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ORIGINAL ARTICLE

Cyclic fatigue and torsional strength of three different thermally treated reciprocating nickel-titanium instruments

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Abstract

Objectives The aim of this study was to evaluate the cyclic and torsional fatigue resistance of the reciprocating single-file systems Reciproc Blue 25.08 (VDW GmbH, Munich, Germany), Prodesign R 25.06 (Easy Dental Equipment, Belo Horizonte, Brazil), and WaveOne Gold 25.07 (Dentsply/Tulsa Dental Specialties, Tulsa, OK, USA).

Materials and methods Sixty reciprocating instruments of the systems Reciproc Blue R25 (RB #25 .08 taper), Prodesign R (PDR #25 .06 taper), and WaveOne Gold (WOG #25 .07 taper) ($n = 20$) were used. Cyclic fatigue resistance testing was performed by measuring the time to failure in an artificial stainless steel canal with a 60° angle of curvature and a 5-mm radius located 5 mm from the tip ($n = 10$). The torsional test (ISO 3630-1) evaluated the torque and angle of rotation at failure of new instruments ($n = 10$) in the portion 3 mm from the tip. The fractured surface of each fragment was also observed using scanning electron microscopy (SEM). In addition, a supplementary examination was performed to measure the cross-sectional area of each instrument 3 and 5 mm from the tip. The data were analyzed using one-way ANOVA and Tukey's test, and the level of significance was set at 5%.

Results The cyclic fatigue resistance values of PDR 25.06 were significantly higher ($P < 0.05$). RB 25.08 showed higher fatigue resistance than WOG 25.07 ($P < 0.05$). The torsional test showed that PDR 25.06 had lower torsional strength ($P < 0.05$). No differences were observed between RB 25.08 and WOG 25.07 ($P > 0.05$). PDR 25.06 showed higher angular rotation values than RB 25.08 and WOG 25.07 ($P < 0.05$). RB 25.08 presented higher angular rotation than WOG 25.07 ($P < 0.05$). The cross-sectional area analysis showed that PDR 25.06 presented the smallest cross-sectional areas at 3 and 5 mm from the tip ($P < 0.05$).

Conclusion PDR 25.06 presented the highest cyclic fatigue resistance and angular rotation until fracture compared to RB 25.08 and WOG 25.07. In addition, RB 25.08 and WOG 25.07 had higher torsional strength than PDR 25.06.

Clinical relevance In endodontic practice, thermally treated reciprocating instruments have been used for the root canal preparation of curved and constricted canals; therefore, these instruments should present high flexibility and suitable torsional strength to minimize the risk of instrument fracture.

Keywords NiTi alloy · Reciprocating motion · Thermal treatment · Cyclic fatigue

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Introduction

Engine-driven nickel-titanium (NiTi) has been widely used in endodontics due to its high level of flexibility and elasticity, providing safe root canal preparation in curved canals [1, 2]. However, instrument fracture continues to be a problem for clinicians. Therefore, several technological improvements have been developed for NiTi instruments to improve their mechanical properties, such as new designs, manufacturing processes, kinematics, and thermal treatments [1–6].

The reciprocating motion involves rotation in counter-clockwise and clockwise directions with 120° of difference between the two movements [3–6]. These kinematics reduce the screwing-in effect and the mechanical stress of the instruments, allowing for the use of single instruments for root canal preparation [3, 4, 6]. In addition, this motion has been shown to be safer than rotary motion during root preparation of curved and constricted root canals, reducing cyclic and torsional fatigue [3, 4, 6, 7]. Cyclic fatigue occurs when the instrument rotates in a curved canal, and repeated tension-compression stress occurs at the point of maximum flexure [8, 9]. Torsional fatigue generally occurs during straight root canal preparation when the tip of the instrument is locked into the dentin walls and the instrument continues to rotate, inducing plastic deformation or fracture [9, 10].

Manufacturers have developed several thermally treated NiTi alloys to improve the mechanical properties of endodontic instruments [1, 2, 5]. Controlled memory technology is a special thermal treatment that induces a certain amount of R-phase and B19 martensite phase, maintaining superelasticity [2]. This treatment increases cyclic fatigue resistance [2, 11] and angular deformation capacity [2, 12] compared with martensite wire (M-Wire) and conventional NiTi wire (NiTi-Wire). Thermal treatments have been widely used to improve the mechanical properties of rotary files and have also been used for reciprocating instruments [5, 6].

In 2015, a new reciprocating system—the WaveOne Gold (WOG; Dentsply/Tulsa Dental Specialties, Tulsa, OK, USA) system—was introduced to be used with the same reciprocating motion of the WaveOne file (Dentsply/Tulsa Dental Specialties) (M-Wire). However, the WOG instruments are manufactured with a new thermal treatment procedure called Gold treatment [13, 14]. This system presents different designs and sizes: #20, #25, #35, and #45 tip sizes and tapers of 0.07, 0.07, 0.06, and 0.05, respectively. The cross-sectional design of these instruments is a parallelogram design with two cutting edges [13]. In the Gold thermal process, the NiTi instrument undergoes a slow heating-cooling process that creates Ti_3Ni_4 precipitates dispersed on the NiTi surface [15], inducing martensitic transformation to occur in two steps and increasing the flexibility [13, 16, 17]. According to previous studies [13, 14], WOG 25.07 has higher cyclic fatigue resistance than the Reciproc (VDW GmbH, Munich, Germany) (M-Wire) and Wave One (M-Wire) systems. Furthermore, WOG presents higher torsional strength until fracture than Reciproc (M-Wire) [18].

Recently, a new generation of the Reciproc system—Reciproc Blue—was introduced. This reciprocating system has the same S-shaped cross section, instrument tip sizes, and tapers as the Reciproc (M-Wire) system. However, the manufacturer replaced the M-Wire alloy with a new thermal treatment called Blue treatment [5]. This thermal treatment is a special heating-cooling method that results in instruments with a blue color due to a titanium oxide layer [5, 19]. This treatment reduces the shape memory alloy of the NiTi and induces the occurrence of martensitic transformation in two phases [19, 20], increasing the cyclic fatigue resistance and flexibility compared with Reciproc M-Wire instruments [5].

The Prodesign R (Easy Dental Equipment, Belo Horizonte, MG, Brazil) is a new reciprocating single-file system that uses controlled memory technology. This system has two instruments presenting an S-shaped cross section: one size 25 with a taper of 0.06 and one size 35 with a taper of 0.05. Previous studies have reported that the 25.06 instrument has higher cyclic fatigue resistance than Reciproc (M-Wire) [21, 22] and WaveOne (M-Wire) [21].

Despite the importance of the effects of these thermal processes on the mechanical properties of NiTi instruments, there have been no studies comparing the mechanical properties among these new thermally treated reciprocating instruments. 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, WaveOne Gold 25.07, and Reciproc Blue 25.08 instruments. The null hypotheses tested were as follows: (1) there is no difference in the cyclic fatigue resistance among the instruments, and (2) there is no difference in the torsional resistance among the instruments.

Materials and methods

Sample size calculation was performed before the mechanical testing using G*Power v. 3.1 for Mac (Heinrich Heine, University of Düsseldorf) and by selecting the Wilcoxon–Mann–Whitney test from the *t* test family. The alpha-type error of 0.05, beta power of 0.95, and N2/N1 ratio of 1 were also stipulated. The test calculated a total of eight samples for each group as the ideal size for noting significant differences. However, we used an additional 20% of the total instruments to compensate for possible atypical values that might lead to sample loss.

A total of 60 NiTi instruments (length, 25 mm) were used for this study. The samples were divided into three groups ($n = 20$ per system) as follows: Reciproc Blue (RB #25, 0.08 taper), Prodesign R (PDR #25, 0.06 taper), and WaveOne Gold (WOG #25, 0.07 taper). All of the instruments were inspected under a stereomicroscope (Carl Zeiss, LLC, USA) at × 16 magnification to detect possible defects or deformities before the mechanical testing; none were discarded.

Cyclic fatigue test

The static cyclic fatigue test was performed in a custom-made device that simulated an artificial canal made of stainless steel, with a 60° angle of curvature and a 5-mm radius of curvature located 5 mm from the tip, as previously described [22]. During activation of the instruments, the artificial canal was lubricated with a synthetic oil (Super Oil; Singer Co. Ltd., Elizabethport, NJ, USA). All of the instruments were activated until fracture occurred, and the time to fracture was recorded using a digital chronometer. Throughout the testing, video recordings were obtained simultaneously, and the videos were observed to ensure the exact time of instrument fracture.

A total of ten instruments coupled to a VDW Silver Motor (VDW GmbH) connected to the cyclic fatigue device for each reciprocating system were used. The preset programs were selected according to the manufacturers' recommendations. RB 25.08 and PDR 25.06 were operated with the "Reciproc All" program, and WOG 25.07 was operated with the "WaveOne All" program. The length of the fractured tip was measured using digital calipers (Digimatic, Mitutoyo Co., Kawasaki, Japan) [10].

Torsional test

The torsional tests were performed, based on the International Organization for Standardization (ISO) standard 3630-1 (1992), using a torsion machine as previously described by other studies [22–24]. A total of ten instruments, 25 mm in length, for each reciprocating system were used. The purpose of this test was to measure the mean values of torque and maximum angular rotation until instrument fracture.

The torque and angular rotation were measured throughout the entire test, and the ultimate torsional load and angular rotation (°) values were provided by a specifically designed machine (Analógica, Belo Horizonte, MG, Brazil) connected to a computer. All of the data were recorded by a specific program of the machine (MicroTorque; Analógica). Before testing, the handles of all of the instruments were removed at the point where they were attached to the torsion shaft. The 3 mm of the instrument tips was clamped into a mandrel connected to a geared motor. The geared motor operated in the counterclockwise direction at a speed set to 2 rpm for all of the groups.

SEM evaluation

A total of 30 fractured instruments ($n = 10$ per group) were selected for SEM evaluation (JEOL, JSM-TLLOA, JSM-TLLOA, Tokyo, Japan) to determine the topographic features of the fragments after the cyclic and torsional fatigue tests. Before SEM evaluation, the instruments were cleaned in an ultrasonic cleaning device (Gnatus, Ribeirão Preto, SP, Brazil) in saline solution for 3 min. All of the fractured surfaces of the instruments were examined at × 250 magnification after cyclic fatigue testing. In addition, the fractured surfaces of the instruments submitted to torsional testing were examined at × 200 and × 1000 magnification in the centers of the surfaces.

The images of the fractured surfaces obtained by SEM were used to measure the areas of the cross-section configurations at 3 and 5 mm from the tip using software (AutoCAD; Autodesk Inc., San Rafael, CA, USA) [6, 23].

Results

The means and standard deviations of the cyclic and torsional fatigue tests (torque maximum load and angle of rotation) are presented in Table 1. PDR 25.06 had the highest cyclic fatigue resistance compared to all of the other groups ($P < 0.05$). RB 25.08 showed a significantly higher lifetime value than WOG 25.07 ($P < 0.05$).

The maximum torsional strength and angular rotation values are also presented in Table 1. PDR 25.06 showed the lowest torsional strength of all the groups ($P < 0.05$). There was no difference between RB 25.08 and WOG 25.07 ($P > 0.05$). In relation to angular rotation, PDR 25.06 showed higher values than RB 25.08 and WOG 25.07. In addition, RB 25.08 had higher values than WOG 25.07 ($P < 0.05$).

The means and standard deviations of the fragment length and cross-sectional area are presented in Table 2. There were no significant differences among the instruments regarding the fragment lengths ($P > 0.05$). The cross-sectional area 3 mm from the tip showed that PDR 25.06 presented the smallest area of the groups ($P < 0.05$). There was a significant difference between RB 25.08 and WOG 25.07 ($P < 0.05$). At 5 mm, WOG 25.07 presented the largest area of all of the instruments ($P < 0.05$). PDR 25.06 showed a significantly smaller cross-sectional area than RB 25.08 ($P < 0.05$).

SEM evaluation

Scanning electron microscopy of the fragment surfaces showed similar and typical features of cyclic fatigue and torsional failure for all of the instruments tested. After the cyclic fatigue test, all of the fractured instrument surfaces showed microvoids, which are morphologic characteristics of ductile fractures (Fig. 1). Following the torsional tests, all of the instruments showed abrasion marks and fibrous dimples near the center of rotation (Fig. 2).

Discussion

Previous studies have shown that reciprocating motion promoted a significant reduction in cyclic and torsional fatigue resistance compared to rotary motion [4, 6]. However, several other factors also affect the mechanical properties of NiTi instruments such as tip size, taper, cross-sectional design, diameter of the core, and type of thermal treatment of the NiTi

Table 1 Mean cyclic fatigue (time in seconds), torque (N.cm), and angle of rotation (°) of instruments tested

Instruments	Cyclic fatigue (s)		Torque (N.cm)		Angle (°)	
	Mean	SD	Mean	SD	Mean	SD
Reciproc Blue 25.08	876.5[b]	161.30	1.380[b]	0.1395	306.5[b]	8.592
Prodesign R 25.06	2099.8[a]	391.20	1.016[a]	0.0699	318.7[a]	8.396
WaveOne Gold 25.07	409.3[c]	77.24	1.230[b]	0.1859	296.0[c]	8.409

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

SD, standard deviation

alloy [1, 2, 25, 26]. Thus, manufacturers have modified the instrument designs and/or thermal treatment of reciprocating instruments [1, 2, 20]. Therefore, the aim of this study was to evaluate the cyclic and torsional fatigue resistance of reciprocating instruments manufactured with different designs and thermal treatments of the NiTi alloy.

The static cyclic fatigue test was performed in simulated artificial canals in stainless steel blocks, as previously reported [5, 21–23]. Although the dynamic model simulates the clinical pecking motion performed during root canal preparation, a static model was used to reduce some variables, such as the amplitude of axial motion and speed, which are subjective, because the manually controlled axial motion could be performed in different forms by clinicians [27, 28]. The torsional test was performed in accordance with the ISO 3630-1 specification, as in previous studies [22, 24]. A 3-mm point from the tip was chosen because it is the point most susceptible to fracture during constricted root canal preparation [28]. In addition, counterclockwise rotation was used for all of the instruments because it is the direction of their spiraling flutes [6].

PDR 25.06 showed the highest cyclic fatigue resistance compared to the other groups ($P < 0.05$), and RB 25.08 showed higher cyclic fatigue than WOG 25.07 ($P < 0.05$). Thus, our first null hypothesis was rejected. Although all of the tested instruments presented the same tip sizes (#25), the taper, cross-sectional design, and thermal treatment of the NiTi instruments differed among them. PDR, WOG, and RB presented tapers of 0.06, 0.07, and 0.08 mm/mm, respectively, over the first 3 mm from the tip. Usually, instruments with lower taper ensure higher cyclic fatigue resistance [29]; however, our results showed that RB 25.08 had significantly higher cyclic fatigue resistance than WOG 25.07 ($P < 0.05$). Thus, other variables, such as cross-sectional design, diameter of the core, and thermal treatment, also played roles in the results of this study.

In this study, the cyclic fatigue test was performed using the preset programs "Reciproc All" to activate RB25.08 and PDR 25.06 and "WaveOne All" to activate WOG 25.07. The mode "Reciproc All" presents 150° counterclockwise (CCW) and 30° clockwise (CW) angles of rotation and a speed of 300 rpm; the mode "WaveOne All" presents 170° CCW and 50° CW (CW) angles of rotation and a speed of 350 rpm [4]. Previous studies have shown that larger angles of rotation during reciprocating motion [4, 30] and higher rotation speeds tend to decrease the cyclic fatigue time resistance of NiTi instruments [27, 31]. However, it was previously reported that the "Reciproc All" and "WaveOne All" modes did not influence the cyclic fatigue resistance of NiTi instruments [6, 31]. It is likely that the different reciprocating modes used among the instruments did not influence our results.

The cross-sectional design and core diameter have significant effects on the cyclic fatigue resistance of NiTi instruments [8, 26, 29]. PDR 25.06 and RB 25.08 have S-shaped cross sections, and WOG 25.07 has a parallelogram-shaped cross section. In a supplementary examination, we captured the cross-sectional configuration of each instrument 5 mm from the tip by SEM and measured the area using software (AutoCAD) [5, 8]. PDR 25.06 showed the smallest area (236.549 μm^2), followed by RB 25.08 (274.780) and WaveOne Gold (309.861 μm^2) ($P < 0.05$). Previous studies have shown that a larger metal mass volume at the maximum stress point of NiTi instruments affected cyclic fatigue resistance [8, 26, 28], which could concur with the difference in the cyclic fatigue lifetimes of the instruments.

Table 2 Mean of the fragment length (mm) and cross-sectional area at 3 and 5 mm from the tip (μm^2)

Instruments	Fragment length (mm)		Cross-sectional area (3 mm)		Cross-sectional area (5 mm)	
	Mean	SD	Mean	SD	Mean	SD
Reciproc Blue 25.08	5.01[a]	0.066	113.282[c]	0.149	274.780[b]	0.328
Prodesign R 25.06	4.98[a]	0.035	98.825[a]	0.501	236.549[a]	0.216
WaveOne Gold 25.07	5.06[a]	0.054	108.301[b]	0.359	309.861[c]	0.739

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

SD, standard deviation

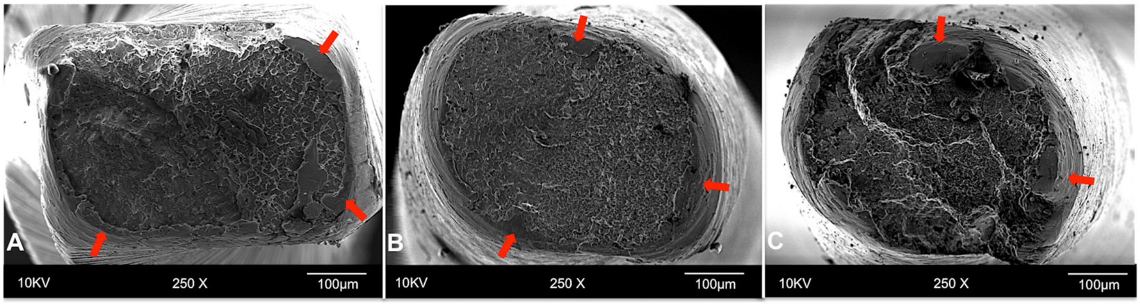

Fig. 1 Scanning electron microscopy images of the fractured surfaces of separated fragments of **a** WaveOne Gold, **b** Reciproc Blue, and **c** Prodesign R after cyclic fatigue testing. The crack origins are identified by red arrows. The images show numerous dimples spread on the fractured surfaces, which constitute a typical feature of ductile fracture

The thermal treatments of the NiTi alloys have strong influences on martensitic/austenitic transformation behavior [15, 19, 20], which could induce a different arrangement of the crystalline structure and a higher percentage of martensite transformation [2]. Previous reports have indicated that a higher percentage of martensitic phase in the NiTi alloy promoted more flexibility and greater fatigue resistance [2, 18, 32]. Our results showed that PDR 25.06 had a higher cyclic fatigue time to fracture values than all of the groups, and RB 25.08 had a higher cyclic fatigue resistance than WOG 25.07. It is likely that the different thermal treatments among them could result in different martensitic phase transformations and could induce different dissipations of the energy required for crack formation and/or propagation during cyclic fatigue testing [2]. Accordingly, Gündoğar and Özyürek [33] showed that RB 25.08 had higher cyclic fatigue resistance than WOG 25.07. In addition, it was previously reported that instruments manufactured with controlled memory technology had higher

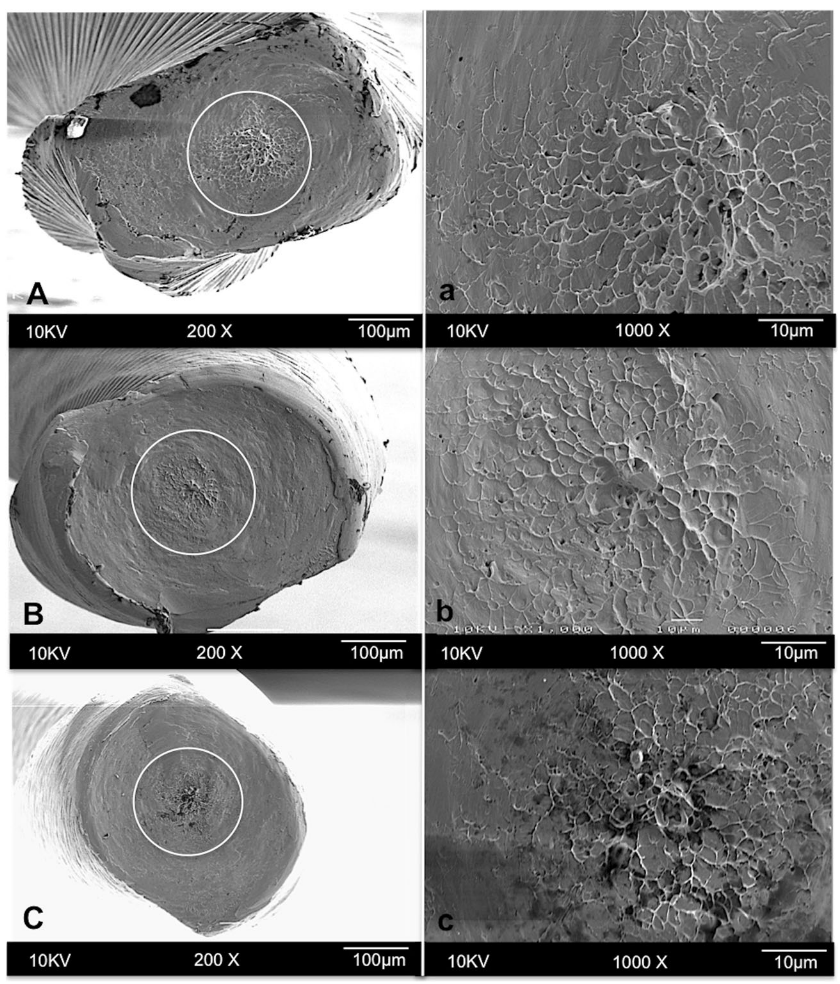

Fig. 2 Scanning electron microscopy images of the fractured surfaces of separate fragments after torsional testing (first row: A, a = WaveOne Gold; second row: B, b = Reciproc Blue; bottom row: C, c = Prodesign R). The left column shows images with the circular boxes indicating concentric abrasion marks at × 200 magnification; the right column shows concentric abrasion marks at × 1000 magnification; and the skewed dimples near the center of rotation are typical features of torsional failure

cyclic fatigue resistance than instruments manufactured by Blue [34] and Gold treatments [26]. The results of this study are in agreement with the aforementioned studies, showing that instruments manufactured with controlled memory technology are likely more fatigue resistant—and more flexible—than those manufactured with Blue and Gold treatments.

In this study, the torsional test evaluated the maximum torsional load and angular rotation to fracture while the instruments were rotating in a counterclockwise direction; however, in clinical situations, the reciprocating motion minimizes the torsional stress when the reverse motion occurs [6]. Thus, this test evaluated the torsional behavior of the instrument when undergoing a high level of torsional stress [32]. PDR 25.06 presented the lowest torsional load, compared with RB 25.08 and WOG 25.07 ($P < 0.05$); no difference was found between RB 25.08 and WOG 25.07. The second null hypothesis was rejected because significant differences were observed among the three tested instruments ($P < 0.05$): PDR 25.06 supported greater angular rotation to fracture, followed by RB 25.08 and WOG 25.07. The results of this study were likely related to the different cross-sectional designs and thermal treatments.

In a supplementary evaluation, the cross-sectional configuration of each instrument was captured in D3 by SEM, and the cross-sectional area was measured by means of software (AutoCAD) before torsional testing [5, 15]. PDR 25.06 showed the smallest area (98.825 μm^2), followed by WOG 25.07 (108.301 μm^2) and RB 25.08 (113.282 μm^2) ($P < 0.05$). Previous studies have shown that instruments with larger cross-sectional areas tend to present higher torsional load [6, 22, 23, 34]. In addition, NiTi instruments manufactured with CM-Wire demanded lower torsional loads and higher angular rotation capacity until fracture than instruments manufactured with Blue [35] and Gold treatments [26]. Our results are in agreement with the aforementioned studies and could explain the results with PDR 25.06, which presented greater deformation capacity and demanded a lower torsional load.

There have been no previous studies comparing the torsional fatigue resistance of RB 25.08 and WOG 25.07. Our results showed that RB 25.08 presented higher angular rotation values than WOG 25.07 ($P < 0.05$), but they presented similar torsional loads. The higher angular rotation values of RB 25.08 might be related to the Blue treatment, which could favor the higher flexibility and greater deformation capacity. Additionally, the different cross-sectional designs and core diameters promoted different torsional stress distribution behaviors, which could affect the susceptibility to fatigue [25, 26, 36].

The SEM analysis showed the typical features of cyclic and torsional fatigue for the three tested reciprocating files. After the cyclic fatigue test, all of the instruments evaluated showed crack initiation areas and overload zones, with numerous dimples spread on the fractured surfaces. After the torsional test, the fragments showed concentric abrasion marks and fibrous dimples at the center of rotation [6, 23, 29].

The reciprocating motion promoted a significant reduction in cyclic and torsional fatigue resistance [4, 6]. However, clinicians should be aware of the differences in mechanical properties of different available NiTi reciprocating systems [1]. According to the present results, the higher cyclic fatigue resistance of PDR 25.06 and RB 25.08 suggested these instruments to be safer than WOG 25.07 for the root canal preparation of curved canals. In contrast, the higher torsional load of RB 25.08 and WOG 25.07 indicated that they could support higher torsional stress during constricted canal preparation. Therefore, the results suggested that PDR 25.06 should be used in association with glide path preparation to decrease torsional stress, thus reducing the risk of fracture.

In conclusion, within the limitations of this study, the instruments f eatures, such as cross-sectional design, taper, and thermal treatments, had significant influences on the mechanical properties of the NiTi instruments. Our results showed that PDR 25.06 had the highest cyclic fatigue resistance and highest angular rotation values to fracture, compared with RB 25.08 and WOG 25.07. However, RB 25.08 and WOG 25.07 showed higher torsional resistance to fracture than PDR 25.06.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

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