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Dimensional characterization and mechanical behaviour of K3 rotary instruments

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Abstract

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Aim To correlate the mechanical behaviour in torsion, bending and fatigue tests of K3 instruments with their dimensional characteristics.

Methodology Instrument length, tip angle, distance between blades (pitch length) and the diameter at each millimetre from the tip of sizes 20, 25 and 30, 0.04 taper and sizes 20 and 25, 0.06 taper K3 rotary instruments were measured in an optical microscope equipped with digital micrometers. The cross-sectional area at 3 mm from the tip of the same instruments was determined using digital image analysis of scanning electron microscopy images. Maximum torque and angular deflection, as well as bending moment at 45° were measured according to specification of ISO 3630-1. Fatigue resistance of instruments size 30, 0.04 taper, and sizes 20 and 25, 0.06 taper was determined in a fatigue test bench device.

Results The analysed instruments presented no uniformity in the distance between adjacent blades, but the measured diameters at each millimetre from the tip were regular, showing compliance with manufacturing standards. Torque and bending moment of the tested instruments increased significantly with diameter and cross-sectional area at 3 mm from the instrument tip. The fatigue resistance of the instruments showed a tendency to decrease as the diameter of the instruments increased.

Conclusions The bending moment at 45° and the torsional resistance of K3 instruments can be predicted using instrument diameter and cross-sectional area at 3 mm from the tip. Fatigue resistance decreased as the instrument diameter increased.

Keywords: cross-sectional area, diameter, fatigue resistance, flexibility, K3 instruments, torsional resistance.

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Introduction

Rotary nickel–titanium (NiTi) instruments are known for their efficient preparation of the root canal (Glosson *et al.* 1995). This is mainly because of the superelasticity of the NiTi alloy, which gives an increased flexibility and allows the instruments to efficiently follow the original path of the root canal (Thompson 2000).

The occasional fracture of an instrument in root canals continues to be an inherent hazard in root canal treatment. Flexural fatigue and torsional overload have been identified as the main reasons for rotary NiTi instrument failure (Sattapan *et al.* 2000), both of which might contribute to fracture depending on canal curvature, instrument design, and diameter. Continuous rotation of instruments in curved root canals

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requires the instrument to flex during each rotation, resulting in cyclic compression and tension, which in turn produces material fatigue (Pruett *et al.* 1997, Bahia & Buono 2005). On the other hand, the tip or any part of the endodontic instrument might become wedged in constricted areas producing the so-called 'taper lock' effect. The torque required to rotate the shaft of a 'taper-locked' instrument might exceed its torsional strength, leading to separation (Peters *et al.* 2003).

Many 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. The factors affecting the performance include the depth of the flute, area of the inner core, radial land and peripheral surface ground (Gambarini 2005, Xu & Zheng 2006). In addition, stress on NiTi instruments is also strongly dependent on canal curvature, dentine hardness and anatomical complexities (Haïkel *et al.* 1999, Parashos & Messer 2006).

The development of new design features, such as varying tapers, noncutting safety tips and varying length of cutting blades has resulted in new rotary endodontic instruments. Within this concept, the K3 rotary instruments (SybronEndo, Orange, CA, USA) present, according to the manufacturers, the following design features and associated properties: (i) a slightly positive 'rake' angle providing a more effective cutting surface; (ii) a variable core diameter to enhance flexibility over the entire cutting length; (iii) three asymmetrical radial lands: two are broad and recessed, whilst the third is a narrow, full land; the relieved portion of the recessed lands minimizes resistance whilst the extended width maximizes strength; and (iv) a variable flute pitch to help prevent the screwing-in effect and to promote debris removal (Mounce 2003, Gambarini 2005).

Several authors have investigated the shaping ability (Schäfer & Florek 2003, Schäfer & Schlingemann 2003) and clinical behaviour (Ankrum *et al.* 2004, Di Fiore *et al.* 2006, Troian *et al.* 2006) of K3 instruments. Lask *et al.* (2006) have studied the variability of diameter and taper of size 30, 0.04 taper K3 instruments, whilst Schäfer *et al.* (2003) correlated the bending properties of sizes 25, 30 and 35, 0.04 and 0.06 tapers K3 instruments with their cross-sectional area at 3 mm from the tip. The torsional behaviour of new and used K3 instruments has been considered by Yared *et al.* (2003a,b), who observed that the torque at fracture of the new instruments increased significantly with their diameter and that the repeated use in resin blocks affected the torque at fracture of the instruments. More recently, fatigue resistance was investigated in sizes 25 and 40, 0.04 and 0.06 tapers K3 instruments by Yao *et al.* (2006) and in size 25, 0.06 taper K3 instruments by Tripi *et al.* (2006). In both studies, the authors concluded that instrument design, size and taper were important factors in the fatigue behaviour of NiTi instruments. The differences in methodology, size and taper of the K3 instruments investigated make it difficult to draw a more precise account of the influence of geometrical and dimensional characteristics on their mechanical behaviour. The purpose of this study was to characterize the dimensional aspects of K3 instruments and to assess their potential for breakage by evaluating their mechanical properties in torsion, bending, and fatigue tests.

Materials and methods

Analysis of dimensional uniformity

Twelve new K3 instruments (SybronEndo) of each type, sizes 20, 25, and 30, 0.04 taper and sizes 20 and 25, 0.06 taper in a total of 60 instruments were examined under an optical microscope equipped with digital micrometers (Mitutoyo TM, Tokyo, Japan), at 30× magnification. The total instrument length, tip angle, distance between blades (pitch length) and diameter at each millimetre from the tip were measured by inserting each instrument into the measuring device of the microscope. By instrument diameter, it means the largest distance between its extremities in the section perpendicular to the long axis.

The cross-sectional area of each type of instrument was determined at 3 mm from the tip by interpolating, using the least square approximation with 95% confidence level, pairs of values measured before and after this point. Five instruments, one of each size and taper were glued together by the handle in a thin rectangular mould and embedded in a transparent metallographic resin (Struers EpoFix, Ballerup, Denmark). Using the optical microscope as described above, the length of the active part of each embedded instrument was measured. Approximately 2.5 mm of the instruments tip was cut using a diamond saw blade (IsoMet 4 000, Buehler, Lake Bluff, IL, USA), and the actual remaining lengths of the active part of the instruments were remeasured. The cross-section of each instrument was imaged in a scanning electron microscope (SEM; Jeol JSM 6 360, Tokyo, Japan) at a magnification of 150×. Following that, the cross-sectional surfaces were polished again and their remaining length measured in the same manner and another set of SEM images was recorded again. By this procedure, two sets of images taken at precisely measured distances 3 mm from the tip of each instrument were obtained. The images were then analysed using Image Pro-Plus 6.0 (Media Cybernetics, Silver Spring, MD, USA) and the cross-sectional surface area was measured with a relative error of 0.01%.

Torsion tests

Twelve new K3 instruments of each sizes 20, 25, and 30, 0.04 taper and sizes 20 and 25, 0.06 taper, totally 60 files were torsion tested until rupture to establish the mean values of torque to failure and maximum angular deflection of each type of instrument. The torsion tests were performed based on ISO 3630-1 (International Organization for Standardization ISO 3630-1 1992) using a torsion machine described in detail elsewhere (Bahia *et al.* 2006). In brief, torque values were assessed by measuring the force exerted on a small load cell by a lever arm linked to the torsion axis. Measurement and control of the rotation angle was performed by a resistive angular transducer connected to a process controller. The rotation speed was set clockwise to 2 rpm.

Before testing, each instrument handle was removed at the point where the handle is attached to the shaft. The shaft's end was clamped into a chuck connected to a reversible geared motor. Three millimetres of the instrument's tip were 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 were provided by a specifically designed computer program (Analógica, Belo Horizonte, MG, Brazil).

Bending tests

Twelve new K3 instruments of each size 20, 25, and 30, 0.04 taper and twelve of each size 20 and 25, 0.06 taper, totally 60 files were tested for bending resistance according to specification ISO 3630-1 (International Organization for Standardization ISO 3630-1 1992) to evaluate their flexibility. The apparatus and test conditions were similar to that described in the specification, with the instrument fixed at 3 mm from the tip, perpendicular to the axis of the geared motor running clockwise at 2 rpm. The bending moment (M_B) was automatically recorded by the load cell in N cm. The bending angle was measured and controlled by a resistive angular transducer connected to a process controller. A specifically designed computer program (Analógica) adjusted the zero angular position when the bending lever touched the instrument shaft and set the lever in motion until the instrument was bent by 45° with respect to its long axis.

Fatigue tests

New K3 instruments of size 30, 0.04 taper and sizes 20 and 25, 0.06 taper, twelve of each type, totally 36 instruments were tested until failure in a fatigue test bench device to determine their mean number of cycles to failure (NCF). These instruments were chosen because of their larger diameters, which make them more prone to fatigue failure during clinical use (Haïkel *et al.* 1999, Gambarini 2001, Melo *et al.* 2002, Bahia & Buono 2005). The tests were carried out in a bench device described elsewhere (Bahia & Buono 2005), where in the instruments rotate freely inside an artificial canal made of AISI H13 tool steel consisting of an arch whose angle of curvature was 45°, radius of 5 mm and a guide cylinder 10 mm in diameter, made of the same material. Because each instrument was adjusted to the guide cylinder, all instruments were tested with the same radius of curvature of 5 mm measured tangentially to the open side of their curved region. The artificial canal geometry was chosen in accordance with the mean values of angle and radius of curvature previously determined in molars (Bahia & Buono 2005, Martins *et al.* 2006, Vieira *et al.* 2008). The chosen geometry placed the area of maximum tensile strain amplitude at about 3 mm from the tip of the instrument. After machining, the artificial canal was quenched to prevent wear by friction with the rotating files. During the tests, friction was minimized by the use of a mineral oil as a lubricant. The time to fracture was recorded using a digital chronometer and converted to NCF by multiplying it by the rotation speed (300 rpm). The point of fracture in relation to the tip of the instrument was determined by measuring the broken file with an endodontic rule.

The fracture surfaces of three instruments of each size and taper, randomly selected after the fatigue tests were analysed by SEM to evaluate the features associated with the failure process. Before SEM evaluation, instruments were ultrasonically cleaned to remove the mineral oil used as lubricant during fatigue testing.

Statistical analysis

Data obtained in the torsion, bending, and fatigue tests were subjected to a one-way analysis of variance (ANOVA). Significance was determined at the 95% confidence level.

Results

Dimensional uniformity

The results reported hereafter correspond to mean values ± SDs. The mean value of the total length of K3 instruments of the sizes and tapers analysed was 16.7 mm (SD = 1.8 mm). Mean tip angle was 45.3° (SD = 2.7°) for all instruments. With respect to the length of the pitches, the mean values (SD ≤ 10% of the mean values) shown in Fig. 1a indicate that no uniformity in the distance between adjacent blades existed. Otherwise, when considering each type of instrument, it was observed that the thinnest instruments presented greater number of pitches distributed throughout the shaft, with shorter distances between the blades.

The measured diameters at each millimetre from the tip were regular, showing compliance with manufacturing standards, as indicated in Fig. 1b, which shows mean values (SD ≤ 4%) measured at 1 mm intervals along the cutting blades. Mean taper values obtained were 0.040 (SD = 0.002) for instrument sizes 20, 25, and 30, 0.04 taper and 0.059 (SD = 0.004) and 0.060 (SD = 0.004) for instruments sizes 20 and 25, 0.06 taper, respectively. Table 1 lists the mean values of the diameter at 3 mm from the tip–D_3 (SD ≤ 0.01 mm) and of the cross-sectional area at 3 mm from the tip (SD ≤ 0.0001 mm^2) of the instruments analysed. As expected, D_3 increased with increasing size and taper of the instruments and was observed to be smaller for size 20, 0.06 taper than for size 30, 0.04 taper instruments. Moreover, the latter instruments had the same mean value of D_3 as the instruments size 25, 0.06 taper. Statistical analysis, using one-way ANOVA of the measured values of D_3 confirmed the observed regularity and compliance with manufacturing standard: statistically significant differences ($P \leq 0.05$) were obtained for all the pairs analysed, except between instruments size 30, 0.04 taper and size 25, 0.06 taper ($P > 0.05$). On the other hand, statistically significant differences ($P \leq 0.05$) were obtained for all pairs analysed, when the cross-sectional area at 3 mm from the tip is considered.

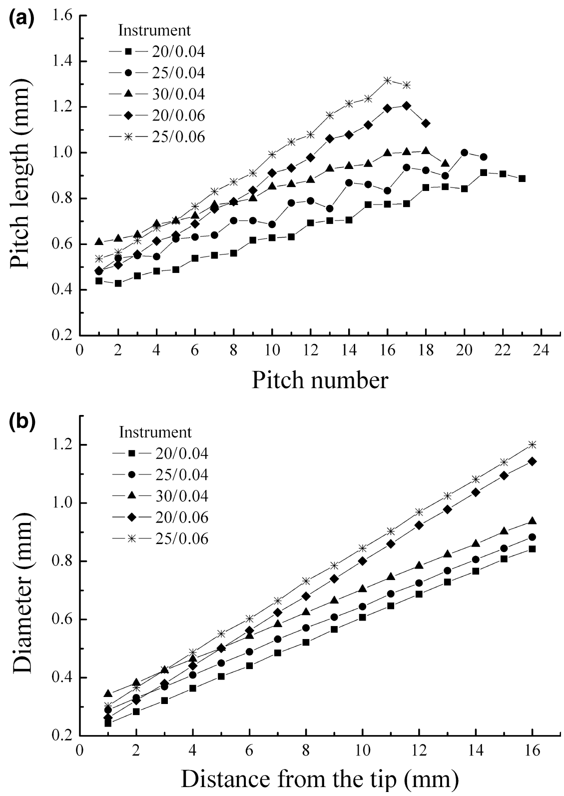

Figure 1 Mean values of (a) pitch length and (b) of diameter at each millimeter from the tip, for the K3 instruments analysed.

Table 1 Mean values of diameter D_3 (SD ≤ 0.01) and cross-sectional area at 3 mm from the tip (SD ≤ 0.0001) of new K3 instruments

Instrument	Diameter D_3 (mm)	Cross-sectional area (mm^2)
20/0.04	0.32	0.0543
25/0.04	0.37	0.0857
30/0.04	0.43	0.0992
20/0.06	0.38	0.1007
25/0.06	0.43	0.1314

Torsional behaviour

The mean values and SDs of maximum torque and angular deflection are shown in Table 2 for the K3 instruments tested in torsion. The maximum torque tended to increase with instrument diameter. A similar

Table 2 Mean values of maximum torque and angular deflection measured in torsion tests and bending moment at 45° measured in bending tests of new K3 instruments

Instrument	Maximum torque (N cm) (SD)	Maximum angular deflection (°) (SD)	Bending moment at 45° (N cm) (SD)
20/0.04	0.524 (0.058)	813 (95)	0.206 (0.024)
25/0.04	0.813 (0.085)	938 (101)	0.395 (0.036)
30/0.04	1.365 (0.124)	826 (105)	0.832 (0.050)
20/0.06	0.952 (0.109)	805 (110)	0.560 (0.041)
25/0.06	1.411 (0.138)	790 (71)	0.863 (0.055)

behaviour is observed for the maximum angular deflection for 0.06 taper instruments, but the tendency of this parameter to increase with instrument diameter is not evident for 0.04 taper instruments.

The maximum torque to failure were statistically different between various instruments ($P < 0.05$), except for size 30, 0.04 taper versus size 25, 0.06 taper. When maximum angular deflection was considered, no statistically significant difference was obtained amongst the instruments, except between instruments of size 30, 0.04 taper and size 20, 0.06 taper ($P > 0.05$).

The plots in Fig. 2 show the variation of mean values of maximum torque (torsional moment, M_T) with measured diameters, D_3 (Fig. 2a), and cross-sectional areas, A_3 (Fig. 2b), at 3 mm from the instruments tip. The solid lines in both figures are the results of linear fits of the data points by the least squares approximation, performed to evaluate the weight of the geometrical parameters on the torsional behaviour of the instruments. The linear equations shown as insets on the top-left side of Figs. 2a,b relate M_T with D_3 and A_3, respectively. The correlation coefficients R, obtained for a 95% confidence level are also shown in Fig. 2.

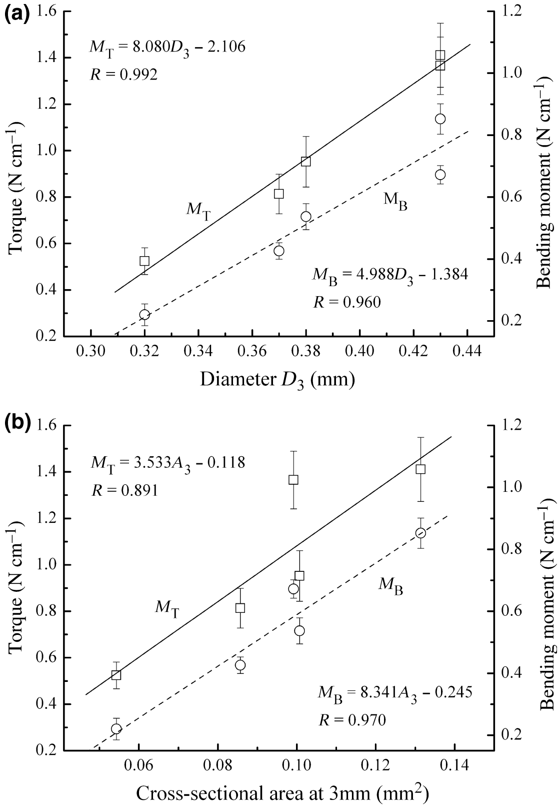

Figure 2 Mean values of maximum torque (torsional moment, M_T) and bending moment at 45° (M_B) of the K3 instruments as a function of the measured values of (a) file diameter D_3, and (b) cross-sectional area A_3 at 3 mm from the tip.

Flexibility

The flexibility of K3 instruments is characterized by the mean values and SD of M_B given in Table 2. Flexibility is higher when the M_B of the instrument is lower. When the M_B of the instruments were compared between pairs of different size and taper, statistically significant differences ($P < 0.05$) were found for all pairs analysed, except between instruments of size 30, 0.04 taper and size 25, 0.06 taper. This behaviour is similar to that of the maximum torque, suggesting that a correlation between flexibility and instrument diameter might also exist. The dashed lines shown in the plots of Fig. 2 were drawn to fit the data points by the least squares approximation with a 95% confidence level and have the same meaning as for the M_T: to evaluate how predictable M_B values are in terms of D_3 and A_3. The equations and corresponding correlation coefficients obtained are shown in the insets on the lower-right side of Figs. 2a,b.

Fatigue behaviour

The mean NCF values and SDs determined in the fatigue tests of the new K3 instruments are shown in Table 3, together with the fracture position, measured in millimetres from the tip, and the maximum tensile strain amplitudes at 3 mm from the instrument tip, calculated according to Bahia & Buono (2005). The fatigue resistance of the instruments measured by the NCF values had a tendency to decrease as the diameter of the instruments increased reflecting the influence of the maximum tensile strain amplitudes shown in Table 3. Accordingly, statistical analysis showed no significant differences ($P > 0.05$) amongst the NCF values of instrument size 30, 0.04 taper, and size 25, 0.06 taper. On the other hand, a significant difference ($P < 0.05$) was found when comparing instrument of size 20, 0.06 taper with that of size 25, 0.06 taper, or size 30, 0.04 taper. The location of fracture was comparable ($P > 0.05$) for all instruments tested (Table 3).

The observed fracture surfaces of the instruments tested in fatigue revealed small smooth areas at the periphery of the fracture, associated with crack nucleation and propagation, and a large central fibrous area containing dimples, which corresponds to the final ductile fracture. Figure 3 shows typical images observed in all files examined. The microfractrography of the transition between the smooth region and the central area (Fig. 3b) reveals the presence of fatigue striations and secondary cracks.

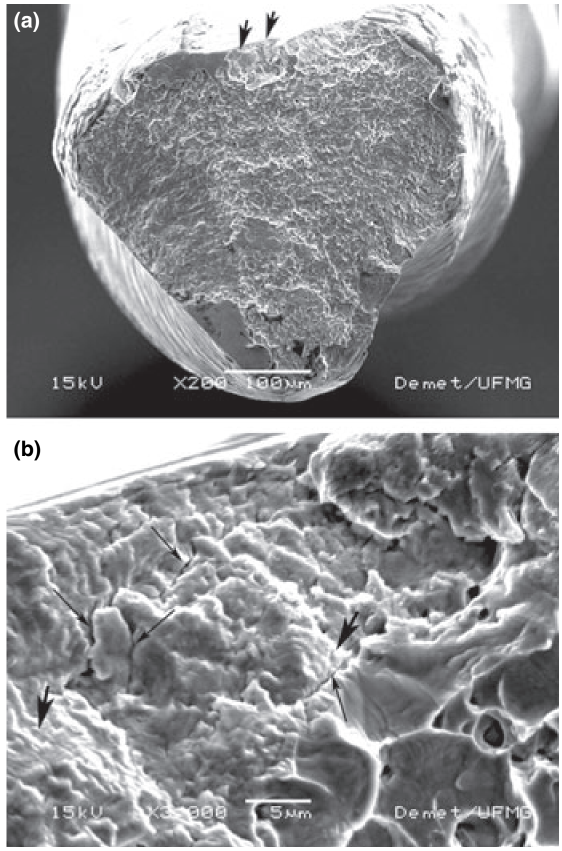

Figure 3 Fracture surface of a size 25, 0.06 taper K3 instrument showing (a) one of the regions of crack initiation (arrows), and (b) the transition between the smooth region and the central fibrous area with fatigue striations (thick arrows) and secondary cracks (thin arrows).

Discussion

It is generally assumed that the adoption of prescribed dimensions and tolerance limits might increase the efficiency of rotary instruments and reduce the incidence of file separation (Zinelis *et al.* 2002). Standards for size, taper and acceptable tolerance limits of rotary instruments with tapers >0.02 are not currently available. The establishment of ISO (publication 3630-1) and ANSI/ ADA Council on Dental Materials and Devices (1976) (Specification No. 28) standards was not sufficient to reduce variations in instrument taper and nominal diameter, as shown by Lask *et al.* (2006). In the present work, the tapers of the K3 instruments analysed were compatible with the manufacturer definition. It is interesting to note that there was no direct correlation between file diameter and cross-sectional area at 3 mm from the tip, as indicated in Table 1: instrument size 30, 0.04 taper and size 25, 0.06 taper had approximately the same diameter but a statistically significant difference in cross-sectional area.

The geometrical shapes and dimensions of the NiTi instruments might have a crucial effect on their behaviour as regards flexibility and torsional and flexural resistance. The K3 instruments have been designed with constant tapers but with variable pitch and helical angles (the angle that the cutting edge makes with the long axis of the file) to reduce the sense of the file getting threaded into the canal and more effectively guide debris out of the root canal. In addition, a smaller pitch distance would give more resistance to the file and less cutting efficiency, whilst a larger pitch length would permit higher cutting efficiency and a more efficient removal of debris

Table 3 Mean number of cycles to failure (NCF) and location of fracture determined for new K3 instruments tested in fatigue, and maximum strain amplitudes estimated at 3 mm from the tip in a root canal with a radius of curvature of 5 mm

Instrument	NCF (SD)	Location of fracture from the tip (SD)/mm	Estimated strain amplitude (%)
30/0.04	696 (67)	3.0 (0.1)	4.49
20/0.06	750 (58)	3.0 (0.1)	3.95
25/0.06	699 (57)	3.0 (0.1)	4.49

(Mounce 2003). According to the manufacturer, K3 instruments were designed to maintain small distances between pitches near the tip, together with an increase in this distance toward the handle to combine desirable properties where needed. However, the measurements made along the length of the active part of the instruments examined showed no particular pattern for the variation in pitch length.

Early studies showed that NiTi rotary instrument fracture is mainly because of torsional stress (Sattapan *et al.* 2000, Peters & Barbakow 2002). The rupture occurs when the torsional stress at the point where the instrument is locked in dentine walls becomes higher than the maximum torque the instrument can withstand at that point. The results of the torsion tests obtained herein, following ISO 3630-1 (International Organization for Standardization ISO 3630-1 1992) standards, indicated that K3 instruments resistance to torsional loads at D_3 increased significantly with instrument diameter and are in agreement with other reports on ProFile (Wolcott & Himel 1997, Svec & Powers 1999, Peters & Barbakow 2002, Bahia *et al.* 2006), ProTaper (Peters *et al.* 2003), and K3 instruments (Yared *et al.* 2003a,b). The fact that no statistically significant difference was observed amongst the values of maximum torque measured for size 25, 0.06 taper, and size 30, 0.04 taper, K3 instruments, which have approximately the same diameter at 3 mm from the tip provides further evidence of the relationship between torque and instrument diameter. According to engineering mechanics, the shear stress τ, at the surface of a cylindrical bar of diameter D subjected to M_T, is given by

$$\tau = \frac{M_T}{2I_p} D \qquad (1)$$

where I_p is the polar moment of inertia of the bar, which in this case is equal to $\pi D^4/32$ (Timoshenko 1983). For each instrument, the maximum torque measured in the torsion tests was that corresponding to the ultimate shear stress, τ_u, of the material causing the rupture of the instrument. In the case of a cylindrical bar, the maximum torque should thus vary with the third power of its diameter, that is,

$$M_T = \frac{\pi D^3}{16} \tau_u \qquad (2)$$

Because of the complex form of K3 instruments cross-section, the evaluation of their polar moments of inertia is not straightforward. On the other hand, considering that the range of D_3 values for the K3 instruments analysed is not large, the extent to which the maximum torque of these instruments can be predicted using their D_3 values can be evaluated by means of the least squares approximation. The linear relation obtained is stated by equation (3), correlating the mean values of torque, M_T (in N cm), with D_3 (in mm), with $R = 0.992$ (Fig. 2a):

$$M_T = 8.080D_3 - 2.106 \qquad (3)$$

Yared *et al.* (2003a,b), assessing the torsional resistance of 0.04 and 0.06 tapers K3 instruments found a similar pattern for the torsional resistance, with values of torque increasing linearly as the instrument diameter increased. However, it is important to mention that Miyai *et al.* (2006) observed no clear correlation between instrument diameter and maximum torque for size 30, 0.06 taper EndoWave, Hero 642, K3, ProFile and ProTaper instruments. Although the relationship between maximum torque in the torsion tests and instrument cross-sectional area is certainly also nonlinear from the point of view of engineering mechanics, a similar approach can be used to evaluate whether mean A_3 values can be used to predict the instruments maximum torque. Equation (4) correlates M_T with the cross-sectional area at 3 mm from the tip, A_3 (in squared mm), with $R = 0.891$ (Fig. 2b):

$$M_T = 3.533A_3 - 0.118 \qquad (4)$$

The values of the correlation coefficients found for equations (3) and (4) show that the maximum torque or M_T of the K3 instruments analysed has a stronger linear correlation with instrument diameter than with cross-sectional areas. The results of the bending tests can be analysed following the same approach described above. The M_B required to deflect a beam by a given angle is directly proportional to its flexural rigidity, which is the product of the elastic modulus of the material and the moment of inertia of its cross-section. For a cylindrical bar with diameter D, the latter is given by $\pi D^4/64$ (Timoshenko 1983). Again, taking into account that the range of D_3 values for the K3 instruments analysed is not large, the extent to which the M_B found for these instruments can be predicted using their D_3 or A_3 values can be evaluated by means of the least squares approximation. The results obtained herein lead to the following linear equations (Figs. 2a,b), relating the M_B (in N cm) of the instruments with D_3 (in mm), eq. (5), or with A_3 (in square mm), eq. (6):

$$M_B = 4.988D_3 - 1.384 \quad (5)$$

$$M_B = 8.341A_3 - 0.245 \quad (6)$$

In this case, the correlation coefficients of 0.960 and 0.970 obtained for D_3 and A_3, respectively are both high and their values are similar, meaning that both geometrical parameters, instrument diameter and cross-sectional area at 3 mm from the tip have a strong linear correlation with flexibility. Schäfer *et al.* (2003) found that the flexibility of K3 instrument sizes 25, 30 and 35, 0.04 and 0.06 tapers, varied linearly with A_3, but did not attempt to find a similar correlation with D_3. Various reports (Camps & Pertot 1994, 1995, Schäfer & Tepel 2001) argued that resistance to bending of root canal instruments depends not only on the alloy mechanical properties and instrument size, but also on their cross-sectional design. Turpin *et al.* (2000) calculated the cross-sectional area of triple-helix and triple-U instruments and found that the former had approximately 30% greater areas than the latter files, when compared at the same distance from the instrument tip. Because of the more massive structure of the triple-helix file, these instruments should be stiffer than the triple-U files. Accordingly, Schäfer *et al.* (2003) found that K3 instrument sizes 25, 30 and 35, 0.04 and 0.06 tapers were significantly stiffer than all other NiTi rotary instruments of the same size and taper. Resistance to torsion and bending are related to cross-sectional design by the engineering principles mentioned before, maximum torque and M_B being direct functions of the moment of inertia of the instrument area. Thus, instruments having a triple-helix section with radial planes and wide contact areas should be more torque-resistant, as long as they are made of materials bearing similar mechanical properties. Besides the direct mechanical influence of the moment of inertia of the instrument area, other factors must be also considered. For instance, the amount of torque generated during shaping of root canals clearly depends on the size of the contact areas between the instruments and the canal walls, as demonstrated by Blum *et al.* (1999). In fact, according to Peters *et al.* (2003) and Gambarini (2005), one method to reduce torsional fracture is to modify the cross-sectional geometry of the instrument, thereby increasing cutting efficiency and consequently reducing contact areas and torsional loads. However, because of the static characteristic of the tests employed in the present study, the higher values of K3 instruments torque observed, when compared with other NiTi systems (Yared & Kulkarni 2003c, Bahia *et al.* 2006, Miyai *et al.* 2006) should be associated only with the increased radial land of K3 files. Concerning the resistance of rotary instruments to flexural fatigue, it has been demonstrated that canal curvature and the diameter of the instrument are the important parameters: the smaller the radius of curvature, the shorter the lifespan of the instrument when rotating (Pruett *et al.* 1997, Haïkel *et al.* 1999). Similarly, some studies have shown that an increased diameter at the point of maximum curvature of the instrument reduces the time to fracture (Haïkel *et al.* 1999, Gambarini 2001, Melo *et al.* 2002, Bahia & Buono 2005). Thus, the observed decrease in fatigue resistance associated with the increase in instrument diameter (Table 2) is in agreement with the literature. Moreover, evaluation of the tensile strain amplitudes on the surface of ProFile instruments, taking into account instrument diameter and radius of curvature of the canal (Bahia & Buono 2005), indicated that fatigue resistance decreases as maximum tensile strain amplitude increases. In a recent study, Cheung & Darvell (2007) found a similar result for ProFile instruments tested in a much broader range of strain amplitudes. Their results showed that low cycle fatigue of NiTi endodontic instruments follows the Coffin–Mason relation between strain amplitude and the NCF (Suresh 1998). For the majority of materials, this relation states that the NCF varies approximately as the inverse of the squared strain amplitude. Accordingly, the greatest value of NCF found in the present study was that of instruments size 20, 0.06 taper, which presents the smallest strain amplitude, 3.95%, in a canal with a curvature radius of 5 mm (Table 3). For instruments of size 25, 0.06 taper, and size 30, 0.04 taper, where the difference between NCF was not statistically significant, the same values of maximum strain amplitude, 4.49%, were found. Because of the mentioned difference in cross-sectional area between these two instruments, no direct correlation between fatigue resistance and cross-sectional area could be obtained with the results reported herein. The relatively high strain amplitudes employed in the fatigue tests are responsible for the appearance of the fracture surfaces examined by SEM, the small smooth area being a direct consequence of this. Ullmann & Peters (2005), Bahia & Buono (2005) and Grande *et al.* (2006) observed similar features. The presence of secondary cracks (Fig. 3b) is also a typical feature of this type of failure in NiTi alloys (Bahia *et al.* 2005).

Conclusions

The analysed K3 rotary instruments showed compliance with manufacturing standards in terms of diameter and taper, but no particular pattern for the variation in pitch length was observed. Their mechanical behaviour analysed by means of measured values of maximum torque and M_B can be predicted using instrument diameter and cross-sectional area at 3 mm from the tip. Fatigue resistance was observed to decrease as instrument diameter increased.

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