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Influence of multiple clinical use on fatigue resistance of ProTaper rotary nickel-titanium instruments

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Abstract

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Aim To examine the influence of clinical use on the occurrence of deformation and fracture and on the fatigue resistance of ProTaper rotary instruments.

Methodology Root canal treatments were performed on patients using the ProTaper rotary system. Ten sets of instruments were used by an experienced endodontist, each set in five molars. Another 10 sets of instruments were used by the same operator, each set in eight molars. In addition, 10 sets of instruments were used, each set in five molars, by undergraduate students with no clinical experience with the system. After clinical use, S1, S2, F1 and F2 instruments were analysed for damage by optical and scanning electron microscopy. The used sets, along with a control group of 12 sets of new instruments, were then tested in a bench device for fatigue resistance.

Results The use of the ProTaper rotary instruments by an experienced endodontist allowed for the cleaning and shaping of the root canal system of up to eight molars without fracture. During the students work, six instruments fractured. Fatigue resistance decreased upon clinical use for all instruments analysed.

Conclusions Fatigue resistance of used instruments was reduced, but no significant change was observed amongst the instruments used for shaping the canals of five and eight molars. Operator experience affected the occurrence of fracture and plastic deformation during shaping.

Keywords: clinical use, endodontic instruments, fatigue resistance, nickel-titanium, operator proficiency, ProTaper.

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Introduction

Since the introduction of nickel-titanium (NiTi) rotary instruments in root canal treatments, the shaping of curved canals has become more predictable, reducing operator fatigue and the time required to complete the preparation (Thompson & Dummer 1997). Moreover, procedural errors frequently found when using manual stainless steel instruments have been minimized (Glosson *et al.* 1995). Since then, an increasing number of NiTi rotary systems have been marketed by various manufacturers. These systems differ from one another in the design of the cutting blades, body taper and configuration of the file tip. Despite the purported clinical advantages of the rotary techniques, unexpected instrument fracture is not uncommon, especially for less-experienced operators (Mandel *et al.* 1999, Yared *et al.* 2001, 2002, 2003, Peters & Barbakow 2002).

The fracture of rotary instruments takes place in different ways: due to torsion, fatigue flexure or by a

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combination of both (Sattapan *et al.* 2000). Torsional failure occurs when the tip, or any other part of the instrument, binds in the canal, leading to an increase in the shear stress as the motor continues to drive the shaft. When the elastic limit of the material is exceeded, plastic deformation and ultimately fracture take place. This type of fracture has been associated with the application of excessive apical force during instrumentation (Sattapan *et al.* 2000). On the other hand, in flexural fatigue failure, the instrument does not bind in the canal, but rotates freely until the fracture occurs at the point of maximum flexure, without any visible signs of permanent deformation. When an instrument rotates within an imposed curvature, repeated compression and tension stresses occur on either side of the instrument on every revolution. Cyclic loading is one of the generic characteristic features of many of the present applications of NiTi superelastic alloys. It is well appreciated that the behaviour of different engineering materials under cyclic loading depends on material strength, microstructure, surface quality and loading type. Structural fatigue is the term used to characterize the microstructural damage that accumulates during cyclic loading (Eggeler *et al.* 2004).

The fatigue life of rotary NiTi endodontic instruments is related to the degree to which the instrument is flexed when placed in a curved root canal, with greater angles of curvature and smaller radius leading to shorter life expectation (Pruett *et al.* 1997, Haïkel *et al.* 1999, Gambarini 2001, Melo *et al.* 2002, Peters & Barbakow 2002, Fife *et al.* 2004, Bahia & Buono 2005, Ullmann & Peters 2005). Evaluation of the tensile strain amplitudes on the surface of ProFile instruments, taking into account instrument diameter and radius of curvature of the canal, indicated that fatigue resistance apparently varies inversely with the maximum tensile strain amplitude to which the instruments are submitted in the root canal, which in turn is a direct function of instrument diameter (Bahia & Buono 2005).

The cumulative effects of multiple clinical uses on the incidence of fatigue and instrument separation have been analysed in various studies (Yared *et al.* 1999, 2000, Gambarini 2001, Bahia & Buono 2005). The manufacturers state that the only predictable way to prevent failure is to discard rotary instruments regularly after a certain number of uses. However, there is no agreement about the exact number of uses to which an instrument can be submitted before failure. Some researchers suggest that NiTi instruments could be reused in up to 10 canals (Yared *et al.*1999, Bahia & Buono 2005) or more (Yared *et al.* 2000, Gambarini 2001, Foschi *et al.* 2004). In some cases, the instruments should be discarded after a single use, especially in very complex, calcified and curved canals, or selectively discarded to increase safety in clinical practice (Pruett *et al.* 1997, Arens *et al.* 2003, Bahia & Buono 2005).

There have been reports of defects found in ProTaper instruments after clinical use (Cheung *et al.* 2005, Peng *et al.* 2005), but only ProTaper S1 instruments were analysed. The influence of operator experience was also assessed in previous studies, which showed that proper tuition or experience was necessary to minimize the incidence of rotary NiTi instrument fracture (Mandel *et al.* 1999, Yared *et al.* 2001, 2002, 2003). Results by Yared *et al.* (2003) are indicative of the need to improve competence through learning and experience to prevent deformation and fracture of ProTaper instruments. The purpose of this study was to evaluate how multiple clinical uses of these instruments, by an experienced endodontist or by undergraduate students with no experience with the system, influence the deterioration of their fatigue resistance and the surface damages caused by structural fatigue.

Material and methods

Forty-two sets of ProTaper instruments (Dentsply Maillefer, Ballaigues, Switzerland), type S1, S2, F1 and F2, totalling 168 files, were analysed in this study. They were divided into four groups, as follows:

1. Control Group (CG): with 12 sets of new instruments, which were fatigue tested until rupture to determine their fatigue resistance;

2. Group A: with 10 sets of instruments, each set used clinically in five molars (15–20 canals) by an endodontist with experience using the ProTaper system;

3. Group B: with 10 sets of instruments, each set used clinically in eight molars (24–32 canals) by the same endodontist; and

4. Group C: with 10 sets of instruments, each set used clinically in five molars (15–20 canals) by undergraduate students at the School of Dentistry of the Federal University of Minas Gerais (UFMG), whose previous experience with the ProTaper system was training on two molar teeth in the laboratory.

The 30 sets of instruments analysed in experimental groups A–C were used during root canal treatments performed on patients during a period of approximately 2 years. The SX and F3 instruments were used, but they were not analysed as these instruments work only in the straight portion of the canals (SX) or in preparation of straight canals (F3).

Only teeth with mature apices were included in the study; pulpal and periradicular diagnoses were not used as criteria for inclusion. Direct and angled radiographs of each tooth were obtained using a paralleling technique to evaluate its anatomy, as well as to determine the canal radius and angle of curvature, as defined by Pruett *et al.* (1997), and its approximate length. The measurement of these parameters was performed by projecting the radiographic images in a profile projector (Mitutoyo, Tokyo, Japan) at 10× magnification. Statistical analysis using the Mann–Whitney test was employed to compare the root canal curvature between groups.

After the appropriate anaesthesia, the access cavity was prepared, the orifices located, and the canal explored with sizes 10 and 15 stainless steel K-files (Dentsply Maillefer). The cleaning and shaping of the canals were completed in accordance with a crown-down technique recommended by the manufacturer, using the following operative sequence:

1. shape the coronal two-thirds (to resistance) with Gates Glidden 4, 3 and 2, S1, S2 and SX instruments;
2. determination of the working length (WL, at 0.5 mm from the apical foramen) using Root ZX apex locator (J Morita, Kyoto, Japan) and then radiographically verified;
3. shape the apical one-third (to WL) with S1, S2, F1 and F2 instruments. After each use of rotary instrument, recapitulations using a patency file (size 10 file) were performed.

A 5.25% sodium hypochlorite solution was used for irrigation, and Rc-prep (Premier Dental Products, Norristown, PA, USA) was used as a lubricant. The rotational speed was 300 rpm, applied by an endodontic electric motor (Endo Plus, VK Driller, São Paulo, SP, Brazil), operating with a torque of 5 N cm with a hand piece of 16 : 1 reduction (W&H 975; Dentalwerk, Bürmoos, Austria).

Preparations were performed following the guidelines described by Ruddle (2005). Once a glide path had been created, the ProTaper shaping instruments were used like a 'brush' to laterally and selectively cut dentine on the outstroke. The preparation was finished using the ProTaper finishing instruments F1 and F2 in a 'nonbrushing' manner. Apical pressure on the instruments during the shaping was light. The clinical protocol was followed with recapitulations until the working length, established at 0.5 mm short of the canal patency length, could be reached by at least an F2 instrument, at which point shaping was considered complete. Whenever file fracture or permanent deformation took place, the entire set to which the file belonged was discarded and replaced by a new set of instruments. The new set of instruments was then clinically used as originally planned, that is, in five or eight molars.

After use, the instruments were washed, ultrasonically cleaned for 5 min in ethanol and steam autoclave sterilized. The S1, S2, F1 and F2 instruments of the experimental groups A–C were observed by optical microscopy (Mitutoyo TM, Tokyo, Japan), at 30× magnification, to determine the presence of distortion, unwinding defects and macroscopic deformation. Before being tested to fatigue failure, 12 sets of these instruments, belonging to the CG of new instruments and to the experimental groups A–C, three sets of each group, totalling 48 instruments, were randomly selected and examined by scanning electron microscopy (SEM) (Jeol JSM 6360, Tokyo, Japan) to assess their surface characteristics. By placing the instruments with the handle always in the same position and measuring the distance relative to the instrument tip, the same selected areas could be observed before and after shaping the root canals. Secondary electron images were recorded at length intervals that enabled the observation of the cutting sections from the instrument tip to approximately 6 mm from the tip, thus encompassing the area submitted to the most severe conditions of cyclic loading during curved root canal shaping. The choice of three sets of each group was based on technical considerations, since the surface cracks in NiTi files are generally fine, requiring the use of high magnifications, typically between 1000× and 2000×, to be resolved. At a magnification of 1000 times, a 12-cm wide picture covers only 0.12 mm of the instrument length. Thus, a quantitative analysis of number of cracks and/or crack length taking into account all instruments employed would be excessively time consuming.

Twelve sets of new instruments and 10 sets of instruments of each experimental groups A–C were fatigue tested. The tests were carried out in a bench test device that allowed the files to rotate freely inside an artificial canal made of AISI H13 tool steel, consisting of an arch, whose angle of curvature was 45 degrees with a radius of 5 mm, and a guide cylinder of 10 mm in diameter made of the same material (Bahia & Buono 2005). The chosen geometry placed the area of maximum canal curvature at about 3 mm from the tip of the instruments. 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 lubricant. The number of cycles to failure (NCF) was obtained by multiplying the rotation speed used in the fatigue test device, 300 rpm, by the test time registered with a digital chronometer. The point of fracture in relation to the tip of the instrument was determined by measuring the fractured file with an endodontic rule. To determine the statistical significance of differences in the measured parameters amongst different groups, data obtained were subjected to a one-way analysis of variance (ANOVA). Significance was determined at the 95% confidence level.

The fracture surface of randomly selected instruments after the fatigue test, three sets of each group, totalling 48 instruments, was analysed by SEM (Jeol JSM 6360) to evaluate their features associated with the failure process.

Results

The mean values of radius and angle of curvature characterizing the geometry of the instrumented curved root canals are listed in Table 1. The five molars instrumented with each of the 10 sets of files in group A had an average of 18 canals (13 curved) in total; in group B, an average of 28 canals (20 curved) were instrumented with each of the 10 sets of files and in group C, the average number of canals per set of files was 18 (10 curved). Statistical analysis using the Mann–Whitney test showed no significant difference ($P > 0.05$) in root canal geometries amongst canals in groups A and B, whilst significant differences ($P < 0.05$) were found in the values of curvature radius amongst canals in groups B and C and in curvature angles amongst canals in groups A and C and in B and C. In other words, curved canals in group C exhibited, on average, milder curvature than in groups A and B.

During canal shaping by the endodontist with experience using the ProTaper system (groups A and B), no fractures occurred and only two instruments were permanently deformed at the end of preparation: (i) one S1 instrument from group A was unwound between 0.7 and 1.5 mm from the tip and (ii) one F2 instrument from group B was unwound between 1.2 and 2.9 mm. In contrast, during the students work (group C), six S1 instruments fractured. The fractured instruments belonged to sets with a different number of uses, with one S1 file having separated in its first use in a mesiobuccal canal with angle of curvature of 67 degrees and radius of 2.0 mm. In addition, deformation was observed in seven other instruments of group C: (i) two S1 instruments were unwound between 0.9 and 2.9 mm from the tip, (ii) three S2 instruments were unwound between 1.2 and 3.6 mm from the tip and (iii) two F2 instruments were unwound between 1.8 and 2.7 mm from the tip.

Table 1 Mean values and standard deviations of radius and angle of curvature of curved canals

Canal geometry	Group A	Group B	Group C
Radius (mm)	4.8 ± 2.1	4.1 ± 2.1	5.3 ± 2.2
Angle (degrees)	37.1 ± 13.9	34.8 ± 13.0	27.5 ± 10.7

After canal shaping, all instruments examined by SEM had microcracks and widening of machine grooves, as well as wear and blunting of the cutting edges. These surface characteristics were qualitatively similar in all three sets of each group of randomly selected instruments from groups A to C. Examples of wear marks and crack patterns found in S1 instruments after use in five (group A) and eight molars (group B) are shown in Fig. 1. The cracks were transverse to the cutting edge, running along the milling marks, probably associated with instrument bending in the curved section of the root canals. A tendency of concentration of larger and wider cracks in the region between 2.0 and 3.5 mm from the instruments tip was observed. Longitudinal cracks, that is, cracks parallel to the long axis of the file, were also found in instruments after shaping the root canals. Generally, these cracks showed a tendency of concentration between 2 and 3 mm from the instrument tip. The S1 instruments presented the greatest incidence of these cracks, and they were found until 5 mm from the tip. Figure 2 shows longitudinal cracks found after the use of instruments in the root canals.

Subjectively, there seemed to be a higher incidence of defects in the S1 and S2, compared with F1 and F2 instruments, for those in groups A (five molars) and B (eight molars). Little difference between the same instruments of groups A and B, however, was observed.

The mean values and standard deviations of the NCF obtained in the fatigue tests of the instruments previously used in the clinical practice are shown in Fig. 3, together with those obtained for the CG of new instruments. The average 'consumed fatigue life', given by the ratio between the average values of NCF for each type of instrument after clinical use by the corresponding average value for new instruments, is also shown in

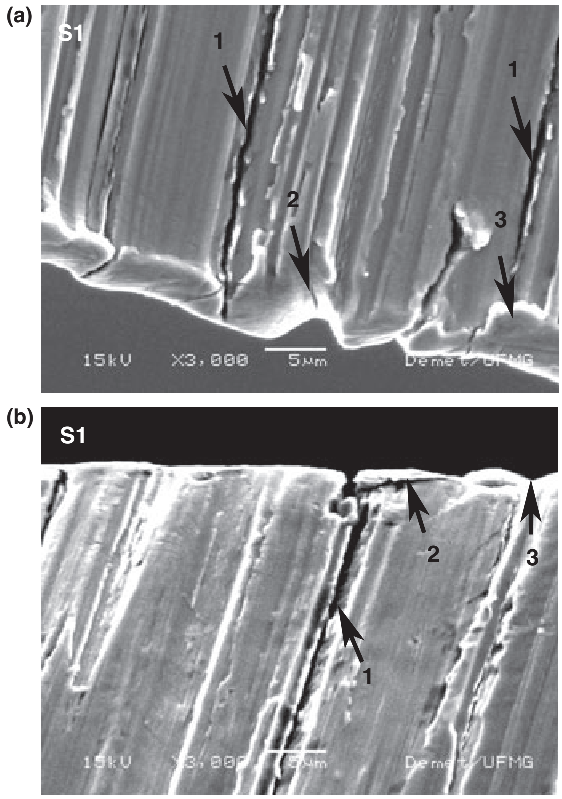

Figure 1 Typical crack patterns in S1 instruments used for cleaning and shaping (a) five molars (group A) and (b) eight molars (group B). Arrows number (1) microcracks; (2) wear mark; (3) blunted edge.

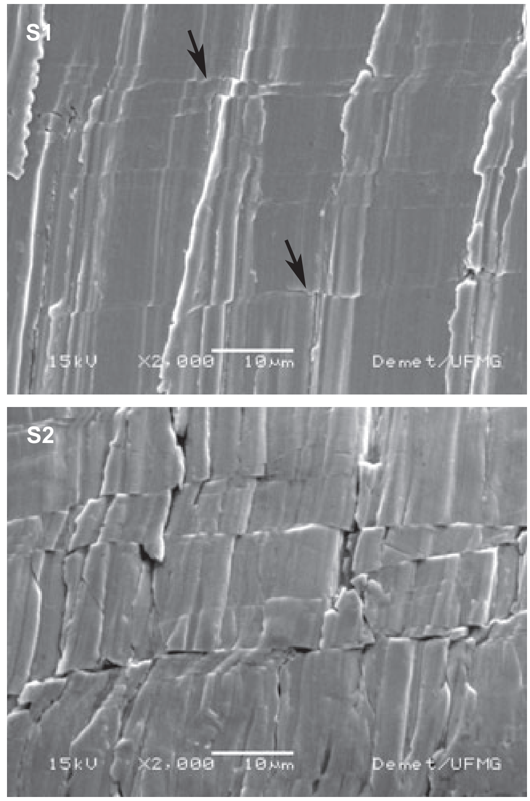

Figure 2 Typical longitudinal cracks in S1 (arrowed) and S2 instruments used for cleaning and shaping five molars (group A).

Fig. 3. When the NCF values obtained for different ProTaper instruments of CG (new instruments) are compared amongst each other using one-way ANOVA, statistically significant differences ($P < 0.05$) are found for all combinations, except when S1 instruments are compared with F2 instruments.

The fatigue resistance of ProTaper rotary instruments, measured by the NCF values, showed a tendency to progressively decrease with clinical use for all instruments analysed (Fig. 3a). Accordingly, the comparative analysis of the remaining NCF values using one-way ANOVA showed statistically significant differences ($P < 0.05$) in this parameter amongst all types of same size instruments used in group A (five molars prepared by an experienced endodontist), B (eight molars prepared by the same endodontist) and C (five molars prepared by undergraduate students), when compared with similar instruments in CG (new instruments). However, no statistically significant differences in NCF were found between similar instruments used in groups A and B. Although the curved canals in group C exhibited, on average, milder curvature than in groups A and B, no statistically significant differences in NCF were found for instruments between groups A and C and between B and C, except for the instruments F1 and F2 in the latter two groups.

The trend emerging from Fig. 3b, showing the average consumed fatigue life of instruments in groups A–C, is that, except for S2 instruments, cleaning and shaping of eight molars in group B consumed more instruments' fatigue resistance than the preparation of five molars in groups A and C. It can also be observed that there is a tendency for the consumed fatigue life of the instruments used by the experienced operator in five molars (group A) to be higher than that of the instruments used by the students (group B).

Table 2 shows the mean values and standard deviations of fracture points of each instrument type in the different groups, expressed as the distance relative to their tips. Data showed no statistically significant

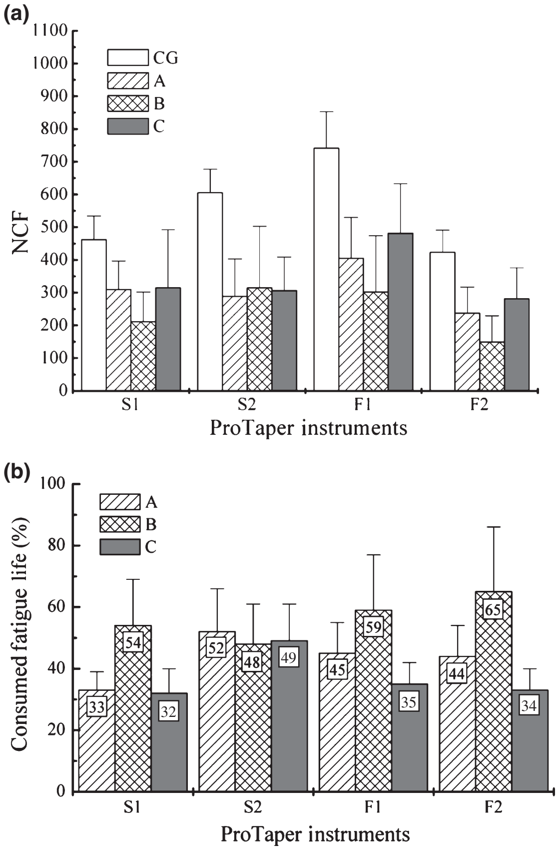

Figure 3 Mean values of (a) NCF in fatigue tested new (n = 12 for each instrument type) and used instruments (n = 10 for each instrument type) and (b) consumed fatigue life in fatigue tested used instruments; standard deviations shown as error bars.

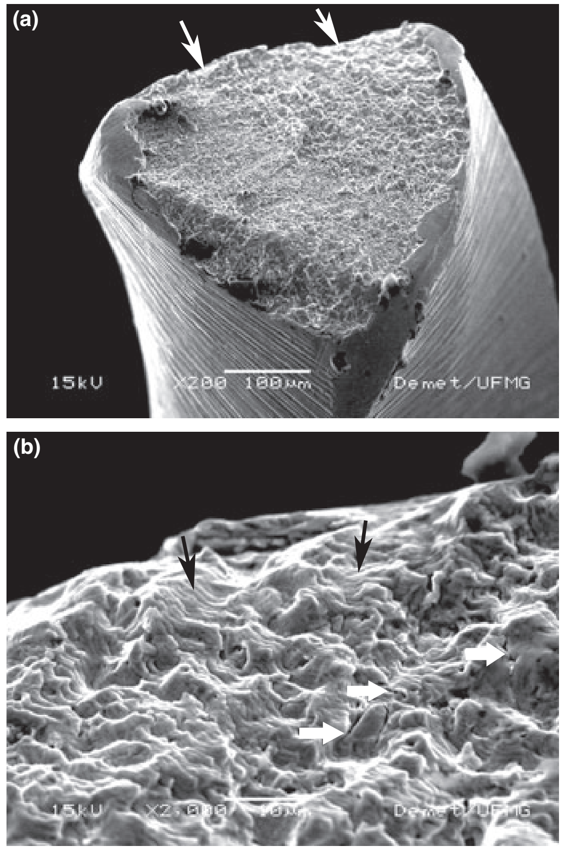

Figure 4 Fracture surface of a fatigue tested F1 instrument of group C. (a) Smooth regions at the edges of the cross-section (arrowed) and fibrous region at the centre; (b) Detail of the smooth region, showing fatigue striations (dark arrows) and secondary cracks (white arrows).

Table 2 Mean values and standard deviation of the fracture points of fatigue tested new and used instruments

Instrument	Control	Group A	Group B	Group C
S1	3.0 ± 0.2	3.0 ± 1.1	3.5 ± 1.3	3.0 ± 1.0
S2	3.1 ± 0.2	3.1 ± 0.6	3.4 ± 0.7	3.4 ± 0.5
F1	3.2 ± 0.3	3.2 ± 0.7	3.5 ± 0.4	3.0 ± 0.6
F2	2.6 ± 0.4	3.2 ± 0.5	3.0 ± 0.8	2.9 ± 0.6

difference ($P < 0.05$) amongst the fracture points of all instruments tested in any of the groups analysed. However, there is considerable scatter (i.e. greater SD values) in the fracture points of instruments used clinically, in comparison with those of the CG.

The fracture surfaces of fatigue tested instruments observed by SEM were all similar and exhibited the typical features of this fracture mode. The secondary electron images shown in Fig. 4 illustrate the observations recorded: at lower magnifications (Fig. 4a), the cross-sectional edges of the fractured instruments, which were not deformed by contact with the steel artificial canal after breakage, show the presence of small areas of nucleation and slow crack propagation, called smooth regions. In the central region, a large fibrous area associated with the final ductile failure can be observed. Fatigue striations and secondary cracks can be seen in the smooth regions of the fracture surface when observed at higher magnifications (Fig. 4b), confirming that the instruments failed due to fatigue.

Discussion

The machining of NiTi endodontic instruments is a complex procedure, generally resulting in surfaces with defects, such as milling marks (Marending *et al.* 1998, Eggert *et al.* 1999, Martins *et al.* 2002). Previous studies reported that the clinical use of NiTi files may generate, as observed herein, a considerable amount of additional surface defects, such as blunting (rolling-over) of the cutting edges and microcracks (Eggert *et al.* 1999, Tripi *et al.* 2001, Martins *et al.* 2002, Alapati *et al.* 2003, Bahia & Buono 2005, Peng *et al.* 2005).

When NiTi rotary instruments are used to clean and shape curved root canals, they undergo cyclic loading in the canal's region of curvature, leading to mechanical fatigue (Pruett *et al.* 1997). It is well known 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). The observed reduction on the remaining fatigue life of the clinically used instruments (Fig. 3) is thus a common feature of the rotary NiTi endodontic files, as previously reported by various authors for a variety of instrument types (Gambarini 2001, Fife *et al.* 2004, Bahia & Buono 2005). Specifically in the case of ProTaper instruments, the results presented here show a statistically significant decrease in fatigue resistance with the clinical use for all instruments analysed. Fife *et al.* (2004) found similar results for S2, F1, F2 and F3 instruments after cleaning and shaping two and four molars, but their S1 instruments behaved differently and no decrease in fatigue resistance was observed.

Previous studies on fatigue of NiTi rotary instruments confirmed that root canal geometry determines their fatigue behaviour during clinical use because the stress levels they reach depend on the curvature radius of the canal as well as on the diameter of the file at its maximum bending point (Pruett *et al.* 1997, Haïkel *et al.* 1999, Yared *et al.* 1999, Gambarini 2001, Bahia & Buono 2005). Moreover, the same authors found that the smaller the diameter of the NiTi instruments with a fixed taper, the more resistant they would be to fatigue. Evaluation of the tensile strain amplitudes on the surface of ProFile instruments, taking into account instrument diameter and 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, which in turn is a direct function of instrument diameter (Bahia & Buono 2005).

The ProTaper shaping instruments (S1, S2, and SX) present a unique feature that each has multiple 'increasing' percentage tapers over the length of its cutting blades. This feature allows each instrument to engage a smaller zone of dentine, performing its own 'crown down' work, reducing torsional loads, the number of recapitulations needed to achieve length, and the potential for breakage (Ruddle 2005). However, this multi-tapered geometry promotes, in the shaping files, a large increase in diameter between D_6 and D_9, resulting, probably, in a fatigue behaviour different than that of the regularly tapered NiTi files. It may be for this reason that S2 instruments, with a larger diameter in D_3 (the point of maximum curvature in the artificial canal) than S1 instruments, presented higher average NCF value than S1 instruments. Similar results were obtained by Fife *et al.* (2004) and Grande *et al.* (2006) and were attributed to stress building up at different levels along the fluted shaft of each instrument. Nevertheless, it must be emphasized that Ullmann & Peters (2005) found higher fatigue resistance for S1 files in comparison with S2 files, indicating that a clear account of the fatigue behaviour of ProTaper shaping instruments has not yet been achieved. In fact, the fatigue behaviour of new S1 files (CG) is already difficult to understand, as their NCF values are statistically different from the values of all the other files, except from F2 files, which, amongst the instruments analysed, have the largest diameter. This observation cannot be explained in terms of the strain amplitude, which is given by $D/(2R–D)$, where D is the instrument diameter and R the radius of curvature of the canal (Bahia & Buono 2005), as it should be smaller for S1 files than for any other file working in the same curved root canal or in the artificial canal of the fatigue test device.

In the case of F1 and F2 finishing instruments, which have fixed tapers between D_1 and D_3 (0.07 and 0.08 respectively) and decreasing tapers between D_4 and D_{14}, the tendency found for other NiTi rotary instruments prevails, that is, their fatigue resistance decreases as the diameter increases. Thus, comparing the NCF of F1 and F2 instruments in all groups assessed in this study, the average NCF values of F1 files are greater than those of F2 files. Similar results were obtained by Fife *et al.* (2004) and Grande *et al.* (2006) for fatigue tested ProTaper finishing instruments.

It has been suggested that instrument failure is a multifactorial clinical problem with variables due to the operator and root canal anatomy being more influential than the instruments themselves (Parashos *et al.* 2004). Nevertheless, there is a perception amongst clinicians and researchers that the number of uses of an endodontic instrument may be an important factor controlling instrument failure, which in turn is directly related to pre-existing surface defects and to those generated during canal instrumentation. However, there is no consensus in the literature concerning a recommended number of uses of rotary NiTi instruments, which varies from 1 to 27 canals, with a mean value of approximately 11 canals (Yared *et al.* 2000, Gambarini 2001, Peters *et al.* 2003, Bahia & Buono 2005). The findings of the present work regarding ProTaper instruments are consistent with data on ProFile instruments (Yared *et al.* 2000, Gambarini 2001, Bahia & Buono 2005), demonstrating the possibility of a safe reuse of NiTi rotary instruments, provided no iatrogenic errors are made.

Regarding the fatigue behaviour of the instruments after clinical use, it is important to notice that the lack of statistically significant differences in NCF values amongst instruments used in five (group A) and eight molars (group B) has been observed before with files used in two and four molars by Fife *et al.* (2004). This seems to be a characteristic of the fatigue behaviour of NiTi files and has also been observed in NiTi superelastic wires (Bahia *et al.* 2005). It is a strong indication that the changes in the material substructure due to cyclic loading take place mainly in initial deformation cycles. This can be the reason why the images shown in Fig. 2 seem to indicate that the surface damage caused by the clinical use of the instruments in five (group A) and eight (group B) molars had a similar appearance. If the fatigue cracks nucleate mainly during the initial deformation cycles in clinical use, their approximate density on the surface of the instruments should not change substantially after additional cycling, but their depth would increase continually until fracture occurred. Thus, as previously discussed elsewhere (Bahia & Buono 2005), crack propagation, rather than the nucleation process, appears to be the most influential step towards fatigue failure of endodontic NiTi rotary instruments. This type of process is usually described in fracture mechanics by stating that crack nucleation is rapid, whereas crack propagation is slow and controls the failure process as a whole (Courtney 1990). One possible reason for slow crack propagation in metallic and nonmetallic structures is the ramification of the existing cracks into adjoining secondary cracks, dissipating the energy which would be used for rapid propagation of the main cracks. The presence of a large number of secondary cracks on the fracture surface of the instruments, as illustrated in Fig. 4b, indicates that this mechanism may be operating in fatigue failure of NiTi rotary instruments.

In addition, no statistically significant difference was observed when the remaining fatigue life of the same size instruments were compared in groups A and C, that is, amongst the instruments used, respectively, by the experienced endodontist and by the students to shape the root canals of five molars. Although this result seems to indicate that operator experience is not a determining factor, one must consider that significant differences in canal geometry were found amongst the curved canals shaped in the two groups, with those of group C exhibiting, on average, milder curvature than those of group A. Thus, the positive influence of a more favourable canal geometry on the fatigue behaviour of the instruments probably balanced the negative influence of the operator's lack of experience. Nevertheless, this lack of experience manifested itself in the number of fractures (six files) and permanent deformations (seven files) in group C instruments, as aforementioned. These results are in agreement with those of Mandel *et al.* (1999), who suggested that the effect of operator experience was the most consistent and predictable parameter in instrument fracture.

In the present work, during the cleaning and shaping of the curved canals, the method of maximum removal of restrictive dentine from the coronal two-thirds of the canal before initiating procedures in the deeper and typically more complicated apical region was employed. Before introducing any rotary NiTi instruments, stainless steel sizes 10 and 15 hand files created a glide path into this secured length of the canal. This procedure, which could be better followed by the experienced operator, most likely contributed to the absence of instrument separation and low deformation rates during canal shaping in groups A and B. Berutti *et al.* (2004) noted that the creation of a glide path is indispensable in understanding the original anatomy and preventing S1 instrument tips from developing torsion upon entering a canal region with small cross-sectional diameter. Similarly, the large number of canals that could be prepared without instrument failure in this study is probably the result of strict adherence to the recommended technique, in which the shaping files are used like a 'brush', to laterally and selectively cut dentine on the outstroke. This brushing action creates lateral space which facilitates the larger shaping files with stronger and more active cutting blades to safely and progressively move deeper into the canal. Another feature which may have contributed to the success of preparing a large number of canals without fracture was the use of a high torque value (5 N cm), preventing auto-reverse motion of the instruments inside the canals. As observed by Berutti *et al.* (2004) during shaping of acrylic blocks, a larger number of canals could be shaped before file fracture when high instead of low torque settings were used.

The fact that no statistically significant difference was observed for the position instrument fracture is evidence that fracture in a fatigue testing system is believed to occur with the greatest likelihood near the point of maximum flexure of the shaft (Pruett *et al.* 1997, Bahia & Buono 2005). This result demonstrates that the choice of testing geometry in such a way that the maximum tensile amplitude coincides with the region in which the instruments suffer the highest deformation during shaping of curved canals is the most appropriate for assessing the remaining fatigue life of clinically used instruments. Furthermore, results of the fatigue tests (Table 2) showed higher standard deviation values for instruments used clinically, groups A–C, when compared with the new instruments of CG. This greater scatter in fragment length is associated with the fact that clinical instrumentation, due to differences in canal geometry, causes variable stress on rotary instruments, whereas in the fatigue tests it is concentrated in the region of maximum curvature of the artificial canal.

Finally, the presence of longitudinal cracks (Fig. 4), in addition to the more commonly observed transverse ones, in instruments used clinically analysed by SEM, should be noted. Such direction of cracking has previously been described by Alapati *et al.* (2003), Peng *et al.* (2005) and Tripi *et al.* (2006), who suggested that it reflects the direction of the stress on the surface of the instrument under torsional load. In fact, these cracks possibly are a result of both repeated flexural and torsional loading, indicating that instrument fracture may take place due to triaxial stresses.

Conclusions

Proper use of the ProTaper rotary instruments by an experienced endodontist allowed for the cleaning and shaping of eight molars. The fatigue resistance of ProTaper rotary instruments, measured by the NCF values of similar instruments, showed a statistically significant decrease upon clinical use for all instruments analysed. Structural fatigue took place during the clinical use of NiTi instruments and, in addition to the usual transverse cracks generate by rotation bending, longitudinal cracks were also observed in the surface of the used instruments. However, the remaining fatigue life of instruments used in five and eight molars was similar. Operator experience affected the occurrence of fracture and plastic deformation of the files during shaping.

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