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Bending Resistance and Cyclic Fatigue of a New Heat-Treated Reciprocating Instrument

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Summary: The current study aimed to evaluate the bending resistance and the cyclic fatigue life of a new heat-treated reciprocating instrument (ProDesign R). Untreated ProDesign R, Reciproc R25, and WaveOne Primary instruments were used as reference instruments for comparison. The bending resistance was performed in ten instruments of each system by using a universal testing machine and a proper apparatus. The cyclic fatigue resistance was tested measuring the number of cycles to failure in an artificial stainless steel canal. Scanning electron microscopy analysis was performed to determine the mode of fracture and possible deformations at the helical shaft. Statistical analysis was performed by using parametric methods; one-way analysis of variance plus post hoc pair-wise Tukey test for multiple comparisons ($p < 0.05$). Untreated ProDesign R presented significantly higher bending resistance than the other tested systems ($p < 0.05$). No differences were observed between ProDesign R and Reciproc files regarding the bending resistance ($p > 0.05$). Moreover, ProDesign R revealed a significantly longer cyclic fatigue life ($p < 0.05$). In contrast, Untreated ProDesign R and WaveOne instruments presented significantly lower cyclic fatigue life than Reciproc ($p < 0.05$). The new heat-treated reciprocating instrument ProDesign R have higher cyclic fatigue resistance than Untreated ProDesign R, Reciproc, and WaveOne instruments. ProDesign R and Reciproc were significantly more flexible than Untreated ProDesign R and WaveOne files. SCANNING 38:837–841, 2016. © 2016 Wiley Periodicals, Inc.

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Introduction

Nickel-titanium (NiTi) rotary instruments have been widely used for mechanical root canal preparation. Different alloys and cross-sectional designs have been proposed to increase the flexibility and resistance to fatigue fracture of endodontic instruments (Ankrum *et al*., 2004; Gambarini *et al*., 2012; Plotino *et al*., 2012). In addition to these modifications, the introduction of a new kinematics (reciprocating motion) has impacted on the overall lifespan of NiTi instruments compared to continuous rotation movement (De-Deus *et al*., 2010; Plotino *et al*., 2012; Kiefner *et al*., 2014). Instruments driven under reciprocating motion travel a shorter and controlled angular distance than rotary instruments, which are subject to lower stress values, rendering an extended fatigue life (De-Deus *et al*., 2010; Kiefner *et al*., 2014). Reciproc (VDW, Munich, Germany) and WaveOne (Dentsply Maillefer, Baillagues, Switzerland) are the main examples of currently commercially available reciprocating systems.

Recently, a novel single-file reciprocating system was launched into the market (ProDesign R; Easy Equipamentos Odontológicos, Belo Horizonte, Brazil). According to the manufacturer, ProDesign R instrument has an ISO size 25 at the tip and a taper of 0.06, an S-shaped cross section design, variable helical angles, and a cutting counterclockwise direction, such as Reciproc and WaveOne files. In addition, this instrument is made from a NiTi wire subjected to proprietary thermomechanical processing, which increases the austenite transformation temperature above 37°C, leaving the NiTi file in the twinned martensitic phase at operating temperature in a similar way as the controlled memory process (Shen *et al*., 2011a). This heat treatment is known to produce a better arrangement of the crystal structure, thus improving the flexibility (Shen *et al*., 2011a,b; Testarelli *et al*., 2011). Moreover, the switch to martensitic phase results in a NiTi file with little to no memory, thus decreasing the instrument tendency to straighten during its use. This results in a more flexible file (Testarelli *et al*., 2011), with increases resistance to both cyclic fatigue and torsional fracture (Shen *et al*., 2011b). However, up to now, there is no independent evidence on the mechanical properties of this new endodontic instrument. Therefore, the present study aimed to evaluate the bending resistance and the cyclic fatigue life of ProDesign R. Untreated ProDesign R, Reciproc R25, and WaveOne Primary instruments were used as reference instruments for comparison. The null hypotheses tested were as follows: (1) that there are no differences in the cyclic fatigue fracture resistance between the instruments; and (2) that there are no differences in the bending resistance between the instruments.

Materials and Methods

A sample of 80 NiTi instruments (25 mm in length) for use under reciprocation movement (Untreated ProDesign R, ProDesign R, Reciproc, and WaveOne) were tested. Untreated ProDesign R, ProDesign R, Reciproc R25, and WaveOne Primary files, which all had a nominal size of 0.25 mm at D_0, were selected. Untreated ProDesign R and ProDesign R have a nominal taper of 0.06 mm/mm, whereas Reciproc R25 and WaveOne Primary have 0.08 mm/mm. For standardization and reliability of the experiment, the tested instruments were previously examined for defects or deformities under a stereomicroscope.

Bending Resistance Test

The bending resistance test was performed in ten randomly selected instruments of each system by using a universal testing machine (DL 200MF; Emic, São José dos Pinhais, Brazil). A 20 N load was applied at 15 mm/min by means of a flexible stainless steel wire with one end fastened to the testing machine head and the other end attached 3 mm from the instrument tip as previously described (Lopes *et al*., 2010). This test was conducted until the tip of each specimen underwent an elastic displacement of 45°. The maximum load to bend each file was recorded and statistically analyzed. The force values were acquired in 45° position.

Cyclic Fatigue Test

Cyclic fatigue test was performed by using a custom-made device. For this test, an artificial canal measuring 1.4 mm in diameter and 19 mm total length was fabricated from a stainless steel tube. A 9 mm long curved segment with 6 mm radius (measured at the internal concave surface of the tube) was created between two straight segments that measured 7 and 3 mm. The test was performed as previously described (Lopes *et al*., 2010).

Ten instruments of each reciprocating system were activated by using a 6:1 reduction hand piece (Sirona Dental Systems GmbH, Bensheim, Germany) powered by a torque-controlled motor (Silver Reciproc; VDW) using the pre-setting programs for Reciproc and WaveOne systems ("RECIPROC ALL" and "WAVEONE ALL," respectively) and with "RECIPROC ALL" program for Untreated ProDesign R and ProDesign R, as recommended by the manufacturer. All instruments were driven following the manufacturer's instructions until a fracture occurred. The instruments rotated freely within the stainless tube that was filled with glycerin to reduce friction and heat production. Each instrument was positioned in a contra-angle hand piece and introduced into the canal until the tip touched a shield positioned at the other extremity. This shield was subsequently removed, once it was only used to standardize the instrument penetration into the canal. The time was recorded and stopped as soon as a fracture was detected visually and/or audibly. To avoid human error, video recording was performed simultaneously, and the recordings were then observed to cross-check the time of file fracture (Pedullà *et al*., 2013).

A scanning electron microscope (SEM) was used to analyze the fracture surfaces and the helical shaft of the fractured instruments to determine the fracture mode and the occurrence of plastic deformation in the helical shaft. Different magnifications were used (100× and 500×) and photomicrographs were taken for further analyses.

Statistical Analysis

Because the preliminary analysis of the raw pooled and isolated data revealed a bell-shaped distribution (D'Agostino and Person omnibus normality test), statistical analysis was performed by using parametric methods (one-way analysis of variance). Post hoc pair-wise comparisons were performed by using Tukey test for multiple comparisons. The alpha-type error was set at 0.05. SPSS 11.0 (SPSS Inc; Chicago, IL) and Origin 6.0 (Microcal Software Inc; Northampton, MA) were used as analytical tools.

Results

Untreated ProDesign R presented significantly higher bending resistance than the other systems ($p < 0.05$). No differences were observed between ProDesign R and Reciproc files regarding the bending resistance ($p > 0.05$). Moreover, ProDesign R showed a significantly longer cyclic fatigue life ($p < 0.05$). In contrast, Untreated ProDesign R and WaveOne instruments presented significantly lower cyclic fatigue life than Reciproc ($p < 0.05$). The means and standard deviations of bending resistance and cyclic fatigue tests are shown in Table I.

SEM analysis revealed that all tested instruments demonstrated morphologic characteristics of ductile fracture. No plastic deformation occurred in the helical shaft of the instruments (Fig. 1).

Discussion

Previous studies suggested a dynamic cyclic fatigue model to evaluate cyclic fatigue resistance of NiTi files (De-Deus *et al.*, 2014; Kiefner *et al.*, 2014). In fact, dynamic models approximate a clinical brushing or pecking motion (Plotino *et al.*, 2009); however, they have some limitations. First, the instruments being tested are not constrained in a precise trajectory. Also, the speed and amplitude of the axial movements could be standardized in a dynamic model, but these variables are completely subjective and it is doubtful that they are constant and reproducible in a clinical situation because this up-and-down motion is manually controlled (Wan *et al.*, 2011). Therefore, in order to minimize confounding causes by other mechanisms of instrument separation apart from cyclic fatigue, the static model was selected herein.

The first results of the current study demonstrated that the cyclic fatigue time of ProDesign R instrument was significantly higher than that of the Untreated ProDesign R, Reciproc, and WaveOne instruments. Thus, the first null hypothesis was rejected. Several previous studies already showed the difference of cyclic fatigue life time of Reciproc and WaveOne instruments (Arias *et al.*, 2012; Plotino *et al.*, 2012; De-Deus *et al.*, 2014). Nevertheless, to the best of the author's knowledge, this is the first attempt to evaluate the cyclic fatigue of ProDesign R system.

Although the tip sizes of Untreated ProDesign R, ProDesign R, ReciprocR25, and WaveOne Primary instruments were the same (25), the taper differs among themselves; while Reciproc R25 and WaveOne Primary have a nominal taper over the first apical millimeters of 0.08 mm/mm, Untreated ProDesign R and ProDesign R has 0.06 mm/mm. This difference helps to explain the greater stiffness of Reciproc and WaveOne files. The different cross-sections may also influence the fatigue results as the larger the cross-sectional area is, the higher is the flexural and torsional stiffness (De-Deus *et al.*, 2014). In the same way, file design (diameters of core, number of threads, helical angle) would also have a significant influence on the fatigue resistance. Moreover, Reciproc and WaveOne files are both made of the same NiTi alloy (M-Wire), which is different from the alloy of Untreated ProDesign R (conventional NiTi) and ProDesign R instruments (heat-treated); the different alloys might also explain the differences on the obtained results. Previous studies have also demonstrated higher cyclic fatigue resistance of heat-treated rotary files compared to M-Wire or conventional NiTi alloys (Shen *et al.*, 2011a; Campbell *et al.*, 2014). During the manufacturing process, machining defects were made, and the SEM analysis showed different patterns in surface finish that also influenced the fatigue lifetime (Lopes *et al.*, 2010).

Pre-setting programs ("RECIPROC ALL" and "WAVEONE ALL") of reciprocating motion present different angles of rotation and speed: 150° counterclockwise and then 30° clockwise rotation with a speed of 300 rpm for the "RECIPROC ALL" mode and 170° counterclockwise and then 50° clockwise rotation with a speed of 350 rpm for the "WAVEONE ALL" mode. This situation might also influence on the cyclic fatigue resistance of reciprocating files. However, a recent study using a high-speed video method revealed that the reciprocating kinematics is more complex than it seems (Fidler, 2014), as the observed values differed from the manufacturer's declared values, especially for the engaging and disengaging angles. "RECIPROC ALL" demonstrated a $158.60° \pm 1.56°$ counterclockwise and $34.65° \pm 1.13°$ clockwise rotation with a speed of 282.92 ± 3.70 rpm while "WAVEONE ALL" demonstrated a $159.85° \pm 1.04°$ counterclockwise and $41.44° \pm 1.49°$ clockwise rotation with a speed of 346.36 ± 2.81 rpm (Fidler, 2014). As the angles are very similar, it is expected to have no differences between the two pre-setting programs, which is in agreement with a recent study in which different presets of reciprocating motions did not have any influence on the cyclic fatigue failure (Kim *et al.*, 2012). Therefore, the decision to use "RECIPROC ALL" or "WAVEONE ALL" programs were based on the manufacturer's recommendations ("RECIPROC ALL" for Untreated ProDesign R, ProDesign R, and Reciproc, and "WAVEONE ALL" for WaveOne).

The second result from this study indicated that Untreated ProDesign R files required significantly greater loads than other tested systems to reach 45°

TABLE I Mean and standard deviation of bending resistance values and time to failure of the instruments subjected to static test

Instruments	Maximum load (g)	Time to failure (sec)
Untreated ProDesign R	758.0 ± 22.34^C	93.4 ± 10.8^C
ProDesign R	286.2 ± 16.49^A	566.6 ± 45.7^A
Reciproc	280.2 ± 17.15^A	203.5 ± 32.8^B
WaveOne	536.3 ± 21.2^B	94.9 ± 15.1^C

Different superscript letters represent statistical differences ($p < 0.05$).

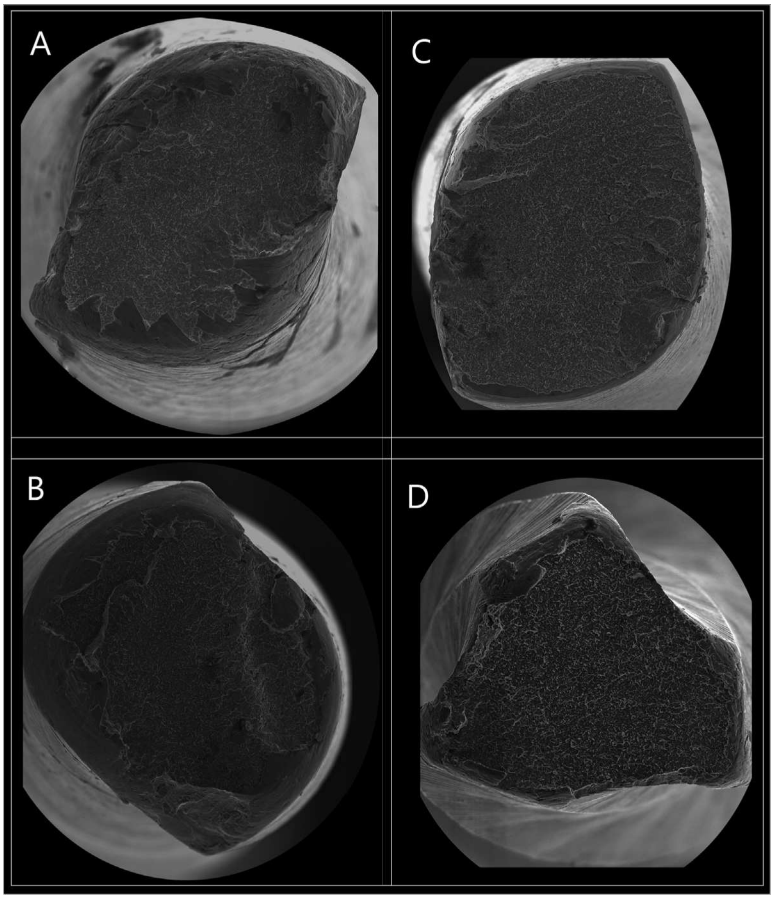

Fig. 1. Fractured surfaces of instruments showing morphologic characteristics of the ductile type (250× magnification). (A) ProDesign R; (B) Untreated ProDesign R; (C) Reciproc; and (D) WaveOne.

deflection ($p < 0.05$). Moreover, ProDesign R required lower load than Reciproc and WaveOne ($p < 0.05$). This indicates that ProDesign R is significantly more flexible than the other instruments. Thus, the second null hypothesis was also rejected. Overall, rigid instruments present a lower number of cycles to fracture because of the buildup of tensions at the point of maximum flexure, as observed in the present study which is in accordance with previous studies (Lopes *et al.*, 2010; De-Deus *et al.*, 2014).

SEM analysis showed typical ductile fractographic appearances of cyclic fatigue fractures with micro voids. The instruments presented crack initiation areas and overload fast fractures zones, with no morphologic differences among the three different systems. The heat-treated alloy did not prevent but has delayed the onset of catastrophic failure (unstable and fast crack growth) of the material.

Torsional stress is generated by the twisting of a file over its longitudinal axis at one end while the other end is fixed. This is related to how much a file can twist before fracture and it is desirable in the preparation of narrow and constricted canals as the file is subjected to high torsional loads. Although this property was not evaluated in the present study, it is important to emphasize that previous studies have reported that conventional NiTi and M-Wire instruments generally possess greater torque resistance but smaller angles of rotation before fracture than controlled memory wire files (Ninan and Berzins, 2013; Pedullà *et al.*, 2016). Future studies should evaluate this property in ProDesign R instruments.

Conclusions

Under the conditions of the current study, it can be concluded that the heat-treated reciprocating instrument ProDesign R resisted significantly more to cyclic fatigue than Reciproc and WaveOne instruments. Furthermore, WaveOne files were significantly less flexible than ProDesign R and Reciproc instruments.

References

Ankrum MT, Hartwell GR, Truitt JE. 2004. K3 Endo, ProTaper, and ProFile systems: breakage and distortion in severely curved roots of molars. J Endod 30:234–237.

Arias A, Perez-Higuerras JJ, de la Macorra JC. 2012. Differences in cyclic fatigue resistance at apical and coronal levels of Reciproc and WaveOne new files. J Endod 38:1244–1248.

Campbell L, Shen Y, Zhou HM, Haapasalo M. 2014. Effect of fatigue on torsional failure of nickel-titanium controlled memory instruments. J Endod 40:562–565.

De-Deus G, Moreira EJ, Lopes HP, Elias CN. 2010. Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement. Int Endod J 43:1063–1068.

De-Deus G, Vieira VT, Silva EJ, et al. 2014. Bending resistance and dynamic and static cyclic fatigue life of Reciproc and WaveOne large instruments. J Endod 40:575–579.

Fidler A. 2014. Kinematics of 2 reciprocating endodontic motors: the difference between actual and set values. J Endod 40:990–994.

Gambarini G, Rubini AG, Al Sudani D, et al. 2012. Influence of different angles of reciprocation on the cyclic fatigue of nickel-titanium endodontic instruments. J Endod 38:1408–1411.

Kiefner P, Ban M, De-Deus G. 2014. Is the reciprocating movement per se able to improve the cyclic fatigue resistance of instruments? Int Endod J 47:430–436.

Kim HC, Kwak SW, Cheung GS, et al. 2012. Cyclic fatigue and torsional resistance of two new nickel-titanium instruments used in reciprocation motion: Reciproc versus WaveOne. J Endod 38:541–544.

Lopes HP, Elias CN, Vieira VT, et al. 2010. Effects of electropolishing surface treatment on the cyclic fatigue resistance of BioRace nickel-titanium rotary instruments. J Endod 36:1653–1657.

Ninan E, Berzins DW. 2013. Torsion and bending properties of shape memory and superelastic nickel-titanium rotary instruments. J Endod 39:101–104.

Pedullà E, Grande NM, Plotino G, Gambarini G, Rapisarda E. 2013. Influence of continuous or reciprocating motion on cyclic fatigue resistance of 4 different nickel-titanium rotary instruments. J Endod 39:258–261.

Pedullà E, Lo Savio F, Boninelli S, et al. 2016. Torsional and cyclic fatigue resistance of a new nickel-titanium instrument manufactured by electrical discharge machining. J Endod 42:156–159.

Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. 2009. A review of cyclic fatigue testing of nickel-titanium rotary instruments. J Endod 35:1469–1476.

Plotino G, Grande NM, Testarelli L, Gambarini G. 2012. Cyclic fatigue of Reciproc and WaveOne reciprocating instruments. Int Endod J 45:614–618.

Shen Y, Qian W, Abtin H, Gao Y, Haapasalo M. 2011. Fatigue testing of controlled memory wire nickel-titanium rotary instruments. J Endod 37:997–1001.

Shen Y, Zhou H, Zheng Y, et al. 2011. Mettalurgical characterization of controlled memory wire nickel-titanium rotary instruments. J Endod 37:1566–1571.

Testarelli L, Plotino G, Al-Sudni D, et al. 2011. Bending properties of a new nickel-titanium alloy with a lower percent by weight of nickel. J Endod 37:1293–1295.

Wan J, Rasimick BJ, Musikant BL, Deutsch AS. 2011. A comparison of cyclic fatigue resistance in reciprocating and rotary nickel-titanium instruments. Aust Endod J 37: 122–127.