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Effect of root canal curvature on the failure incidence of ProFile rotary Ni–Ti endodontic instruments

E. Kosti[1], S. Zinelis[2], I. Molyvdas[1] & T. Lambrianidis[1]

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

Abstract

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Aim To investigate the effect of root canal curvature on the failure incidence and fracture mechanism of ProFile rotary Ni–Ti endodontic instruments.

Methodology Three hundred mesial root canals of mandibular molars were instrumented using the ProFile system in a crown-down technique up to size 25 0.06 taper. Root canals were classified according to the angle and radius of curvature to: straight (group A: 0 + 10°, radius 0 mm), moderately curved (group B: 30 ± 10°, radius 2 ± 1 mm) and severely curved (group C: 60 ± 10°, radius 2 ± 1 mm). After each use, instruments were cleaned ultrasonically and autoclaved. Instruments that prepared 20 root canals, fractured or were plastically deformed without fracture were retrieved and substituted. Kaplan–Meier estimator was used for survival analysis and *post hoc* test for determination of significant differences ($a = 0.05$). All fractured instruments were subjected to fractographic analysis under SEM, and all used instruments were viewed under the metallographic microscope.

Results Regardless of the size of instrument, fracture and overall failure were significantly more frequent ($P < 0.05$) in group C. SEM examination of the fracture surfaces revealed mainly the characteristic pattern of ductile failure, whereas examination under the metallographic microscope revealed no sign of cracks.

Conclusions The abruptness of root canal curvature negatively affected the failure rate of ProFile rotary Ni–Ti instruments. The fractographic results confirmed that failure of Ni–Ti files was caused by a single overload during chemomechanical preparation.

Keywords: curvature, ductile fracture, fracture incidence, Nickel–Titanium, ProFile, rotary endodontic instruments.

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Introduction

Several factors have been implicated in the failure of rotary endodontic instruments. The alloy properties (Thompson 2000, Darabara *et al.* 2004, Zinelis *et al.* 2010), the design of the instrument (taper, cross-section, tip-design, size and rake angle) (Wildey *et al.* 1992, Camps *et al.* 1995, Parashos *et al.* 2004), rotational speed (Daugherty *et al.* 2001), torque (Gambarini 2000), number of uses (Yared *et al.* 2000, Arens *et al.* 2003, Bahia & Buono 2005), sterilization method (Serene *et al.* 1995, Hilt *et al.* 2000, Alexandrou *et al.* 2006), method of use (instrumentation technique and use of a lubricant) (Blum *et al.* 1999, 2003, Boessler *et al.* 2007), operator proficiency (Parashos *et al.* 2004) and root canal configuration (Pruett *et al.* 1997, Martin *et al.* 2003) are amongst these factors. Although these parameters have been extensively

Correspondence: Eleni Kosti, 17 Agias Sofias street, 54623 Thessaloniki, Greece (Tel.: +2310 235816; fax: +2310 275071; e-mail: elkosti@dent.auth.gr).

studied, the failure mechanism of rotary Ni–Ti endodontic instruments in clinical practice remains to be clarified.

In an attempt to elucidate the fracture incident, investigators have suggested possible mechanisms. The cyclic loading of an instrument rotating within a curved root canal may potentially give rise to metal fatigue. Failure because of fatigue is initiated by crack introduction and propagation leading to mechanical degradation of the instrument and ultimately its fracture (Pruett *et al.* 1997). The fatigue fracture theory is reinforced by the fact that the manufacturing process of the instruments incorporates defects and microcracks in the instrument body, which could act as the initiating sites of fatigue (Eggert *et al.* 1999, Tripi *et al.* 2001, Alapati *et al.* 2003, Parashos & Messer 2006).

Another mode of failure is torsional failure that develops when friction between the instrument and root canal dentine leads to increased torque that exceeds the torsional strength of the instrument, resulting in deformation and fracture (Blum *et al.* 2003). Torsional failure is also the cause of fracture when the instrument rotates in the canal with its tip locked (Sattapan *et al.* 2000).

After fractographic analysis of rotary instruments of the ProTaper system that were retrieved from several dental practices (Spanaki-Voreadi *et al.* 2006), it was suggested that Ni–Ti instruments fail because of a single overloading event that causes ductile fracture rather than because of a fatigue accumulation process. This theory explains the inconsistency of the number of uses before fracture that have been reported in the literature, which can be between 1 and 27 root canals (Yared *et al.* 2000, Peters *et al.* 2003, Bahia & Buono 2005). In an *in vivo* study where 7159 used Ni–Ti rotary instruments were collected from 14 endodontic practices from four countries (Parashos *et al.* 2004), instrument fracture was recorded even after a very limited number of uses (3.7 ± 2 teeth), whereas there were instruments that presented deformation without fracture after more uses (4.5 ± 2 teeth). The investigators concluded that other factors need to be considered in terms of the longevity of endodontic instruments, most probably operator proficiency and root canal curvature.

The aim of this study was to evaluate the effect of root canal curvature on the failure incidence and the fracture mechanism of rotary Ni–Ti instruments of the ProFile system (Dentsply Maillefer, Ballaigues, Switzerland) that have been used under standardized simulated clinical conditions for a known number of consecutive uses.

Materials and methods

Three hundred mesial root canals of recently extracted fully formed human mandibular molars, selected from a pool of extracted teeth, were used. The procedures of the present investigation were contacted in accordance with the protocol outlined by the Research Committee of Aristotle University of Thessaloniki, Greece. Following extraction, teeth were immersed in 5.25% sodium hypochlorite solution for 30 min to remove organic residue and after rinsing were kept in 10% formalin until use. The teeth were sectioned by means of a cutting disc and the mesial roots embedded in resin blocks, with their apices exposed. Initial radiographs were taken with the paralleling technique in a buccolingual and mesiodistal direction. Access cavities were prepared with diamond burs, and root canal patency was established with a size 10 K-File (Dentsply Maillefer). Criteria for root canal selection included:

1. Separate buccal and lingual root canals established radiographically.
2. One plane of root canal curvature observed after radiographic examination with a size 10 K-File placed in the root canal.
3. No signs of internal or external resorption, caries, fracture or crack (magnifying loops at 4.5× magnification; Carl Zeiss Surgical Inc, Dublin, CA, USA).
4. Fully formed apices.
5. Only root canals in which a size 10 K-File provided an initial snug fit were used.

Using this same K-File, radiographs were obtained as before to determine root canal curvature. Root canals were classified according to the angle and radius of curvature (Pruett *et al.* 1997) into: straight (group A: 0 + 10°, radius 0 mm), moderately curved (group B: 30 ± 10°, radius 2 ± 1 mm) and severely curved (group C: 60 ± 10°, radius 2 ± 1 mm). The working length of each root canal was determined by introducing a size 10 K-File until it was visible through the apical foramen minus 1 mm. Instrumentation was performed according to the manufacturer's instructions (Table 1). All instruments were used on a 16 : 1 reduction handpiece (Kavo Dental GmbH, Biberach/Riß, Germany) adjusted to a torque control machine (Technika, ATR, Pistoia, Italy), operating at the speed and torque values given by the manufacturer. Instruments were used with a slight apical pressure, and each

Table 1 Instrumentation protocol

Instrumentation stage	Instrument
Working length determination	Size 10 K-File
Crown-down technique: each instrument progressing in the root canal and gradually reaching working length	ProFile O.S.3 (40/0.06)
	ProFile O.S.2 (30/0.06)
	ProFile 25/0.06
	ProFile 20/0.06
	ProFile 25/0.04
Instrumentation of the apical region at working length	ProFile 20/0.04
	ProFile 25/0.04
Final flare	ProFile 20/0.06
	ProFile 25/0.06

instrument was used for 5–10 s with a limited in and out movement 2–3 mm in range. All instrumentation was performed by a single operator, an endodontist trained in the use of the ProFile system, with 5 years experience.

A small amount of EDTA gel (17%) (Glyde; Dentsply Maillefer) was introduced with the instrument tip in the root canal before each use. Between successive instruments, root canals were irrigated with 2.5% NaOCl solution with a 5-mL syringe and a size 27 needle (Endo-Eze, Ultradent Products, South Jordan, UT, USA), placed passively in the root canal without binding. Each time an instrument was removed from the root canal, it was wiped clean using a sponge moistened with 0.12% chlorhexidine solution (Paroex; Buttler, Sarrono, Italy), until no debris was detected at 4.5× magnification. Instruments were kept in the clean stand until instrumentation was concluded and cleaning and sterilization procedures followed. Prior to the first use and after the completion of each instrumentation, the set of instruments was cleaned in an ultrasonic bath containing 17% EDTA·3NaOH solution for 9 min. The EDTA·3NaOH solution was prepared by mixing 17 g Trisodium EDTA salt (Triplex III; Rhône-Poulenc, Courbevoie, France) with 100 mL distilled water. Instruments were subsequently autoclaved at 134 °C for 30 min.

Instruments were inspected before and after each instrumentation with 4.5× magnifying loops for signs of plastic deformation and were classified into four categories: (a) instruments that concluded the instrumentation of 20 root canals without fracture or deformation, (b) fractured instruments without plastic deformation, (c) fractured instruments with plastic deformation and (d) plastically deformed instruments. Categories b–d were all considered as failure of the instrument, as according to Davis *et al.* (1998), the term failure in material science implies that the part in service has become completely inoperable, is still operable but incapable of satisfactorily performing its intended use, or has deteriorated seriously to the point that has become unreliable or unsafe for continued use. Instruments that either concluded instrumentation of 20 root canals or failed were retrieved and substituted with new ones. The number of uses each instrument was subjected to represented the number of root canals instrumented and sterilization cycles before retrieval was recorded.

Three hundred root canals were instrumented, 100 from each group and a total of 75 instruments were collected, consisting of instruments 0.06 taper sizes 25 and 20 and 0.04 taper sizes 25 and 20. Instruments Orifice Shapers 2 and 3 were not investigated microscopically nor included in the statistical analysis, as they negotiated only the coronal part of the root canal, and therefore the effect of the curvature on their longevity was irrelevant. Twenty-two instruments were used in group A, 23 in group B and 30 in group C. Fractured instruments were cleaned in an ultrasonic bath containing 17% EDTA·3NaOH for 9 min. Following ultrasonic cleaning instruments were rinsed with running tap water for 20 min.

All fractured instruments were investigated under scanning electron microscope (SEM) to observe the entire fracture surface in detail and identify any detrimental points, possible cracks and signs of fatigue and corrosion. Instruments were held in a custom made jig and were studied under SEM (Quanta 200; FEI, Hillboro, OR, USA).

Finally, all used instruments as well as four unused instruments, one of each size, were embedded along their longitudinal axis in epoxy resin. The specimens were ground to a smooth surface using 320–1200 grit size SiC papers, and a final polish was given using a 3-μm diamond paste. All specimens were ultrasonically cleaned in an alcohol bath for 9 min, dried with high pressure air and studied in a metallographic microscope (Eclipse; ME 600 Nikon, Tokyo, Japan) in magnification 200, 500 and 1000× for the detection of internal defects.

Kaplan–Meier estimator was used for survival analysis and *post hoc* test (Cox–Mantel) for determination of significant differences ($a = 0.05$).

Results

No instrument fractured during the instrumentation of 100 straight root canals (group A), whereas 3 of 22 instruments used (14%) presented signs of macroscopic plastic deformation. During the instrumentation of 100

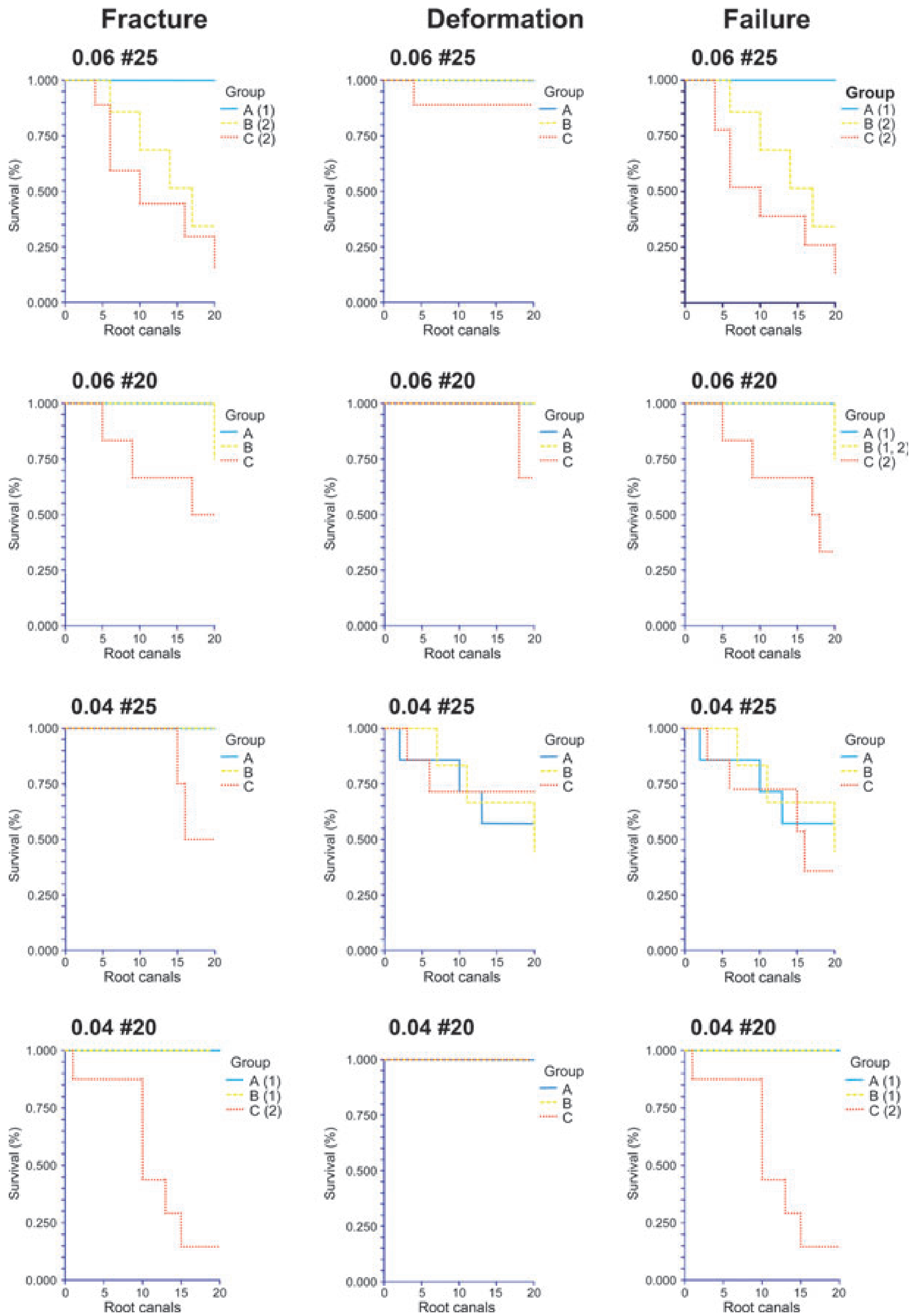

Figure 1 Survival plots for fracture (right column), deformation (middle column) and overall failure (left column) for straight root canals (group A), moderately curved canals (group B) and severely curved canals (group C), for each instrument. The numbers in parenthesis next to groups indicate significant differences ($P < 0.05$), whereas absence of a number or the same number denote a non-significant difference.

moderately curved root canals (group B) 5 of 23 instruments used fractured (22%) and three deformed plastically (13%), whilst during the preparation of the 100 severely curved canals (group C) 15 of 30 instruments fractured (50%), seven were deformed (13%) and two fractured with plastic deformation (7%).

Regardless of the size of the instrument, fracture and failure were more frequent ($P < 0.05$) in group C, whereas the groups were comparable regarding deformation. When exploring the effect of curvature on the behaviour of each instrument, fracture and failure were more frequent for size 25, 0.06 taper instrument amongst groups B and C compared with group A ($P < 0.05$), whilst groups B and C were comparable. For instrument size 20, 0.06 taper, although fracture and deformation did not differ statistically amongst groups, failure overall was more frequent in group C, and the difference was statistically significant ($P < 0.05$) only when comparing groups A and C. There was no significant difference for fracture, deformation and failure for all groups for instrument size 25, 0.04 taper. Finally for size 20, 0.04 taper instrument fracture and failure were more frequent in group C, followed by groups B and A, with no difference between the latter groups ($P > 0.05$). The incidence of deformation on the other hand did not differ amongst groups for that instrument.

Figure 1 shows the survival probability curves for all instruments used in groups A, B and C in relation to fracture, deformation and failure incidence (right, middle and left column, respectively). For instruments size 25, 0.06 taper, the survival curve revealed that after 10 uses in straight canals, there was a 100% probability they would be intact and therefore reusable, whereas in group B, there was a 70% probability that the instruments would be reusable; in group C, the probability was 45%. After 20 uses, the probability that size 25, 0.06 taper instruments would be intact in group A remained at 100%, whereas in curved canals dropped to 35% for group B and to 15% for group C. For instruments size 20, 0.06 taper after 10 uses in straight canals, there was a 100% probability that all instruments would be intact, whereas in group B, there was a 75% probability that the instruments would be reusable, and in group C, a 65% probability. For instruments size 20, 0.04 taper after 20 uses survival probability for groups A and B was 100%. For group C, after 10 uses there was a 45% probability that the instrument would be reusable and after 20 uses the probability dropped to 15%. Independent of the type of instrument used (Fig. 2), survival dropped after 10 uses in group A (straight root canals) to 90%, in group B (moderately curved) to 80% and in group C (severely curved) to 60%, and after 20 uses, there was a further reduction, 5%, 20% and 35% for groups A, B and C, respectively.

The SEM investigation of the fractured surfaces of the ProFile instruments showed mainly the characteristic pattern of ductile fracture with the predominance of dimples. The surface texture was similar for all fractured instruments regardless of the type of the instrument or the type of root canal it was used in, and it was identical for instruments fractured with or without deformation. No cracks were detected that would verify the presence of metal fatigue either on fractured instruments (Figs 3 and 4) or on deformed ones. Observation under the metallographic microscope (Fig. 5) did not reveal any signs of cracks in any of the instruments studied, that is, unused instruments, instruments fractured with or without deformation,

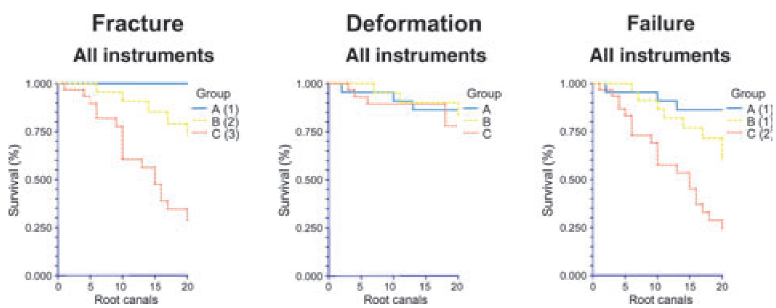

Figure 2 Survival plots for fracture (right column), deformation (middle column) and overall failure (left column) for straight root canals (group A), moderately curved canals (group B) and severely curved canals (group C), independent of the instrument type. The numbers in parenthesis next to groups indicate significant differences ($P < 0.05$), whereas absence of a number or the same number denote non-significant differences.

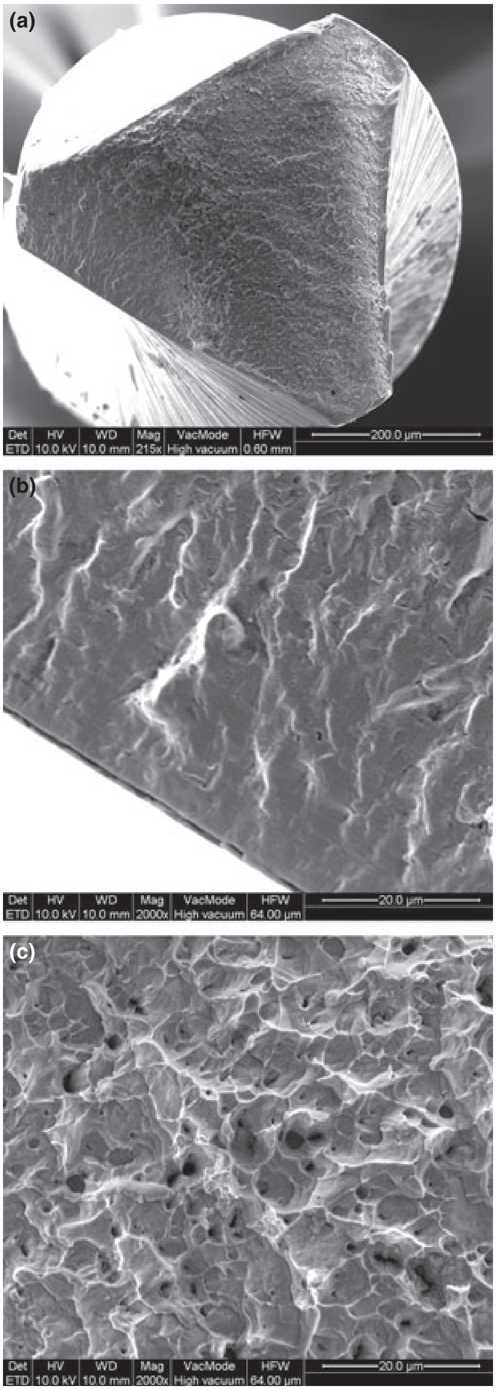

Figure 3 Secondary electron images from the fractured surface of a ProFile instrument. (a) Overall fractured surface. (b) Area on the left side of the fracture surface where a 'river-like' pattern, characteristic of cleavage fracture is apparent. (c) Central area with deep dimples produced by tensile stress. A shear lip formation is visible on the right margin of the fracture surface in (a).

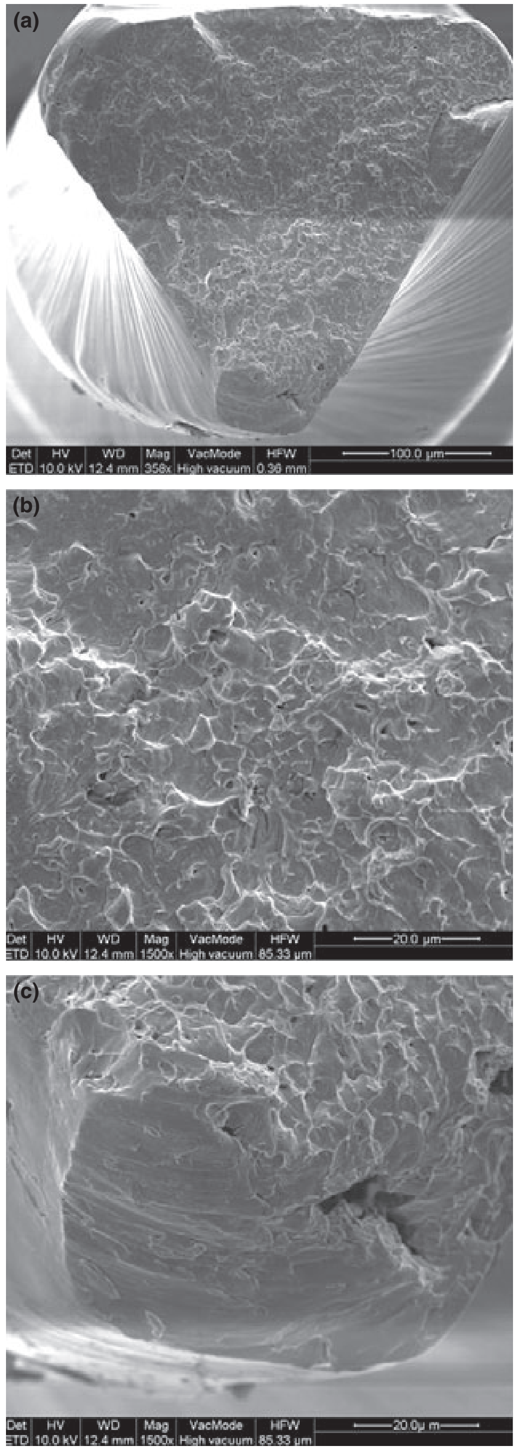

Figure 4 Secondary electron images from the fractured surface of a ProFile instrument. (a) Overall fractured surface, (b) central area with shallow dimples and (c) lower corner region with flat surfaces consisting of elongated dimples at a horizontal level caused by shear stress.

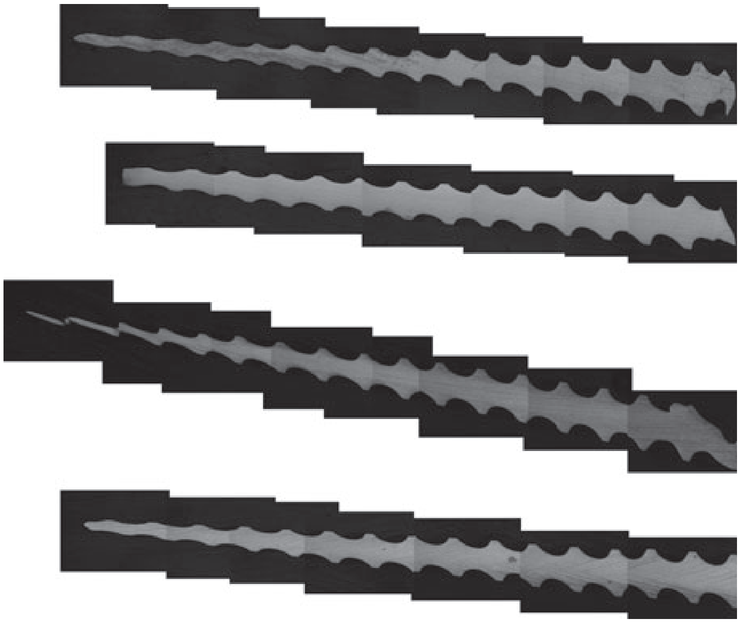

Figure 5 Reconstructed images from metallographic microscope. (a) Unused ProFile instrument, (b) fractured instrument, (c) deformed instrument and (d) instrument after instrumentation of 20 root canals. No cracks were detected.

deformed instruments and instruments that concluded the instrumentation of 20 root canals.

Discussion

In the present study, all factors involved in the chemomechanical preparation and implicated in the failure process were standardized (operator, method of use, sterilization method and maximum times of use), to investigate the effect of the abruptness of the curvature on the incidence of fracture and overall failure.

Under the conditions of this study, fracture and overall failure were more frequent in severely curved canals (angle 60 ± 10° and radius 2 ± 1 mm) than in straight and moderately curved canals (30 ± 10° angle and the same radius), when measured according to Pruett *et al.* (1997). This can be explained by the overloading induced on the instrument by an abrupt change in canal curvature which restrains the rotating instrument (Spanaki-Voreadi *et al.* 2006), giving rise to multidirectional loading (tension, bending and torsion) that lead to ductile fracture. In an *ex vivo* study (Di Fiore *et al.* 2006), it was found that 78% of the ProFile instruments were fractured in canals with curvature >25°, according to Schneider (1971). Accordingly, in a different *ex vivo* study (Zelada *et al.* 2002), all ProFile instrument fractures were recorded in root canals with angle of curvature ≥30° and acute radius (≤3 mm), according to Pruett *et al.* (1997). In a follow-up study, the same study group observed that an increase in angle of curvature from <30° to >30° led to significant increase in fracture incidence for ProTaper (Dentsply Maillefer) and K3 (Kerr/SybronEndo, Orange, CA, USA) instruments, whereas a decrease in radius of the curvature did not significantly affect fracture incidence (Martin *et al.* 2003).

The finding that survival probability dropped after repeated uses supports the notion that failure is a cumulative phenomenon, linked to a fatigue fracture mechanism. However, a closer observation of the recorded cycles of use when fracture and deformation occurred, as depicted in the survival curves (Figs 1 and 2), reveals that instruments fractured arbitrarily after 1–20 uses in moderately curved and severely curved canals. This finding is in accordance with the notion that number of uses of an instrument does not affect its longevity (Parashos *et al.* 2004). Hence, the fatigue theory for the fracture of Ni–Ti rotary instruments does not seem valid; otherwise, it would imply increase in fracture incidence with use, because of mechanical degradation (Spanaki-Voreadi *et al.* 2006). Moreover, the coexistence of fracture and plastic deformation, although in a small percentage of the instruments examined, denotes that for at least these few cases, failure was caused by a combination of tensile and torsion overloading (Vander Voor 1987). Whilst the majority of the failed instruments were fractured without signs of plastic deformation, which could by itself be considered evidence of fatigue failure (Sattapan *et al.* 2000), all fractured surfaces studied presented ductile fracture with the characteristic pattern of dimples. There was no evidence of fatigue crack propagation under the SEM as well as under the stereomicroscope (Fig. 5), as it was observed for stainless steel H-Files used in a clinical simulation study (Kosti *et al.* 2004) or retrieved after clinical use (Zinelis & Margelos 2001). Other investigators that used fractographic analysis of *in vivo* failed Ni–Ti instruments reported the rare presence of cracks (Spanaki-Voreadi *et al.* 2006). Yet, the very low incidence of the cracks, their location at a lower level than the fracture plane and their limited extend led to the conclusion that they were not involved in the fracture mechanism and fatigue patterns and were more of a random finding than the cause of fracture.

Another important finding in the present report is that dimples observed amongst fractured surfaces examined as well as amongst different regions of the same fractured surface presented diversity in size, depth and deformation (elongation) (Figs 3c and 4b,c). This can be explained by the fact that fracture occurred because of a combination of loading modes (tension and shear) combined with a constant change in orientation of the local plane of the fracture as it propagated, which resulted in asymmetrical strain (Kerlins & Phillips 1987). Besides ductile fracture in many of the surfaces examined cleavage fracture was evident with the distinct surface features such as cleavage steps and river patterns (Kerlins & Phillips 1987) (Fig. 3b), which have been observed in other studies also (Alapati *et al.* 2005, Cheung & Darvell 2007). Another feature observed was shear lip (Fig. 3a) that denotes the last area to be detached from the body of the instrument (Kerlins & Phillips 1987).

Conclusions

Under the conditions of this study, the type of curvature proved to be a defining factor involved in the longevity of Ni–Ti instruments. Fracture was more frequent in root canals with severe curvature with incidence raising by 35% when angle of curvature increased from $0 \pm 10°$ to $30 \pm 10°$, whereas increase in angle from $30 \pm 10°$ to $60 \pm 10°$ resulted in a further increase by 22%. Failure was attributed to a single overloading of the rotating instrument and was not related to a gradual degradation caused by fatigue. The failure mechanism was identical for all instruments fractured in moderately and severely curved root canals.

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