Failure mechanism of ProTaper Ni–Ti rotary instruments during clinical use: fractographic analysis

A. P. Spanaki-Voreadi[1], N. P. Kerezoudis[1] & S. Zinelis[2]

[1]Departments of Endodontics; and [2]Biomaterials, University of Athens School of Dentistry, Athens, Greece

Abstract

Spanaki-Voreadi AP, Kerezoudis NP, Zinelis S. Failure mechanism of ProTaper Ni–Ti rotary instruments during clinical use: fractographic analysis. *International Endodontic Journal*, **39**, 171–178, 2006.

Aim To evaluate the failure mechanism of ProTaper Ni–Ti rotary instruments fractured under clinical conditions.

Methodology A total of 46 ProTaper instruments that failed (fractured and/or plastically deformed) during the clinical use were collected from various dental clinics, whereas a new set of ProTaper instruments served as control. After inspection under stereomicroscopy the instruments were classified into three categories: (i) plastically deformed but not fractured, (ii) fractured with plastic deformation and (iii) fractured without plastic deformation. Three instruments from each group were analysed with computerized X-ray microtomography (micro-XCT) to detect surface and internal defects, whilst all the fracture surfaces were investigated under SEM.

Results Stereomicroscopic inspection showed that 17.4% of the discarded instruments were only plastically deformed, 8.7% were fractured with plastic deformation and 73.9% were fractured without plastic deformation. Micro-XCT revealed instruments without any surface or bulk defects along with a few files with crack development below the fracture surface. No defects were identified in the unused instruments. SEM examination of fractured surfaces demonstrated the presence of dimples and cones, a typical pattern of dimple rupture developed because of ductile failure.

Conclusions The results suggest that a single overloading event causing ductile fracture of ProTaper instruments is the most common fracture mechanism encountered under the clinical conditions.

Keywords: failure mechanism, fracture, Ni–Ti, ProTaper, rotary files.

Received 20 May 2005; accepted 11 October 2005

Introduction

Root canal preparation in narrow, curved canals is a challenge even for experienced endodontists. Shaping of curved canals became more effective after the introduction of nickel–titanium (Ni–Ti) endodontic instruments. Despite the advantages of Ni–Ti rotary instruments, intracanal fracture is the most common procedural accident that occurs with these instruments during clinical use. It is a common experience between clinicians that Ni–Ti rotary instruments may undergo unexpected fracture without any visible warning, such as any previous permanent defect or deformation (Sattapan *et al.* 2000, Martín *et al.* 2003).

Many investigators have tried to determine the mechanisms of Ni–Ti instrument failure associating the cyclic loading of engine-driven Ni–Ti instruments with the fatigue failure mechanism. In most cases (Pruett *et al.* 1997, Haïkel *et al.* 1999, Yared *et al.* 1999, Li *et al.* 2002), tests have been performed under laboratory conditions and in some studies instruments were used clinically but fractured under the laboratory conditions (Yared *et al.* 2000, Gambarini 2001, Fife *et al.* 2004). Only in a few studies were clinically discarded instruments investigated (Sattapan *et al.* 2000, Zinelis & Margelos 2001, 2003, Alapati *et al.* 2004, 2005, Parashos *et al.* 2004).

Correspondence: Dr Spiros Zinelis, Department of Biomaterials, University of Athens, School of Dentistry, 2 Thivon Str, Goudi, 115 27Athens, Greece (Tel.: +32107461102; fax: +32107461306; e-mail: szinelis@dent.uoa.gr).

Some possible failure mechanisms of Ni–Ti instruments have been described in previous studies (Pruett *et al.* 1997, Sattapan *et al.* 2000, Martín *et al.* 2003). Metal fatigue caused by cyclic loading of the instrument when freely rotated in curved canals is believed to be an important failure mechanism of Ni–Ti instruments (Pruett *et al.* 1997). Fatigue failure occurs after mechanical degradation because of crack initiation and propagation. Instrument failure is also believed to occur when friction between an instrument and the canal wall required to cut dentine may necessitate a torque higher than the fracture stress of the alloy (torsional failure) (Blum *et al.* 2003). The latter is also the case when the instrument tip is locked in a canal whilst the shaft of the file continues to rotate (Sattapan *et al.* 2000).

Recently, ProTaper Ni–Ti instruments (Dentsply Maillefer, Ballaigues, Switzerland) were introduced with a unique design of variable taper within one instrument and continuously changing helical angles. The basic series of ProTaper comprises of three shaping instruments (Sx, S1, S2) for coronal and mid-root preparation, and three finishing instruments (F1, F2, F3) to prepare the apical area (Clauder & Baumann 2004). ProTaper rotary instruments are claimed to generate lower torque values during the use because of their modified nonradial landed cross-section that increases the cutting efficiency and reduces contact areas. On the other hand, the variable taper within one instrument is believed to reduce the 'taper lock' effect (torsional failure) in comparison with similarly tapered instruments (Peters *et al.* 2003). Nevertheless, ProTaper instruments undergo fracture without warning (Ankrum *et al.* 2004) that is difficult, if not impossible, to predict clinically.

The purpose of this study was to evaluate the failure mechanism of ProTaper Ni–Ti rotary instruments under the clinical conditions.

Materials and methods

A total of 46 ProTaper instruments that failed during clinical use were collected from various dental practices. The term 'failure' is used in materials science to imply that (i) a part in service has become completely inoperable, (ii) it is still operable but incapable of satisfactorily performing its intended function, or (iii) has deteriorated seriously to the point that it has become unreliable or unsafe for continued use (Davis *et al.* 1998). The term 'failure' is deliberately used in this manuscript in order to simultaneously characterize the deformed instruments, fractured instruments, as well as fractured and deformed instruments. The criterion for instrument collection was the fracture or deformation of the instruments. The preparation was performed by clinicians using low-toque control motor (Tecnika; ATR, Pistoia, Italy) in the pre-set torque levels recommended by the manufacturer. During chemomechanical preparation, all instruments had been used in conjunction with 2.5% NaOCl irrigant and RC-Prep lubricant. The instruments were sterilized with heat sterilization (1 h at 180 °C) or autoclave sterilization (20 min at 120 °C). The time of use of each discarded instrument was not recorded. A new set of ProTaper instruments (Lot No. 3613400) served as control.

All the clinically used instruments were ultrasonically cleaned in a 17% EDTA.3NaOH aqueous solution for 9 min, inspected under a stereomicroscope (Elvar Leitz, Weltzar, Germany) under 5× original magnification and classified into three categories: (i) plastically deformed but not fractured, (ii) fractured with plastic deformation and (iii) fractured without deformation. Finally, clinically failed and reference instruments were investigated in a SEM (Quanta 200; FEI Hillsboro, OR, USA) operating under high vacuum mode, 10 kV accelerating voltage and 110 μA beam current.

Furthermore, three selected instruments from each category and the reference group were investigated by means of computerized X-ray microtomography (micro-XCT) to detect possible internal defects. The files were imaged by micro-XCT, employing a scanner (1072 High resolution micro-CT system, SkyScan, Belgium) operated under the following conditions: Wo Ka source (100 kV, 98 μA), 1.8 μm pixel size at 1024 × 1024 resolution (156× magnification), rotation 180°, rotation step 0.23 exposure time 1.9 s averaging by two frames and 1 mm Al filter. Three-dimensional images of the instruments were reconstructed by dedicated software (Ant; SkyScan, Aartselaar, Belgium).

Results

The results of macroscopic evaluation are shown in Fig. 1. From the discarded instruments, eight were plastically deformed (category A: 17.4%), four fractured with plastic deformation (category B: 8.7%) and the vast majority (34) fractured without macroscopic plastic deformation (category C: 73.9%).

The SEM investigation of ProTaper instruments showed that some clinically deformed and fractured instruments presented surface cracks originating from the cutting edges of the instruments (Fig. 2b). However, the majority of the discarded instruments and all the unused instruments were free of cracks (Fig. 2a). Figure 3(a,b) demonstrate representative secondary

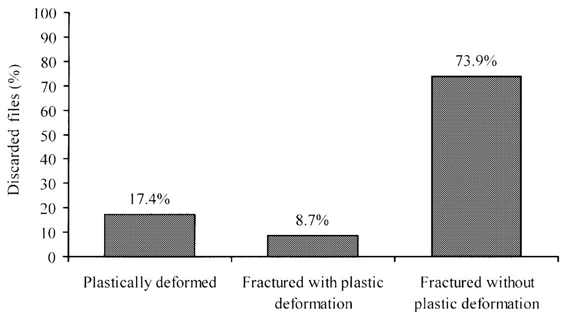

Figure 1 Percentage distribution of discarded instruments after clinical use based on stereomicroscopic investigation. The vast majority of ProTaper instruments (73.9%) failed without macroscopically evident plastic deformation.

electron images (SEI) from the fracture plane of clinically fractured instruments showing the characteristic surface pattern of ductile rupture. No differences in surface texture were found amongst fractured instruments with and without macroscopic plastic deformation. In a limited number of five instruments, the fracture planes at the borders of cross section were at different levels from the main fracture planes. An instrument fractured in this way is shown in Fig. 4a. The characteristic surface pattern of ductile rupture predominates at the fracture plane, except from the upper and lower left corners where the fracture planes were located at different levels (Fig. 4b,c). Secondary cracks below the fracture plane are clearly observed in Fig. 4(a,b). Figure 4d depicts at higher magnification the central area, where the characteristic pattern of tensile failure (dimples and cones) coexists with the pattern of shear fracture (elongated dimples at a horizontal level). The latter are recognized as regions with flat surfaces. Figure 5a shows the fracture plane of a clinically fractured ProTaper instrument with a main characteristic pattern of ductile rupture, except from the left- and right-down corners, where the fracture plane was at a lower level. At higher magnification (Fig. 5b), surface striations appeared that were assumed to arise from fatigue failure mechanism originated from the cutting edge. This limited area of fatigue striations was the only evidence associated with the fatigue mechanism amongst all the instruments tested.

Figure 6(a,b) demonstrate two longitudinal section views of a three-dimensional reconstructed micro-XCT model of two ProTaper endodontic instruments fractured *in vivo*. The left one (Fig. 6a) shows the presence of a secondary crack below the fracture plane without other internal defects.

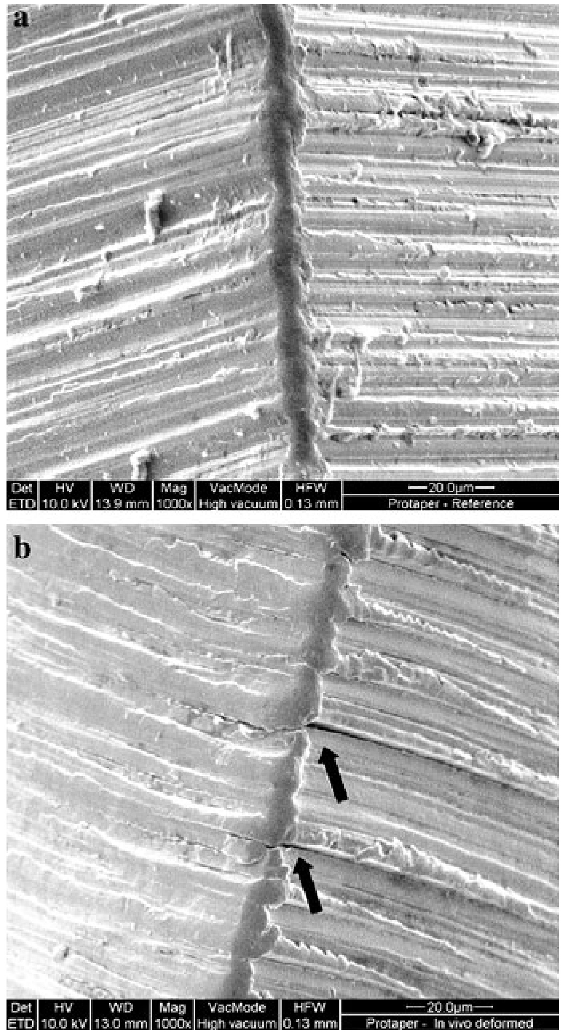

Figure 2 Secondary electron images of the cutting edges of as received (a) and *in vivo* used instruments (b). A limited number of clinically deformed or fractured instruments demonstrate surface cracks at the cutting edges as shown in (b). (Original magnification 1000×).

Discussion

According to the stereomicroscopic investigation, the incident of fracture (82.6%, categories B and C) is more common compared with plastic deformation (17.4%, category A) amongst discarded ProTaper instruments, meaning that fracture still remains a problem during chemomechanical preparation of root canals. The coexistance of plastically deformed and fractured instruments is in agreement with the findings of previous studies, although the percentage is strongly influenced by a variety of factors such as operators'

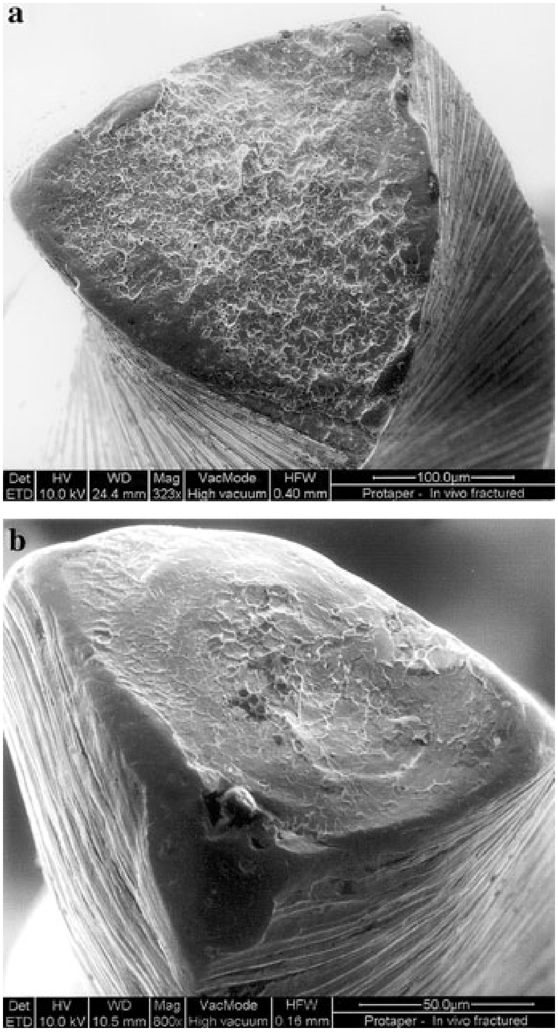

Figure 3 a) Secondary electron images of clinically failed ProTaper instruments. Representative fracture surfaces of instruments with macroscopically evident plastic deformation (Original magnification 323×). b) Fracture surface of a instrument broken without macroscopic plastic deformation and much shallower dimples (Original magnification 800×).

skill, root canal anatomy, etc. (Yared *et al.* 2003, Ankrum *et al.* 2004, Parashos *et al.* 2004, Alapati *et al.* 2005). Finally, as it will be presented later, the fact that the failure mechanism identified in the samples was the same implies that grouping classification applies only for descriptive purposes.

The finding that some fractured instruments showed plastic deformation under stereomicroscopic investigation implies that at least these failed because of a combination of tensile and torsion overloading (Vander Voort 1987). This is also confirmed by the characteristic dimple rupture patterns of the fractured surfaces (Kerlins & Phillips 1987) (Fig. 3). Although the appearance of failed parts is strongly associated to the loading conditions, this information is not enough to characterize the failure mechanism itself (Kerlins & Phillips 1987, Peng *et al.* 2005). The type of principal loading stresses, the origin of fracture, the extent of stress concentration factor, the effect of in-service environment conditions and other critical details used to determine the failure process can be defined only by standard fractographic analysis (Kerlins & Phillips 1987). Although the vast majority (73.9%) of discarded ProTaper instruments fractured without plastic deformation (Fig. 1), a behavior indicative of fatigue fracture, all the fracture surfaces demonstrated the characteristic pattern of dimple rupture without evidence of crack introduction and propagation. The fracture plane in 29 out of 34 fracture instruments without evidence of stereomicroscopically detected plastic deformation was oriented at an almost perpendicular level to the longitudinal axis of the instrument, showing dimple rupture without any characteristic of fatigue surface patterns (Fig. 3). This denotes that fracture was caused by a sudden overloading of the instrument rather than a progressive mechanical deterioration imposed by the fatigue mechanism. Another interesting finding was that the depth of dimples varied in extent (Fig. 3), which is in accordance to the results of Alapati *et al.* (2005) who found that clinically fractured Ni–Ti instruments demonstrated much shallower dimples than the laboratory tested stainless steel rotary endodontic instruments. This behaviour can be appended to the fact that the extent of plastic deformation is heavily constrained (Gillis & Gross 1985) by the high strain rates developed during the fracture by mechanical rotation of instruments during the chemomechanical preparation of root canals.

An other important finding was that five out of 34 fractured instruments, without plastic deformation, presented a fracture surface with different planes (Figs 4a,b and 5a). Additionally, these areas were very similar amongst each other as they resembled the sectors originating from the cutting tips. The location of these fracture planes at different levels from the main plane may be assigned to the fact that they are the last areas connected to the main fracture plane. This implies that although their presence decreases the mechanical strength of instruments, they may not contribute to fracture initiation. The presence of these sectors should be associated

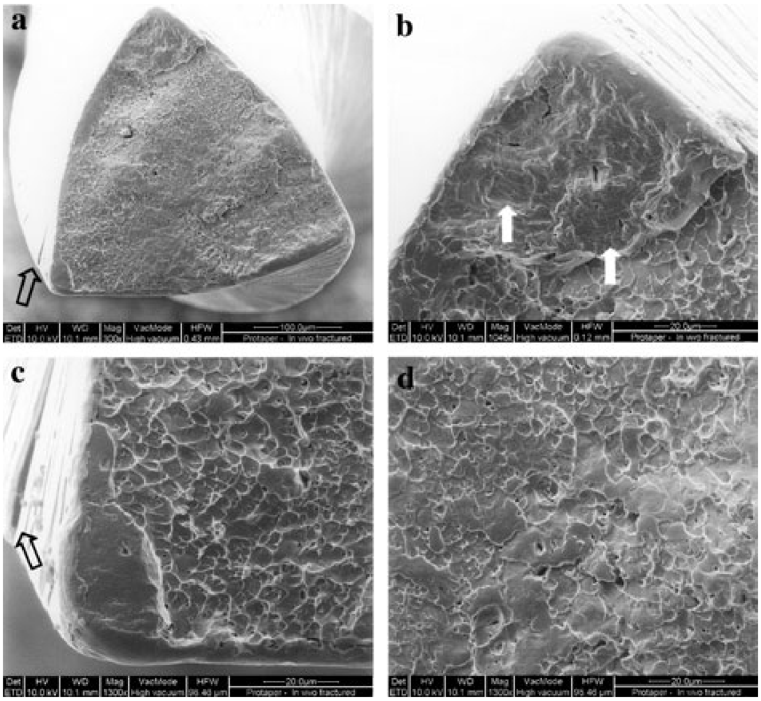

Figure 4 Secondary electron images from the fractured surface of a ProTaper instrument, a) Overall fracture surface (Original magnification 500×). The characteristic surface pattern with dimples and cones produced by ductile rupture is observed at the fracture plane, except from the upper and down left corners where the fracture plane is at a different level as readily shown in fig b (Original magnification 1046×) and c (Original magnification 1300×), A secondary crack is also shown in fig a and c. b) Elongated dimples are shown along the horizontal plane denoting that the fracture within the sector was caused due to shear overloading. In addition the typical deformation lines are hardly shown at this magnification (areas pointed by the arrows). Figure d (Original magnification 1300×) shows a higher a magnification of central areas whereas the characteristic pattern of tensile failure (dimples and cones) coexist with the pattern of shear fracture (elongated dimples in horizontal level) (regions with flat surfaces).

with the surface cracks found on the surfaces of the deformed instruments (Fig. 2) as below the fracture surface of broken instruments in Figs 4a,c, 5a and 6a. Generally, the presence of these cracks is associated with the fatigue mechanism and has been detected in clinically fractured Hedstroem files that failed by fatigue (Zinelis & Margelos 2002). However, the fractographic analysis showed that all these sectors have been introduced by a shear overloading (Fig. 4b), whilst only one sector demonstrated the characteristic fatigue striations along a path of <15 μm and thus is considered as a random finding. Although a few instruments showed the presence of these cracks, this finding can easily explain the results of Fife *et al.* (2004) regarding the fatigue resistance of ProTaper rotary instruments after the multiple clinical uses. These authors found a statistically significant difference in the number of rotations until the fracture only for S2 and F2 instruments, a finding mostly attributed to the presence of surface cracks induced during the clinical use. Moreover, Fife *et al.* (2004) concluded that other factors rather than the fatigue mechanism may be more accountable for intracanal instrument separation of ProTaper instruments.

The results of the present study and the proposed fracture mechanism are in full agreement with the results of Alapati *et al.* (2005), who examined 12 clinically fractured ProTaper instruments. The clinically fractured instruments presented the characteristic surface pattern of dimple rupture and the authors concluded that fracture *in vivo* is caused by a single overloading incident rather than the fatigue mechanism after a large number of loading cycles. Finally, Cheung *et al.* (2005) have also concluded that the same fracture mechanism along with fatigue failure exist after the fractographic evaluation of clinically discarded ProTaper files.

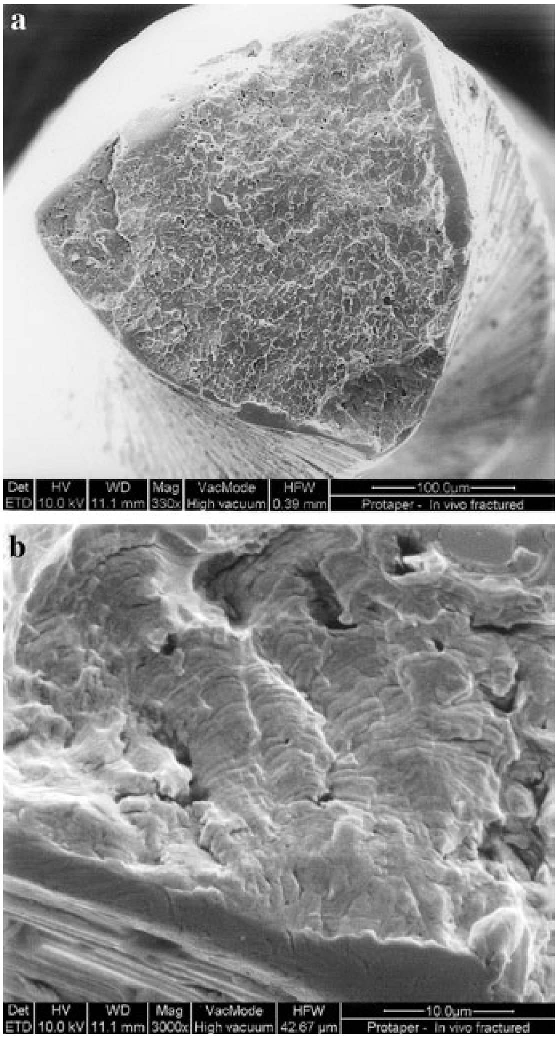

Figure 5 Secondary electron images of clinically fractured ProTaper instrument. a) The fracture plane demonstrates the characteristic pattern of ductile fracture except from the left and right-down corners whereas the fracture plane is in a lower level. b) Higher magnification of surface striations assumed to arise from fatigue failure originated from the cutting edge. This finding of fatigue striations along a path of less than 15μm is the only evidence associated with the fatigue mechanism among all instruments tested and thus it may be considered as a random finding (Original magnification 3000×).

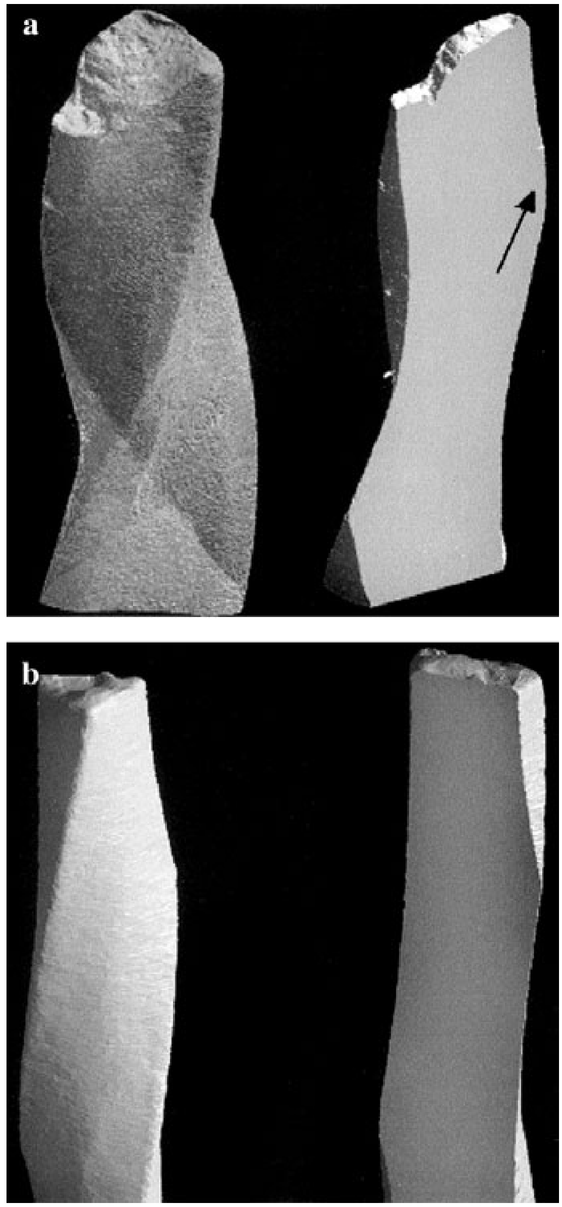

Figure 6 Cross sectional views of three dimensional X-ray microtomographic images of two ProTaper endodontic instruments fractured in vivo. a) The presence of a second crack below the fracture plane is evident. b) Despite the fracture there is no evidence of external or internal defects.

The above failure mechanism is supported by findings of studies that evaluate different factors that influence ProTaper instrument failure. It was noted that most ProTaper instruments failed when used by untrained operators, probably because excessive apical pressure was exerted (Yared *et al.* 2003). Furthermore, it was confirmed that torque is correlated not only to the apically exerted force, but also to preoperative canal volume. Hence, preparation of narrow and constricted canals could subject rotary instruments to higher torsional loads (Peters *et al.* 2003). It was also supported that manual pre-flaring of the root canal increased the times of use before failure of ProTaper instruments was observed because pre-flaring enables torsional stress to be drastically reduced as the canal width becomes at least equal to the diameter of the tip of the instrument to be used, as well as enabling the original anatomy to be preserved (Berutti *et al.* 2004). Consequently, factors such as operator and root canal anatomy that may contribute to sudden overloading become clinically important in order to avoid failure of ProTaper rotary instruments.

Although the fatigue failure of Ni–Ti engine-driven instruments has been accepted amongst the clinicians and researchers, the analysis of *in vivo* fracture instruments showed that fracture was caused by a single overloading. Zinelis & Margelos (2001, 2003) proposed the mechanism of single overloading for the clinically fractured GT Rotary Ni–Ti instruments, a finding that is also confirmed by the study of Alapati *et al.* (2005), in which the same fracture mechanism was found for ProFile instruments. Indirect evidence that a fatigue mechanism is not implicated in Ni–Ti fracture has been reported by Parashos *et al.* (2004) who confirmed that the incidence of fracture was independent of the number of uses. If the fatigue mechanism was valid, the incident of fracture should increase with the repeated uses because of mechanical degradation of instruments. In contrast, the random distribution of fracture incidence (10% for one use, 23% for two uses, 14% for three uses, 26% for four uses, 7% for six uses and 20% for more or equal to six uses) denotes that another mechanism should be implicated in the fracture phenomenon. The difference between clinical and laboratory results can be readily explained by the fact that simulation models often yield information that is not relevant to clinical practice because the controlled experimental conditions of laboratory studies typically do not properly account for variables existing clinically that can yield entirely different failure mechanisms.

The determination of failure mechanism of Ni–Ti files under the clinical conditions has several consequences. First, as the failure mechanism is not associated with any cumulative damage (i.e. fatigue mechanism), the concept of using Ni–Ti files in a limited number of root canals to avoid failure is unrealistic. Furthermore, the knowledge of failure mechanism provides crucial information for the development of rotary instruments with improved resistance to fracture. For files that failed under overloading, Ni–Ti base alloys with the increased yield point and fracture strength should be selected to decrease the failure susceptibility of instruments under the clinical conditions.

According to the results of this study, the fracture of ProTaper instruments is caused by a single overloading that causes dimple rupture during the chemomechanical preparation of root canals. Such overloading can be induced by an abrupt change in canal curvature, clogging of the cutting instrument and other factors that cause stress development during the instrumentation. The failure mechanism of a single overloading denotes that factors (i.e. handling parameters, root canal anatomy, instrumentation techniques operator experience, etc.) which may increase the stresses during instrumentation play a crucial role on the intracanal fracture of ProTaper instruments.

Conclusions

Under the clinical conditions, the fracture of ProTaper instruments is caused by a single overloading incident that causes ductile fracture during chemomechanical preparation of root canals.

Acknowledgements

The authors wish to thank Mr Peter Tsakiridis for providing his expertise for the μCT analysis of the specimens and the production of video file for the online version of this manuscript.

References

Alapati SB, Brantley WA, Svec TA, Powers JM, Nusstein JM, Daehn GS (2004) Proposed role of embedded dentin chips for the clinical failure of nickel–titanium rotary instruments. *Journal of Endodontics* **30**, 339–41.

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* **30**, 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.

Berutti E, Negro AR, Lendini M, Pasqualini D (2004) Influence of manual preflaring and torque on the failure rate of ProTaper rotary instruments. *Journal of Endodontics* **30**, 228–30.

Blum J-Y, Machtou P, Ruddle C, Micallef JP (2003) Analysis of mechanical preparations in extracted teeth using ProTaper rotary instruments: value of the safety quotient. *Journal of Endodontics* **29**, 567–75.

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

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

Davis J, Destefani J, Frissell H, Crankovic G, Jenkins D et al. (1998) Glossary of terms. In: *Corrosion, ASM Handbook*, Vol. 13, 6th edn. Materials Park, OH, USA: ASM International, pp. 6.

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

Gillis P, Gross T (1985) Effect of strain rate on flow properties. In: Davis J, Rejsnes S, Dieterich D, Frissell H, Jenkins D, Cubberly W et al., eds. *Mechanical Testing, ASM Handbook*, Vol. 8, 6th edn. Materials Park, OH, USA: ASM International, pp. 38–46.

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.

Kerlins V, Phillips A (1987) Modes of fracture. In: Mill K, Davis J, Destejani J, Dieterich D, Frissell H, Crankovic G et al. eds. *Fractography, ASM Handbook*, Vol. 12, 3rd edn. Materials Park, OH, USA: ASM International, pp. 12–71.

Li U-M, Lee B-S, Shih C-T, Lan W-H, Lin C-P (2002) Cyclic fatigue of endodontic nickel titanium rotary instruments: static and dynamic tests. *Journal of Endodontics* **28**, 448–51.

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

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 Cheung P, Xia T (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 (1997) Cyclic fatigue testing of nickel–titanium endodontic instruments. *Journal of Endodontics* **23**, 77–85.

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

Vander Voort G (1987) Visual examination and light microscopy. In: Mill K, Davis J, Destefani J, Dieterich D, Frissell H, Crankovic G, et al., eds. *Fractography, ASM Handbook*, Vol. 12, 3rd edn. Materials Park, OH, USA: ASM International, pp. 96–97.

Yared GM, Dagher FEB, Machtou P (1999) Cyclic fatigue of profile rotary instruments after simulated clinical use. *International Endodontic Journal* **32**, 115–9.

Yared GM, Dagher FEB, Machtou P (2000) Cyclic fatigue of profile rotary instruments after clinical use. *International Endodontic Journal* **33**, 204–7.

Yared GM, Dagher FEB, Kulkarni K (2003) Influence of torque control motors and the operator's proficiency on ProTaper failures. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics* **96**, 229–33.

Zinelis S, Margelos J (2001) Assessment of fracture mechanism of endodontic files. In: Lambrianidis T, ed. *Risk Management in Root Canal Treatment*, 1st edn. Thessaloniki, Greece: University Studio Press, pp. 239–43.

Zinelis S, Margelos J (2002) Failure mechanism of endodontic files *in vivo*. *Journal of Endodontics* **28**, 471–3.

Zinelis S, Margelos J (2003) In vivo aging of endodontic instruments and materials. In: Eliades G, Eliades T, Brantley WA, Watts DC, eds. *Dental Materials In Vivo: Aging and Related Phenomena*, Chapter 11, 1st edn. Chicago IL, USA: Quintessence, pp. 179–92.

