Cyclic and torsional fatigue resistance of four rotary NiTi instruments with similar cross-sectional design and different thermal treatments

Michel Espinosa **KLYMUS**[1]
Murilo Priori **ALCALDE**[2]
Rodrigo Ricci **VIVAN**[1]
Bruno Carvalho de **VASCONCELOS**[3]
Marcus Vinícius Reis **SÓ**[4]
Marco Antonio Hungaro **DUARTE**[1]

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ABSTRACT

Objective: The aim of this study was to evaluate the cyclic and torsional fatigue resistance of Nickel-Titanium rotary instruments with similar cross-sectional design and manufactured by different thermal treatments: Hyflex CM (HCM 25/.06) Vortex Blue (VB 25/.06), Sequence Rotary File (SRF 25/.06) and EdgeSequel (EDF 25/.06) (n=20). **Material and Methods:** Cyclic fatigue test evaluated the time and number of cycles to failure (NCF) in an artificial stainless steel canal with 60° and 5-mm radius of curvature (n=10). The torsional test (ISO 3630-1) evaluated he maximum torque and distortion angle to failure at 3 mm from the tip (n=10). After the torsional and cyclic fatigue test the instruments were evaluated by scanning electron microscope (SEM). Data were analyzed using one-way ANOVA and Tukey tests, and the level of significance was set at 5%. **Results:** The HCM presented the longest time and highest NCF to fatigue than all the groups ($P<0.05$). The SRF presented similar time ($P>0.05$) and lower NCF ($P<0.05$) to fatigue than VB. Regarding to the torsional test, HCM presented the lowest torque load and the highest distortion angle of all the groups ($P<0.05$). No significant difference was found among VB, SRF and EDF regarding the distortion angle ($P>0.05$). **Conclusion:** The HCM presented the highest cyclic fatigue resistance and distortion angle to failure. However, the VB showed higher torsional load to failure.

Keywords: Dental Instruments. Endodontics. Nickel. Titanium

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[1] Universidade de São Paulo, Departamento de Dentística, Endodontia e Materiais Odontológicos (Bauru/SP, Brazil).

[2] Universidade do Sagrado Coração, Departamento de Odontologia (Bauru/SP, Brazil).

[3] Universidade Federal do Ceará, Departamento de Odontologia (Sobral/CE, Brazil).

[4] Universidade Federal do Rio Grande do Sul, Departamento de Odontologia (Porto Alegre/RS, Brazil).

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Contact address: Murilo Priori Alcalde
Al. Octávio Pinheiro Brisola no. 9-75
CEP: 17.012-901 – Bauru/SP, Brazil
E-mail: murilo_alcalde@hotmail.com

Introduction

Engine-driven Nickel-Titanium (NITI) instruments have been widely used for shaping curved root canals due to their high flexibility and elasticity, ensuring safe root preparation.[1,2] However, unexpected instrument fracture can occur and many variables may contribute to this occurrence. The most common causes are cyclic and torsional stress.[3,4]

Cyclic fatigue occurs by repeated compressive and tensile stress when the instrument rotates in a curved canal.[4,5] Torsional fatigue occurs when the tip of instrument locks in the root canal walls while the shank continues to rotate.[4,5] This can happen especially in constricted canals, when the instruments are susceptible to higher torsional stress.[4,5] Therefore, the manufacturers have developed instruments with different designs (tapers, cross-section, and tip size) and thermal treatments of NiTi alloys to improve the mechanical properties and reduce the risks of instrument fracture.[1-6]

Previous reports have indicated that instrument designs affect the cyclic and torsional fatigue resistance of NiTi instruments.[1,2,6-10] Therefore, it might be speculated that NiTi instruments with same design features present similar mechanical properties. Nevertheless, NiTi instruments with similar tip size, cross-sectional design and taper present different cyclic and torsional fatigue resistance when manufactured from different NiTi alloy.[9,11-15] Therefore, the type of NiTi should be considered when evaluating the mechanical properties of endodontic instruments.

Thermal treatments assist to control the transition temperatures of NiTi alloy and induce a better arrangement of the crystal structure.[1,2,10-12] Depending on the type of thermal treatment, a higher percentage of martensite or R-Phase can be induced, increasing the flexibility and reducing the risk of instrument fracture.[1,6,10-12]

The Hyflex CM rotary system (HCM; Coltene, Whaladent, Switzerland) has instruments with a triangular cross-section,constant taper and they are manufactured by a thermal treatment named controlled memory technology (CM Wire; DS Dental, Johnson City, TN)[16]. Several previous studies have shown that instrument made with CM-Wire have superior flexibility and fatigue resistance compared with instruments made of conventional NiTi and other thermally treated NiTi instruments.[2,5,16,17]

The EdgeSequel Sapphire rotary system (EdgeEndo, Albuquerque, TN, USA) has triangular a cross-section, constant taper and is manufactured by a proprietary thermal treatment named Fire-wire. According the manufacturers, this treatment controls the memory of the NiTi, in a manner similar to that of the controlled memory technology, and induces a high degree of flexibility of the NiTi.[18] There is a lack of information regarding the mechanical properties these instruments.

The Vortex Blue (VB) rotary system is designed with a constant taper, convex triangular cross-section and is manufactured by a special thermal process, named Blue treatment.[13] A previous study showed that VB had lower cyclic fatigue resistance than HCM at room temperature.[19]

Recently, a new rotary system was introduced on the market, Sequence Rotary File (Mk Life, RS, Brazil). This system has five instruments presenting a triangular cross-section and constant taper: 15/.04, 20/.04, 25/.06 and 35/.04. According the manufacturer, these instruments are manufactured by a proprietary thermal treatment that results in instruments with a blue color due to a titanium oxide layer, similar to that of the Blue treatment of VB.

Despite the impact of thermal treatments on the mechanical properties of NiTi instruments, few studies have investigated their effect on the mechanical properties of NiTi instruments with similar features in terms of cross-sectional design and taper. Therefore, the aim of this study was to evaluate the cyclic and torsional fatigue resistance of Nickel-Titanium rotary instruments with similar features and manufactured by different thermal treatments. The null hypotheses tested were as follows: (1) there would be no differences in the cyclic fatigue resistance among the instruments and (2) there would be no differences in the torsional resistance among the instruments.

Materials and Methods

Before the cyclic and torsional tests, the sample calculation was performed by using the G*Power v3.1 for Mac (Heinrich Heine, University of Düsseldorf) and 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 10 samples per group were indicated as the ideal size required for noting significant differences. Every instrument was inspected for defects or deformities before being tested under a stereomicroscope (Carls Zeiss, LLC, EUA) at 16x magnification; none were discarded. All files used were 25-mm long, with 10 instruments of each brand being used for cyclic and torsional testing.

A total of 80 NiTi instruments of four rotary systems (n = 20 per system) were used in this study, as follows: Hyflex CM (HCM; #25/.06; Coltene-Whaladent, Switzerland) Vortex Blue (VB; #25/.06; Dentsply Maillefer, Ballaigues, Switzerland), Sequence Rotary File (SRF; #25/.06; MK Life, RS, Brazil) and EdgeSequel (EDF; #25/.06; EdgeEndo, NM USA).

Cyclic fatigue Test

The static cyclic fatigue tests were performed using a custom-made device that allowed simulation of an artificial curved canal with 60° angle of curvature and a 5-mm radius of curvature, as in previous study.[20] The curvature of the stainless-steel artificial canal was fitted onto a guide cylinder made of the same material. The artificial canal had a 1 mm deep groove, which served as guide path for the instruments, maintaining them on the curvature and allow freely to rotate (Fig 1).

Ten instruments of each rotary 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) in accordance with the manufacturers' instructions. The HCM, VB and EDF were used at 500 rpm, whereas the

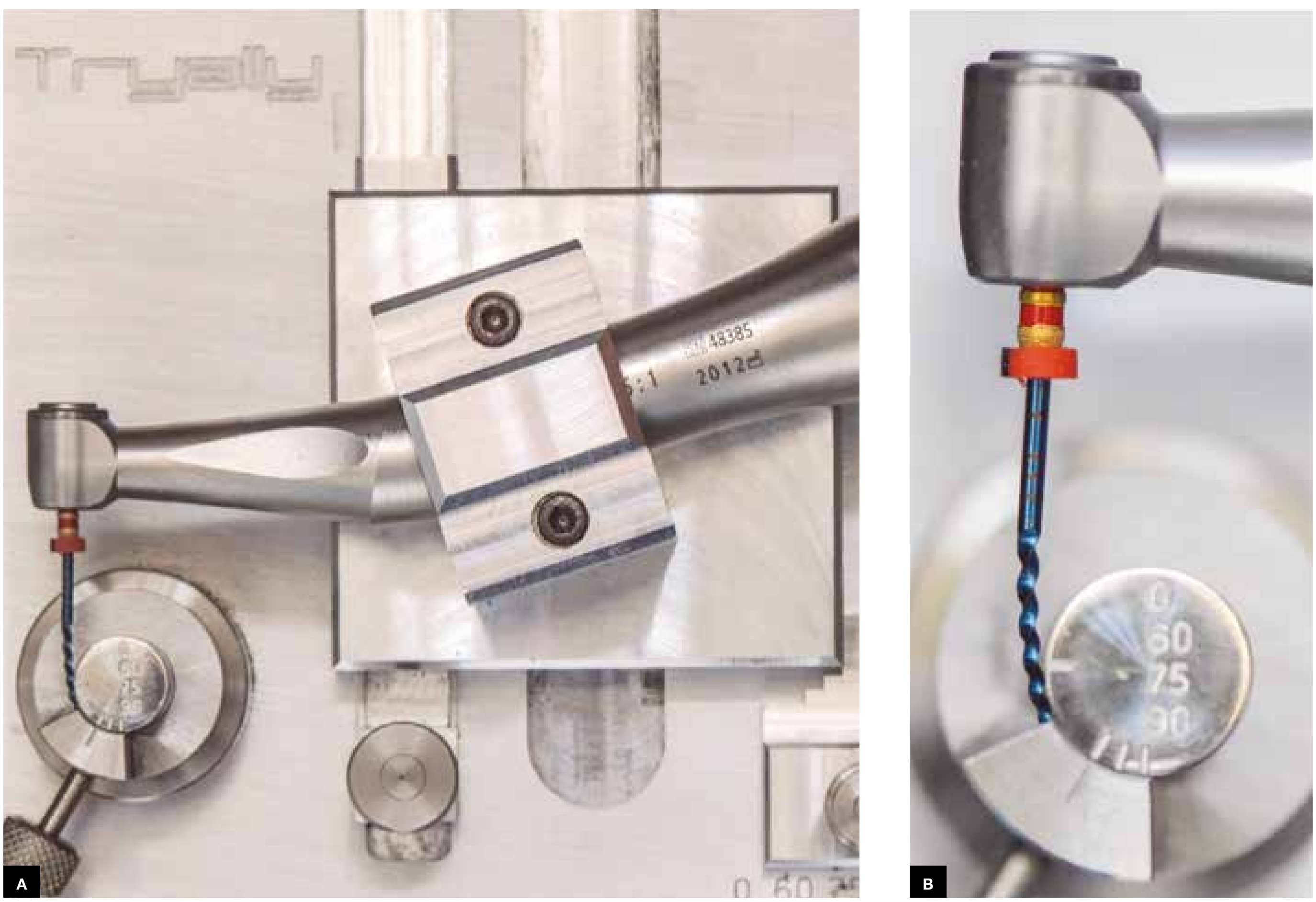

Figure 1. A) The instrument positioned in the cyclic fatigue test device. (**B**) The artificial canal with an angle of curvature of 60° and a radius of 5 mm.

SRF was used at 400 rpm until failure. During activation of the instruments, the artificial canal was lubricated with synthetic oil (Super Oil; Singer Co. Ltd., Elizabethport, NJ, USA). The instruments were activated until failure occurred, and the time was recorded using a digital chronometer. In addition, a video recording was made simultaneosly. The time to failure in seconds was multiplied by the number of rotations per minute (RPM)/60 (number of rotations per seconds) to obtain the number of cycles to failure (NCF) for each instrument.

Torsional fatigue Test

The torsion tests were performed, based on the International Organization for Standardisation ISO 3630-1 (1992) specification, by using a torsion machine as previously described.[21,22] All files used were 25-mm long and 10 instruments of each system were used to test the torsion to establish maximum torque load and distortion angle to failure.

Before the test, the handles of all of the instruments were removed at the point where they were attached to the torsion shaft. The torque and distortion angle values were provided by a specifically designed torsion machine (Analógica, Belo Horizonte, MG, Brazil) connected to a computer. Three millimeters of the instrument tips were clamped into a mandrel connected to a geared motor. 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 geared motor operated in the clockwise direction at a speed set to 2 rpm. All data were recorded by a specific program of the machine (MicroTorque; Analógica).

SEM Evaluation

The fractured surface of all the instruments were examined by scanning electron microscopy (JEOL, JSM-TLLOA, Tokyo, Japan) to determine the topographic features of the fragments after the cyclic and torsional fatigue tests.Before SEM evaluation, instruments were ultrasonically cleaned to remove debris. The fractured surfaces of the instruments submitted to cyclic fatigue testing were assessed at 150x magnification. Furthermore, images were taken at 1000x magnification, in the center of the surfaces of the instruments submitted to the torsional test.

Statistical Analysis

Data were first examined by using the Shapiro-Wilk test for normality of distribuition. The results were analysed by using one-way ANOVA and Tukey tests, and the level of significance was set at 5%.

Results

The mean and standard deviations of the cyclic fatigue (time in seconds and number of cycles) and torsional fatigue resistance (torque maximum load and distortion angle) are presented in Table 1. The HCM showed longest time and highest NCF to cyclic fatigue in comparison with all the groups ($P<0.05$). The SRF presented similar time ($P<0.05$) and lower NCF ($P<0.05$) to fatigue than VB. The EDF presented the lowest time and NCF compared with the other groups ($P<0.05$). In relation the torsional test, HCM presented the lowest torque load and highest distortion angle compared with all the groups ($P<0.05$). The SRF and EDF presented

Table 1. Mean values of time (in seconds), number of cycles (NCF), Torque (N.cm) and Distortion Angle (°) of instruments tested

Instruments	Cyclic Fatigue				Torsional Fatigue			
	Time (seconds)		Cycles (NCF)		Torque (N.cm)		Angles (°)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HCM 25.06	222.5[a]	26.30	1853[a]	219.1	0.69[a]	0.072	659.6[a]	79.22
VB 25.06	178.1[b]	10.43	1484[b]	86.88	1.35[b]	0.068	388.0[b]	24.47
SRF 25.06	168.8[b]	3.17	1124[c]	21.15	1.25[c]	0.077	413.5[c]	25.86
EDF 25.06	112.0[c]	3.26	933.1[d]	27.17	1.27[c]	0.040	395.6[d]	6.34

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

similar torque load (P>0.05). There was significantly difference among VB, SRF and EDF relative to distortion angle (P>0.05).

SEM evaluation

Scanning electron microscopy of the fractured surface showed similar and typical topographic features of cyclic fatigue and torsional failure for all instruments. In the cyclic fatigue test, the instruments displayed fractured surfaces with microvoids, and morphological characteristics of ductile fracture (Fig 2). In the torsional test, the instruments showed concentric abrasion marks and fibrous dimple marks in the center of rotation for torsional failure (Fig 3).

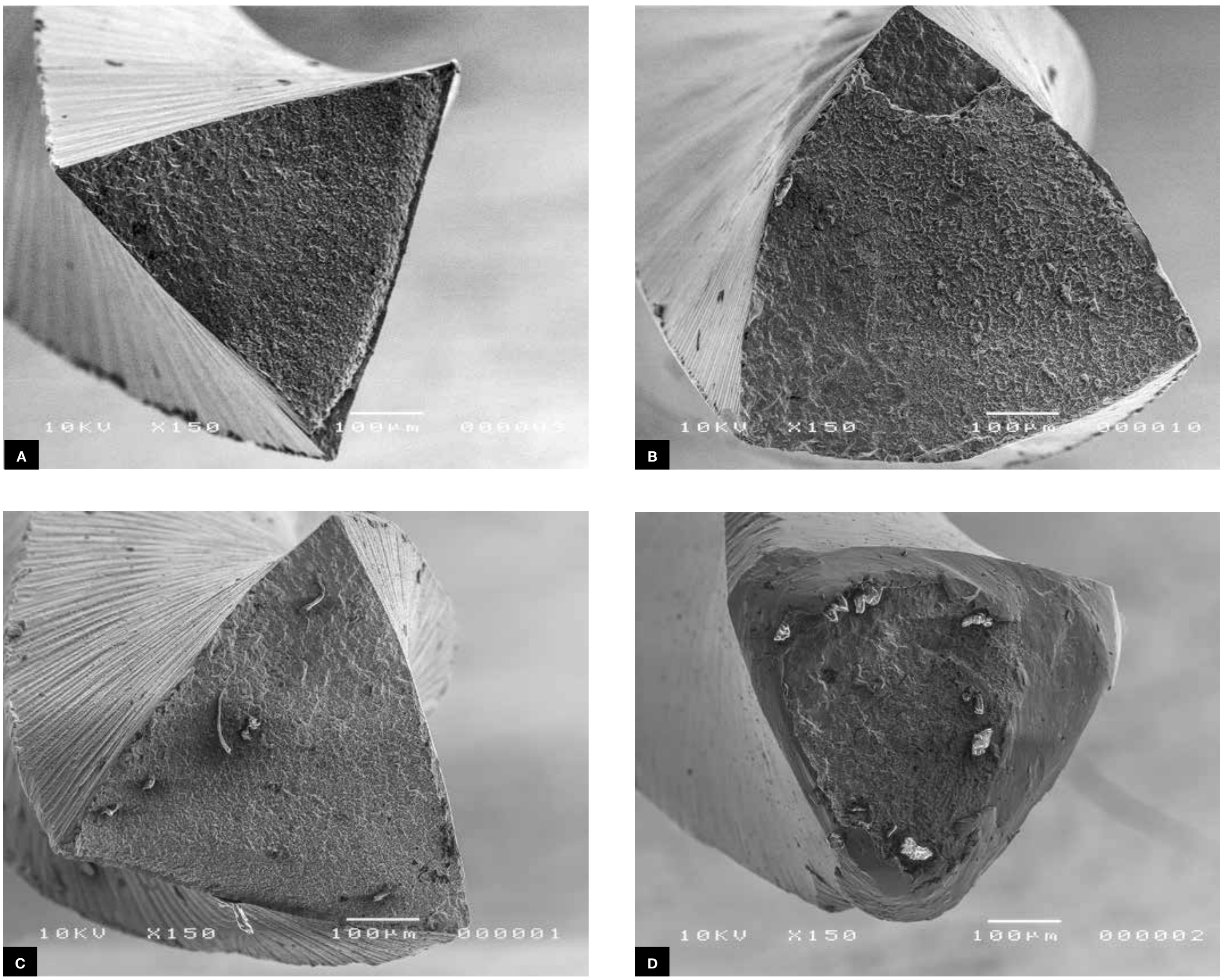

Figure 2. SEM images of fractured surfaces of separated fragments of (**A**) Hyflex CM, (**B**) Vortex Blue, (**C**) Sequence Rotary File and (**D**) EdgeSequel after cyclic fatigue testing. The images show numerous dimples, a feature of ductile fracture.

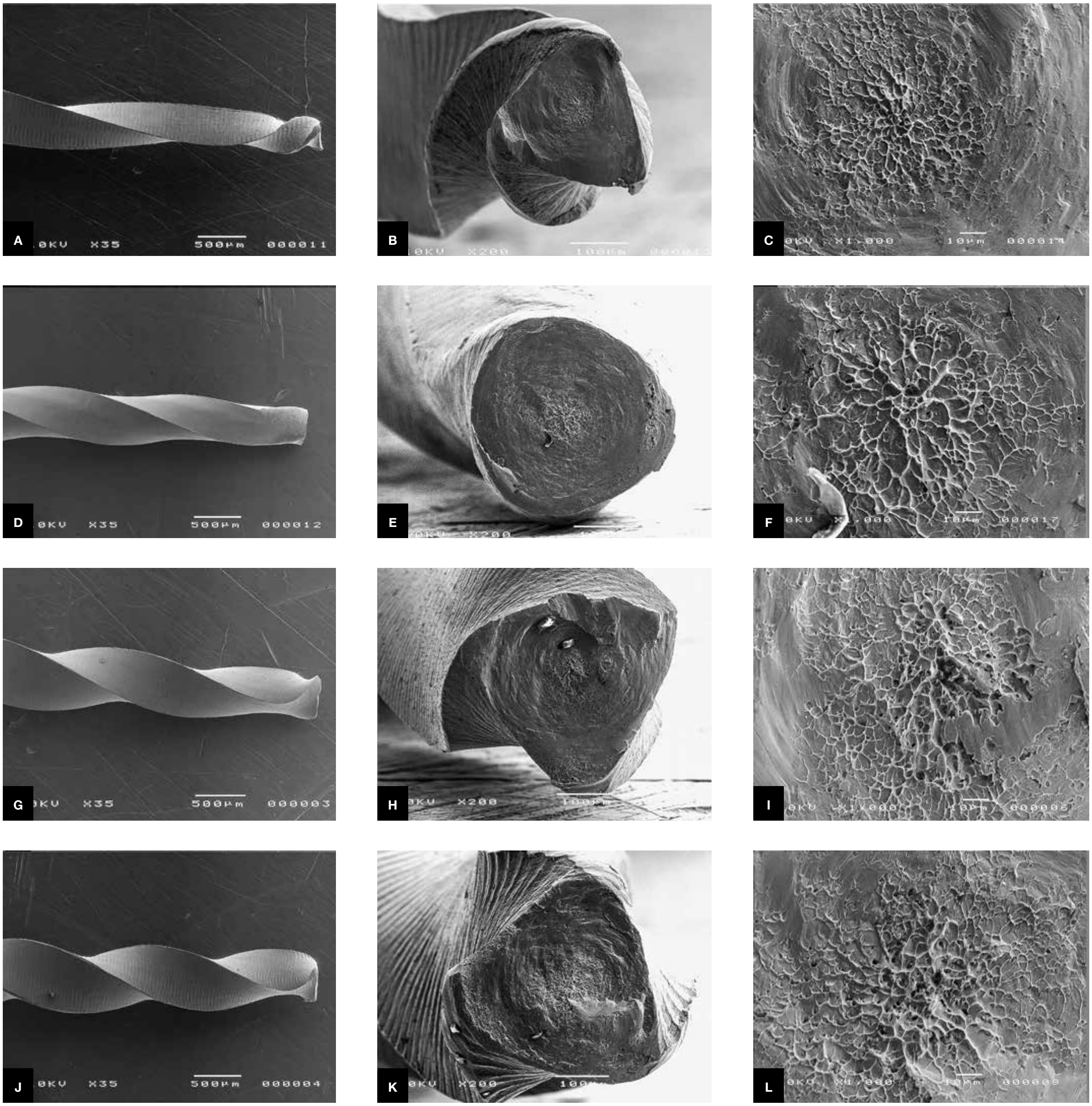

Figura 3. MEV das superfícies dos instrumentos fraturados nos testes de torção: **A-C)** Hyflex CM; **D-F)** Vortex Blue; **G-I)** Sequence Rotary File; e **J-L)** EdgeSequel. A primeira coluna é uma vista lateral dos instrumentos com aumento de 35x, demonstrando a deformação plástica das espiras de corte; a segunda coluna demonstra uma vista frontal da superfície fraturada com 200x de magnificação; a terceira coluna demonstra as abrasões concêntricas com 1000x de magnificação, demonstrando os aspectos de abrasões no centro de rotação dos instrumentos, imagens típicas de fadiga por torção.

Discussion

Despite several modifications on the instruments designs and NiTi alloy, the risk the of instrument failures during root canal preparation in curved canals continue to be a concernment to the clinicians.[2,5] Several factors affect the cyclic and torsional fatigue resistance of NiTi rotary instruments such as, cross-sectional design, taper, tip size and thermal treatment of the NiTi.[1,2,6,9] Therefore, it is important to investigate the mechanical properties of the NiTi rotary files to ensure their safe clinical use.

In this study, the static cyclic fatigue model was used, as previously used in several previous studies.[5,6,9,11,22] Despite the dynamic model simulates the pecking motion accomplished during root canal preparation,[23] the static model reduces some biases, such as amplitude of axial motions and speed, which are completely subjective because their reproduction is manually controlled.[23] The cyclic fatigue test using simulated stainless steel artificial canals has been previously reported by several authors.[6,9,11,22] The torsional fatigue test was used to assess the maximum torque load and the distortion angle of the instruments to failure, according the ISO Standard 3630-1 and has been described in previous studies.[21,22] The 3 mm of the tip and shaft of all instruments were fastened, and clockwise rotation was applied due to their spiraling flutes.

The HCM had the highest cyclic fatigue resistance (time and NCF) when compared with the others groups (P<0.05). The SRF presented similar time (P<0.05) and lower NCF (P<0.05) to fatigue than VB. The EDF presented the lowest time and NCF when compared with the other groups (P<0.05). Thus, the first null hypothesis was rejected. In this study, all the instruments had the same tip size (#25), taper and similar cross-sectional design, which could ensure similar cyclic fatigue resistance among them. Thus, the thermal treatment of the NiTi alloy should be considered in the outcomes of this study.

The results of HCM and VB in this study were in agreement with those of a previous study (24) that showed HCM was more cyclic fatigue resistant than VB at room temperature. The thermal treatments modify the martensitic/austenitc transformation behavior, which can induce a higher level of flexibility due to a different arrangement of the crystalline structure and a higher percentage of martensite or R-phase.[1,2,11,15,16] In addition, the martensite phasefavor a much slower fatigue crack propagation speed than that of the austenite phase.[2,24,25] Therefore, the different phase transformation of the NiTi probably affected our results.

The controlled memory instruments have a martensite and R-phase,[2,16,24] while Blue treatment of VB induces a classic R-phase.[13,19] HCM group probably presented higher percentage of martensite phase, which could explain the best performance. The results of VB and SRF groups could be related to the similar thermal treatment between them. Lastly, EDF probably presented a high percentage of austenite phase.

During the cyclic fatigue test all instruments were used in accordance with the manufacturer's recommendations. HCM, VB and EDF were used at 500 rpm for cyclic fatigue test, while SRF, at 400 rpm. The higher rotational speed increases the cyclic fatigue stress due to inducing more compressive and tensile stresses in the NiTi instruments.[25] Therefore, if all instruments were used at 500 RPM, probably the results of SRF could be negative affected. The results of EDF group suggest that would be safer to use them at a lower speed than that specified in the manufacturer's instructions, reducing the risk of instrument failures.

The torsional test determined the maximum torque load and distortion angle to failure at the 3 mm of the instrument tip, according ISO Standard 3630-1. HCM had the lowest torque load when compared with the other groups (P<0.05). VB presented the highest torque load in comparison with all the groups (P<0.05); no difference was found between SRF and EDF (P>0.05). In relation the distortion angle, HCM showed higher angle values than the other groups (P<0.05). There was no difference among VB, SRF and EDF (P>0.05). Thus, the second null hypothesis was rejected. The design features (taper, tip size, cross-section and core diameter) of NiTi instruments affected the torsional resistance.[7,5,6,8] All the instruments used in this study presented similar design features (taper, cross-section and tip size), which should have ensured similar torsional resistance. However, this did not occur.

Previous studies have shown there was an inverse tendency between flexibility and core diameter.[7,8,10,12] Thus, based on our results, it might be speculated that HCM presented smaller core diameter. Additionaly, depending on the type of thermal treatment, a different arrangement of the crystal structure could be induced, changing the mechanical properties.[2,25,10,11] CM-Wire instruments presented low torsional loads and high distortion angle to failure[16,20,21] due to the presence of martensite and R-phase, which reduced the elastic modulus and increased the deformation capacity.[2,15,24] The thermal treatments probably induced different martensite transformation of the NiTi among them. Therefore, the core diameter and thermal treatments played an important role in our results.

The SEM analysis showed the typical features of cyclic and torsional fatigue for all instruments. After the cyclic fatigue test, the instruments showed crack initiation areas and overload zones, with numerous dimples spread across the fractured surfaces. After the torsional test, the fragments showed concentric abrasion marks and fibrous dimples at the center of rotation.

Improvements in the metallurgy of NiTi rotary instruments have a significant impact on the mechanical properties.[2,15,24,25] The higher levels of flexibility and ductility allow safe preparation with less risk of instrument failures.[2,6,25,24] The results of this study showed that different thermal treatments induced different mechanical properties in instruments with similar design features.

Conclusions

In conclusion, within the limitations of this study, the thermal treatments of the NiTi are important determinants of the mechanical properties of the NiTi instruments. The HCM demonstrated the highest cyclic fatigue resistance and distortion angle to failure then all de instruments. However, the VB showed highest torque load and lowest distortion angle to failure.

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