr Hyeon-Cheol Kim, DDS, MS, PhD, Assistant Professor, Department of Conservative Dentistry, Pusan National University School of Dentistry, 1-10, Ami-dong, Seo-gu, Busan 602-739, Korea (Tel.: +82 51 240 7978; fax: +82 51 254 0575; e-mail: golddent@pusan.ac.kr).

France) have a regularly tapered shaft, but with different cross-sectional designs; some also possess ‘radial lands’ (Schäfer 2001, Hata *et al.* 2002). Amongst these systems, the ProFile system is best known for its U-file design (i.e. with a concave, ‘U-shaped’ flutes in cross-section; Fig. 1a), and for its flexibility and better centering ratio than some other systems (Park *et al.* 2003, Walsch 2004, Kim *et al.* 2005). In contrast, the ProTaper system (Dentsply Maillefer) has a unique design for its shaft with a ‘progressively changing’ taper (Bergmans *et al.* 2003, Clauder & Baumann 2004). The original cross-sectional configuration of the ProTaper system was triangular with convex sides (Fig. 1b). The sharp cutting edge (instead of a radial land) is claimed to reduce the contact area between the file and dentine, thus enhancing the cutting efficiency of the instrument (Clauder & Baumann 2004). However, it has been reported that the ProTaper system tends to produce more aberrations, transportation or straightening of the canal (Yun & Kim 2003, Calberson *et al.* 2004, Schäfer *et al.* 2004). To overcome the problem, which

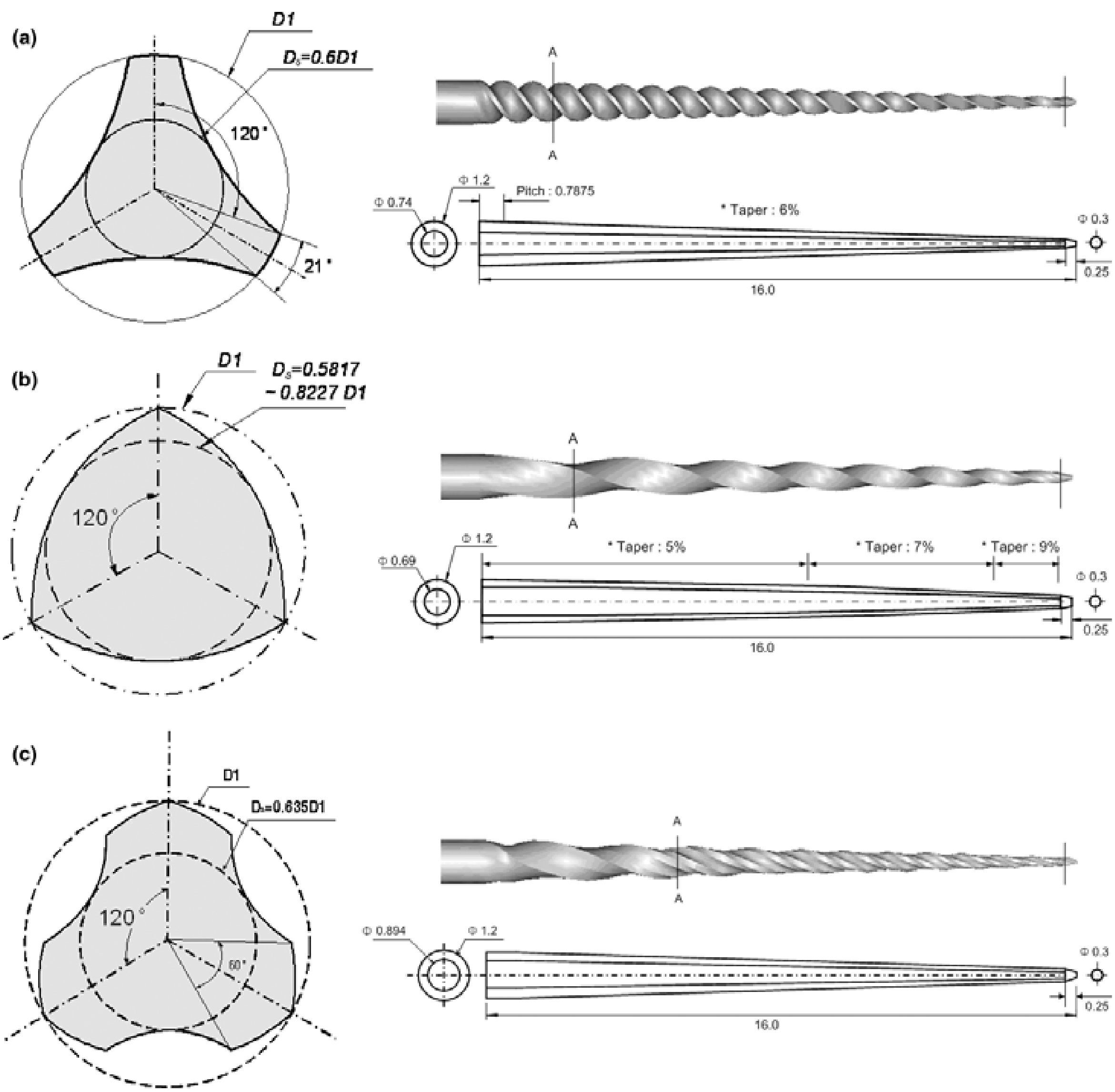

Figure 1 Schematic drawings of the cross-sectional and longitudinal geometry of three NiTi files after the real-size, three-dimensional image from micro-CT: (a) ProFile size 30, 0.06 taper; (b) ProTaper F3 and (c) ProTaper Universal F3.

may be related to a slightly greater rigidity (partly because of the cross-sectional area; another factor being the taper of the instrument), compared with ProFile instruments of similar cross-sectional dimension, a new version with a modified cross-sectional design for the larger instruments of the original system has been marketed as ProTaper Universal. The F2 and F3 instruments of the ProTaper Universal system have incorporated an additional groove in the middle of each side of the 'convex-triangular' cross-section in an attempt to increase its flexibility (Fig. 1c).

Clinically, there is a potential risk of rotary NiTi instruments fracturing in the canal – even new instrument may demonstrate unexpected failure in use (Arens *et al.* 2003). On the other hand, little is known about the distribution of stresses, an important factor related to instrument fracture, when the instrument is subjected to bending or torsional load. It has been reported that fracture of an engine-file may occur in either one or a combination of two ways: torsional and flexural (i.e. fatigue) (Sattapan *et al.* 2000, Cheung *et al.* 2005, Wei *et al.* 2007); the geometrical design is an important determinant because of the effect on the torsional and bending properties of the instrument (Camps *et al.* 1995). Several studies of the stresses generated in NiTi instrument have been completed using finite-element (FE) analysis (Turpin *et al.* 2000, 2001, Berutti *et al.* 2003); however, they evaluated a simulated, cylindrical shape and ignored the taper of the root canal instrument when constructing the models. Recently, Xu *et al.* (2006) have reported on the effect of cross-section configuration on the mechanical behaviour of root canal files by examining an idealized cross-sectional configuration with FE analysis, but they did not seem to have verified the actual geometry of the real product. Indeed, there could be discrepancies between the idealized design and the actual product (Low *et al.* 2006). Thus, the purpose of this study was to compare the stress distribution of the two ProTaper designs under bending and torsional stresses by inputting the actual shape of the instruments for three-dimensional (3D) FE analysis. A U-file design (ProFile) was also examined as a control.

Materials and methods

Modeling of NiTi rotary file

Real-size, digitized models of three brands of NiTi instrument: ProFile size 30 (0.06 taper), ProTaper F3 and ProTaper Universal F3 (all from Dentsply Maillefer) were obtained by first scanning them at 2-μm intervals in a micro-CT scanner (HMX; X-Tek Group, Santa Clara, CA, USA). Then, the outline of the instrument was extracted from the stacks of 3D data in software (IDEAS11 NX; UGS, Plano, TX, USA). Finally, a mesh of linear, eight-noded, hexahedral elements was overlaid onto the rendered 3D image. Such a 3D model consisted of 11880 elements with 16318 nodes for ProFile, 7560 elements with 9017 nodes for ProTaper, or 8964 elements with 10668 nodes for ProTaper Universal (Fig. 1). This numerical model of each instrument was entered into a 3D FE analysis package (ABAQUS V6.5-1; SIMULIA, Providence, RI, USA) with the *z*-axis running from the tip to the shaft of the instrument.

A nonlinear, stress–strain behaviour of the NiTi material (Wang 2007) was entered for the NiTi material during the mathematical analysis (Fig. 2): OA represents the elastic deformation of austenite, AB the pseudoelastic range (plateau spanning over about 4% strain) because of stress-induced martensitic (SIM) transformation, BC the elastic deformation of martensite, and CD the plastic deformation of the transformed martensite. Plastic deformation (a result of because of crystallographic slip) is unrecoverable, whereas elastic and SIM transformation strains are mostly recoverable (Duerig & Pelton 1994). The Young's modulus of the alloy was 36 GPa and the

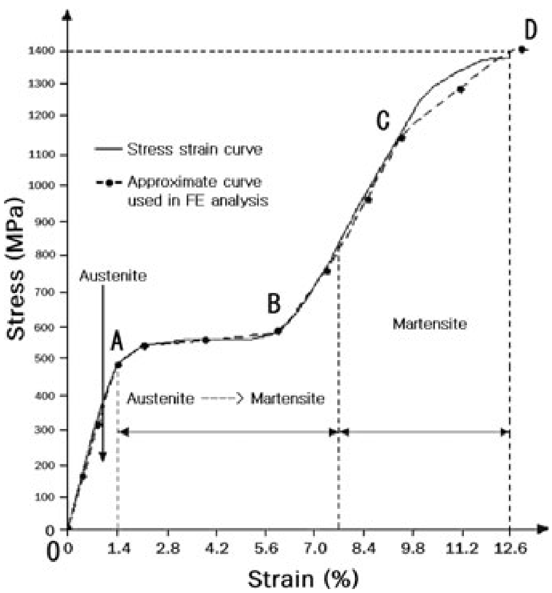

Figure 2 Stress–strain relationship of the NiTi material (from Wang 2007).

Poisson's ratio 0.3. The critical stress at the beginning of the SIM phase transformation was chosen to be 504 MPa and that at the end was 755 MPa (Wang 2007).

Experimental conditions of simulation

The behaviours of the three instruments were analysed numerically under the following simulated conditions in the FE analysis (Fig. 3):

1. Cantilever bending with a constant load – deformation in the form of cantilever bending was simulated by applying a concentrated load of 1 N at the tip of the file with its shaft rigidly held in place (Fig. 3a). The vertical displacement was measured and the von Mises stress distribution was evaluated.

2. Stress distribution under cantilever bending at fixed displacement – under a similar condition as (a) above, the tip of the file was deflected for a distance of 2 mm (Fig. 3b) and held there. The von Mises stress distribution was examined.

3. Application of a shear moment (torsion) – a 2.5 Nmm moment of force was applied to the shaft in a clockwise direction normal to the long axis of the instrument (Fig. 3c), whilst 4 mm of the tip was rigidly constrained. The stress distribution was evaluated.

4. Stress distribution at a fixed angular deflection – the von Mises stress distribution over the instrument was examined after the instrument was rotated by 10° clockwise with its tip rigidly fixed at 4 mm (Fig. 3d).

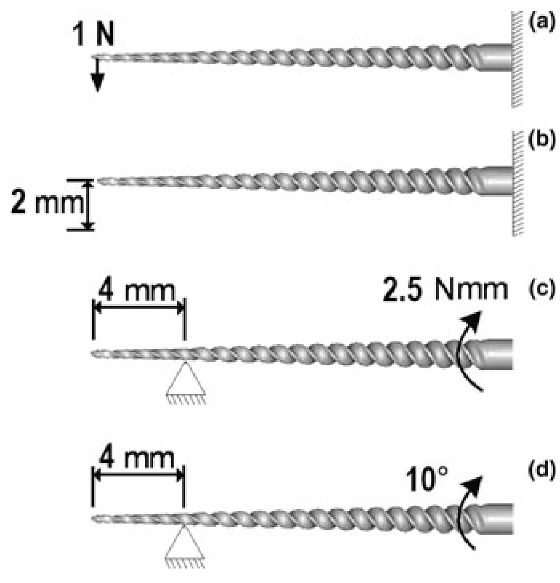

Figure 3 Simulated conditions applied in this study: (a) cantilever bending with a concentrated load of 1 N applied to the tip of the instrument; (b) cantilever bending until the tip was displaced by 2 mm; (c) Shear moment of 2.5 Nmm applied to the shaft, with the instrument rigidly fixed at 4 mm from its tip and (d) Similar condition as (c) but with the torque applied until the shaft was rotated by 10°.

Results

Cantilever bending

At a concentrated load of 1 N, the end deflection for ProFile was 4.6 mm, ProTaper 2.5 mm and ProTaper Universal 3.1 mm, indicating a greater flexibility for ProFile instrument. A maximum von Mises stress of 577 MPa was found at 8.4 mm from the tip of the ProFile instrument; the values were 349 MPa at 3.7 mm for ProTaper, and 547 MPa at 3.6 mm for ProTaper Universal (Fig. 4). The bending force required to deflect the instrument from its resting position was greatest for ProTaper, followed by ProTaper Universal and ProFile (Fig. 5a). For the same amount of end deflection (2 mm), a maximum von Mises stress of 387 MPa was noted for ProTaper Universal, again, at 3.6 mm from the instrument tip. The values were 350 MPa at 3.7 mm for ProTaper, and 275 MPa at 8.4 mm for ProFile instrument respectively (Fig. 6a). The highest stress was observed at the surface at the cutting edge of ProTaper, but at a very short distance from such edge for ProTaper Universal and ProFile, and at the base of the opposing flute during cantilever bending.

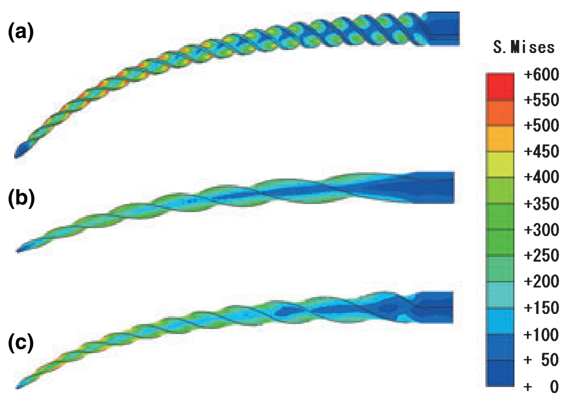

Figure 4 Relative deflection (to scale) of the tip, and stress distribution under cantilever loading (1 N applied to the tip) for each instrument: (a) ProFile; (b) ProTaper and (c) ProTaper Universal.

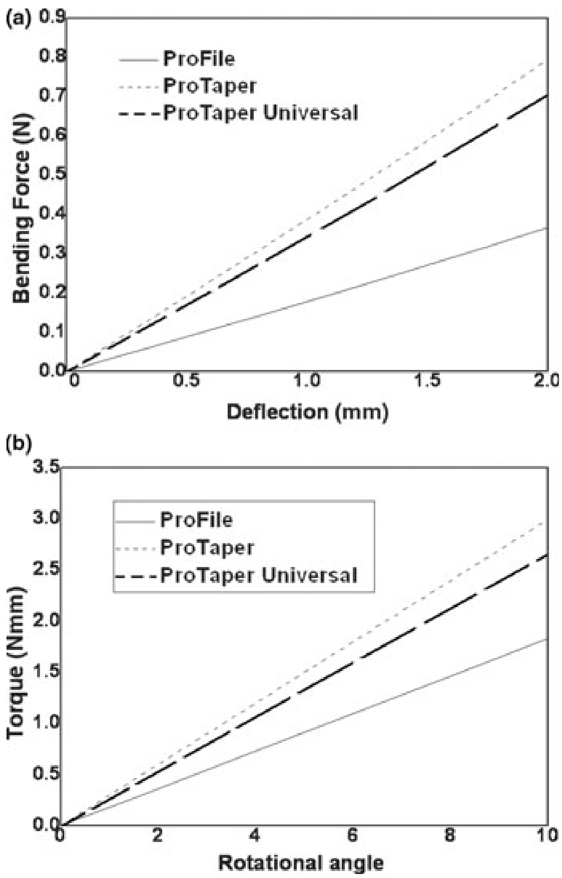

Figure 5 (a) Bending moment needed to deflect the tip and (b) the torque required to rotate each file under the restrained condition.

Shear moment (torsion)

When a torque of 2.5 Nmm was applied, the original ProTaper design showed the lowest value (350 MPa) for the maximum von Mises stress, followed by 384 MPa for ProTaper Universal (Fig. 6b). The ProFile showed the highest stress of 455 MPa, running along at the base (bottom) of the U-shaped flutes. The angular deflection was 0.691, 0.826 and 0.995 degrees for ProTaper, ProTaper Universal and ProFile respectively.

The resistance to torsion mirrored the flexural rigidity of the instrument: a higher torque was required to angularly deflect the ProTaper than the other two instruments (Fig. 5b). The highest von Mises stress (constrained region not compared) recorded for ProFile was 333 MPa, ProTaper 359 MPa and ProTaper Universal 388 MPa, all situated at the base of the flutes in cross-section (Fig. 6c).

Discussion

In the last decade, the use of NiTi rotary instruments has grown in popularity and there has been an increasing number of proprietary systems introduced commercially. NiTi engine-files operate by way of continuous rotation in the root canal and, as such, are subjected to unidirectional torque (assuming no stalling). The value of the shear (torsional) stress varies depending on the canal size (Hübscher *et al.* 2003, Peters *et al.* 2003), hardness of the dentine to be cut (Berutti *et al.* 2003) and the use of a lubricant (Boessler

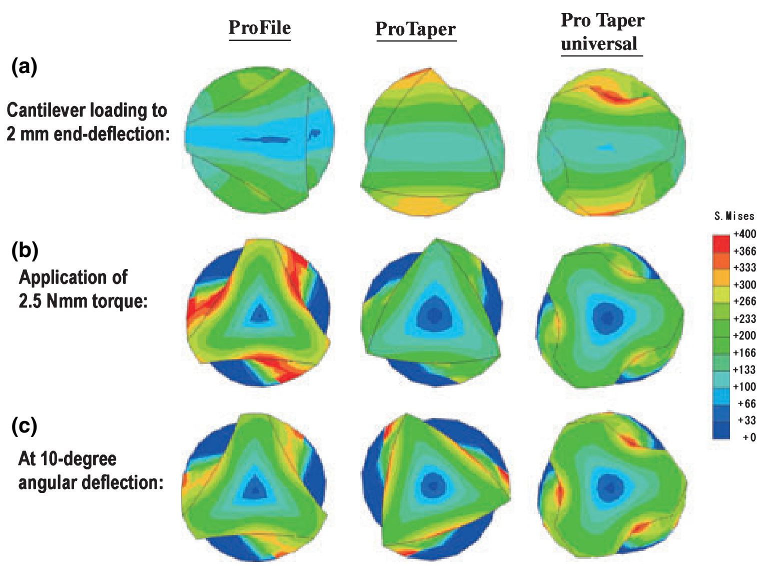

Figure 6 Distribution of von Mises stresses under various conditions for the three instruments tested, the maximum stress values (in MPa) for each case being: (a) ProFile 275, ProTaper 350, ProTaper Universal 387; (b). ProFile 455, ProTaper 350, ProTaper Universal 384 and (c) ProFile 333, ProTaper 359, ProTaper Universal 388.

et al. 2007). The cross-sectional configuration is also an important determinant of the distribution of stresses on the instrument (Tripi *et al.* 2006). To avoid dimensional discrepancy, the three brands of NiTi instrument examined in this present study were first scanned to obtain a real representation of the 3D shape prior to entry into the mathematical simulation.

Studies of NiTi instrument breakage are usually completed by means of post-mortem SEM examination of the fracture mode after clinical or simulated use. Such evaluation would not reveal the stresses on the instrument during bending or rotation. Based on a mathematical comparison of the behaviour of two theoretical cross-sections of ProTaper and ProFile, it has been reported that ProTaper might be more suitable for enlarging the (coronal portion of) canals during the initial phase of shaping, and that ProFile might be more suitable for wider canals and in the final phase of shaping (Berutti *et al.* 2003). Turpin *et al.* (2000) have studied the influence of the idealized cross-sectional profile (ProFile vs. Hero) on the torsional and bending stresses using a boundary integral method, and also suggested that instruments of different cross-sectional design should be used for different procedures.

The amount of end deflection under cantilever loading is a measure of the instrument's flexural rigidity, the product of the elastic modulus of the material and second moment of inertia of the part (Timoshenko & Goodier 1970). ProFile had a greater deflection than other systems, indicating that ProFile possesses a lower flexural rigidity, i.e. higher flexibility. As the mechanical property of the raw material is the same for the three designs (from the same manufacturer), the difference in flexural rigidity of the various makes is a result of the different geometry. ProTaper had the greatest flexural rigidity, lower end deflection, and the least concentration of stress over the surface when subjected to a load of 1 N. Berutti *et al.* (2003) have also reported that ProTaper had lower and more evenly distributed stresses, compared with the ProFile model, under similar type of loading. However, in the clinical situation, the stress generated in an instrument arises from it having to conform to the root canal curvature (i.e. fixed deflection) but not due to an externally applied force. Thus, the situation where the various brands were subjected to the same amount of end deflection (i.e. Fig. 3b) would be more relevant than application of an arbitrary load – both the ProTaper and ProTaper Universal showed a greater value of internal stresses than ProFile. The highest stress concentration was found at the cutting edge of ProTaper and ProTaper Universal, and near the cutting edge of the ProFile, and at the bottom of the directly opposite flute (see Fig. 6a). This is expected from the mechanics of bending a beam of triangular cross-section. Generally, flexural (bending) deflection is proportional to the bending moment and inversely proportional to sectional modulus (Timoshenko & Goodier 1970). A correlation between stiffness of an instrument and its cross-sectional area has been suggested in many studies (Haïkel *et al.* 1999, Turpin *et al.* 2000, Schäfer *et al.* 2003). In view of the similar longitudinal outline of the ProTaper and ProTaper Universal instrument, the addition of a groove (flute) at the centre of each side of the 'convex-triangular' cross-section has effectively reduced the second moment of inertia for the latter. On the other hand, this groove seems to have served as a stress-raiser in torsion.

The torsional rigidity, which is proportional to the applied torque and the polar moment of inertia of the part, was evaluated in the present study by measuring the angular deflection of the instrument. ProTaper was the most rigid, whereas ProFile the least. However, unlike bending of the instrument being governed by the canal curvature, shear stresses are generated in an engine-file because of friction and the (resistance of dentine to) cutting action. Thus, it would be more logical to examine the stress distribution under a similar torsional moment (Fig. 6b) rather than at the same twist-angle (Fig. 6c). It seems that ProFile is going to experience a much greater stress than ProTaper instrument in such a situation (see Fig. 6c), a finding corroborating that of other studies using FE analysis (Turpin *et al.* 2000, 2001, Berutti *et al.* 2003, Xu *et al.* 2006). Concentrations of (torsional) stress were observed at the bottom of the U-shaped flutes for ProFile and at the concave groove at each side of the triangular cross-section for ProTaper Universal, the stress of which was much higher than that for the original ProTaper. Hence, there is a greater chance of SIM transformation, and even plastic deformation of the transformed martensite there. This may explain a higher reported incidence of unwinding defects (with or without breakage) for discarded, clinically used, engine-driven ProFile than ProTaper (Shen *et al.* 2006) or K3 instrument (Ankrum *et al.* 2004). Enlarging the canal to a size of 15 or 20 before using the instrument would help to reduce the torsional stress experienced by the instrument (Hübscher *et al.* 2003) and lower the risk of shear fracture. Incorporating a U-shaped groove for the original ProTaper design, i.e. ProTaper Universal, would lead to some stress concentration at the bottom of the groove, as expected. It would be a weaker point than with the ProTaper, but still be better than ProFile in strength in order to resist torsion.

The reaction stresses in an instrument (of the same material and dimensions) are dependent on the geometry of the working part relative to the operating load. Factors affecting the stress distribution include the cross-sectional configuration, the depth of the flute, area of the inner core and (the bulk of) peripheral mass in cross-section; all these influence the magnitude of the second and polar moments of inertia. Not one of the systems studied was both highly flexible and yet able to withstand and distribute the stress evenly in bending and torsion. Indeed, it is obvious that different parameters are operating when the fracture susceptibility of an instrument (because of torsion vs. rotational bending) is concerned (Cheung *et al.* 2005). Clinicians should understand not only the general guidelines for NiTi rotary instrumentation, but also the structural characteristics which might influence the durability or the risk of an engine-file to fracture. To increase safety, endodontic educators must emphasize the need for mastering the skill for rotary instruments through appropriate, supervised training (Mandel *et al.* 1999, Yared *et al.* 2001). Despite a truer representation of the actual geometry of the instrument in this study, the actual stresses may differ when the instrument is actively filing against the dentine wall during clinical use. Further studies through other methods to verify the relationship between instrument design, stress distribution, fatigue fracture and the influence of microscopic notches, are required.

Conclusions

This study examined the stress distribution under bending or torsional load using a 3D FE analysis for three NiTi instruments of various cross-sectional configurations. It is concluded that the U-file design had the lowest flexural rigidity, compared with a 'convex-triangular' cross-section with or without an additional flute, but a higher magnitude of stress concentration at the bottom of the flute in torsion. Bending led to the highest surface stress at or near the cutting edge of all three instruments. The convex-triangular cross-section was able to distribute the shear stresses initially, but had similar stress concentrations at the same degree of angular deflection. Incorporating a U-shaped groove for the ProTaper design results in an instrument with intermediate properties between the two.

References

Ankrum MT, Hartwell GR, Trutt 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.

Bergmans L, Van Cleynenbreugel J, Beullens M, Wevers M, Van Meerbeek B, Lambrechts P (2003) Progressive versus constant tapered shaft design using NiTi rotary instruments. *International Endodontic Journal* **36**, 288–95.

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.

Boessler C, Peters OA, Zehnder M (2007) Impact of lubricant parameters on rotary instrument torque and force. *Journal of Endodontics* **33**, 280–3.

Calberson FL, Deroose CA, Hommez GM, De Moor RJ (2004) Shaping ability of ProTaper nickel–titanium files in simulated resin root canals. *International Endodontic Journal* **37**, 613–23.

Camps JJ, Pertot WJ, Levallois B (1995) Relationship between file size and stiffness of nickel titanium instruments. *Endodontics and Dental Traumatology* **11**, 270–3.

Chen JL, Messer HH (2002) A comparison of stainless steel hand and rotary nickel–titanium instrumentation using a silicone impression technique. *Australian Dental Journal* **47**, 12–20.

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

Clauder T, Baumann MA (2004) ProTaper NT system. *Dental Clinics of North America* **48**, 87–111.

Duerig TW, Pelton AR (1994) Ti–Ni shape memory alloys. In: Boyer R, Welsch G, Collings EW, eds. *Materials Properties Handbook: Titanium Alloys*. Materials Park: ASM International, pp. 1035–48.

Garip Y, Gunday M (2001) The use of computed tomography when comparing nickel–titanium and stainless steel files during preparation of simulated curved canals. *International Endodontic Journal* **34**, 452–7.

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.

Hata G, Uemura M, Kato AS, Imura N, Novo NF, Toda T (2002) A comparison of shaping ability using ProFile, GT file, and Flex-R endodontic instruments in simulated canals. *Journal of Endodontics* **28**, 316–21.

Hübscher W, Barbakow F, Peters OA (2003) Root canal preparation with FlexMaster: assessment of torque and force in relation to canal anatomy. *International Endodontic Journal* **36**, 883–90.

Kim HC, Park JK, Hur B (2005) Relative efficacy of three Ni-Ti file systems used by undergraduates. *Journal of Korean Academy of Conservative Dentistry* **30**, 38–48.

Lee CH, Cho KM, Hong CU (2003) Effect of various canal preparation techniques using rotary nickel–titanium files on the maintenance of canal curvature. *Journal of Korean Academy of Conservative Dentistry* **28**, 41–9.

Low D, Ho AW, Cheung GS, Darvell BW (2006) Mathematical modeling of flexural behavior of rotary nickel titanium endodontic instruments. *Journal of Endodontics* **32**, 545–8.

Mandel E, Adib-Yazdi M, Benhamou LM, Lachkar T, Mesgouez C, Sobel M (1999) Rotary Ni–Ti profile systems for preparing curved canals in resin blocks: influence of operator on instrument breakage. *International Endodontic Journal* **32**, 436–43.

Park SH, Cho KM, Kim JW (2003) The efficiency of the Ni–Ti rotary files in curved simulated canals shaped by novice operators. *Journal of Korean Academy of Conservative Dentistry* **28**, 146–55.

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.

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

Schäfer E (2001) Shaping ability of Hero 642 rotary nickel–titanium instruments and stainless steel hand K-Flexofiles in simulated curved root canals. *Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics* **92**, 215–20.

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.

Schäfer E, Schulz-Bongert U, Tulus G (2004) Comparison of hand stainless steel and nickel titanium rotary instrumentation: a clinical study. *Journal of Endodontics* **30**, 432–5.

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

Timoshenko SP, Goodier JN (1970) *Theory of Elasticity*. New York: McGraw-Hill.

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 stresses of nickel–titanium root canal instrument models. *Journal of Endodontics* **26**, 414–7.

Turpin YL, Chagneau F, Bartier O, Cathelineau G, Vulcain JM (2001) Impact of torsional and bending inertia on root canal instruments. *Journal of Endodontics* **27**, 333–6.

Walia H, Brantley WA, Gerstein H (1988) An initial investigation of the bending and torsional properties of Nitinol root canal files. *Journal of Endodontics* **14**, 346–51.

Walsch H (2004) The hybrid concept of nickel–titanium rotary instrumentation. *Dental Clinics of North America* **48**, 183–202.

Wang GZ (2007) A finite element analysis of evolution of stress–strain and martensite transformation in front of a notch in shape memory alloy NiTi. *Materials Science and Engineering A* **460–461**, 383–91.

Wei X, Ling J, Jiang J, Huang X, Liu L (2007) Modes of failure of ProTaper nickel–titanium rotary instruments after clinical use. *Journal of Endodontics* **33**, 276–9.

Xu X, Eng M, Zheng Y, Eng D (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 (2001) Influence of rotational speed, torque and operator's proficiency on ProFile failures. *International Endodontic Journal* **34**, 47–53.

Yun HH, 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.