Cyclic and Torsional Fatigue Resistance of Reciprocating Single Files Manufactured by Different Nickel-titanium Alloys

Murilo P. Alcalde, MSc, Mario Tanomaru-Filho, PhD,† Clovis M. Bramante, PhD,* Marco Antonio H. Duarte, PhD,* Juliane Maria Guerreiro-Tanomaru, PhD,† Jader Camilo-Pinto, DDS,† Marcus Vinicius Reis Só, PhD,‡ and Rodrigo Ricci Vivan, PhD**

Abstract

Introduction: The aim of this study was to evaluate the cyclic and torsional fatigue resistance of the following reciprocating single-file systems: ProDesign R 25.06 (Easy Equipamentos Odontológicos, Belo Horizonte, Brazil), Reciproc R25 (VDW GmbH, Munich, Germany), and Unicone L25 (Medin SA, Nové Město in Moravě, Czech Republic). **Methods:** Sixty instruments of the ProDesign R, Reciproc R25, and Unicone L25 systems ($n = 20$) were used. Cyclic fatigue resistance was tested measuring the time to failure in an artificial stainless steel canal with a 60° angle and a 5-mm radius of curvature ($n = 10$). Torque and angle of rotation at failure of new instruments ($n = 10$) in the 3 mm from the tip portion were measured during torsional testing according to ISO 3630-1. The fractured surface of each fragment was examined by scanning electron microscopy. Data were analyzed using 1-way analysis of variance and Tukey tests, and the level of significance was set at 5%. **Results:** The cyclic fatigue resistance values of ProDesign R 25.06 were significantly higher than the other groups ($P < .05$). Reciproc R25 showed higher fatigue resistance than Unicone L25 ($P < .05$). In relation to the torsional test, the ProDesign R 25.06 and Unicone L25 systems showed higher angular rotation until fracture than Reciproc R25 ($P < .05$). However, Reciproc R25 and Unicone L25 showed higher torque load than ProDesign R 25.06 ($P < .05$). Scanning electron microscopic analysis showed similar and typical features of cyclic and torsional failure for all instruments tested. **Conclusions:** ProDesign R presented the highest cyclic fatigue resistance and angular rotation to failure compared with Reciproc and Unicone. However, Reciproc showed higher torsional strength to failure. *(J Endod 2017;43:1186–1191)*

Key Words

Cyclic fatigue, nickel-titanium, reciprocating systems, torsional resistance

Significance

New reciprocating systems were introduced with different designs and NiTi alloys. Instrument separation can occur, and the causes are flexural and torsional stress. ProDesign R presented higher cyclic fatigue resistance and Reciproc showed higher torsional strength to failure.

Nickel-titanium instruments (NiTi) show flexibility and elasticity to provide safe root canal preparation in curved canals (1, 2). However, unexpected instrument separation can occur, and many variables may contribute to this occurrence. The most common causes are flexural and torsional stress (3, 4).

Cyclic flexural fatigue occurs by repeated compressive and tensile stresses when the instrument rotates in a curved canal (3), which often happens clinically (3, 5). Torsional failure occurs when the tip of the instrument is locked in the canal while the shank continues to rotate (3). This can happen in straight or curved canals, especially in the preparation of narrow and constricted canals when the file is susceptible to high torsional loads (3, 5). Torsional failure is characterized by a maximum torsional load and angle of rotation. This property reveals the ability of the file to twist before fracture (6). Therefore, to minimize this drawback, the manufacturers developed several strategies such as new cross sections, designs, thermomechanical processes, and kinematics (1, 2, 6–8).

The reciprocating motion used in reciprocating single-file systems has been shown to be safe and effective in the preparation of curved root canals, reducing cyclic fatigue, torsional stress, and working time (9–11). Reciproc (VDW GmbH, Munich, Germany) is fabricated from M-Wire alloy. This NiTi alloy shows more flexibility and mechanical strength than NiTi wire (2, 12). M-Wire instruments are produced by transforming an NiTi wire in the austenite phase into the R-phase, an intermediate phase formed during the transformation from martensite to austenite on heating and reverse transformation on cooling the material (2, 12).

Recently, new reciprocating systems were introduced using different designs and NiTi alloys. ProDesign R (Easy Equipamentos Odontologicos, Belo Horizonte, MG, Brazil) has 2 instruments with #25 and #35 tip sizes and 0.06 and 0.05 tapers, presents an S-shaped cross section, and is manufactured by a special thermomechanical process

From the *Department of Operative Dentistry, Endodontics and Dental Materials, Bauru School of Dentistry, University of São Paulo, São Paulo, Brazil; †Department of Restorative Dentistry, Araraquara Dental School, São Paulo State University, São Paulo, São Paulo, Brazil; and ‡Department of Restorative Dentistry, Federal University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil.

Address requests for reprints to Dr Rodrigo Ricci Vivan, Bauru School of Dentistry, University of São Paulo, Al Octávio Pinheiro Brisolla, 9-75, 17012-901 Bauru, SP, Brazil. E-mail address: rodrigo.vivan@fob.usp.br

0099-2399/$ - see front matter

http://dx.doi.org/10.1016/j.joen.2017.03.008

that controls the memory of the NiTi. These instruments are mainly in the martensite phase, which provides more flexibility, cyclic fatigue resistance (2, 7, 12, 13), and high deformation capacity during torsional testing (12–14). Unicone (Medin, Nov e Mesto na Morave, Czech Republic) is an NiTi (proprietary treatment not reported by the manufacturer) reciprocating instrument with an inactive tip and a convex triangular cross section; it is composed of 3 instruments with #20, #25, and #40 tip sizes and a 0.06 taper size. Some authors have reported that this instrument has low flexibility and a short lifetime during cyclic fatigue test (15, 16).

There are no studies regarding the cyclic and torsional fatigue resistance of ProDesign R. Furthermore, there is no report of the torsional properties of Unicone. The aim of this study was to evaluate the cyclic and torsional fatigue (maximum torque load and angular rotation) of the ProDesign R 25/.06 and Unicone 25/.06 systems and compare them with the Reciproc R25 instrument. The null hypotheses tested were as follows:

1. There are no differences in the cyclic fatigue resistance among the instruments.
2. There are differences in the torsional resistance among the instruments.

Methods

The sample calculation was performed using G*Power v3.1 for Mac (Heinrich Heine, University of Düsseldorf, Düsseldorf, Germany) by selecting the Wilcoxon-Mann-Whitney test of the *t* test family. An alpha-type error of 0.05, a beta power of 0.95, and a ratio N2/N1 of 1 were also stipulated. A total of 8 samples per group were indicated as the ideal size required for noting significant differences. Ten samples per group were used because an additional 20% was calculated to compensate for possible outlier values that might lead to sample loss.

A sample of 60 NiTi instruments (length = 25 mm) of 3 different reciprocating systems (n = 20 per system) were used in this study as follows: ProDesign R (size #25, 0.06 taper), Reciproc R25 (size #25, 0.08 taper), and Unicone L25 (size #25, 0.06 taper). Every instrument was inspected for defects or deformities before being tested under a stereomicroscope (Carl Zeiss, LLC, Oberkochen, Germany) at 16× magnification; none were discarded. All files used were 25-mm long, with 10 instruments of each brand used for cyclic and torsional fatigue testing.

Cyclic Fatigue Test

The static cyclic fatigue tests were performed using a custom-made device that allowed a reproducible simulation of an instrument confined in an artificial curved canal as previously described (17). The artificial canal was manufactured by reproducing the instrument size and taper, thus providing the instrument with a suitable trajectory with a 60° angle of curvature and a 5-mm radius of curvature (Fig. 1*A* and *B*). The curvature of the stainless steel artificial canal was fitted onto a guide cylinder made of the same material (angle of curvature = 60°, radius = 5 mm). Both the arch and the guide cylinder had a 1-mm-deep groove located 5 mm from the top to match the height of the counterangle. The groove served as a guide path for the instrument, which remained curved and free to rotate between the cylinder and external arch.

Ten instruments of each reciprocating system were activated by using a 6:1 reduction handpiece (Sirona Dental Systems GmbH, Bensheim, Germany) powered by a torque-controlled motor (Silver Reciproc, VDW) using the preset programs "Reciproc ALL" and "WaveOne ALL" to activate Reciproc R25 and ProDesign R 25.06 and Unicone L25, respectively. The preset programs were selected according to the manufacturers' instructions. To reduce the friction of the instrument as it came into contact with the artificial canal walls, a special high-flow synthetic oil prepared for lubrication of mechanical parts (Super Oil; Singer Co Ltd, Elizabethport, NJ) was applied. The time from motor activation was recorded and stopped as soon as a fracture was detected visually and/or audibly on a digital timer. During this step, a video recording was performed simultaneously, and the recordings were observed to ensure the accurate time of instrument fracture.

Torsional Fatigue Test

The torsion tests, based on ISO 3630-1 (1992), were performed by using a torsion machine described in detail elsewhere (18). All files used were 25-mm long, and 10 instruments of each system were used to

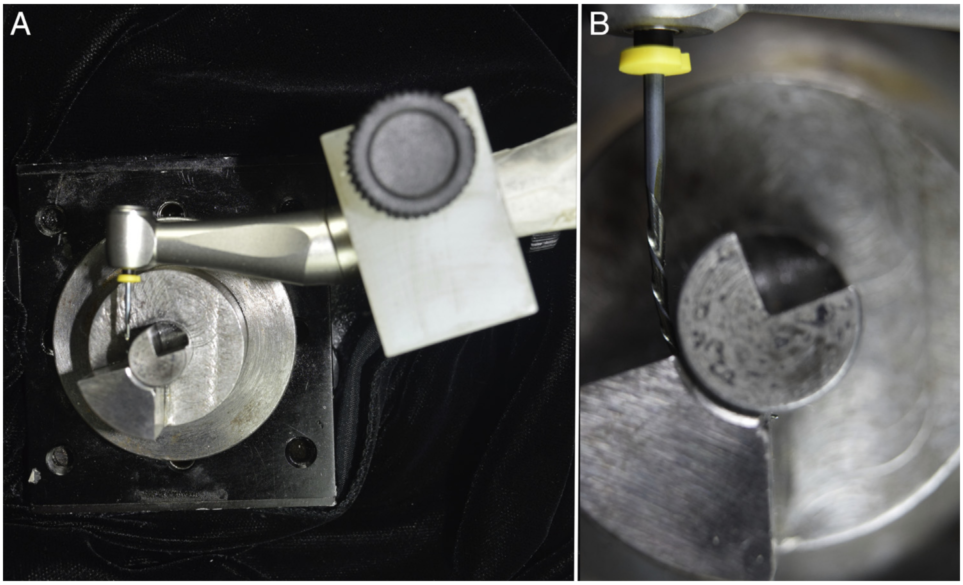

Figure 1. (*A*) The instrument positioned in the cyclic fatigue test device. (*B*) The artificial canal with an angle of curvature of 60° and a radius of 5 mm.

establish the mean values of torque and maximum angular deflection necessary until rupture.

The torque values were assessed by measuring the force exerted on a small load cell by a lever arm linked to the torsion axis. The rotation angle was measured and controlled by a resistive angular transducer connected to a process controller. Before testing, each instrument handle was removed at the point where the handle was attached to the shaft. The end of the shaft was clamped into a chuck connected to a reversible geared motor. Three millimeters of the instrument tip were clamped in another chuck with brass jaws to prevent sliding. The counterclockwise rotation speed was set to 2 rpm. Continuous recording of torque and angular rotation was monitored, and the ultimate torsional strength and angular rotation (°) were provided by a specifically designed computer program (Analógica, Belo Horizonte, MG, Brazil) and recorded.

Scanning Electron Microscopic Evaluation

The fractured surfaces of 5 instruments of each brand, randomly selected after the cyclic and torsional fatigue test to failure, were examined by scanning electron microscopy (JSM-TLLOA; JEOL, Tokyo, Japan) to look for the topographic features of the fractured instruments. Before scanning electron microscopic (SEM) evaluation, instruments were ultrasonically cleaned to remove debris. The photomicrographs were taken at 250× magnification. Furthermore, additional photomicrographs were taken at 1000× magnification in the center of the fractured surface of the instruments submitted to torsional testing.

Results

The mean and standard deviations of the cyclic and torsional fatigue resistance (torque maximum load and angle of rotation) for each instrument are presented in Table 1. ProDesign R 25.06 had significantly higher cyclic fatigue resistance values than the other groups ($P < .05$). Reciproc R25 showed significantly higher cyclic fatigue resistance than Unicone ($P < .05$).

The maximum torsional strength values of ProDesign R 25.06 were significantly lower than those of Reciproc R25 and Unicone L25 ($P < .05$). Furthermore, there was a significant difference between Reciproc R25 and Unicone L25. In relation to the angular rotation, ProDesign R and Unicone L25 showed a significant difference in comparison with Reciproc R25 ($P < .05$). No difference was found between ProDesign R 25.06 and Unicone L25 ($P > .05$).

SEM Evaluation

Scanning electron microscopy of the fractured surface showed similar and typical features of cyclic fatigue and torsional failure for all brands tested. In the cyclic fatigue test, all the instruments displayed fractured surfaces with microvoids, morphologic characteristics of ductile fracture (Fig. 2*A–C*). In the torsional test, all the instruments showed concentric abrasion marks and fibrous dimple marks in the center of rotation for torsional failure (Fig. 3*A–C* and *a–c*).

Discussion

The cyclic and torsional resistance of NiTi instruments can be affected by instrument size, taper, cross-sectional design, diameter of core, and manufacturing process (1, 12, 19, 20). At present, many changes in instrument design and manufacturing processes have been proposed to improve their mechanical properties and clinical performance (2, 21, 22). Therefore, the aim of this study was to compare the cyclic and torsional resistance of 3 reciprocating files with different designs and manufacturing processes.

The dynamic model approximates a clinical pecking motion accomplished during root canal preparation (23). However, in this study, the static cyclic fatigue model was selected, as used in previous studies (14–16, 24). The static model allows a precise trajectory in the artificial canal and decreases some variables, such as the amplitude of axial movements and speed, which are completely subjective and in a clinical situation their reproduction is unreliable because the axial motion is manually controlled (24). The use of a simulated artificial canal in a stainless steel block was used for cyclic fatigue analysis and has previously been reported (1, 9, 11, 14–17). In this study, the torsional fatigue resistance (maximum torque load and angle of rotation) to fracture was compared. The torsional tests were performed in accordance with ISO 3630-1 as in previous studies (4, 18). After fastening the 3 mm of the tip and shaft of the instruments, a rotational counterclockwise direction rotation was set in a counterclockwise direction for all instruments because of their spiraling flutes (25).

The first result of this study showed that ProDesign R 25.06 had higher cyclic fatigue resistance values than the other groups. Thus, the first null hypothesis was rejected. The ProDesign R, Reciproc, and Unicone instruments have the same tip sizes (#25). However, the tapers differ among them; ProDesign R and Unicone have a taper of 0.06 mm/mm, and Reciproc R25 has a nominal taper of 0.08 mm/mm over the first 3 mm from the tip. The lower taper value of ProDesign R and Unicone when compared with Reciproc R25 should ensure a higher cyclic fatigue time; nevertheless, our results showed that only ProDesign R presented better results than Reciproc and Unicone. In addition, the Reciproc group showed a significantly higher cyclic fatigue resistance value than the Unicone group ($P < .05$). Thus, other variables, such as cross-sectional design, diameter of core, and manufacturing process, should be taken into account for the outcomes of this study.

The results of this study were probably caused by the different cross-sectional designs and types of NiTi alloy of the instruments, which affect the mechanical properties of NiTi instruments (2, 15, 23, 25–28). ProDesign R and Reciproc have S-shaped cross sections with 2 cutting edges, and Unicone has a convex triangular cross section. In a supplementary examination, we captured the cross-sectional configuration of each instrument at 5 mm from the

TABLE 1. Mean Cyclic Fatigue (Time in Seconds), Torque (Ncm), and Angle of Rotation (°) of the Instruments Tested

	Cyclic fatigue (seconds)		Torque (Ncm)		Angle (°)	
Instruments	Mean	SD	Mean	SD	Mean	SD
Reciproc R25	699[b]	111.6	1.401[a]	0.1295	224.4[b]	30.43
ProDesign 25.06	2149.2[a]	403.38	1.011[c]	0.0984	315.5[a]	6.74
Unicone L25	151.2[c]	17.34	1.237[b]	0.1801	286.9[a]	34.93

SD, standard deviation.

Different superscript letters in the same column indicate statistical differences among groups ($P < .05$).

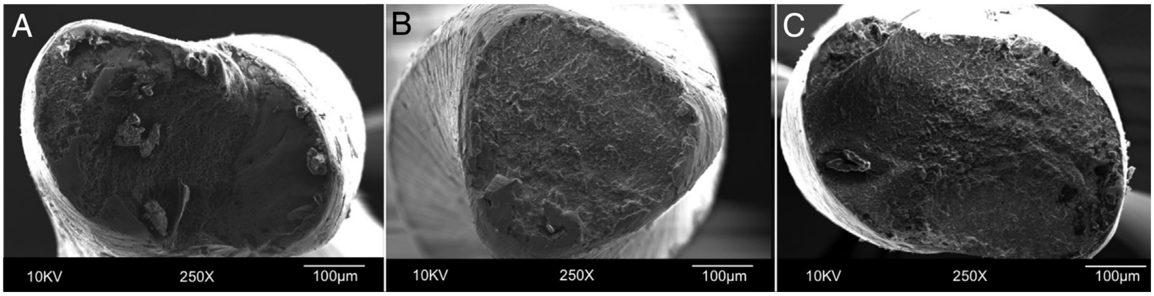

Figure 2. SEM images of fractured surfaces of separated fragments of (*A*) ProDesign R, (*B*) Unicone, and (*C*) Reciproc after cyclic fatigue testing. The images show numerous dimples, a feature of ductile fracture.

tip using scanning electron microscopy and measured the area using software (AutoCAD; Autodesk Inc, San Rafael, CA) (25). ProDesgin R showed the smallest area (239.219 μm^2) followed by Unicone (245.95 μm^2) and Reciproc (274.890 μm^2). NiTi instruments with larger cross-sectional areas present lower cyclic fatigue resistance (19, 23, 25, 26, 28). Therefore, this could contribute to the difference in cyclic fatigue resistance of these instruments.

The mechanical properties of NiTi instruments are affected by the type of alloy used in the manufacturing process (1, 2, 7, 12, 14). All the instruments used in this study were manufactured from different NiTi

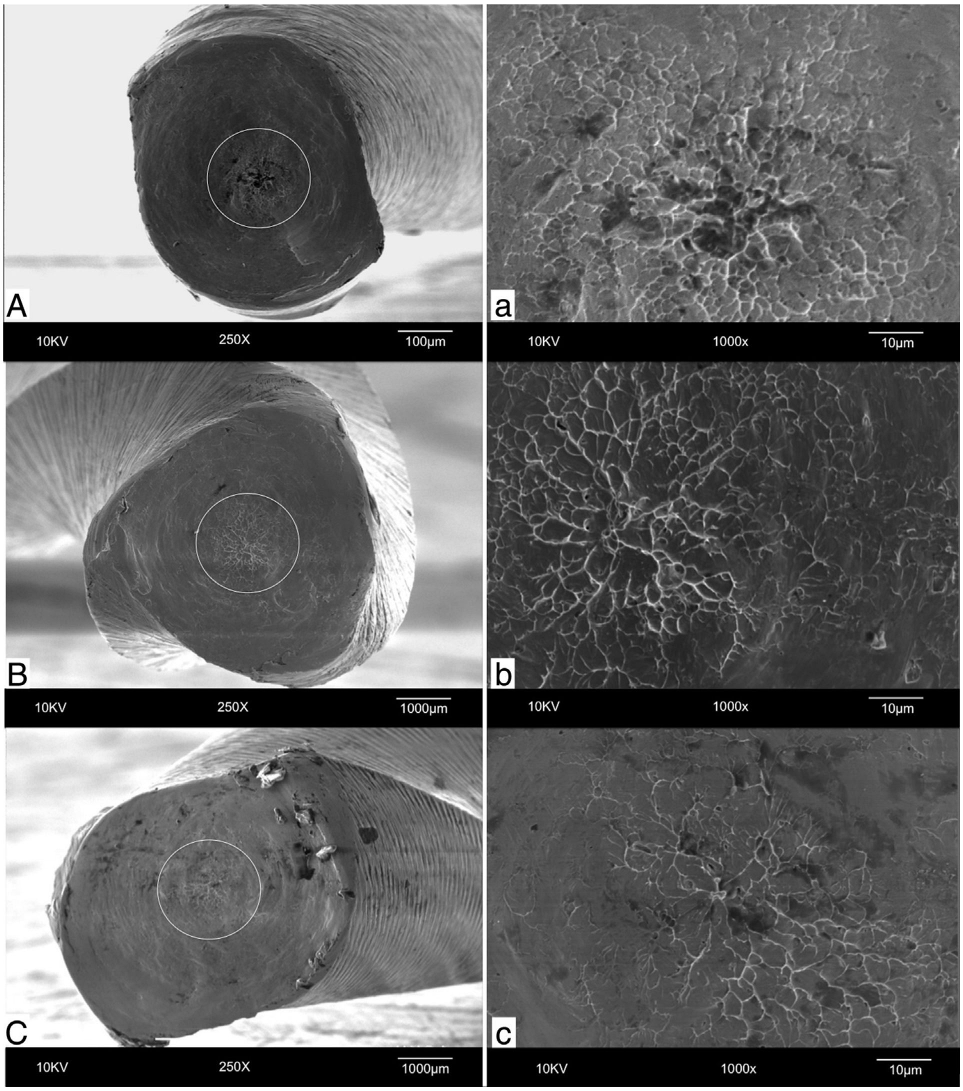

Figure 3. SEM images of the fractured surface of separated fragments (first row: *A* and *a* = ProDesign R; second row: *B* and *b* = Unicone; and bottom row: *C* and *c* = Reciproc R25). The left column shows the images after the torsional test, with the circular box indicating the concentric abrasion mark; the right column shows the concentric abrasion mark at 1000× magnification. The skewed dimples near the center of rotation are typical features of torsional failure.

alloys. ProDesign R had significantly higher cyclic fatigue resistance than the other groups tested, and Reciproc had higher cyclic fatigue resistance than Unicone. ProDesign R was the only instrument made of controlled memory (CM) wire, and this could explain the better results shown in the cyclic fatigue test. It has previously been reported that CM wire instruments have greater flexibility and cyclic fatigue resistance than M-Wire and conventional NiTi instruments (2, 14, 29). There were only 2 previous studies evaluating the mechanical properties of Unicone instruments (15, 16). In agreement with our results, Silva et al (15) showed that Unicone had the lowest cyclic fatigue resistance when compared with Reciproc and WaveOne (Dentsply Maillefer, Ballaigues, Switzerland). These authors reported that the cross-sectional design and the NiTi alloy (proprietary treatment not reported by the manufacturer) of the Unicone instruments could explain these results.

The second result of this study showed that ProDesign R had the lowest maximum torsional strength in comparison with Reciproc and Unicone ($P < .05$). Furthermore, ProDesign R and Unicone supported a greater angular rotation than Reciproc until fracture ($P < .05$). Thus, the second null hypothesis was rejected. The results of this study were probably related to the different cross-sectional designs and NiTi alloy of the instruments, which have a significant influence on the torsional resistance (1, 5, 7, 25, 29–31).

The torsional test was performed by clamping 3 mm of the instrument tip. Thus, in a supplementary examination, we captured the cross-sectional configuration of each instrument in 3 mm from the tip using scanning electron microscopy and measured the area using software (AutoCAD) before the torsional test (14). ProDesign R showed the smallest area (98.521 μm^2) followed by Unicone (110.395 μm^2) and Reciproc (112.686 μm^2). The Reciproc and Unicone groups showed significantly higher torsional strength until fracture than ProDesign R ($P < .05$), but the Unicone group showed lower torsional strength than Reciproc ($P < .05$). It has previously been reported that instruments with larger cross-sectional areas generally present higher torsional stiffness (20, 25, 31). Furthermore, the M-Wire instruments, such as Reciproc, generally had greater torsional stiffness but a smaller angle of rotation to fracture than CM wire instruments, such as ProDesign R (2, 14, 29, 30). Our results were in agreement with the aforementioned studies and could be explained because of the high flexibility of CM wire, providing greater deformation capacity and demanding lower torsional strength values (2, 12–14). There were no previous studies evaluating the torsional fatigue resistance of Unicone instruments. Our results showed that Unicone had greater maximum torsional strength than ProDesign R ($P < .05$). However, it had a similar angle of rotation ($P > .05$). The different alloys and cross-sectional designs of these instruments might also explain the differences in the results obtained.

SEM analysis showed typical fractographic appearance of cyclic fatigue and torsional fractures, with a similar appearance among the 3 brands. After the cyclic fatigue test, the instruments showed crack initiation areas and overload (fast fracture) zones, with numerous dimples spread on the fractured surface. After the torsional test, the fragments demonstrated the typical features of shear failure, including concentric abrasion marks and fibrous microscopic dimples at the center of rotation (1, 6, 14, 25). The CM wire did not prevent but did delay the onset of catastrophic failure (unstable and fast crack growth) of the material.

The higher cyclic fatigue resistance of ProDesign R indicated that these instruments were very flexible and safe for preparing curved root canals and could perhaps cause fewer undesirable changes in the root canal anatomy during instrumentation. Furthermore, the greater angular distortion of ProDesign R could be beneficial and may provide clinicians with an indication that there was plastic/permanent deformation and imminent fracture (29). On the other hand, in constricted and curved canals, the instrument would be submitted to higher torsional load stress, which could induce plastic deformation more easily than the Reciproc and Unicone instruments. Therefore, a glide path would be necessary before the use of the ProDesign R instrument to provide pre-enlargement and reduce the torsional stress. In relation to the Unicone instrument, it should be used with caution for the preparation of curved root canals.

In conclusion, within the limitations of this study, our results showed that ProDesign R had the highest cyclic fatigue resistance values and angular rotation to fracture in comparison with Reciproc and Unicone. However, Reciproc showed higher torsional strength to failure.

Acknowledgments

Supported by the State of São Paulo Research Foundation FAPESP (2014/25520-0).

References

1. Lopes HP, Gambarra-Soares T, Elias CN, et al. Comparison of the mechanical properties of rotary instruments made of conventional nickel-titanium wire, M-wire, or nickel-titanium alloy in R-phase. J Endod 2013;39:516–20.
2. Shen Y, Zhou HM, Zheng YF, et al. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. J Endod 2013;39:163–72.
3. Sattapan B, Nervo GJ, Palamara JE, et al. Defects in rotary nickel–titanium files after clinical use. J Endod 2000;26:161–5.
4. Pedulla E, Lo Savio F, Boninelli S, et al. Influence of cyclic torsional preloading on cyclic fatigue resistance of nickel - titanium instruments. Int Endod J 2015;48: 1043–50.
5. Wycoff RC, Berzins DW. An *in vitro* comparison of torsional stress properties of three different rotary nickel-titanium files with a similar cross-sectional design. J Endod 2012;38:1118–20.
6. Elnaghy AM, Elsaka SE. Torsion and bending properties of OneShape and WaveOne instruments. J Endod 2015;41:544–7.
7. Zhou HM, Shen Y, Zheng W, et al. Mechanical properties of controlled memory and superelastic nickel-titanium wires used in the manufacture of rotary endodontic instruments. J Endod 2012;38:1535–40.
8. Karataş E, Arslan H, Büker M, et al. Effect of movement kinematics on the cyclic fatigue resistance of nickel-titanium instruments. Int Endod J 2016;49:361–4.
9. De-Deus G, Moreira EJL, Lopes HP, et al. Extended cyclic fatigue life of F2 ProTaper instruments used in reciprocating movement. Int Endod J 2010;43:1063–8.
10. Varela-Patiño P, Ibañez-Párraga A, Rivas-Mundiña B, et al. Alternating versus continuous rotation: a comparative study of the effect on instrument life. J Endod 2010;36: 157–9.
11. Gavini G, Caldeira CL, Akisue E, et al. Resistance to flexural fatigue of Reciproc R25 files under continuous rotation and reciprocating movement. J Endod 2012;38: 684–7.
12. Pereira ES, Peixoto IF, Viana AC, et al. Physical and mechanical properties of a thermomechanically treated NiTi wire used in the manufacture of rotary endodontic instruments. Int Endod J 2012;45:469–74.
13. Peters OA, Gluskin AK, Weiss RA, et al. An *in vitro* assessment of the physical properties of novel Hyflex nickel-titanium rotary instruments. Int Endod J 2012;45: 1027–34.
14. Pedullà E, Lo Savio F, Boninelli S, et al. Torsional and cyclic fatigue resistance of a new nickel-titanium instrument manufactured by electrical discharge machining. J Endod 2016;42:156–9.
15. Silva EJ, Villarino LS, Vieira VT, et al. Bending resistance and cyclic fatigue life of Reciproc, Unicone, and WaveOne reciprocating instruments. J Endod 2016;42: 1789–93.
16. de Almeida-Gomes F, de Matos HR, Nunes RF, et al. Cyclic fatigue resistance of different continuous rotation and reciprocating endodontic systems. Indian J Dent Res 2016;27:278–82.
17. da Frota MF, Espir CG, Berbert FL, et al. Comparison of cyclic fatigue and torsional resistance in reciprocating single-file systems and continuous rotary instrumentation systems. J Oral Sci 2014;56:269–75.
18. Bahia MG, Melo MC, Buono VT. Influence of simulated clinical use on the torsional behavior of nickel-titanium rotary endodontic instruments. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2006;101:675–80.
19. Turpin L, Chagneau F, Vulcain JM. Impact of two theoretical cross-sections on torsional and bending stresses of nickel-titanium root canal instrument models. J Endod 2000;26:414–7.

20. Zhang EW, Cheung GS, Zheng YF. A mathematical model for describing the mechanical behaviour of root canal instruments. Int Endod J 2011;44:72–6.
21. Peters OA. Current challenges and concepts in the preparation of root canal systems: a review. J Endod 2004;30:559–67.
22. Capar ID, Ertas H, Ok E, et al. Comparative study of different novel nickel-titanium rotary systems for root canal preparation in severely curved root canals. J Endod 2014;40:852–6.
23. Plotino G, Grande NM, Cordaro M, et al. A review of cyclic fatigue testing of nickel titanium rotary instruments. J Endod 2009;35:1469–76.
24. Wan J, Rasimick BJ, Musikant BL, et al. A comparison of cyclic fatigue resistance in reciprocating and rotary nickel-titanium instruments. Aust Endod J 2011;37:122–7.
25. Kim HC, Kwak SW, Cheung GS, et al. Cyclic fatigue and torsional resistance of two new nickel-titanium instruments used in reciprocation motion: Reciproc versus WaveOne. J Endod 2012;38:541–4.
26. Grande NM, Plotino G, Pecci R, et al. Cyclic fatigue resistance and three-dimensional analysis of instruments from two nickel-titanium rotary systems. Int Endod J 2006;39:755–63.
27. De-Deus G, Vieira VT, Silva EJ, et al. Bending resistance and dynamic and static cyclic fatigue life of Reciproc and WaveOne large instruments. J Endod 2014;40:575–9.
28. Kaval ME, Capar ID, Ertas H, Sen BH. Comparative evaluation of cyclic fatigue resistance of four different nickel-titanium rotary files with different cross-sectional designs and alloy properties. Clin Oral Investig 2017;21:1527–30.
29. Ninan E, Berzins DW. Torsion and bending properties of shape memory and superelastic nickel-titanium rotary instruments. J Endod 2013;39:101–4.
30. Gao Y, Gutmann JL, Wilkinson K, et al. Evaluation of the impact of raw materials on the fatigue and mechanical properties of ProFile Vortex rotary instruments. J Endod 2012;38:398–401.
31. Baek SH, Lee CJ, Versluis A, et al. Comparison of torsional stiffness of nickel-titanium rotary files with different geometric characteristics. J Endod 2011;37:1283–6.