Universidade Federal de Minas Gerais
Faculdade de Odontologia

“Avaliação da vida restante em fadiga de instrumentos rotatórios de NiTi *ProTaper* após uso clínico múltiplo”.

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Dissertação apresentada ao Programa de Pós-Graduação da Universidade Federal de Minas Gerais, como requisito parcial à obtenção do título de Mestre em Odontologia.

Área de Concentração – Endodontia

Orientadora: Profª. Drª. Maria Guiomar de Azevedo Bahia
Co-orientador: Prof. Dr. Vicente Tadeu Lopes Buono

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Dedicatória

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Sumário

Resumo

A proposta desse estudo foi avaliar a vida restante em fadiga, bem como comparar os danos superficiais devido à fadiga estrutural, de instrumentos rotatórios de NiTi *ProTaper* utilizados na clínica para a limpeza e formatação do sistema de canais radiculares de cinco e oito molares. Quarenta e dois jogos de instrumentos *ProTaper*, tipo S1, S2, F1 e F2, foram analisados. Eles foram divididos em Grupo Controle (GC) com 12 jogos de instrumentos novos e três grupos experimentais: G1 e G2, cada um com 10 jogos de instrumentos, cada jogo usado clinicamente por um endodontista experiente com o sistema em cinco e oito molares, respectivamente; e G3, com 10 jogos de instrumentos, cada jogo usado clinicamente em 5 molares por estudantes de graduação inexperientes com o sistema. Antes e após o uso clínico, todos os instrumentos foram analisados pela presença de danos superficiais por microscopia ótica e três jogos de cada grupo de instrumentos usados, selecionados ao acaso, foram examinados por microscopia eletrônica de varredura (MEV). Os instrumentos foram em seguida testados em dispositivo de bancada para avaliação de sua resistência à fadiga. Os resultados obtidos foram analisados estatisticamente pelo teste ANOVA, com coeficiente de confiabilidade de 95%. Uma grande quantidade de microtrincas transversais foi observada em todos os instrumentos, bem como trincas longitudinais em menor número, indicando que eles sofreram fadiga estrutural. Foi observada uma redução da resistência à fadiga após o uso clínico para todos os instrumentos avaliados. A experiência do operador afetou a ocorrência deformação plástica e fratura das limas durante o uso clínico. Os resultados obtidos indicaram que o uso clínico múltiplo consome a vida em fadiga dos instrumentos, mas a vida restante em fadiga foi essencialmente a mesma nos instrumentos usados em cinco e oito molares.

Palavras-chave: instrumentos de NiTi, uso clínico múltiplo, resistência à fadiga, danos superficiais

Evaluation of remaining fatigue life of *ProTaper* rotary nickel-titanium instruments after multiple clinical use

Abstract

The purpose of this study was to evaluate the remaining fatigue life, as well as to compare surface damage due to structural fatigue, of rotary NiTi ProTaper instruments clinically used for cleaning and shaping the root canal system of five and eight molars. Forty-two sets of ProTaper instruments, type S1, S2, F1, and F2, were analyzed. They were divided into a Control Group (CG) with twelve sets of new instruments and three experimental groups: G1 and G2, each with ten sets of instruments, each set clinically used by an endodontist, with experience using the ProTaper system, in five and eight molars, respectively; and G3, with ten sets of instruments, each set clinically used in five molars by undergraduate students inexperienced with the system. Before and after the clinical use, all instruments were analyzed by optical microscopy for the presence of surface damage and three sets of each group of used instruments, randomly selected, were examined by scanning electron microscopy (SEM). The instruments were then tested in a bench device for evaluation of their fatigue resistance. The results obtained were statistically analyzed by one way ANOVA tests, at the 95% confidence level. A large amount of transverse microcracks were observed in all instruments, as well as a smaller number of longitudinal microcracks, indicating that they suffered structural fatigue. After the clinical use, a decrease in fatigue resistance was observed for all instruments evaluated. Operator experience affected the occurrence of plastic deformation and fracture of the files during shaping. The results obtained indicate that multiple clinical uses consume the fatigue life of the instruments, but the remaining fatigue life was essentially the same for instruments used in five and eight molars.

Keywords: NiTi instruments, multiple clinical use, fatigue resistance, surface damage

1. INTRODUÇÃO

Os conceitos de limpeza e formatação estabelecidos por Schilder (1974) constituem a base da terapia endodôntica, juntamente com a obturação tridimensional do sistema de canal radicular (SCR). Estes conceitos são inseparáveis e necessários para o sucesso da terapia endodôntica.

Esta etapa é relativamente simples de ser alcançada em canais retos, mas o preparo de canais curvos torna-se mais complexo, podendo ocasionar falhas, como a formação de degraus ou *zips*, transportes e perfurações do canal radicular e, mesmo, fratura dos instrumentos. A maior rigidez das limas de aço inoxidável dificulta a manutenção do trajeto original de um canal curvo. Desenvolvidas nos anos 60, as ligas de níquel-titânio (NiTi) de composição aproximadamente equiatômica, proporcionou um importante desenvolvimento das técnicas de limpeza e formatação dos canais radiculares, minimizando os erros de procedimentos durante a instrumentação de canais curvos (Serene et al., 1995). Estas ligas apresentam duas propriedades especiais: o efeito memória de forma e a superelasticidade.

Efeito memória de forma é o comportamento apresentado por certos materiais que, após sofrerem deformação aparentemente permanente, recuperam sua forma original quando aquecidos. Alguns desses materiais podem ser “programados” pela seleção de composições químicas e tratamentos termomecânicos apropriados, para que a recuperação de forma se dê apenas com a retirada da tensão, sem necessidade de aquecimento. Esse efeito permite a recuperação de grandes deformações, conferindo ao material o que se convencionou chamar de “superelasticidade”.

Entretanto, apesar das vantagens como grande flexibilidade, resistência à corrosão e excelente biocompatibilidade, os instrumentos de NiTi podem sofrer fratura inesperada, sem quaisquer sinais visíveis de deformação prévia. A inspeção visual, portanto, não é um método confiável para a avaliação destes instrumentos. A durabilidade dos instrumentos rotatórios de NiTi é diretamente proporcional à amplitude de deformação a que são submetidos, refletindo no número de ciclos realizados até a fratura.

Durante a formatação de canais radiculares, o instrumento rotatório pode prender-se às paredes do canal e sofrer fratura por sobrecarga de torção. Além disso, na instrumentação de canais curvos, os instrumentos de NiTi podem fraturar de maneira inesperada por fadiga flexural (Sattapan *et al.*, 2000). O carregamento cíclico a que são submetidos induz a nucleação de trincas que crescem, coalescem e se propagam até a fratura final do instrumento. A amplitude máxima de deformação durante o carregamento cíclico é dependente da geometria da curvatura e do diâmetro do instrumento na área de curvatura máxima do canal radicular (Pruett *et al.*, 1997; Bahia & Buono, 2005).

De um modo geral, a fadiga nos materiais se refere às mudanças nas propriedades resultantes da aplicação de tensões cíclicas. Nas ligas com memória de forma, pode-se subdividir o processo de fadiga em fadiga estrutural e funcional. Fadiga estrutural se refere aos danos microestruturais acumulados durante o carregamento cíclico, e que eventualmente levam à fratura por fadiga. Este acúmulo de defeitos está associado à formação de trincas superficiais e seu posterior crescimento, indicando que as ligas com memória de forma estão sujeitas a falhas como qualquer material. O termo fadiga funcional indica que durante o carregamento cíclico, as ligas com memória de forma geralmente sofrem uma redução nas suas propriedades funcionais, associada a um aumento na deformação residual causada por uma transformação reversa incompleta e mudança nas temperaturas de transformação (Eggeler *et al.*, 2004).

A estabilidade do efeito memória de forma tem sido a propriedade mais requisitada nas aplicações das ligas NiTi como atuadores mecânicos, e, até recentemente, o efeito da deformação cíclica aplicada no regime superelástico não era uma questão importante. Com o uso dos instrumentos endodônticos acionados a motor para limpeza e formatação de canais curvos, a resistência à fadiga mecânica das ligas NiTi superelásticas tornou-se, assim, uma questão relevante.

Parece haver consenso na literatura de que a experiência do operador com um determinado sistema rotatório reduz a incidência de fratura dos instrumentos de NiTi

(Mandel *et al.* 1999; Yared *et al.* 2001, Yared *et al.* 2002, Peters & Barbakow, 2002, Yared *et al.* 2003).

Neste trabalho, pretendeu-se avaliar a influência do uso clínico de instrumentos rotatórios de NiTi *ProTaper* sobre os danos superficiais causados pela fadiga estrutural, bem como a vida restante em fadiga dos mesmos associada a um operador experiente comparada a outros com pouca experiência com o sistema *ProTaper*.

2. OBJETIVOS

O objetivo deste trabalho foi avaliar a influência do uso clínico múltiplo de instrumentos rotatórios de níquel-titânio *ProTaper* sobre os danos superficiais e o consumo da resistência à fadiga dos mesmos, após a limpeza e formatação do sistema de canais radiculares de molares. Nesta avaliação, foi considerada a proficiência do operador, comparando-se os resultados obtidos na análise de instrumentos empregados por um endodontista experiente com o sistema analisado e por estudantes de graduação. Buscou-se, desta forma, fornecer subsídios para assegurar o uso clínico prolongado e seguro desses instrumentos.

Os objetivos específicos do estudo foram:

- Observar e comparar os danos superficiais dos instrumentos *ProTaper* associados à fadiga estrutural, após a formatação dos canais radiculares de cinco e oito molares;

- Avaliar a influência da experiência do operador, após o uso clínico múltiplo, no consumo da resistência à fadiga dos instrumentos *ProTaper*;

- Avaliar a influência da experiência do operador, durante o uso clínico múltiplo, na incidência de deformação permanente e fratura nos instrumentos *ProTaper*.

3. ARTIGO

Influence of multiple clinical use on fatigue resistance of ProTaper rotary NiTi instruments

E. P. Vieira[1], E. C. França[1], R. C. Martins[2], V. T. L. Buono[2], M. G. A. Bahia[1]

[1]Department of Restoration Dentistry, Faculty of Dentistry, Federal University of Minas Gerais, Belo Horizonte-MG, Brazil; [2]Department of Metallurgical and Materials Engineering; Engineering School, Federal University of Minas Gerais, Belo Horizonte-MG, Brazil.

Key words: clinical use, endodontic instruments, fatigue resistance, nickel-titanium, ProTaper, operators proficiency

Running title: Clinical use of ProTaper files

Correspondence: Professor Vicente T. L. Buono. Department of Metallurgical and Materials Engineering, Engineering School, Federal University of Minas Gerais, Rua Espirito Santo 35/206, 30160-030, Belo Horizonte, MG – Brazil.

Tel: +55 31 3238-1859, Fax: +55 31 3238-1815,

E-mail: vbuono@demet.ufmg.br

Abstract

Aim The main purpose of this study was to analyse the influence of clinical use on the occurrence of deformation and fracture and on the fatigue resistance of ProTaper rotary instruments.

Methodology Endodontic treatments were performed on patients using the ProTaper rotary system (Dentsply-Maillefer, Ballaigues, Switzerland). Ten sets of files were used by an experienced endodontist, each set in five molars. Another ten sets of files were used by the same operator, each set in eight molars. In addition, ten sets of files were used, each set in five molars, by undergraduate students with no experience with the system. After clinical use, S1, S2, F1, and F2 files were analyzed for damages by optical and scanning electron microscopy. The used sets, along with a control group of twelve sets of new instruments, were then tested in a bench device for fatigue resistance.

Results The use of the ProTaper rotary files by an experienced endodontist allowed for the cleaning and shaping of the root canal system of up to eight molars without file separation. During the students work, six instruments fractured. Fatigue resistance decreased upon clinical use for all instruments analyzed; nevertheless, this property remained virtually unchanged among same size instruments after use in five and eight molars.

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

Introduction

Since the introduction of nickel-titanium (NiTi) rotary instruments in endodontic therapy, the shaping of curved canals has become more predictable, reducing operator fatigue and time required to finish the preparation and, moreover, minimizing procedural errors frequently found when using manual stainless steel instruments (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 evident advantages of the rotary techniques developed based on the superelasticity of the NiTi endodontic instruments (Walia *et al*. 1988), unexpected instrument separation is not uncommon, especially for less experienced operators (Mandel *et al.* 1999, Yared *et al*. 2001, Yared *et al*. 2002, Peters & Barbakow 2002, Yared *et al.* 2003).

The fracture of rotary instruments takes place in different ways: due to torsion, due to fatigue flexure, or by a 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 nickel-titanium endodontic instruments is related to the degree to which the instrument is flexed when placed in a curved root canal, with greater flexures leading to shorter life expectation (Pruett *et al.* 1997, Haikel e*t al.* 1999, Gambarini 2001, Melo *et al.* 2002, Peters & Barbakow 2002, Fife *et al.* 2004, Bahia & Buono 2005, Ulmann & 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 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 analyzed in various studies (Gambarini 2001, Yared *et al.* 1999, Yared *et al.* 2000, Bahia & Buono 2005). The manufacturers state that the only predictable way to prevent failure is to discard rotary files 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).

The ProTaper rotary system (Dentsply-Maillefer, Ballaigues, Switzerland) was designed with shaping and finishing files. The shaping files (S1, S2, and SX) have increasingly larger tapers over the length of their cutting blades, allowing each instrument to engage, cut, and prepare a specific area of the canal. The finishing files (F1, F2, and F3) have been designed to optimally finish the apical one third and progressively blend and expand the shape into the middle one third of the canal. The convex triangular cross-section, as compared to radial-landed instruments, decreases the rotational friction between the blade of the file and the dentin and enhances the cutting action (Ruddle 2005).

There have been reports of defects found in ProTaper instruments after clinical use (Peng *et al.* 2005, Cheung *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 separation (Mandel *et al.* 1999, Yared *et al.* 2001, Yared *et al.* 2002, Yared *et al.* 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 the multiple clinical uses of these instruments, by an experienced endodontist and 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 analyzed in this study. They were divided into four groups, as follows:

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

(ii) Group 1 (G1): with ten sets of instruments, each set clinically used in five molars (15-20 canals) by an endodontist with experience using the ProTaper system;

(iii) Group 2 (G2): with ten sets of instruments, each set clinically used in eight molars (24-32 canals) by the same endodontist; and

(iv) Group 3 (G3): with ten sets of instruments, each set clinically used 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 molars.

The thirty sets of analyzed instruments of experimental groups G1 to G3 were used in endodontic treatments performed on patients during a period of approximately two years. The SX and F3 instruments were used, but they were not analyzed as these instruments work only at 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 criteria for inclusion. Direct and angled radiographs of each tooth were obtained using a paralleling technique to evaluate its anatomical condition, 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 a 10x magnification. Statistical analysis using the Mann-Whitney test was employed to compare curved root canal geometries.

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, Ballaigues, Switzerland). The cleaning and shaping of the canals were done in accordance with a crown-down technique recommended by the manufacturer, using the following operative sequence:

(i) shape the coronal two-thirds (to resistance) with Gates Glidden 4, 3 and 2, S1, S2, and SX files;

(ii) determination of the working length (WL, at 0.5mm from the apical foramen) using Root ZX apex locator (J Morita, Kyoto, Japan) and then radiographically verified;

(iii) shape the apical one-third (to WL) with S1, S2, F1, and F2 files. After each use of rotary instrument, recapitulations using a file patency (size 10 hand 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 5N·cm with a hand piece of 16:1 reduction (W&H 975, Dental Work, Burmoos, 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 "non-brushing" manner. Apical pressure on the instruments during the shaping was light. The clinical protocol was followed with recapitulations until the working length, established at 0.5mm of the canal patency length, could be reached by at least an F2 instrument, at which point shaping was considered complete. Whenever file separation or permanent deformation took place, the entire set to which the file belonged was discarded and replaced by a new set of instruments.

After use, the instruments were washed, ultrasonically cleaned for 5 minutes in ethanol and steam autoclave sterilized. The S1, S2, F1, and F2 files of the experimental groups G1 to G3 were observed by optical microscopy (Mitutoyo TM, Tokyo, Japan), at 30x magnification, to determine the presence of distortion, unwinding defects and macroscopic deformation. Twelve sets of these instruments, belonging to the control group (CG) of new instruments and to the experimental groups G1 to G3, 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. Due to the symmetry of the stresses acting in curved canal shaping by the rotary technique, which are equivalent around the long axis of the instrument, the area thus observed is similar to any other area exposed if the instrument was rotated in the SEM specimen stage. Secondary electron images (SEI) were recorded at length intervals that enabled the observation of the cutting sections from the instrument tip to approximately 6mm 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 very fine, requiring the use of high magnifications, typically between 1000x and 2000x, to be resolved. At a magnification of one thousand times, a 12cm wide picture covers only 0.12mm 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.

Fatigue 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 5mm, and a guide cylinder of 10mm in diameter made of the same material (Bahia & Buono 2005). The chosen geometry placed the area of maximum canal curvature at about 3mm 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, 300rpm, 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 among 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 selected instruments after the fatigue test was analyzed by scanning electron microscopy - SEM (Jeol JSM 6360, Tokyo, Japan) 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 ten sets of files in G1 had an average of 18 canals (13 curved) in total; in G2, an average of 28 canals (20 curved) was instrumented with each of the ten sets of files; and in G3, 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 among canals in G1 and G2, while significant differences ($p \leq 0.05$) were found in the values of curvature radius among canals in G2 and G3 and in curvature angles among canals in G1 and G3 and in G2 and G3. In other words, curved canals in G3 exhibited, on average, lower curvature than in G1 and G2.

During canal shaping by the endodontist with experience using the ProTaper system (groups G1 and G2), no file separation occurred and only two instruments were permanently deformed at the end of preparation: (i) one S1 file from G1 was unwound between 0.7mm and 1.5mm from the tip and (ii) one F2 file from G2 was unwound between 1.2mm and 2.9mm. In contrast, during the students work (G3), six S1 instruments fractured. The fractured instruments belonged to sets with a different number of uses, with one S1 file having separated in a highly curved mesiobuccal canal in its first use. In addition, file deformation was observed in seven other instruments of G3: (i) two S1 files were unwound between 0.9mm and 2.9mm from the tip, (ii) three S2 files were unwound between 1.2mm and 3.6mm from the tip, and (iii) two F2 files were unwound between 1.8mm and 2.7mm from the tip.

New instruments observed by SEM showed the usual milling marks, as illustrated in Figure 1. After canal shaping, all instruments examined by SEM showed 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 G1 to G3. Examples of wear marks and crack patterns found in the instruments after use in five (G1) and eight molars (G2) are shown in Figures 2 and 3, respectively. The cracks were perpendicular to the cutting edge, running along the milling marks, thus indicating that they were formed by the tensile stresses associated with instrument rotation in the curved section of the root canals. A tendency of concentration of larger and wider cracks in the region between 2.0mm and 3.5mm 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 2mm and 3mm from the instrument tip. The S1 instruments presented the greatest incidence of these cracks, and they were found until 5mm from the tip. Figure 4 shows longitudinal cracks found after the use of instruments in the root canals.

A qualitative analysis of crack incidence, size, and width in the three sets of instruments used in G1 (five molars) or G2 (eight molars) showed a higher incidence of defects in

S1 and S2 files, as compared to F1 and F2 files, in both groups. However, no particular difference among files of the same type was observed when instruments used in G1 and G2 groups were compared.

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 Figure 5, together with those obtained for the Control Group of new instruments. When the NCF values obtained for different ProTaper instruments of CG (new instruments) are compared among each other using one way ANOVA, statistically significant differences ($p \leq 0.05$) are found for all combinations, except when S1 files are compared with F2 files.

The fatigue resistance of ProTaper rotary instruments, measured by the NCF values, showed a tendency to progressively decrease with clinical use for all instruments analyzed (Fig. 5). Accordingly, the comparative analysis of the NCF values using one way ANOVA showed statistically significant differences ($p \leq 0.05$) in this parameter among all types of same size instruments used in G1 (five molars prepared by an experienced endodontist), G2 (eight molars prepared by the same endodontist), and G3 (five molars prepared by undergraduate students), as compared to similar instruments in CG (new instruments). However, no statistically significant differences in NCF were found among similar instruments used in G1 and G2, in G1 and G3 and in G2 and G3, except for the instruments F1 and F2 in the last two groups.

When the average values of NCF for each type of instrument after clinical use are divided by the corresponding average value for new instruments, the average “consumed fatigue life” is obtained. The values of this parameter are shown in Figure 6 for the instruments in the experimental groups G1 to G3. The trend emerging from this figure is that, except for instruments S2, cleaning and shaping of eight molars in G2 consumed more instruments' fatigue resistance than the preparation of five molars in G1 and G3. 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 (G1) to be higher than that of the instruments used by the students (G3).

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 difference ($p \leq 0.05$) among the fracture points of all instruments tested in any of the groups analyzed.

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 Figure 7 illustrate the observations recorded: at lower magnifications (200x, Fig. 7a), 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 (2000x, Fig. 7b), 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 (Marsicovetere *et al.* 1996, Marending *et al.* 1998, Eggert *et al.* 1999, Martins *et al.* 2002). These defects were present in the analyzed ProTaper instruments, as in the majority of NiTi endodontic files which are not subjected to electropolishing treatments by the manufacturers (Tripi *et al.* 2006). 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). Cyclic loading is one of the generic characteristic features of many of the present applications of NiTi superelastic alloys. 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 (Figs. 6 and 7) 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 files, the results presented here show a statistically significant decrease in fatigue resistance with the clinical use for all instruments analyzed. 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 files behave 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, Haikel *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 files (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 dentin, 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 fixed-tapered NiTi files. It may be for this reason that S2 files, with a larger diameter in D_3 (the point of maximum curvature in the artificial canal) than S1 files, presented higher average NCF values than do S1 files. 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 mentioned 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 files has not yet been achieved. In fact, the fatigue behaviour of new S1 files (CG) is already difficult to understand, since their NCF values are statistically different from the values of all the other files, except from F2 files, which, among the instruments analyzed, have the largest diameter.

In the case of F1 and F2 finishing files, 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 varies inversely with diameter. Thus, comparing the number of cycles to failure 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 among 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 among instruments used in five (G1) and eight molars (G2) 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, meaning that fatigue of NiTi alloys in the superelastic regime involves rapid nucleation and slow propagation of fatigue cracks. In fact, the images shown in Figures 2 and 3 indicate that the damage to the instruments surface caused by their clinical use in groups G1 and G2 is similar. As previously discussed (Bahia & Buono 2005), crack propagation, rather than the nucleation process, appears to be the most influential step toward fatigue failure of endodontic 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 G1 and G3, that is, among the instruments used by the experienced endodontist (G1) and by the students (G3) 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 among the curved canals shaped in the two groups, with those of G3 exhibiting, on average, lower curvature than those of G1.

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 G3 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 dentin 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 smooth and reproducible 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 G1 and G2. Berutti *et al.* (2004) noted that the creation of a glide path is indispensable in understanding the original anatomy and preventing S1 file 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 dentin on the outstroke. This brush-cutting action creates lateral space which facilitates the shaping files larger, 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 file fracture was the use of a high torque value (5N.cm), preventing auto-reverse motion of the files 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 among the values of the instrument fracture positions is evidence that separation in a fatigue testing system is believed to occur with the greatest likelihood at 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 files suffer the highest deformation during curved canal shaping is the most appropriate for assessing the remaining fatigue life of clinically used instruments.

Finally, the presence of longitudinal cracks (Fig. 4), in addition to the more commonly observed transverse ones, in clinically used instruments analyzed by SEM, should be noted. This occurrence in ProTaper instruments was previously described by Alapati et al. (2003), Peng et al. (2005), and Tripi et al. (2006), who suggested that their orientation reflects the direction of the stress on the surface of the instrument under torsional load. In fact, these cracks are physical evidences that the instruments are simultaneously under the action of both flexural and torsional cyclic loads, indicating that instrument separation may take place by hybrid forces.

Conclusions

Proper use of the ProTaper rotary files by an experienced endodontist allowed for the cleaning and shaping of a large number of 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 analyzed. 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 used instruments surface. However, no additional damage was observed on the surface of instruments used to shape the canals of eight molars, in comparison to those used in five molars and their remaining fatigue life was similar. Operator experience affected the occurrence of fracture and plastic deformation of the files during shaping.

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

Canal Geometry	G1	G2	G3
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

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

Instrument	CG	G1	G2	G3
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

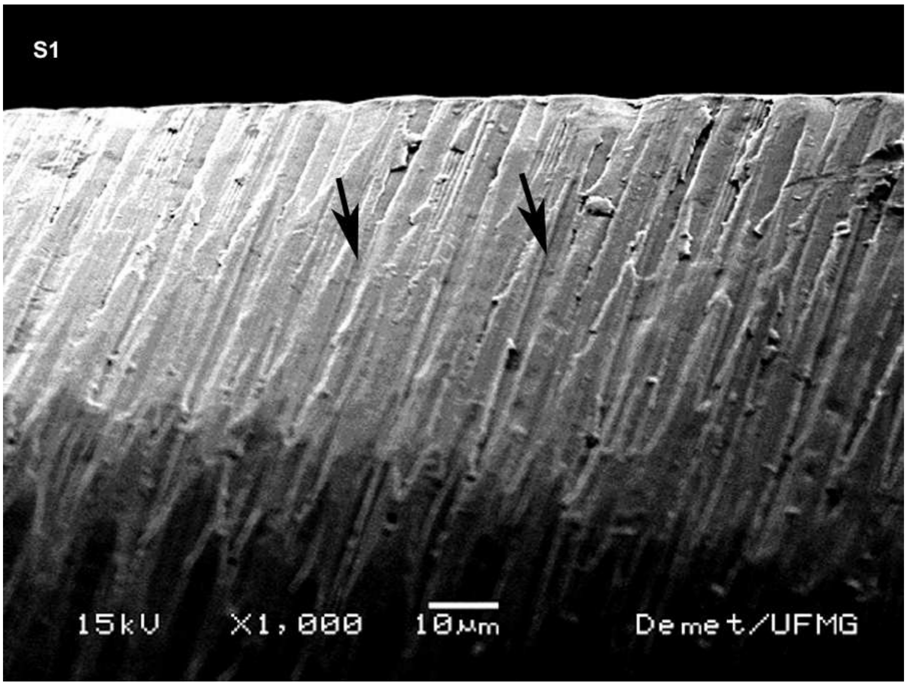

Figure 1 Milling marks (arrowed) in the surface of a new S1 instruments, at approximately 2mm from its tip.

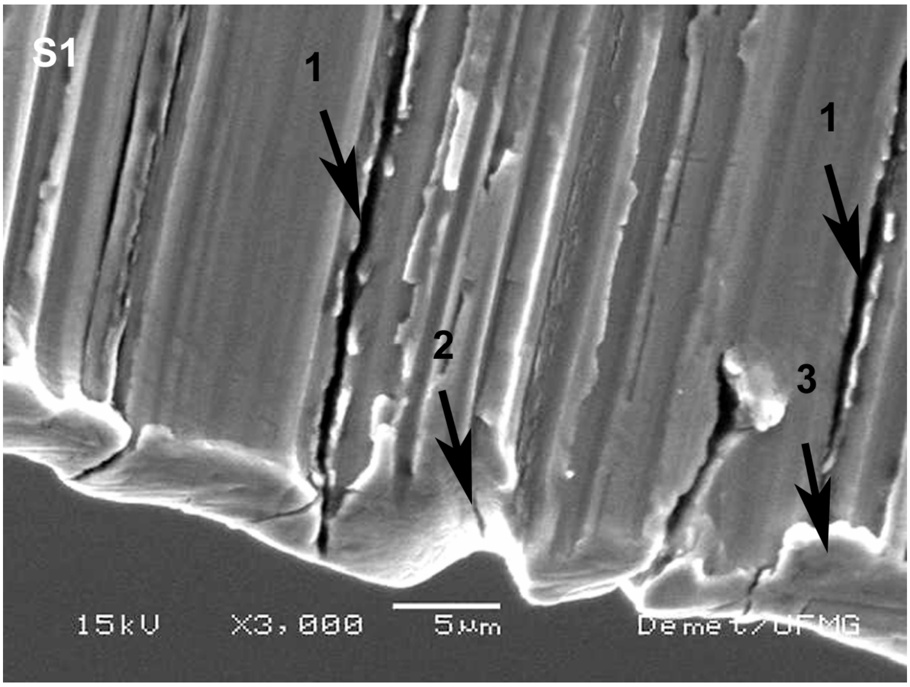

Fig. 2a

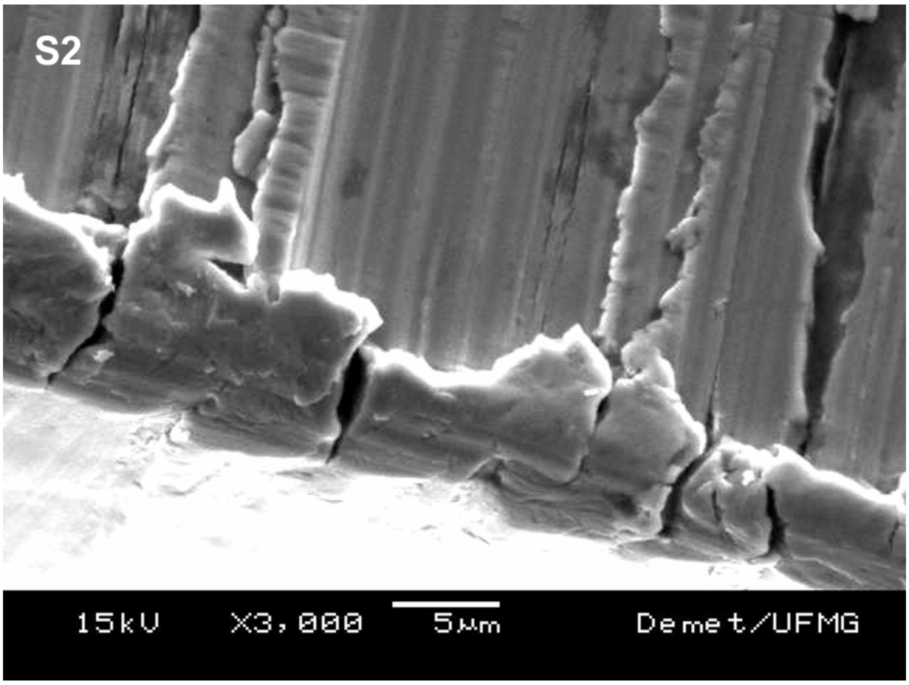

Fig. 2b

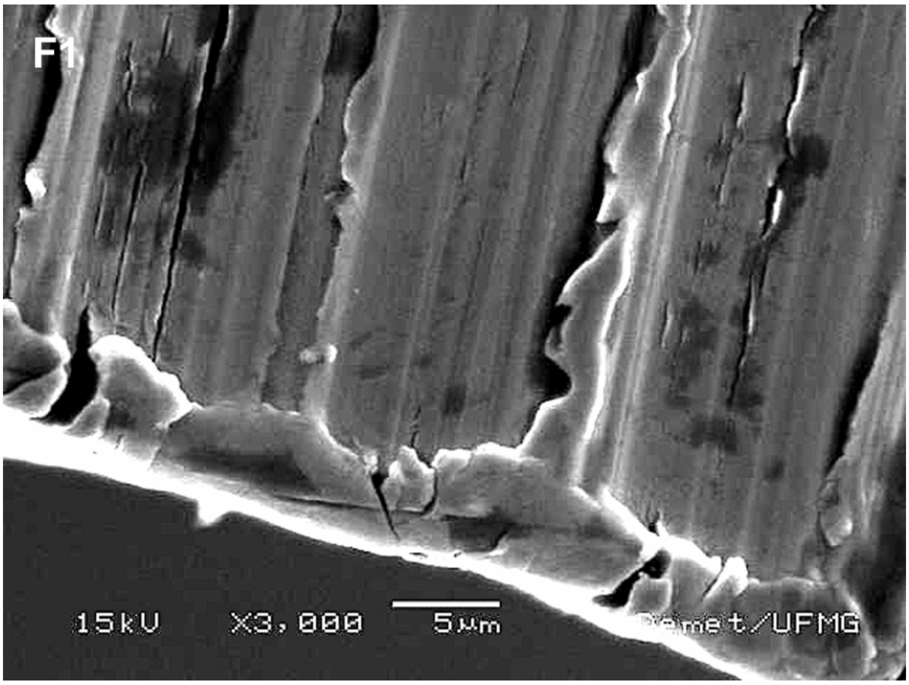

Fig. 2c

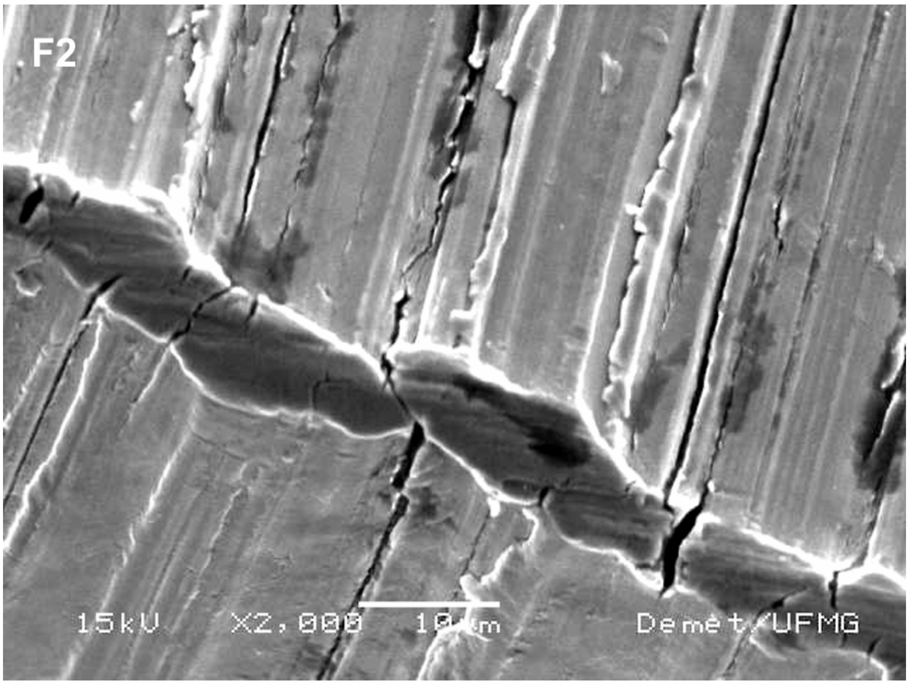

Fig. 2d

Figure 2 Crack patterns in S1, S2, F1 and F2 instruments used for cleaning and shaping 5 molars (G1). Arrows number 1: microcracks; 2: wear mark; 3: blunted edge.

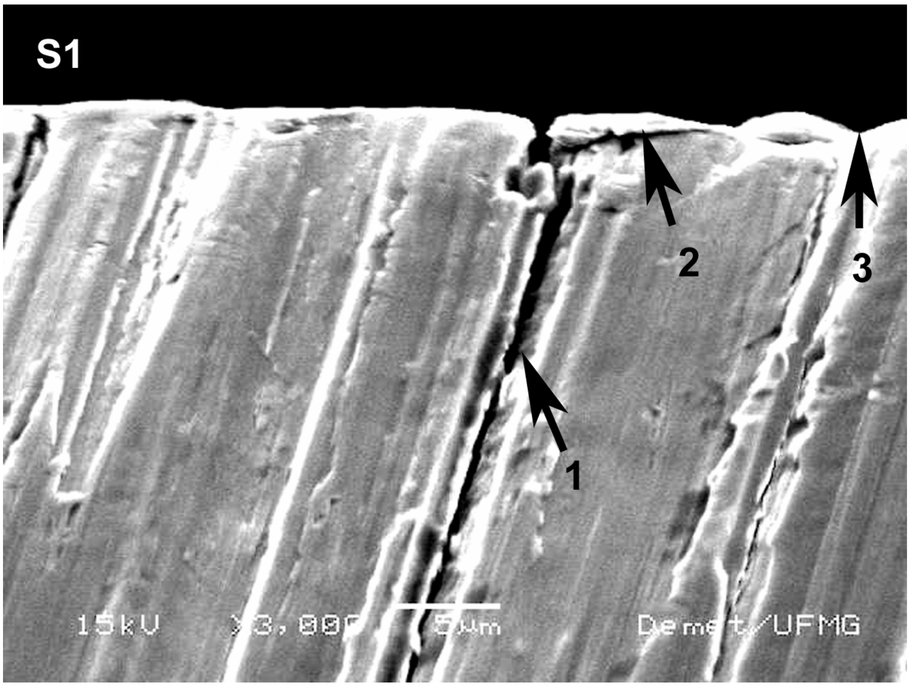

Fig. 3a

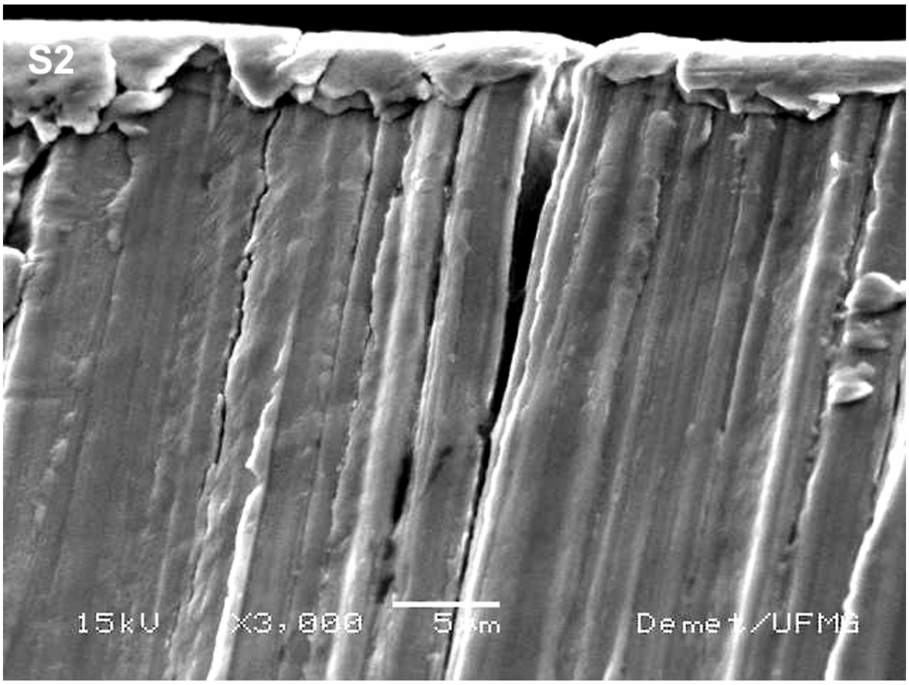

Fig. 3b

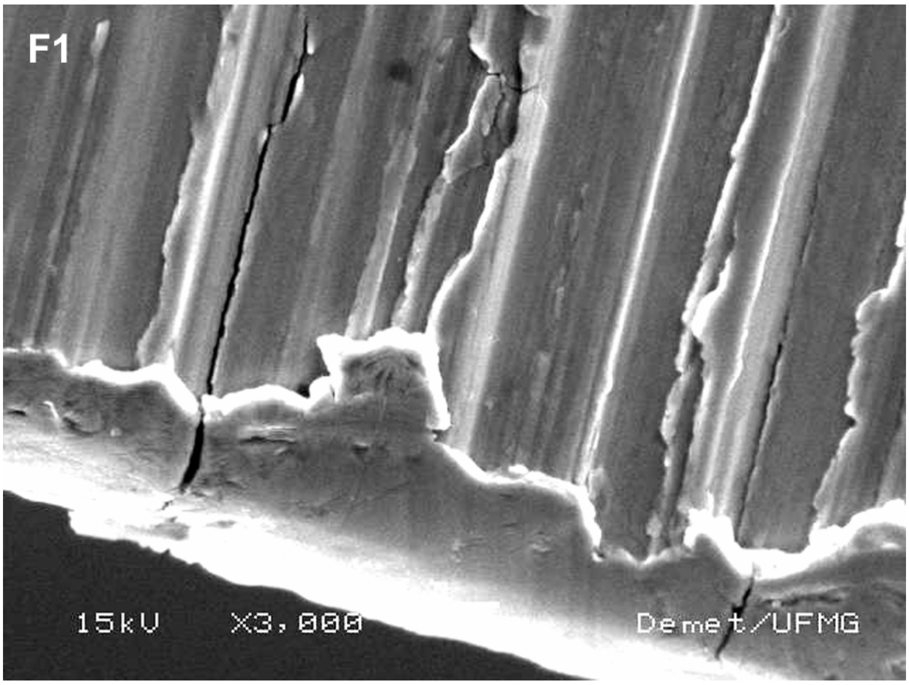

Fig. 3c

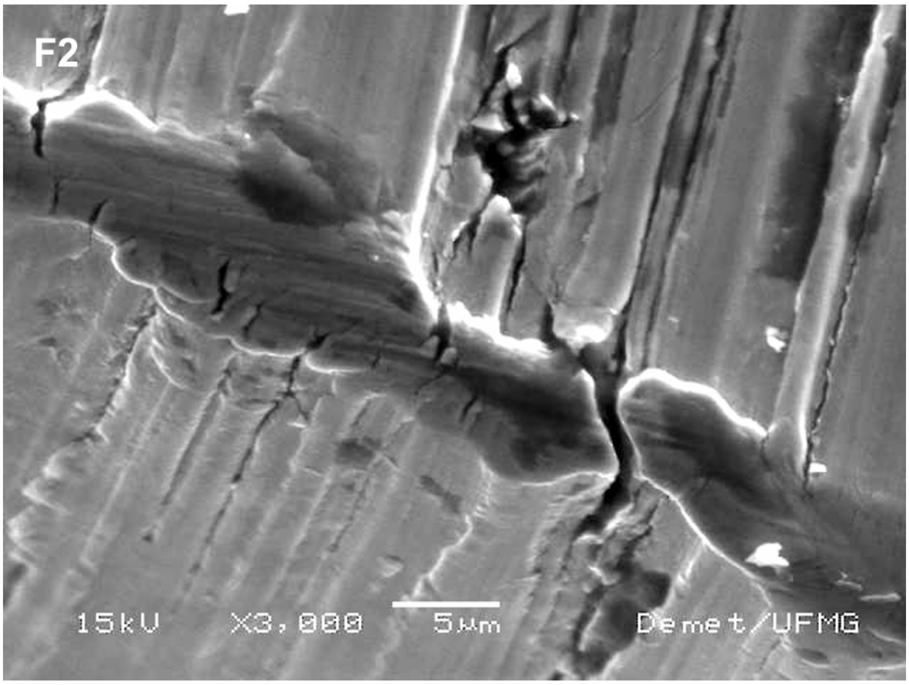

Fig. 3d

Figure 3 Crack patterns in S1, S2, F1 and F2 instruments used for cleaning and shaping 8 molars (G2). Arrows number 1: microcracks; 2: wear mark; 3: blunted edge.

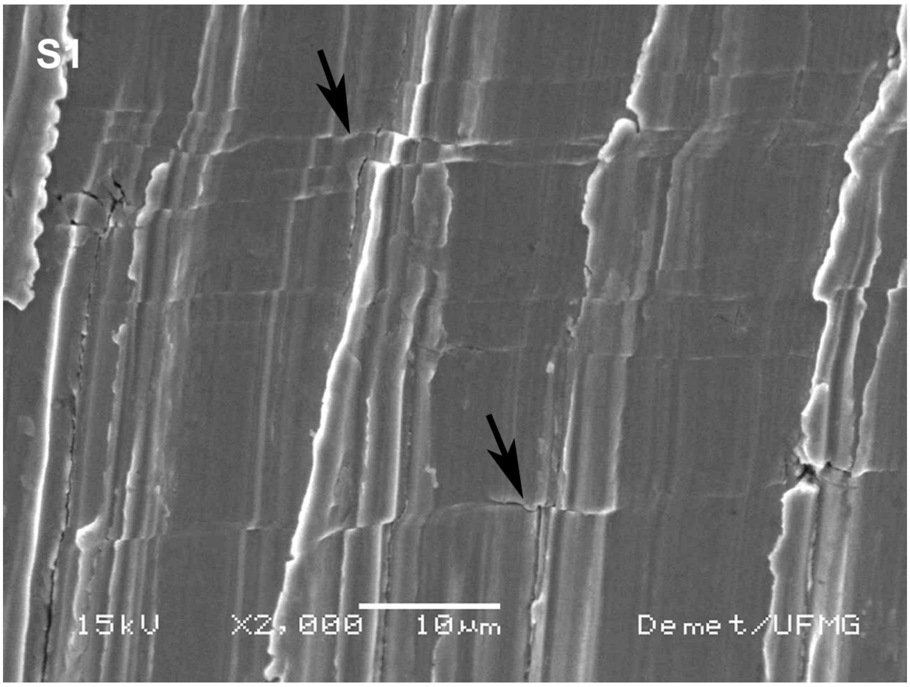

Fig. 4a

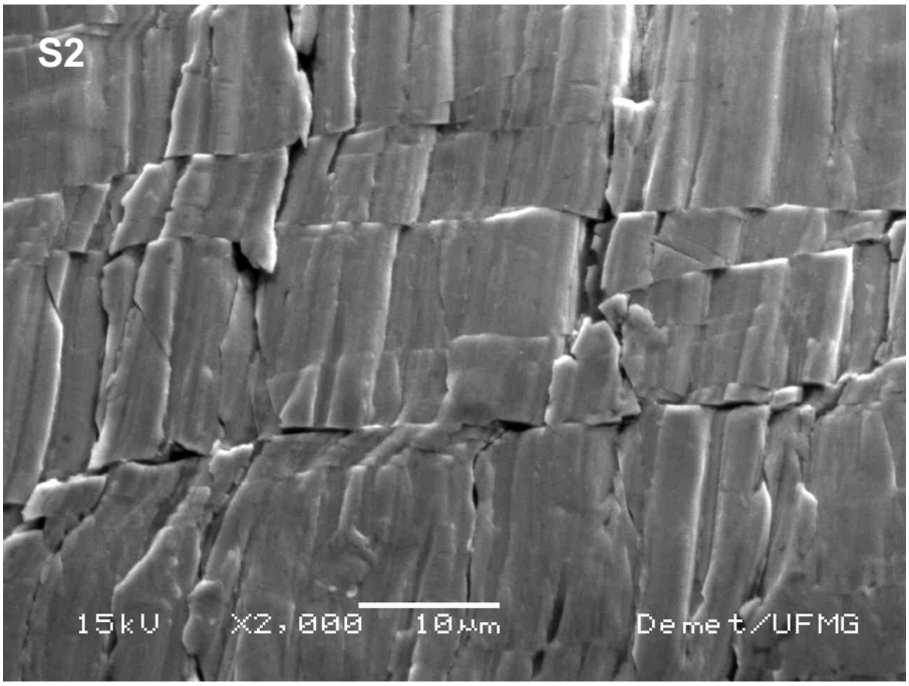

Fig. 4b

Figure 4 Longitudinal cracks in S1 (arrowed) and S2 instruments used for cleaning and shaping 5 molars (G1).

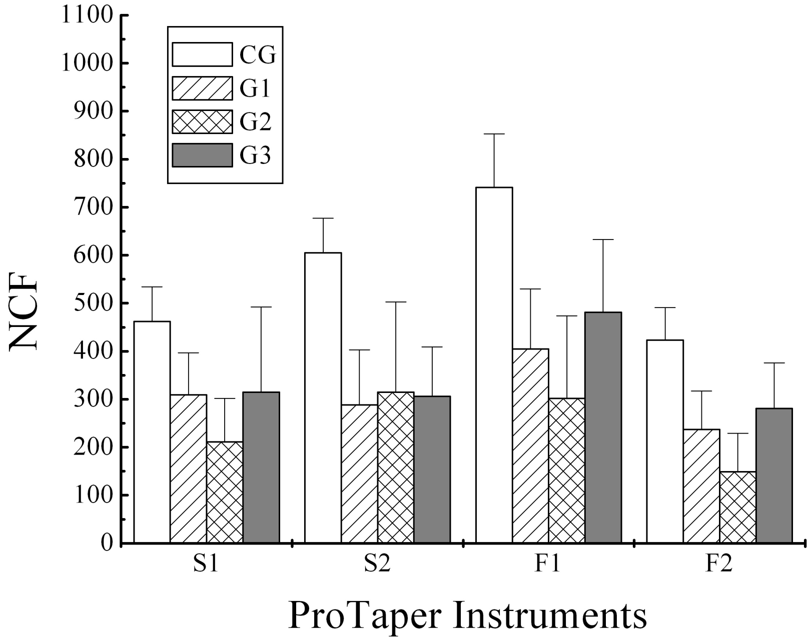

Figure 5 Mean values of NCF in fatigue tested new and used instruments (standard deviations shown as error bars).

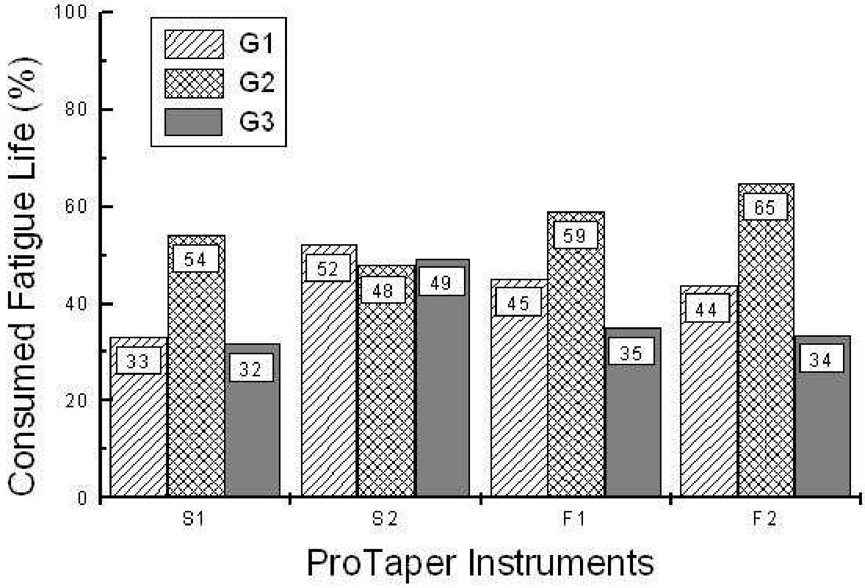

Figure 6 Mean values of consumed fatigue life in fatigue tested used instruments.

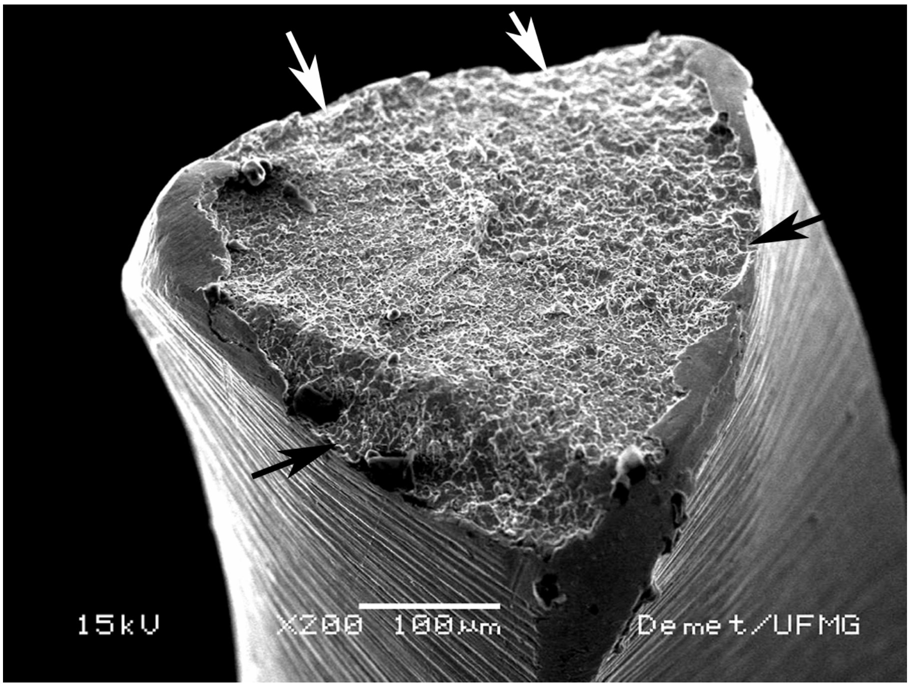

Fig. 7a

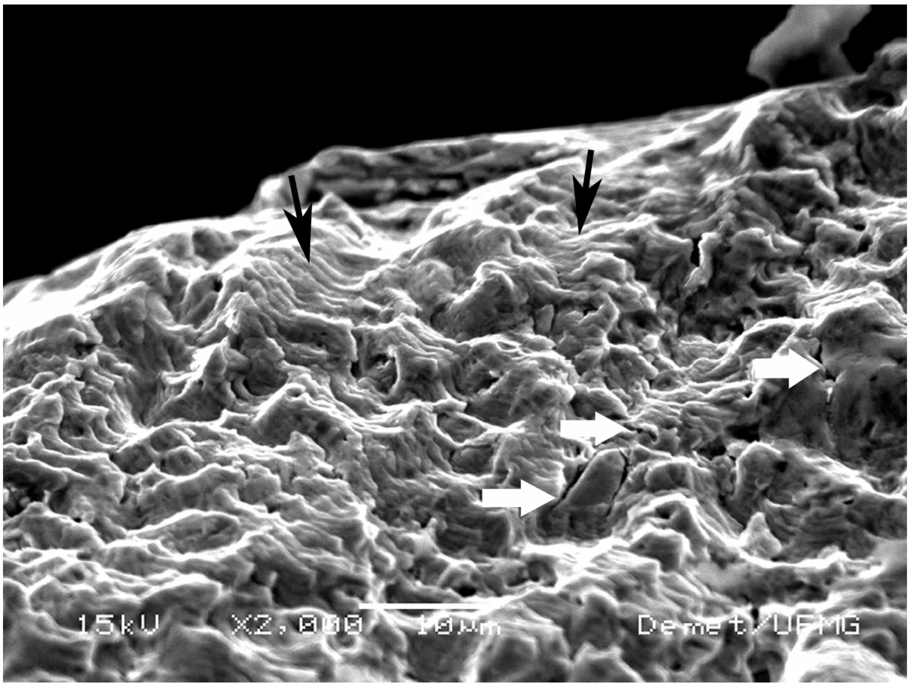

Fig. 7b

Figure 7 Fracture surface of a fatigue tested F1 instrument of group G3. (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).

4. CONSIDERAÇÕES FINAIS

Os resultados obtidos neste trabalho dão suporte às seguintes considerações sobre o uso clínico dos instrumentos rotatórios de NiTi *ProTaper*:

- A ausência de diferença qualitativa na ocorrência dos danos superficiais, devido à fadiga estrutural, nos instrumentos *ProTaper* após a instrumentação dos canais radiculares em cinco e oito molares, sugere que no processo de fadiga destes instrumentos as trincas são nucleadas precocemente, mas a propagação é lenta ocupando a maior parte da vida útil dos mesmos, permitindo assim a sua reutilização, desde que, a técnica preconizada seja seguida corretamente .

- O aparecimento de trincas longitudinais em adição às trincas transversais nas superfícies dos instrumentos utilizados clinicamente, evidencia que durante a formatação dos canais radiculares os instrumentos sofrem tanto tensões cíclicas flexurais como tensões cíclicas torsionais. Conseqüentemente, a fratura final pode ocorrer por uma sobrecarga torsional em um material deteriorado pela fadiga flexural e torsional.

- Os instrumentos *ProTaper* mostraram-se seguros na formatação de até oito molares, sugerindo que o fator principal na prevenção de fratura é a estrita aderência às recomendações do fabricante. Nestes termos, a proficiência do operador passa a ter um papel preponderante.

- Embora a vida consumida em fadiga dos instrumentos S1 não tenha se mostrado maior que dos demais instrumentos, a maior ocorrência de fratura dos mesmos, sugere a necessidade de descarte seletivo para maior segurança na prática clínica.

- Finalmente, foi observado que as razões para a fratura dos instrumentos *ProTaper* são complexas e multi-fatoriais, com as variáveis relacionadas ao operador e à anatomia dental podendo ser mais influentes do que os instrumentos propriamente dito. Conseqüentemente, não é possível definir o número seguro de usos dos mesmos antes do descarte.

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