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Research Article

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Cyclic fatigue, bending resistance, and surface roughness of ProTaper Gold and EdgeEvolve files in canals with single- and double-curvature

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Conflict of Interest
No potential conflict of interest relevant to this article was reported.

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ABSTRACT

Objectives: The purpose of this study was to evaluate the cyclic fatigue, bending resistance, and surface roughness of EdgeEvolve (EdgeEndo) and ProTaper Gold (Dentsply Tulsa Dental Specialties) nickel-titanium (NiTi) rotary files.
Materials and Methods: The instruments (n = 15/each) were tested for cyclic fatigue in single- (60° curvature, 5-mm radius) and double-curved (coronal curvature 60°, 5-mm radius, and apical curvature of 30° and 2-mm radius) artificial canals. The number of cycles to fracture was calculated. The bending resistance of both files were tested using a universal testing machine where the files were bent until reach 45°. Scanning electron microscopy and x-ray energy-dispersive spectrometric analysis were used for imaging the fractured segments, while the atomic force microscope was used to quantify the surface roughness average (Ra).
Results: EdgeEvolve files exhibited higher cyclic fatigue resistance than ProTaper Gold files in single- and double-curved canals ($p < 0.05$) and both files were more resistant to cyclic fatigue in single-curved canals than double-curved canals ($p < 0.05$). EdgeEvolve files exhibited significantly more flexibility than did ProTaper Gold files ($p < 0.05$). Both files had approximately similar Ni and Ti contents ($p > 0.05$). EdgeEvolve files showed significantly lower Ra values than ProTaper Gold files ($p < 0.05$).
Conclusions: Within the limitation of this study, EdgeEvolve files exhibited significantly higher cyclic fatigue resistance than ProTaper Gold files in both single- and double-curved canals.

Keywords: Cyclic fatigue test; EdgeEvolve; Nickel titanium rotary instrument; ProTaper Gold; Scanning electron microscopy; Universal testing machine

INTRODUCTION

Nickel-titanium (NiTi) rotary instruments have been proven to perform well in root canal preparation, with short procedure times and high success rates [1]. However, despite their improved performance in root canal preparation, they are prone to sudden failure through cyclic fatigue because of recurrent tension and compression inside curved canals [2]. Many factors affect cyclic fatigue, including file design, surface treatment, heat-treatment of NiTi alloy, and canal curvature [3]. The root canal curvature affects the file fracture and its lifetime. Double curvature canals exert a high amount of stress and have an adverse effect on fatigue resistance [4-6].

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The thermal treatment of NiTi alloy optimizes the microstructure and transformation behavior and maximizes flexibility and resistance to cyclic fatigue [7,8]. Today, instruments made of controlled memory wires exhibit greater resistance to cyclic fatigue than do conventional NiTi alloys [4,9,10].

ProTaper Gold (Dentsply Tulsa Dental Specialties, Tulsa, OK, USA) is a new heat-treated rotary system that has the same design as the ProTaper Universal, which includes a convex triangular cross section and variable taper of 0.08*v*. The ProTaper Gold has advanced metallurgy for superior flexibility and exhibits 2-stage transformation behavior and a high A_f temperature that is similar to controlled memory wires. Further, the file is more resistant to cyclic fatigue than are the ProTaper Universal, ProTaper Next, and files [8,11]. The EdgeEvolve file (EdgeEndo, Albuquerque, NM, USA) is another heat-treated NiTi rotary system made of an annealed heat-treated, cryogenically tempered NiTi alloy called Fire-Wire. The EdgeEvolve does not have the shape memory properties and has a triangular cross section and a constant taper of 0.08.

No previous study has evaluated the bending resistance and cyclic fatigue of EdgeEvolve rotary files. Thus, the goal of this study was to evaluate the bending resistances, surface roughness and cyclic fatigue of the EdgeEvolve and ProTaper Gold files in artificial canals with single and double curvature. The null hypothesis was that there is no significant difference in the bending resistance and cyclic fatigue of the EdgeEvolve and ProTaper Gold instruments.

MATERIALS AND METHODS

Instruments selection

A total of fifty instruments were utilized in the current study from each rotary system. The instruments with similar ISO tip size of 25, 0.08 taper, and 25 mm length were selected: the instruments tested were the F2 ProTaper Gold (Dentsply Tulsa Dental Specialties) and the size 25 EdgeEvolve file (EdgeEndo). The Metallurgical Microscope (Model: MX7520, MEIJI TECHNO, Saitama, Japan) was used at ×100 magnification to inspect the new instruments for defects. Four new files of each rotary system were selected randomly and examined for machining grooves, manufacturing defects, and surface integrity using scanning electron microscopy (SEM; Quanta 250 FEG, FEI, Eindhoven, The Netherlands). The same operator performed all steps in the laboratory experiment.

Cyclic fatigue test: power analysis

The power of the test was calculated using an independent *t*-test. The authors achieved a power of 0.99 for the given values from the *t*-test with an alpha level of 0.05, and sample size of 60 (15 per group for each outcome: number of cycles at single- and double-curved canals).

Thirty instruments were tested from each system (n = 30/each). Fifteen instruments were tested in single curvature canal and the other fifteen were tested in the double curvature canal. The static mode of cyclic fatigue was selected for this study. The instruments were tested in an artificial canal within a stainless steel block. This canal was milled using a laser with the aid of a computer program that reproduces the instrument size and taper with 19 mm length [12]. In each group, the instruments were tested for cyclic fatigue in two artificial canals (n = 15/each). The first canal had a single curvature (60° curvature, 5-mm radius), and the second had a double curvature (coronal curvature 60°, 5-mm radius, and apical

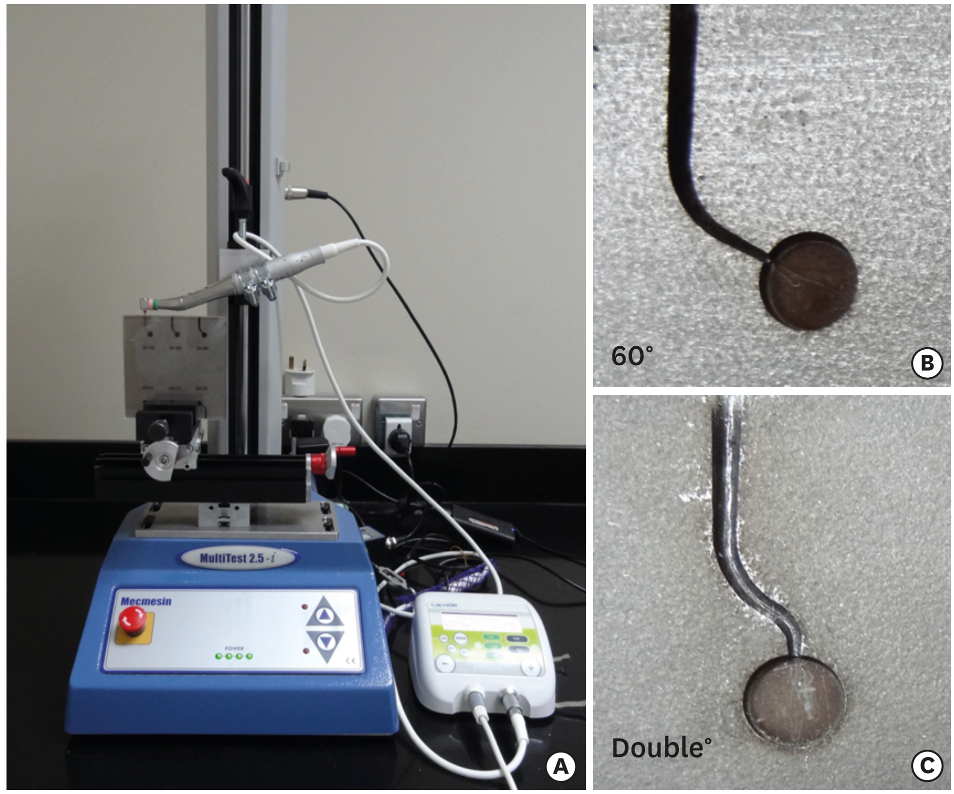

Figure 1. Experimental setup used in this study (A), and single- (B) and double- (C) curved artificial canals.

curvature of 30° and 2-mm radius) as described by Duke *et al.* [6]. The instruments were used according to the manufacturer's recommendations at 300 rpm, and activated by an I-Endo Dual (Acteon, Mérignac, France; **Figure 1**). Artificial oil (Midwest Plus Lubricant, DENTSPLY Professional, Des Plaines, IL, USA) was applied to the canal to decrease the friction between the instrument and the metal canal. The time to fracture was recorded at 1/10 second using a chronometer. The total number of cycles to fracture (NCF) was calculated by multiplying the time (seconds) to fracture by the number of rotations or cycles per seconds. The length of the fractured segments was measured using digital micro-calipers (Filetta, Schut Geometrical Metrology, Ebnatstrasse, Switzerland).

Bending resistance test

The bending resistance test was implemented for 10 files selected randomly from each system using the universal testing machine (MultiTest 2.5*i*, Mecmesin, Slinfold, UK), as described in previous studies [13,14]. A 20-N load cell was used at 15 mm/min by means of a flexible stainless steel wire. One end of the wire was fastened to the machine head, while the other end was attached 3 mm from the tip of the instrument tested. The machine was activated until the tip of the instrument underwent elastic displacement to reach 45°. The machine loading was supported by a computer program that guarantees a reliable 45° position for all instruments tested. The load required at the moment of bending was recorded for each file (Emperor, Mecmesin).

Atomic force microscope

The surface roughness average (Ra) of files new files of both rotary instruments (n = 6/each) was quantified using the Atomic force microscope (AFM; Innova, Bruker, Berlin, Germany). The files were fixed to the glass plate using double-sided adhesive. Fifteen points were scanned randomly along a 3-mm section starting at the file tip. The AFM images were recorded using contact mode under ambient conditions with scan rate of 1 Hz, scan range of 5 µ, and scan area of 5 × 5 µm². The AFM probes (curvature radius < 10 nm) were mounted on cantilevers (250 µm) with a spring constant of 0.1 Nm^{-1}. The three-dimensional image (256 × 256) lines were processed by using NanoScope analysis software (Bruker NanoScope V1.5 data analysis software, Innova, Bruker, Berlin, Germany). The Ra parameter was selected as a property that quantifies the vertical surface topography of the rotary files [15].

Scanning electron microscopy evaluation

Four new files from each group were selected randomly and inspected with the SEM to determine surface integrity and identify machining defects. These new files were analyzed with X-ray energy-dispersive spectrometer to determine the average amounts of nickel (Ni), titanium (Ti), and other elements in the rotary instruments. After cyclic fatigue testing, four samples of each instrument selected randomly from each group, cleaned ultrasonically in absolute alcohol (Power Sonic 405, HWAHIN technology, Seoul, Korea) and imaged with the SEM from the lateral views and the fracture face at various magnifications (×150–×1,500). The cross section of the fracture face was measured for each file using SEM software (Scandium Universal SEM imaging solution, Olympus GMBH, Munster, Germany).

Statistical analysis

SPSS v22 was used to analyze the data (SPSS, Chicago, IL, USA), and the Kolmogorov-Smirnov test was used to determine the normality of the data. To compare the mean levels of the two instruments at each angle, an independent *t*-test was used with a *p* value of 0.05.

RESULTS

Both EdgeEvolve and ProTaper Gold files had significantly higher resistance to cyclic fatigue in the single- than the double-curved canal ($p < 0.05$). The EdgeEvolve file exhibited significantly greater resistance to fracture than did the ProTaper Gold in both the single- and double-curvatures ($p < 0.05$). No significant differences in the segments' length were found between the EdgeEvolve and ProTaper Gold in single- and double-curvatures ($p > 0.05$). There were significantly shorter fractured segments in canals with a double-curvature than in those with a single-curvature ($p < 0.05$, **Table 1**). EdgeEvolve file was significantly less resistant to bending test than ProTaper Gold ($p < 0.05$).

Energy-dispersive spectrometer analysis

In the ProTaper Gold and the EdgeEvolve files, the proportion of Ni 50%–52% was higher than that of Ti 37%–39% (**Figure 2**), and there was no significant differences of Ni and Ti contents between the two files.

Table 1. Number of cycles to fracture (NCF), bending resistance, and surface roughness average (Ra), and fractured segment lengths

Group	NCF		Bending resistance (N)	Ra (nm)	Segment length (mm)	
	Single curvature	Double curvature			Single curvature	Double curvature
EdgeEvolve	$3,871.80 \pm 33.91^{Aa}$	569.10 ± 11.55^{Ab}	0.13 ± 0.01^{A}	27.93 ± 4.30^{A}	5.43 ± 0.21^{Aa}	2.56 ± 0.23^{Ab}
ProTaper Gold	$1,036.40 \pm 59.62^{Ba}$	482.40 ± 13.05^{Bb}	0.28 ± 0.08^{B}	90.36 ± 3.57^{B}	4.80 ± 0.86^{Aa}	2.54 ± 0.74^{Ab}

Different uppercase superscripts indicate statistically significant differences between the files.
Different lowercase superscripts indicate statistically significant differences between single- and double curvature canals.

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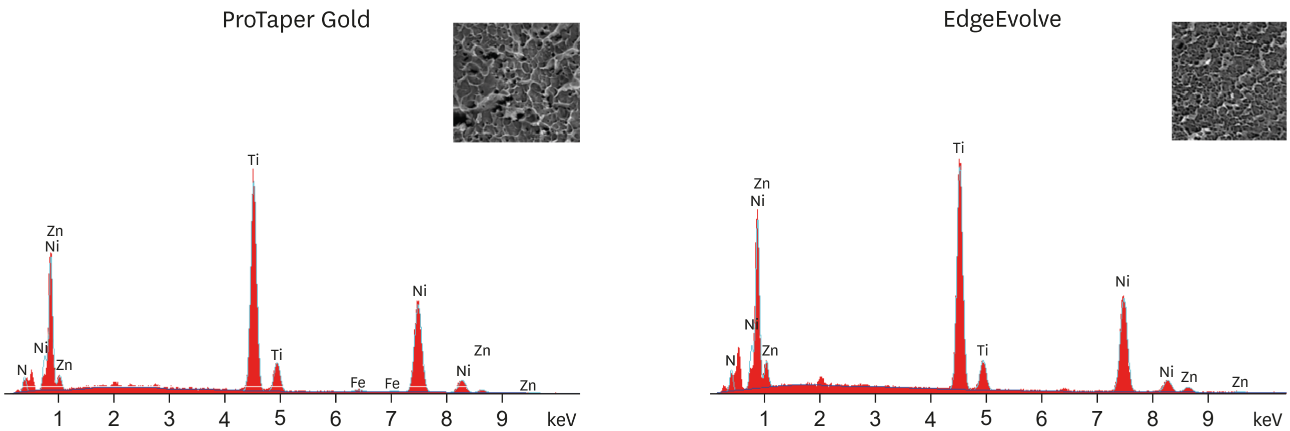

Element	Wt (%)	At (%)	K-ratio	Z	A	F
NK	4.32	14.77	0.0151	1.1570	0.3008	1.0016
TiK	40.54	40.49	0.3989	0.9817	0.9745	1.0285
FeK	0.70	0.60	0.0072	0.9820	0.9550	1.1071
NiK	51.76	42.18	0.5058	0.9989	0.9744	1.0039
ZnK	2.68	1.96	0.0241	0.9537	0.9443	1.0000
Total	100.00	100.00				

Element	Wt (%)	At (%)	K-ratio	Z	A	F
NK	5.78	19.10	0.0200	1.1546	0.2990	1.0015
TiK	39.20	37.89	0.3845	0.9795	0.9741	1.0279
NiK	50.20	39.59	0.4917	0.9966	0.9759	1.0073
ZnK	4.82	3.42	0.0434	0.9515	0.9461	1.0000
Total	100.00	100.00				

Figure 2. X-ray energy dispersive spectrometric analysis of the tested files showing similar nickel and titanium proportions.

Surface roughness

Both instruments had surface irregularities. The EdgeEvolve file had significantly less Ra compared to the ProTaper Gold files ($p < 0.05$, **Figure 3**).

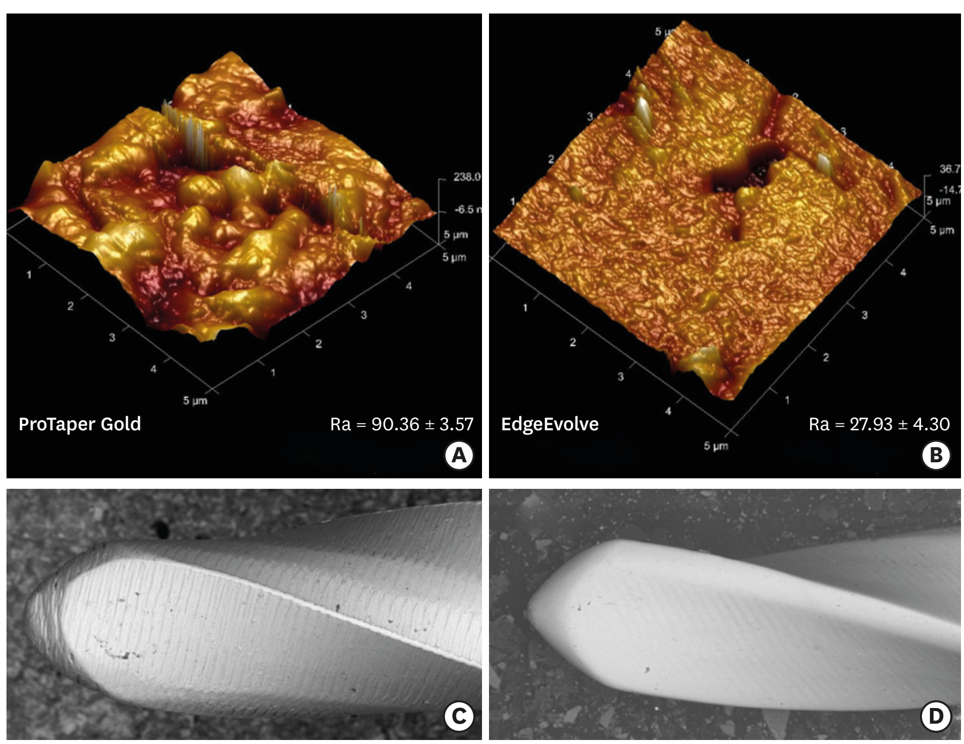

Figure 3. Surface roughness of the tested files. (A, B) Three-dimensional atomic force microscope images and (C, D) scanning electron micrograph images. (A, C) ProTaper Gold; (B, D) EdgeEvolve.
Ra, surface roughness average.

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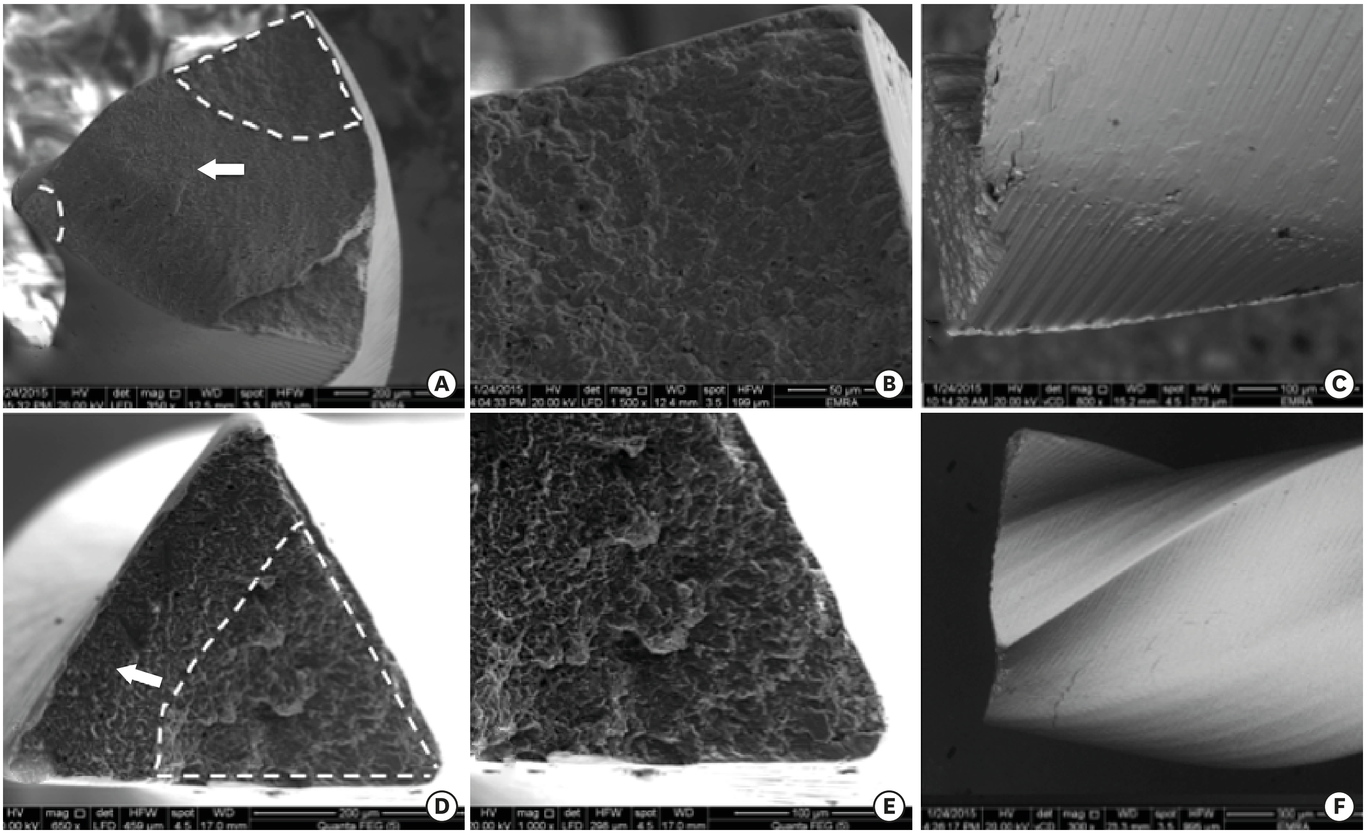

Figure 4. Representative scanning electron micrograph showing cross-sections after cyclic fatigue fracture in (A-C) ProTaper Gold and (D-F) EdgeEvolve files. (A) Representative two-level fracture of the ProTaper Gold. The dotted area corresponds to the fatigue striations and propagation while arrow represent the overload area. (B) Represents magnification of the fatigue striations (dotted) area and crack origin in (A). (C) Back scattered micrograph of the lateral view of the ProTaper Gold showing that the surface pitting and irregular cracks were near the fracture site. (D) Representative cross sections after cyclic fatigue fracture an EdgeEvolve file. The dotted area corresponds to the fatigue striations and propagation while arrows represent the overload area. (E) Magnification of the fatigue striations (dotted) area in (D) showing slow propagation of cracks. (F) Back scattered micrograph showing the lateral view of the EdgeEvolve with zigzagging cracks near the fracture site.

Scanning electron microscopy results

The surface features of the new instruments revealed that the ProTaper Gold files exhibited deep machining grooves. In contrast, the EdgeEvolve file had a smooth electropolished surface. Despite having a smooth surface, the surface of EdgeEvolve files showed a shadow of a remnant of machining grooves (**Figure 3**). The topographic analysis of the fractured surface in the two systems exhibited the same fractographic signs of a typical pattern of ductile fracture without plastic deformation, as characterized by the presence of the crack initiation area, fatigue striations, and overloaded areas. The ProTaper Gold files exhibited either single or double layer fractures with one or more crack initiation areas, micro-voids, and surface pitting near the fracture lines, while the EdgeEvolve files exhibited slow crack propagation with irregular lateral cracks close to the fracture area (**Figure 4**). ProTaper Gold fractured face cross-sectional area measured 4.58 ± 1.51 mm^2 while EdgeEvolve represents 3.80 ± 1.23 mm^2 as a cross-sectional area.

DISCUSSION

Recently, many brands of NiTi rotary files have been introduced to the market. With respect to clinicians' concerns, sudden fracture during treatment is considered a major problem that can affect instrument selection and treatment outcome [16]. Among all factors that contribute to instrument fracture, thermomechanical treatment and canal curvature are considered the most important factors that modify instrument cyclic failure critically. Thermomechanical treatment improves the mechanical properties and flexibility of NiTi files [8,9]. Further, the canal curvature affects the file's resistance to cyclic failure. Double curvatures in root canals represent a much more stressful and challenging anatomy than do single curvature canals, in which fatigue resistance may be affected by an increased canal curvature [5,6,17]. The ProTaper Gold and EdgeEvolve files were selected for this study because they are manufactured from heat-treated NiTi alloy. Both files tested have the same taper of 0.08 with a triangular cross section for EdgeEvolve and a convex triangular cross section for ProTaper Gold. Both files do not have shape memory similar to the files manufactured of controlled memory alloy. Therefore, canals with double curvature were selected to expose them to the maximum cyclic stress load as in previous studies [5,6,10]. In addition, the single curvature canal was selected as a reference for comparison.

Based on the results of the study, we rejected the null hypothesis, as the EdgeEvolve file exhibited significantly greater resistance to cyclic fatigue than did the ProTaper Gold. The EdgeEvolve's high resistance to cyclic failure may be attributable to the temperature and amount of heat treatment each brand receives. Based on Zhang *et al.* [18] results, phase transformation hysteresis ($A_f - M_f$) increases with a decreased cooling rate. The manufacturer of EdgeEvolve claims that the alloy was tempered cryogenically. This heat treatment affects the phase transformation behavior and the microstructure, and consequently affects the degree of flexibility and fracture resistance [19-21]. In addition, the smooth electropolished surface of the EdgeEvolve file seems to prevent the initiation of cracks and hamper their propagation, which consequently delays fracture. This is consistent with Lopes *et al.* [22], who concluded that the depth of surface roughness affects the NCF. Moreover, other studies have found that files with a smooth surface have greater NCF than do those with a rough surface [23].

Based on the results of Grande *et al.* [24], the cross-sectional metal mass influences cyclic fatigue resistance. Accordingly, the small triangular cross section of the EdgeEvolve file is expected to be more resistant to cyclic fatigue than are the large convex triangles of ProTaper Gold. Conversely, in the study of Hieawy *et al.* [8] and Uygun *et al.* [11], the ProTaper Gold and ProTaper Universal have a similar cross-sectional design, but ProTaper Gold instruments exhibited higher resistance to cyclic fatigue than did ProTaper Universal instruments. In this comparison, the thermomechanical treatment-enhanced alloy properties of ProTaper Gold are considered the main reason for those differences, as ProTaper Gold has a two-phase transformation and greater resistance to cyclic failure [25,26].

Yahata *et al.* [19] concluded that the heat treatment will cause a change in the transformation behaviour and subsequently increase the flexibility. Zhang *et al.* [27] reported that rate of cooling has a great influence on the phase transformation temperature and martensitic start and finish temperature, which will decrease when, shorten the rate of cooling. This means the file will contain much matensite at room temperature and will be able to deform easily. Moreover, the correlation between stiffness and cross-sectional area was highly significant [28]. Accordingly, it was expected that the bending resistance of EdgeEvolve file will be less than ProTaper Gold.

A limitation of the study is the static mode used in the cyclic fatigue test, which does not represent the actual pecking motion during mechanical preparation. On the other hand, the computer-assisted programs used in dynamic fatigue testing also do not represent the actual

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clinical movement. Therefore, the authors decreased the variables in this study by selecting two files with a similar geometry. Moreover, irrigation and debris inside the root canal were not modifying factors in the cyclic fatigue of the rotary files in this study, as we used an artificial stainless steel canal.

CONCLUSIONS

The EdgeEvolve files showed higher flexibility and lower surface roughness compared to ProTaper Gold files. Also, cyclic fatigue test results indicated higher cyclic fatigue resistance of EdgeEvolve file than ProTaper Gold files in single- and double-curvature canals.

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