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Influence of cyclic torsional loading on the fatigue resistance of K3 instruments

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Abstract

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Aim To evaluate the influence of cyclic torsional loading on the flexural fatigue resistance and torsional properties of rotary NiTi instruments.

Methodology Twelve sets of new K3 instruments, sizes 20, 25 and 30 with an 0.04 taper, and sizes 20 and 25 with an 0.06 taper, were torsion tested until rupture, to establish their mean values of maximum torque and angular deflection. Twelve new K3 instruments of each of the following dimensions, size 30, 0.04 taper and sizes 20 and 25 with 0.06 taper, were tested to failure by rotation bending in a fatigue test device. Cyclic torsional loading was performed in 20 cycles from zero angular deflection to 180° and then return to zero applied torque. After cyclic loading, the same number of instruments were tested until rupture in torsion and flexural fatigue. Data obtained were subjected to a one way analysis of variance (ANOVA) at 95% confidence level.

Results Cyclic torsional loading caused no significant differences in maximum torque or in maximum angular deflection of the instruments analysed, but comparative statistical analysis between measured NCF values of new and previously cycled K3 instruments showed significant differences for all tested instrument. Longitudinal cracks, that is, cracks apparently parallel to the long axis of the instruments cycled in torsion was observed.

Conclusions Cyclic torsional loading experiments in new K3 rotary endodontic instruments showed that torsional fatigue decreased the resistance of these instruments to flexural fatigue, although it did not affect their torsional resistance.

Keywords: cyclic loading, endodontic instruments, fatigue resistance, longitudinal cracks, nickel–titanium.

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Introduction

The peculiar properties of shape memory alloys are related to a reversible solid-to-solid phase transformation, the martensitic transformation, which can be thermally or stress-induced (Otsuka & Wayman 1998). One of these properties is superelasticity, which has allowed for the development of NiTi endodontic instruments. Facilitating the preparation of curved and narrow root canals whilst maintaining the original anatomy is the major characteristics of these instruments (Schäfer & Florek 2003).

During root canal shaping, rotary NiTi instruments undergo flexural and torsional cyclic loads simultaneously. These time-varying stresses can lead to fatigue and failure (Pruett *et al.* 1997). Cyclic loading is one of the generic characteristic features of many of the present applications of NiTi shape memory alloys. It is well accepted that the behaviour of different engineering materials under cyclic loading depends on material strength, microstructure, surface quality and fatigue loading type (Eggeler *et al.* 2004). Cyclic loading is associated with structural and functional fatigue, both limiting the service life of moving components.

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Structural fatigue relates to the microstructural damage that accumulates during cyclic loading, which eventually leads to fatigue failure. The term functional fatigue indicates that during cyclic loading, the material generally suffers a decrease in functional properties (Eggeler *et al.* 2004).

In rotational bending or torsional fatigue, the material fails after being subjected to repeated cycling at strain levels below those which cause failure upon monotonic loading. So far, the majority of fatigue experiments have been performed under uniaxial or rotational bending conditions (Predki *et al.* 2006). NiTi rotary instruments, however, are generally subjected to multiaxial loading, that is, tension, compression and shear, during curved root canal preparation.

Each time the continually rotating NiTi instrument meets resistance, it undergoes torsional loading. The load is higher whenever the dentine is hard or the canal diameter is small. Acting on the instrument surface, this torsional load can prevent its rotation to a greater or lesser extent. Although this is the principle by which dentine can be removed, in extreme cases, when the resistance is so high that it constrains the instrument, it may fracture (Berutti *et al.* 2003). In addition, the repeated torsional loading and unloading applied to rotary NiTi instruments during clinical use can lead to torsional fatigue.

Rotational bending fatigue of NiTi rotary instruments has been assessed extensively (Pruett *et al.* 1997, Haïkel *et al.* 1999, Yared *et al.* 2000, Bahia & Buono 2005) and appears to have a cumulative effect on instruments, causing a weakening over time. It is affected by the angle and radius of canal curvature and the diameter of the instrument at the point of maximum flexure in the canal (Pruett *et al.* 1997), indicating that the fatigue resistance of the NiTi instruments is inversely proportional to the maximum tensile strain amplitude to which they were submitted (Bahia & Buono 2005, Melo *et al.* 2008). Moreover, recent reports indicated that flexural loads, developed during curved root canal shaping, may decrease the torsional resistance of the instruments (Yared *et al.* 2003a,b, Ullmann & Peters 2005, Bahia *et al.* 2006).

Conversely, the influence of torsional loads on flexural fatigue has received very little attention. The influence of previously applied monotonically torsional loading on the flexural fatigue behaviour has also recently been evaluated by Barbosa *et al.* (2007) in size 25, 0.06 taper K3 instruments. These authors observed that even with torsional loads below the elastic limit of the material, this type of loading significantly decreased flexural fatigue resistance.

There is currently little information available on torsional fatigue itself. Best *et al.* (2004) assessed the endurance limit of a size 30, 0.06 taper ProFile instrument, revealing that 10^6 cycles were completed without instrument fracture at an angular deflection of 2.5°.

This study was performed with the objective of clarifying the effects of cyclic torsional loading on the mechanical behaviour and fatigue resistance of rotary NiTi endodontic instruments. Cyclic torsional loading was carried out in new K3 instruments (SybronEndo, Orange, CA, USA) and its influence was evaluated in torsion and flexural fatigue tests.

Material and methods

A total of 192 new K3 instruments (SybronEndo), in sizes and tapers 20/0.04, 25/0.04, 30/0.04, 20/0.06 and 25/0.06, were evaluated.

Torsion tests

Twelve new K3 instruments of each size and taper considered, totalling 60 instruments, were torsion tested until rupture to establish their mean values of torque to failure and maximum angular deflection. The torsion tests were performed based on 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 were 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 end of the shaft 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).

For cyclic torsional loading testing, the machine was programmed to repeatedly rotate from zero angular deflection to 180° and then return to zero applied torque. Each rotation was defined as one cycle. Twelve new K3 instruments of each size and taper, totalling 60 instruments were subjected to 20 cycles of torsional loading as described. Subsequently, these instruments were tested in torsion until rupture, under the same conditions previously applied to the other set of new instruments.

Fatigue tests

New K3 instruments of size 30, 0.04 taper and sizes 20 and 25, 0.06 taper, 12 of each type, totalling 36 instruments, were tested to failure by means of rotational bending in a fatigue test bench device, to determine their mean number of cycles to failure (NCF). These specific types of instruments were chosen because of their larger diameters, which make them more prone to fatigue failure during clinical use. The tests were carried out in a bench device described by Bahia & Buono (2005), in which the files rotate freely inside an artificial canal made up of AISI H13 tool steel, consisting of an arch whose angle of curvature was 45°, with a radius of 5 mm and a guide cylinder of 10 mm in diameter, made of the same material. The artificial canal geometry was chosen in accordance with previously determined mean values of angle and radius of curvature (Bahia & Buono 2005, Martins *et al.* 2006, Vieira *et al.* 2008). The chosen geometry placed the area of maximum tensile strain amplitude approximately 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 fractured instrument with an endodontic rule.

Thirty-six other new K3 instruments of size 30, 0.04 taper and sizes 20 and 25, 0.06 taper, 12 of each type, were subjected to the same 20 cycles of torsional loading, as described above and then tested until rupture in fatigue through rotational bending. The same conditions applied to the new instruments were also used so as to assess the effect of cyclic straining in torsion on the fatigue resistance of these instruments.

Before and after testing, three instruments of each size and taper, randomly selected, were examined by scanning electron microscopy (SEM) (Jeol 6360LV, Tokyo, Japan) to evaluate their surface characteristics. Secondary electron images were recorded at length intervals that enabled the observation of the cutting sections perpendicular to the electron beam, from the instrument tip onwards, up to approximately 4.0 mm from the tip, thus encompassing the area submitted to the most severe conditions of cyclic straining during the tests.

The fracture surfaces of three instruments of each size and taper, randomly selected after the torsion tests to failure, were analysed by SEM to evaluate the features associated with the failure process. Before SEM evaluation, instruments were ultrasonically cleaned to remove debris.

Statistical analysis

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

Results

Torsional behaviour

Typical cyclic torsional loading curves of a new size 30, 0.04 taper K3 instrument submitted to 20 loading cycles are illustrated in Fig. 1. These curves show that because of the residual deformation, cycling must be performed between 180° and zero applied torque. It can also be observed that there is a tendency towards stabilization of the cyclic torsional behaviour after cycle number 2.

The mean values of maximum torque and angular deflection at fracture of new K3 instruments and of those previously submitted to 20 cycles of torsional

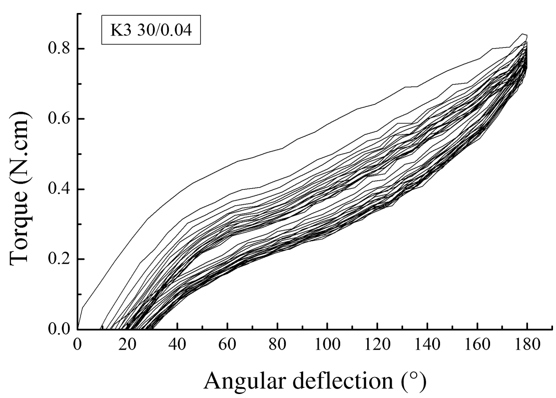

Figure 1 Typical cyclic torsional loading curves of a new size 30, 0.04 taper K3 instrument submitted to 20 loading cycles.

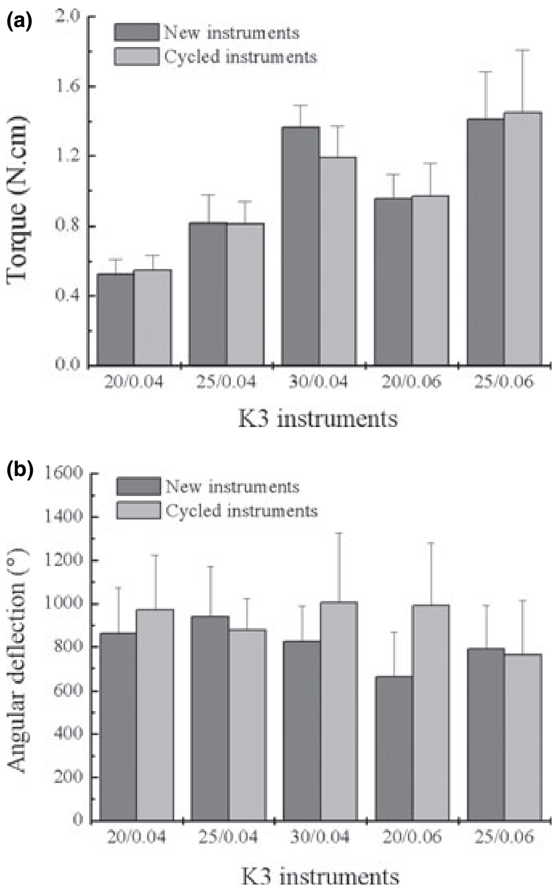

Figure 2 Mean values (standard deviations shown as error bars) of (a) maximum torque and (b) angular deflection at fracture measured in new K3 instruments and in instruments previously cycled in torsion.

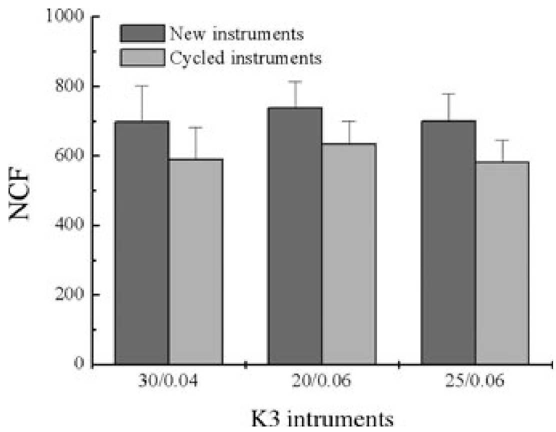

Figure 3 Mean values (standard deviations shown as error bars) of number of cycles to failure (NCF) of new K3 instruments and of instruments previously cycled in torsion.

loading are illustrated in Fig. 2. As usual, torsional resistance increased as the diameter of the instruments increased, but no apparent correlation existed between angular deflection and instrument diameter. Statistical analysis of the influence of cyclic loading in torsion showed no significant differences in maximum torque or in maximum angular deflection between pairs of same size and taper instruments assessed.

Fatigue behaviour

The mean NCF values determined in the fatigue tests of new K3 instruments and of those submitted to cyclic loading in torsion are shown in Fig. 3. Fatigue resistance of new instruments decreased as the diameter of the instruments increased. Comparative statistical analysis between measured NCF values of new and previously cycled K3 instruments showed significant differences for all tested instrument pairs ($P < 0.05$), indicating that cyclic torsional loading decreased the fatigue resistance of these instruments.

The location of fracture, expressed as the distance relative to the instrument tip, presented a mean value of 3.0 ± 0.1 mm, with no statistically significant difference amongst the different sizes or between new and cycled instruments.

Surface characteristics of cycled instruments

As illustrated in Fig. 4, the lateral surfaces of two size 20, 0.06 taper K3 instruments submitted to 20 cycles of torsional loading exhibited longitudinal cracks, that is, cracks apparently parallel to the long axis of the instrument. Remarkable in these images is the fact that the two crack patterns showed a strong similarity between each other. Figure 5 shows examples of the cracks found on the fracture surface of instruments tested in flexural fatigue: in Fig. 5a, where the fracture surface of a new instrument is presented, most of the cracks are perpendicular to the radius of the instrument (dark arrows); in Fig. 5b, showing the fracture surface of an instrument previously submitted to 20 cycles of torsional loading, a crack running along the radius of the instrument's cross-section can be observed (white arrows). Cracks of this type were frequently found on fracture surfaces of instruments cycled in torsion but were not found in fatigue-tested new instruments.

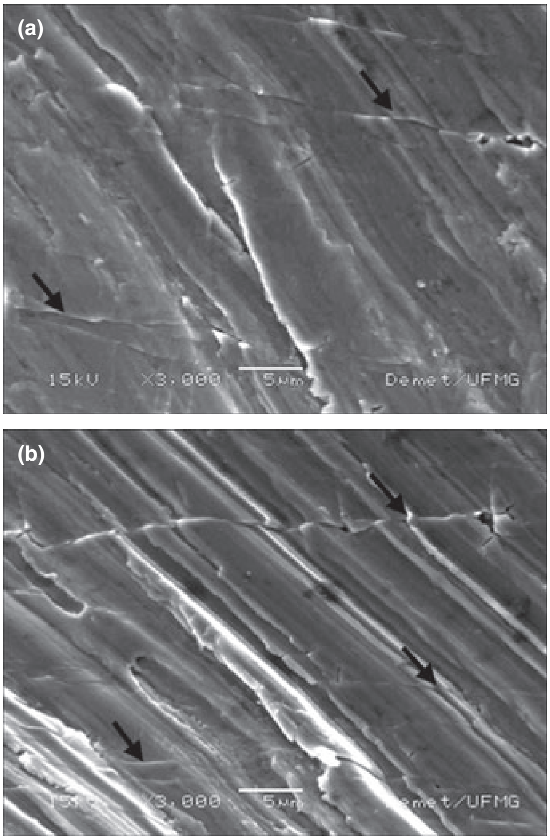

Figure 4 Longitudinal cracks (arrowed) in two size 20, 0.06 taper K3 instruments submitted to 20 torsional loading cycles. Similar crack patterns were found in different instruments, (a) and (b).

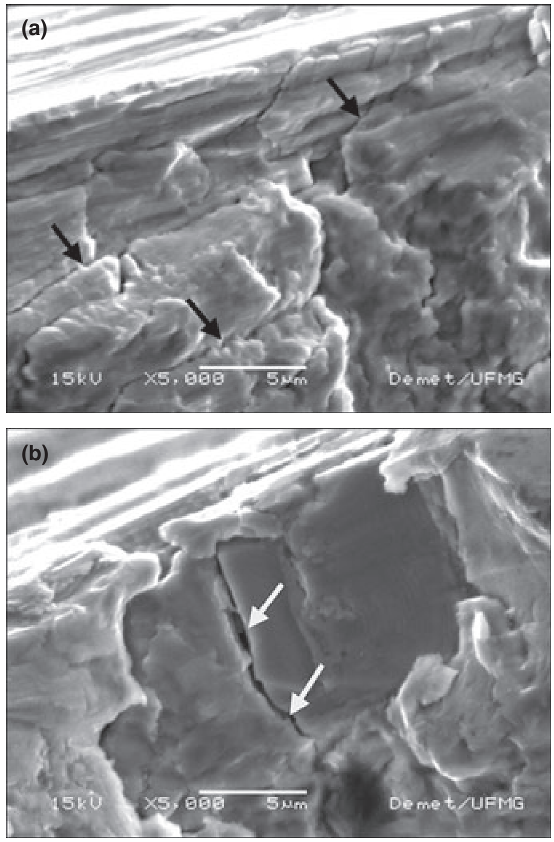

Figure 5 Border of the fracture surface of size 25, 0.06 taper K3 instruments tested in flexural fatigue: (a) new instrument, (b) instrument previously submitted to 20 cycles of torsional loading.

Discussion

According to American Society for Testing of Materials ASTM E 1823 (2005) designation, fatigue is the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. Endodontic instruments are subjected to both torsional and flexural stresses during root canal preparation and these types of stress can lead to metal fatigue and failure. In a recent review, Parashos & Messer (2006) reported that rotary NiTi instrument fracture is most likely a rare occurrence in clinical practice, but structural damage caused by fatigue is frequently observed in endodontic instruments (Bahia & Buono 2005, Peng *et al.* 2005, Vieira *et al.* 2008).

Flexural fatigue and torsional overload have been identified as the main reasons for rotary nickel–titanium instrument fracture (Sattapan *et al.* 2000). Torsional overload generally occurs when a substantial area of an instrument encounters excessive friction on a canal wall, when the instrument tip is larger than the canal, or when excessive pressure is placed on the handpiece. Under these situations, the tip may lock, leading to large increases in torsional stress. The torque developed by the motor may exceed a critical level, thus causing the instrument to undergo plastic deformation and failure (Gambarini 2000).

The results of the torsion tests shown in Fig. 2 indicated that the resistance of K3 instruments to torsional loads significantly increased in accordance with instrument diameter and are in agreement with other reports for K3 (Yared *et al.* 2003a,b, Melo *et al.* 2008) and other instruments such as ProFile (Wolcott & Himel 1997, Svec & Powers 1999, Peters

& Barbakow 2002, Bahia *et al.* 2006) and ProTaper (Peters *et al.* 2003) (ProFile/ProTaper; Dentsply-Maillefer, Ballaigues, Switzerland). In fact, a definite correlation was found between the maximum torque of K3 instruments and the diameter and cross-sectional area at 3 mm from the instrument tip (Melo *et al.* 2008).

Concerning the fatigue resistance of the K3 instruments analysed, the results revealed a tendency of NCF to decrease as the diameter of the instrument increased (Fig. 2), in agreement with the literature. Previous studies demonstrated that canal curvature and instrument diameter at the point of maximum curvature are important parameters: the smaller the radius of curvature and the greater the diameter, the shorter the lifespan of the rotary instrument (Pruett *et al.* 1997, Haïkel *et al.* 1999, Gambarini 2001, Melo *et al.* 2002, Bahia & Buono 2005). In addition, evaluation of the tensile strain amplitudes on the surface of rotary instruments, taking into account the instrument diameter and the radius of curvature of the canal, indicated that fatigue resistance varies inversely with the maximum tensile strain amplitude to which the instruments are submitted in the root canal (Bahia & Buono 2005, Cheung & Darvell 2007).

Flexural fatigue of NiTi rotary instruments has been extensively evaluated in the literature (Pruett *et al.* 1997, Haïkel *et al.* 1999, Gambarini 2001, Melo *et al.* 2002, Peters *et al.* 2003, Bahia & Buono 2005, Grande *et al.* 2006, Cheung & Darvell 2007) and, as previously reported by various authors for a variety of instrument types (Gambarini 2001, Fife *et al.* 2004, Bahia & Buono 2005, Plotino *et al.* 2006, Vieira *et al.* 2008), appears to have a cumulative effect, leading to a reduction in the remaining fatigue life of clinically used instruments. Furthermore, recent reports indicated that flexural loads, developed during curved root canal shaping, may decrease the instrument's torsional resistance (Yared *et al.* 2003a,b, Ullmann & Peters 2005, Bahia *et al.* 2006).

The influence of previously applied monotonical torsional loading on flexural fatigue has recently been evaluated by Barbosa *et al.* (2007) in size 25, 0.06 taper K3 instruments. The authors observed that even with torsional loads below the elastic limit of the material, this type of loading significantly decreased flexural fatigue resistance. However, the actual contribution of cyclic loading in torsion to potential instrument failure has not yet been reported in the literature. Best *et al.* (2004) evaluated the torsional endurance limit of size 30, 0.06 taper ProFile instruments, revealing that 10^6 cycles were completed without instrument fracture at an angular deflection of 2.5°.

Peters *et al.* (2003) established that torque was correlated not only with the apically exerted force, but also with the preoperative canal volume. Hence, the shaping of narrow and constricted canals can subject rotary instruments to higher torsional loads and high apically directed forces. Thus, each time the continually rotating NiTi instrument meets resistance, it also undergoes torsional loading, whose extent depends on dentine hardness and canal diameter. Acting on the instrument surface, this torsional cyclic loading can lead to torsional fatigue.

In this study, a specific loading cycle was used to simulate torsional fatigue in rotary instruments during clinical use. The loading cycle consisted of 20 repetitions of torsion from zero angular deflection to 180° and back to zero load. The last step in this cycle guaranteed that nonrecovered strains remained unchanged for the next cycle (Fig. 1). The occurrence of this type of strain is a common feature in superelastic NiTi alloys, which is associated with the generation of dislocation and the presence of untransformed martensite variants near grain boundaries, as discussed in the findings from Bahia *et al.* (2005). The fact that changes on the load–unload curves of Fig. 1 decreased as the number of cycles increased is related to the saturation of these internal defects. The number of cycles employed in the load–unload tests was selected based on the assumption that an instrument requires an average of 24 revolutions in three strokes to shape one root canal (Peters & Barbakow 2002). Thus, 20 torsional strain cycles should be roughly equivalent to the instrument's use in six root canals, which represents approximately half of the recommended number of uses for rotary instruments (Yared *et al.* 2000, Gambarini 2001, Foschi *et al.* 2004, Bahia & Buono 2005). The maximum angular deflection of 180° was chosen based on results from the torsional behaviour of K3 instruments (Melo *et al.* 2008), showing that this deflection is within the range of superelastic straining in torsion.

The longitudinal cracks observed in instruments submitted to cyclic deformation in torsion analysed by SEM (Fig. 4) have been described previously (Alapati *et al.* 2003, Peng *et al.* 2005, Tripi *et al.* 2006, Vieira *et al.* 2008). It has been suggested that these types of cracks reflect the orientation of the stress on the surface of the instrument under torsional load. During cyclic torsion, planes with a maximum shear stress are either perpendicular or parallel to the longitudinal axis, whilst the normal stress component on the slip plane is zero. Microscopic investigations have shown that microcracks nucleate in a slip band under cyclic torsion and then grow further in a direction perpendicular to the main stress. In a cylindrical bar, this direction makes an angle of 45° with the axis of the bar. As a consequence, cracks in a round axle under cyclic torsion grow as a spiral around its surface (Schijve 2001). The longitudinal appearance of the cracks observed in endodontic instruments is because of the fact that the instruments have helical shapes and that the cracks, being rather small in size, require large magnifications to be observed.

Vieira *et al.* (2008) observed that, after clinical use in five and eight molars, ProTaper instruments had microcracks transverse to the cutting edge, probably associated with instrument bending in the curved section of the root canals and longitudinal cracks, similar to those shown in Fig. 4, suggesting that they reflect the direction of stress on the surface of the instrument under torsional load. In fact, these cracks are possibly the result of both repeated flexural and torsional loading, indicating that instrument fracture may take place as a result of triaxial stresses.

The results of this study showed that torsional cyclic loading did not affect torsional resistance but did decrease the flexural fatigue resistance of K3 instruments. The longitudinal cracks generated during torsional cyclic loading can be responsible for this behaviour because they can act as nucleation sites for flexural fatigue cracks, as the image in Fig. 5b seems to indicate. On the other hand, because of their orientation with respect to the instrument cross-section, running from the surface to the centre along the radius, and not perpendicular to it as do the flexural fatigue cracks, the longitudinal cracks should not significantly affect the torsional resistance because they did not significantly reduce the cross-sectional area.

The fracture by torsional overload has been dealt with using low-torque endodontic motors, which can prevent the application of a higher torque than that which each instrument can bear without failing. This strategy presents two problems: first, the flexural loads, developed during curved root canal shaping, result in a statistically significant reduction of the instrument's torsional resistance (Yared *et al.* 2003a,b, Ullmann & Peters 2005, Bahia *et al.* 2006). Therefore, low-torque motors can only prevent torsional failures when the selected torque value corresponds to that associated with the instrument's stage of usage. The second important point is that low torque motors cannot prevent torsional fatigue. As a matter of fact, the problem may even be worsened if the motors are programmed to reverse the rotational motion when the instrument cannot advance further, considering the fact that this can make the longitudinal cracks propagate even further.

Finally, it is important to observe that the findings of this work suggest that torsional fatigue can play an important role in the failure of rotary endodontic instruments, decreasing their resistance to flexural fatigue. Although this was not tested here, it is also reasonable to expect that if the instrument becomes less resistant to flexural fatigue, its torsional resistance may also decrease (Yared *et al.* 2003a,b, Ullmann & Peters 2005, Bahia *et al.* 2006).

Conclusions

Cyclic torsional loading experiments in new K3 rotary endodontic instruments revealed that torsional fatigue decreased the resistance of these instruments to flexural fatigue, although it did not affect their torsional resistance. This behaviour is probably associated with the generation of longitudinal cracks during torsional loading cycles, which can act as nucleation sites for flexural fatigue cracks but introduce no appreciable change in the cross-sectional area of the instruments. These results suggest that the failure of rotary NiTi endodontic instruments results concomitantly from the processes of torsional overload and flexural and torsional fatigue.

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