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Cyclic and Torsional Fatigue Resistance of Seven Rotary Systems

Renan D Furlan [a], **Murilo P Alcalde** [a], **Marco A H Duarte** [a], **Clovis M Bramante** [a], **Lucila Piasecki** [a], **Rodrigo R Vivan** [a*]

[a] School of Dentistry, University of São Paulo, 17012-901 Bauru, SP, Brazil

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**Corresponding author*: Rodrigo Ricci Vivan, Al. Octávio Pinheiro Brisolla, 9-75, Bauru School of Dentistry, University of São Paulo, 17012-901 Bauru, SP, Brazil.

Tel: +55-14 32358344
E-mail: rodrigo.vivan@fob.usp.br

ABSTRACT

Introduction: This study aims to evaluate the cyclic and torsional fatigue resistance of seven rotary systems. **Methods and Materials**: A total of 140 instruments were tested, 20 of each system including Genius (GN) 25/0.04, TruShape (TS) 25/0.06, Logic (LOG) 25/0.06 taper, Vortex Blue (VB) 25/0.06, ProTaper Gold (PTG) 25/0.08, Hyflex CM (HCM) 25/0.06 and Hyflex EDM (EDM) 25/0.08 taper. Cyclic fatigue resistance testing was performed using an artificial stainless steel canal with a curvature (60° angle and 5-mm radius) located at 5 mm from the tip. The files (n=10) rotated until fracture, and time was recorded in seconds. The torsional test was evaluated according to ISO 3630-1. Data were analysed with one-way ANOVA and Tukey's tests (α=5%). The fractured surface of the instruments were assessed using scanning electron microscopy to confirm the type of fracture. **Results:** The cyclic fatigue resistance value of EDM was significantly higher than those of all tested instruments ($P<0.05$). LOG showed a higher cyclic fatigue resistance than GN or TS ($P<0.05$). There was no difference among the other groups ($P>0.05$). The torsional test showed that PTG 25/0.08 had the highest torsional strength value of all instruments tested followed by VB and EDM ($P<0.05$). The LOG showed significant difference only with GN ($P<0.05$). No difference was found among the other groups ($P>0.05$). In relation to angular deflection, the GN; TS; HCM, and EDM showed significantly higher values until fracture than the other groups ($P<0.05$). No difference was found among PTG, LOG, and VB ($P>0.05$). **Conclusion:** Our *in vitro* study EDM group had the highest cyclic fatigue resistance among all the tested instruments. For the torsional test, the PTG showed highest torsional strength and lowest angular deflection values.

Keywords: Cyclic Fatigue; Root Canal Preparation; Torsional Fatigue

Introduction

Nickel-titanium (NiTi) rotary instruments provide great flexibility and elasticity to perform a safe root canal preparation in curved canals [1-3]. However, unexpected instrument separation might occur, mainly induced by cyclic and torsional fatigue [4, 5]. Cyclic fatigue fracture is caused by the repeated compressive and tensile stresses during instrument rotation in a curved canal [4]. Torsional failure occurs when the tip of the instrument is locked in the dentine walls of the root canal and continues to rotate [5]. The above-mentioned two types of fatigue might occur simultaneously during root canal preparation of a constricted and curved canal [4, 5]. Therefore, to minimize this drawback, the manufacturers have considerably changed the instrument designs, alloy processing and manufacturing processes [6-8].

Several heat treatments have been developed to improve the cyclic and torsional fatigue resistance of the NiTi instruments, with the purpose of improving safety during root canal preparation [6, 8, 9]. Usually, heat treatments change the crystalline disposition of the nickel and titanium atoms that undergo the main shift from a cubic (austenitic phase) to a tetragonal molecular arrangement (martensitic phase), inducing different mechanical properties [7-10]. The high percentage of martensitic phase transformation increases the flexibility and thus, the cyclic fatigue and the deformation capacity during torsional fatigue [6-9]. Therefore, the different thermal treatments will provide the NiTi with different mechanical properties [7, 10].

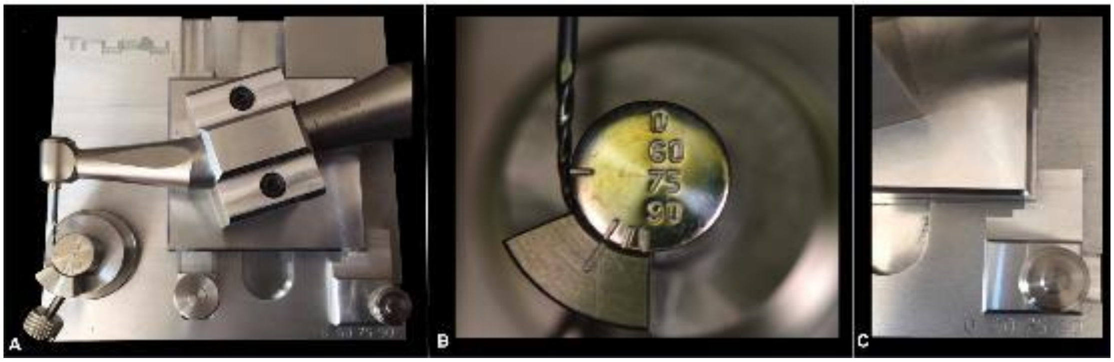

Figure 1. *A*) The instrument positioned in the cyclic fatigue test device; *B*) The artificial canal with a curvature at an angle of 60° and radius of 5-mm; *C*) Markings of the angles chosen for the test, which allow to fix the instruments in the same position

Most of NiTi rotary instruments are manufactured by machining or twisting [2, 7, 8]. However, the rotary system Hyflex EDM (Coltene/Whaledent AG, Altstatten, Switzerland) is manufactured with the use of an innovative electrical discharger machining (EDM) technique that can shape the NiTi wire by forming an electric potential between the NiTi and the tools [9, 11, 12]. The EDM induces a melting process and vaporizes the top layer of the NiTi, creating a hard, rough surface [9, 11, 12]. Pirani *et al.* [9] showed that Hyflex EDM files presented a significantly higher cyclic fatigue resistance compared with that of Hyflex CM (HCM), which is manufactured by machining and with the same NiTi alloy (controlled memory wire). The authors attributed the responsibility for the improvement in its mechanical properties to the EDM manufacturing process.

Currently, several NiTi rotary systems are available in the market, manufactured with different and proprietary heat-treatment and manufacturing processes [6, 8, 9], such as: Vortex Blue (VB) (Dentsply Sirona, York, PA,USA), TruShape (TS) (Dentsply Sirona, York, PA,USA), ProTaper Gold (PTG) (Dentsply Sirona, York, PA,USA), HCM (Coltene/Whaledent AG, Altstatten, Switzerland) and Hyflex EDM (EDM) (Coltene/Whaledent AG, Altstatten, Switzerland). Some previous studies have shown that these instruments have satisfactory mechanical properties, but different mechanical behaviour because of their designs, heat treatments and manufacturing processes [2, 9, 13-15]. There are also, two more rotary systems on the market: the Logic (LOG) (Easy Equipamentos Odontológicos, Belo Honrizonte, MG, Brazil) and Genius (GN) (Ultradent, Utah, USA) systems. These instruments are manufactured with heat treatment and conventional NiTi alloy, respectively, as reported by the manufacturers. To the best of our knowledge, there are few studies evaluating their mechanical properties up until now. It is important to assess the mechanical properties of the NiTi rotary instruments to understand their behaviour and provide clinicians with reliable recommendations [8, 9, 16]. Studies often use the scanning electron microscopy (SEM) to determine the mode of the fracture in instruments tested for fatigue and torsional tests, to evaluate the characteristics of the fracture process for the test conditions [2, 5, 9]. Thus, the aim of this study was to compare the cyclic and torsional fatigue resistance of the seven aforementioned NiTi rotary instruments. The null hypotheses tested were as follows: *1*) there are no differences in the cyclic fatigue resistance among the instruments and *2*) there are no differences in the torsional resistance among the instruments.

Materials and Methods

A total of 140 NiTi instruments (25 mm length) were selected for this study. The sample calculation was performed using the G*Power v3.1 for Mac (Heinrich Heine, University of Düsseldorf, Germany) and by selecting the Wilcoxon Mann-Whitney test of the *t*-test family. The 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 instruments for each group were used as the ideal size for no significant differences. However, an additional 20% of instruments were used to compensate possible atypical values that might lead to samples loss, thus 10 instruments of each system per test were selected.

For each system, a 0.25 mm tip size instrument was selected, as follows: GN 25/0.04, TS 25/0.06, LOG 25/0.06, VB 25/0.06, PTG 25/0.08, HCM 25/0.06 and EDM 25/0.08. All instruments were inspected under a stereomicroscope (Carls Zeiss, LLC, and Thornwood, NY, USA) under 16× magnification before the mechanical test to discard any instrument presenting defects or deformities.

Cyclic fatigue test

The cyclic fatigue test was performed in a custom-made device that simulated an artificial canal made of stainless-steel, with a curvature at an angle of 60° and a 5-mm radius located 5 mm from the tip of the instrument (Figure 1A). The curvature of the artificial

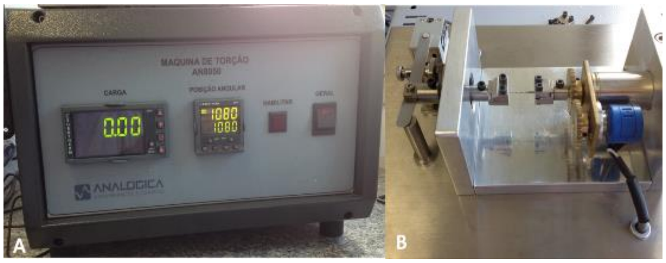

Figure 2. Torsional test machine: maximum torque and angular rotation were measured, and the ultimate torsional load and angular rotation

canal was fitted onto a cylindrical guide made of the same material (radius of 5 mm). There was an external arch with a 1-mm deep groove that served as a guide path for the instruments, which kept the instruments in the curvature to rotate freely during the test. The device allowed the accurate and reproducible position of the curvature for the all instruments (Figure 1B).

During the cyclic fatigue test, the low-speed handpiece remained in a fixed position, held by brackets bolted to the iron base. This iron base had vertical and horizontal movement to allow the instrument to be inserted into the artificial canal. In addition, there were markings with the angles chosen for the test, thus the iron base could always be in the chosen position and be fixed (vertical and horizontal) (Figure 1C). A total of ten instruments for each rotary system were used, coupled to a VDW Silver Motor (VDW, Munich, Germany) connected to the cyclic fatigue device. The "DR'S" program were selected and set according the manufactures recommendations: GN-Genius size 25/0.04: 350 rpm and 0.5 N torque, TS-TruShape size 25/0.06: 300 rpm and 3 N torque, LOG-Logic size 25/0.06 er: 900 rpm and 4 N torque, VB-Vortex Blue size 25/0.06 r: 500 rpm and 2.8 N torque, PTG-ProTaper Gold size 25/0.08: 300 rpm and 3.1 N torque, HCM-Hyflex CM size 25/0.06: 500 rpm and 2.5 N torque and EDM-Hyflex EDM size 25/0.08: 500 rpm and 2.5 N torque.

During the test, the artificial canal was lubricated with a synthetic oil (Super Oil, Singer Co Ltd, Elizabethport, NJ, USA).

Table 1. Mean (SD) of cyclic fatigue (time in seconds) and number of cycles (NCF) of the tested instruments

Instruments	Cyclic Fatigue (seconds)	NCF
	Mean (SD)	Mean (SD)
EDM 25.08	508.10 ^{a} (93.26)	4243.10^{a} (1.325)
HCM 25.06	222.60^{b} (31.97)	1854.20^{b,c} (652.2)
PTG 25.08	191.00^{b,c} (26.97)	955.10^{c} (296.4)
LOG 25.06	197.60^{b,c} (36.03)	2964.20^{b} (1.164)
GN 25.04	191.40^{b,c} (16.38)	1115.80^{c} (91.34)
VB 25.06	170.60^{b,c} (14.54)	1421.09^{b,c} (463.9)
TS 25.06	150.90^{c} (21.72)	754.40c (108.5)

Different superscript letters in the same column indicate statistical differences among groups (P<0.05); SD; standard deviation, EDM; electrical discharger machining, HCM; Hyflex CM , PTG; ProTaper Gold, LOG; Logic, GN; Genius , VB; Vortex Blue, TS; TruShape

All the instruments were rotated inside the artificial canal until test. The time to fracture was recorded using a digital chronometer and a video recording was performed simuteneously to ensure accurate time of instrument fracture. In addition, the number of cycles to failure (NCF) was calculated, according to the rotational speed of the instrument.

Torsional fatigue test

A total of 10 instruments of each rotary system were tested to measure the torque and maximum angular deflection necessary until fracture. The torsional tests were performed according on the International Organization for Standardization (ISO) 3630-1 (1992), using a torsional machine as previously decribed [17-19].

The maximum torque and angular rotation were measured, and the ultimate torsional load and angular rotation values were provided by a specifically designed machine (Analógica, Belo Horizonte, MG, Brazil) (Figure 2) connected to a computer. The data were recorded by the specific software (MicroTorque, Analógica, Belo Horizonte, MG, Brazil) of the machine. Before the test, the instrument handles were removed at the point where they were fixed to the torsion shaft. The three millimeters of the instrument tips were clamped into a mandril connected to a geared motor that operated in clockwise rotation, at a speed set to 2 rpm for all the groups.

SEM evaluation

A total of seventy fractured instruments (*n*=10 per group) were selected for SEM evaluation (JEOL, JSM-TLLOA, Tokyo, Japan) to determine the topographic features of the fragments after the cylic and torsional fatigue tests. All the instruments were cleaned in a ultrasonic device (Gnatus, Ribeirão Preto, São Paulo, Brazil) using distilled water for 3 min after the mechanical tests [20]. The fractured surfaces of the instruments were assessed under 250× magnification after the cyclic fatigue test. In addition, the fractured surface of the instruments used for the torsional test were assessed under 250× and 1000× magnification in the centre of the surface.

Table 2. Torque (Ncm) and angular deflection (°) of the tested instruments

Instruments	Torque (Ncm)	Angles (°)
	Mean (SD)	Mean (SD)
EDM 25.08	1.17^{c} (0.149)	659.70^{a} (82.32)
HCM 25.06	0.66^{e,f} (0.075)	641.50^{a} (53.91)
PTG 25.08	1.74^{a} (0.202)	323.60^{b} (29.55)
LOG 25.06	0.90^{d} (0.165)	444.10^{b} (73.41)
GN 25.04	0.53^{f} (0.084)	739.90^{a} (56.97)
VB 25.06	1.39^{b} (0.071)	393.30^{b} (21.97)
TS 25.06	0.72^{e} (0.154)	742.30^{a} (193.70)

Different superscript letters in the same column indicate statistical differences among groups (P<0.05) , SD; standard deviation, EDM; electrical discharger machining, HCM; Hyflex CM , PTG; ProTaper Gold, LOG; Logic, GN; Genius , VB; Vortex Blue, TS; TruShape

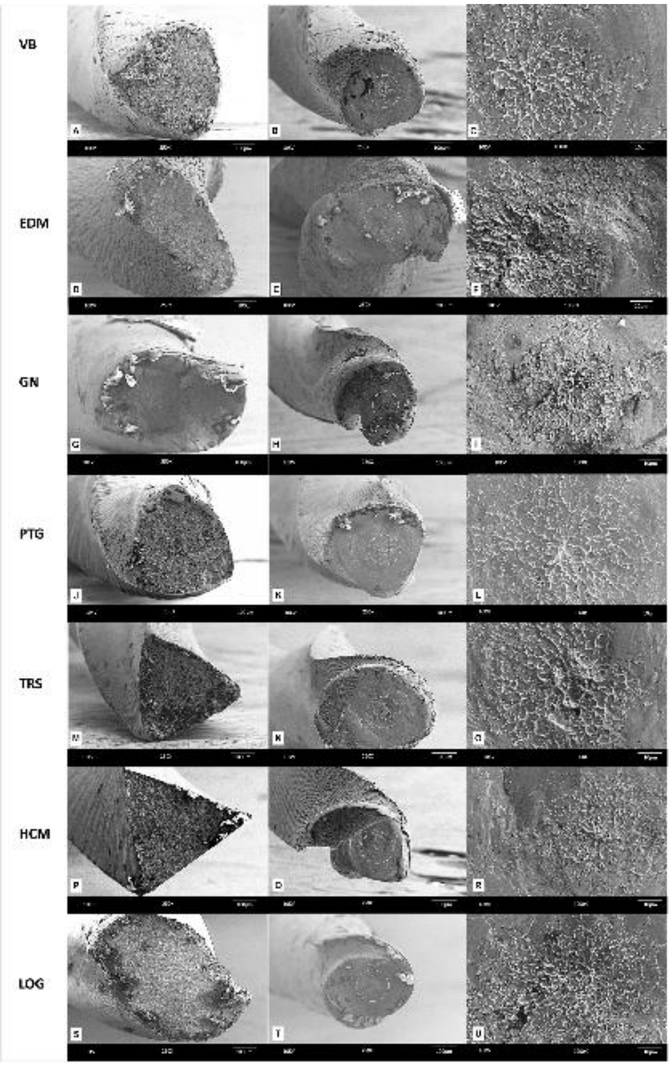

Figure 3. Scanning electron microscopy images of fractured surfaces of separated fragments of different rotary instruments: *A, B, C)* Vortex Blue 25.06; *D, E, F)* Hyflex EDM 25.08; *G, H, I)* Genius 25.04; *J, K, L)* ProTaper Gold 25.08; *M, N, O)* TruShape 25.06; *P, Q, R)* Hyflex CM 25.06; *S, T, U)* Logic 25.06 after torsional and cyclic fatigue testing. The first column shows the front view of the instruments at 250× magnification after the cyclic fatigue testing where appears numerous dimples on the fractures surfaces, which constitute a typical feature of ductile fracture; the second column shows the front view images of the instrument at 250× magnification after torsional fatigue testing; the third column shows the concentric abrasion mark at 1000× magnification of the instrument in the second column; the skewed dimples near the center of rotation are typical features of torsional failure

Statistical analysis

Preliminary analysis of data normality was performed with the Shapiro-Wilk test, showing that the data were normally distributed. The One-way analysis of variance (ANOVA) and Tukey's tests were used for multiple and individual comparisons. The Prism 6.0 software (GraphPad Software Inc., La Jolla, CA, USA) was used as the analytical tool, and the level of significance was set at 5%.

Results

Cyclic fatigue

The mean and standard deviations of time and NCF to fracture are shown in Table 1. The EDM presented the highest time and NCF values among all instruments ($P<0.05$). The TS showed the lowest time to fracture with a significant difference compared with EDM and HCM ($P<0.05$). In relation the NCF, no difference was found among HCM; LOG, and VB ($P>0.05$). The TS showed a significantly lower NCF value in comparison with LOG and EDM ($P<0.05$).

Torsional fatigue

The maximum torsional strength and angular deflection values are presented in Table 2. The PTG showed the highest torsional strength in comparison with all the other groups followed by VB ($P<0.05$). The EDM presented a higher torsional load value than HCM, LOG, GN, and TS ($P<0.05$). The LOG showed higher torsional values in comparison with HCM, GN, and TS ($P<0.05$). The GN showed the lowest torsional load value with no significant difference compared with HCM ($P>0.05$).

In relation the angular deflection, the TS, EDM, GN, and HCM presented similar values with no significant difference among them ($P>0.05$). Moreover, no significant difference was found among LOG, PTG, and VB ($P>0.05$).

SEM evaluation

Scanning electron microscopy of the fragment surfaces showed typical features of cyclic fatigue and torsional failure for all instruments tested. In the cyclic fatigue test, all the fractured instrument surfaces showed micro-voids, morphologic characteristics of ductile fracture. In relation the torsional test, all the instruments showed abrasion marks and fibrous dimples near the centre of rotation (Figure 3).

Discussion

The mechanical properties of NiTi rotary instruments have been improved during the last decades. The manufacturers have developed NiTi instruments with different tip sizes, tapers, cross-sectional design, core diameter, different thermal treatments of the NiTi and manufacturing processes [3, 7-9, 16]. These different features are directly correlated to the mechanical properties and behaviour of the NiTi instruments [6-8, 19]. At the present time, there are several NiTi rotary systems available and it is important to understand their differences, with the purpose of improving safety during root canal preparation [12], and the use of each instrument correctly for different clinical situations such as a constrict canal or a canal with a high curvature.

In this present study, the static cyclic fatigue model was used to ensure the precise position and angle of curvature for all NiTi instruments, irrespective of the taper. Although a dynamic model simulates the clinical pecking motion performed during root canal preparation [16], the static model was used to reduce some variables, such as amplitude of axial motion and speed, which are subjective, because the manually controlled axial motion could be performed in different ways by different clinicians [21]. In relation to the torsional test, this was perfomed in accordance with the ISO 3630/1 specification, as in previous studies [17-19]. The 3 mm of the tip and instrument shaft were fastened, and clockwise rotation was used for all instruments, because this is the direction of their spiral flutes [17-19].

The cyclic fatigue resistance in the present study was reported both as the time to fracture and as NCF. The NCF was calculated because each instrument was used according to the rotational speed recommended by the manufacturers [1, 2]. The EDM presented the highest time to fracture value in comparison with the values of all the groups, and TS showed the lowest time value, with significant difference in comparison with EDM and HCM; moreover, no difference was found among the other groups. Thus, our first null hypothesis was rejected, also the use of time (in sec) and NCF were chosen because several recent published articles present both results [6, 17, 22, 23]. In addition, the NCF is strongly related with the rotational speed indicated by the manufacturers. This fact could be outpointed when comparing the results of LOG and PTG. The LOG presented similar time to fatigue than PTG; however, when observed the NCF, the LOG presented the highest NCF than PTG. These modifications of the results are totally correlated with the different rotational speed indicated by the manufacturers. The LOG was rotated at 900 rpm and the PTG at 300. Therefore, the results could be interpreted by various forms if we use only time or NCF. The authors opted to use both values to become the analyses more complete.

Although all the instruments presented same tip sizes (#25), they had different cross-sections, taper, and thermal treatment of NiTi, which affected their mechanical properties [7, 12, 16, 24]. In agreement with our results, previous studies have shown that EDM had higher cyclic fatigue resistance than other thermal treated NiTi instruments, such as PTG, HCM, WaveOne Gold (Dentsply), Reciproc Blue (VDW, Munich, Germany), and this can be explained as follow: despite the thermal treatment, the EDM is manufactured by the electrical discharge machining method [11, 12, 16, 24], and according to Aminsobhani *et al.* [25], who evaluated the Neoniti (Neolix) by differential scanning calorimetry (DSC), the instrument revealed rhombohedral phase (R-phase) transformtion, which is present in Hyflex EDM, because both are manufactured by the same method.

Generally, the thermal treatments of the NiTi instruments improved the cyclic fatigue resistance in comparison with conventional NiTi instruments, because they induced a higher percentage of martensitic phase and promoted more flexibility [12, 23, 26, 27]. However, our results showed that GN presented a longer lifespan than TS, and was similar to other heat-treated instruments (HCM, LOG, PTG, and VB). A smaller taper and metal mass of the NiTi are known to induce better cyclic fatigue resistance [16, 27, 28]. Therefore, a possible explanation for these results could be the design features of GN, which presented the smallest taper and "S" cross section features, and showed less metalic mass when compared with the other instruments. Accordingly to *Özyürek et al.* [29], who compared GN system with Reciproc Blue (VDW, Munich, Germany) and Wave One Gold (Dentsply Maillefer, Ballaigues, Switzerland) in cyclic fatigue test in reciprocating movement, the GN system showed the highest cyclic fatigue resistance and smallest cross-sectional area. Furthermore, the manufacturing process also plays a role in the fatigue resistance: although EDM and HCM are manufactured with the same thermal treatment, the electrical discharge machining method modifies the shape of a work piece by making an electrical potential between the working piece and the tools without grinding them, may be the main factor in the significantly higher cyclic fatigue resistance of these files [9, 11, 30].

The present results were also reported NCF values because of the variation in the rotational speed that are recommended for each instrument. The results shown in both forms allowed more complete analysis and outpoint that NCF is directly affected by the rotational speed. According to the present results, EDM also presented the highest NCF value compared with those of all the groups while TS showed significantly lower NCF value in comparison with LOG, and EDM. The rotation speed affects the cyclic fatigue because it is related to more repeated compressive and tensile stresses of the NiTi instruments [1, 2, 16]. It has been shown that a higher rotation speed increases the NCF value when compared with other instruments used at a lower speed for the same length of time; on the other hand, some authors demonstrated that there is no direct correlation between rotational speed and NCF, where torsional stresses are greater at lower speeds [22], but a higher speed could generate more heat in the surface of the instrument, generating more stress in the metal causing earlier failure [31]. Therefore, the rotation speed recommended by the manufacturer might have affected the cyclic fatigue resistance in this study, because the instruments used at a higher speed were submitted to more mechanical stress in the root curvature. Probably, if the LOG, GN, TS, and PTG were used at 500 rpm, as were EDM; HCM and VB; the LOG would probably increase the cyclic fatigue resistance, and GN, TS, PTG would present worse results. Future studies should be performed to evaluate the real impact of the different rotational speed on the cyclic fatigue resistance of the instruments used in this study.

The torsional test was performed to evaluate the maximum torsional strength and angular deflection to fracture [5, 17-19, 26]. The results of this study showed that PTG had the highest torsional strength value in comparison with those of all the other groups followed by VB and EDM. The LOG showed higher torsional values in comparison with HCM, GN, and TS. The GN and HCM presented similar torsional strength values between them. In relation with the angular deflection, the TS, EDM, GN, and HCM presented similar values with no significant difference among them. No difference was found among LOG, PTG, and VB. Therefore, the second null hypothesis was rejected.

The heat treatments promoted greater flexibility of the NiTi instruments and in general, favoured a lower torsional load and greater angular deflection [3, 8, 12, 17, 32, 33] . However, our results showed that GN taper presented low torsional load and high angular deflection, such as presented by some heat treated NiTi instruments. Therefore, other variables such as the different cross section design, diameter of core and taper should be considered for this study. Previous reports have indicated that the above-mentioned three factors affected the metal mass volume of the NiTi instruments [7, 8, 34, 35]. The larger metal mass tends to promote a higher torsional load and lower angular deflection of the NiTi instruments [7, 12, 34, 35]. The different cross-section, diameter of core and taper among them probably promoted a different torsional stress distribution behaviour, affecting the susceptibility to fatigue.

The SEM analysis showed the typical features of cyclic and torsional fatigue for all the instruments. After the cyclic fatigue test, all the evaluated instruments showed areas of crack initiation and overload zones, with numerous dimples spread across the fractured surface. After the torsional test, the fragments showed concentric abrasion marks and fibrous dimples at the centre of rotation, as previously reported [12, 17, 26, 33].

Clinicians should understand about the mechanical properties of NiTi rotary instruments to enable them to use them safely in different clinical situations [7, 12]. The metal mass of the instruments influences its cyclic fatigue resistance decreasing as the instrument diameter increase. Varied cross-sections may also interfere in the resistance of the instrument, and instrument with larger cross-sectional areas present greater torsional rigidity , and consequently lower resistance to cyclic fatigue [20], corroborating to our results. Among the instruments tested in this study, EDM presented the more favourable mechanical properties. The clinical implication of the high angular deflection and suitable torsional strength of the EDM is the possible detection of plastic/permanent deformation signs prior to an eminent instrument fracture, because its plastic/permanent deformation may be easily detected [35]. In addition, the higher cyclic fatigue resistance could ensure the safe root canal preparation of a severely curved canal. Fractures are a complex and multifactorial clinical situation [36]. Factors such as neglecting perception of a severe to moderate curvature, diameter and taper of the instrument, taper of the canal, metallurgical properties of the instruments, mechanical stress caused by the operator, such as choosing wrong speed and torque for the instrument, can cause a premature fracture of the instrument [36].

The heat treated instruments suffer interferences by the body temperature, affecting the flexural resistance of the NiTi instruments, because it is capable of modifying the transformation temperatures of the NiTi, decreasing the fatigue life of the instruments [37, 38]. This study present limitations because it was carried out in room temperature, and may be staggering the results. It could be stated that there are no better or worse instrument, but the one that suites the best for a clinical situation such as a severe curved or a constricted canal where the operator should know which instrument to choose.

Conclusion

Within the limitations of this *in vitro* study, the EDM presented the highest cyclic fatigue resistance in time and NCF when compared with all the instruments tested. In addition, the PTG showed the highest torsional strength and a low angular deflection.

In endodontic practice, instruments with higher cyclic fatigue resistance will minimize the risk of instrument fracture especially in curved canals, so will the use of instruments with higher torsional strength in constricted canals.

Conflict of Interest: 'None declared'.

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