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ORIGINAL ARTICLE

Cyclic fatigue using severely curved canals and torsional resistance of thermally treated reciprocating instruments

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Abstract
Objectives To evaluate the cyclic fatigue using severely curved canals and torsional resistance of ProDesign R (Easy Equipamentos Odontológicos, Belo Horizonte, MG, Brazil), Reciproc Blue (VDW, Munich, Germany), and WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland) reciprocating instruments

Materials and methods Twenty instruments of the ProDesign R (25/0.06) system, 20 instruments of the Reciproc Blue (25/0.08v) system, and 20 instrument of the WaveOne Gold (25/0.07v) system were used. Cyclic fatigue resistance was tested measuring the time to fracture and the number of cycles to fracture in an artificial stainless steel severely curved canal with 80° angle and a 3-mm radius of curvature ($n = 10$). Torque and angle of rotation at failure of new instruments ($n = 10$) were measured according to ISO 3630-1. The fracture surfaces of all fragments were examined with a scanning electron microscope. Results were statistically analyzed using one-way ANOVA and Tukey's test at a significance level of $p < 0.05$.

Results ProDesign R instruments showed a significantly longer cyclic fatigue life than the other tested instruments ($p < 0.05$). Reciproc Blue showed longer cyclic life than WaveOne Gold ($p < 0.05$). Reciproc Blue showed the higher torsional strength, followed by WaveOne Gold and ProDesign R instruments ($p < 0.05$). Moreover, Reciproc Blue showed significantly higher angular rotation to fracture than ProDesign R ($p < 0.05$). WaveOne Gold showed intermediary results regarding angular rotation to fracture with no differences when compared to Reciproc Blue or ProDesign R instruments ($p < 0.05$).

Conclusions ProDesign R presented the highest cyclic fatigue resistance in severely curved canals when compared with Reciproc Blue and WaveOne Gold. However, Reciproc Blue showed the higher torsional strength overall and higher angular rotation to fracture when compared to ProDesign R.

Clinical relevance Despite the numerous advantages of reciprocating instruments, these instruments still have some risk of fracture during its use, especially in severely curved canals. The present study evaluated the cyclic fatigue and torsional resistance of thermally treated reciprocating instruments.

Keywords Cyclic fatigue · Torsional resistance · Thermal treatment · Reciprocating instruments

Introduction

Despite the numerous advantages of nickel-titanium (NiTi) rotary instruments, these instruments present risk of fracture during its use in curved canals, which might compromise the prognosis of root canal treatment [1]. Many methods are developed and tried in order to prevent the fracture of NiTi instruments. The introduction of reciprocating movement has raised new perspectives for root canal preparation. The reciprocating motion relieves the stress on the instrument by asymmetric counterclockwise (cutting action) and clockwise

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(release of the instrument) movements. It has been shown that changing the rotary to reciprocating kinematics increases the cyclic fatigue life and torsional resistance of NiTi instruments [2]. In addition, thermal treatment of NiTi alloys (e.g., controlled memory wire, blue wire, and gold wire) has been recently used to improve the mechanical properties of endodontic instruments such as fatigue resistance, flexibility, cutting efficiency, and canal centering ability [1, 3–5]. Reciproc Blue (VDW, Munich, Germany) has a similar design of its predecessor Reciproc (VDW) with a complex heating-cooling proprietary treatment that results in a blue visible titanium oxide layer in the surface of the instrument. Such as other thermal treatment, it controls the phase transition temperatures, creating a shape memory alloy, that provides superior mechanical properties [5]. WaveOne Gold (Dentsply Maillefer, Ballaigues, Switzerland) is the new version of WaveOne files (Dentsply Maillefer), with changes in their NiTi alloy, dimensions, cross-section, and geometry. The cross-section of the file was modified to a parallelogram, having two cutting edges. Moreover, the off-center design used in ProTaper Next (PTN, Dentsply Maillefer) files is also used in WOG files. The files are manufactured using gold heat treatment [6]. ProDesign R (Easy Equipamentos Odontológicos, Belo Horizonte, MG, Brazil) is a system that presents an S-shaped cross-section, variable helical angles, and a cutting counterclockwise direction, such as Reciproc and WaveOne files. In addition, this instrument is made from a NiTi wire subjected to proprietary thermomechanical processing that controls the memory of NiTi, increases the austenite transformation temperature above 37 °C, and leaves the NiTi file in the twinned martensitic phase at operating temperature [7]. When compared to conventional NiTi, these controlled memory alloys enhance the flexibility and the cyclic fatigue life of the instruments [8].

The aim of the present study was to evaluate the cyclic fatigue and torsional resistance of ProDesign R 25/.06, Reciproc Blue R25, and WaveOne Gold primary instruments. The null hypotheses tested were as follows:

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

Materials and methods

A total of 60 new instruments of three different NiTi reciprocating systems ($n = 20$ per system) were used in this study: ProDesign R size #25, 0.06 taper (lot number 170096); Reciproc Blue R25 size #25, 0.08v taper (lot number 37631); and WaveOne Gold Primary size #25, 0.07v taper (lot number 1226916). All files used were 25-mm long, with 10 instruments of each brand used in cyclic fatigue and torsional resistance tests. All instruments were inspected for visible defects or deformities before the experiment under a stereomicroscope (OPTZS; Opticam, São Paulo, Brazil); none was discarded.

Cyclic fatigue test

The cyclic fatigue test was performed using a custom-made device that allowed a reproducible simulation of an instrument confined in a severely curved canal. It consists of an artificial canal with 80° angle of curvature and 3 mm radius of curvature. The center of the curvature was 4 mm from the tip of the instrument, and the curved segment of the canal was 5.5 mm in length (tip #30, taper 0.08). The artificial canal was open in its upper part and covered with tempered glass to prevent the instruments from slipping out (Fig. 1).

Ten ProDesign R 25/0.06, ten Reciproc Blue R25, and ten WaveOne Gold Primary instruments were activated with a 6:1 reduction handpiece (Sirona Dental Systems GmbH, Bensheim, Germany) powered by a torque-controlled motor (Silver Reciproc; VDW), according to the manufacturers' recommendations (RECIPROC ALL for Reciproc Blue and ProDesign R instruments and WAVEONE ALL for WaveOne Gold instruments). The electric handpiece was mounted on a device to allow for precise and reproducible placement of each file inside the simulated canal.

All instruments were driven following the manufacturer's instructions until fracture occurred. The instruments rotated freely within the simulated canal, which was filled with distilled water. The time was recorded and the experiment stopped as soon as a fracture was detected visually and/or audibly. Moreover, the number of cycles to failure (NCF) of each file was calculated using the following formula: NCF = revolution per minute (rpm) × time (s)/60. To avoid human error, video recording was performed simultaneously, with the recordings then observed to cross-check the time of file fracture.

Torsional test

The torsional load was applied until fracture to estimate the mean ultimate torsional strength and angle of rotation of the instruments ($n = 10$ for each system) tested using a custom-made device produced following ISO 3630-1 [9]. Each file was clamped at 3 mm from the tip using a chuck connected to a torque-sensing load cell; after that, the shaft of the file was fastened into an opposing chuck able to be rotated with a stepper motor. All instruments were rotated in the counterclockwise direction at a speed of 2 rpm until file separation. The torque load (Ncm) and angular rotation (°) were monitored continuously using a torsiometer (ODEME; Luzerna, SC, Brazil), and the ultimate torsional strength and angle of

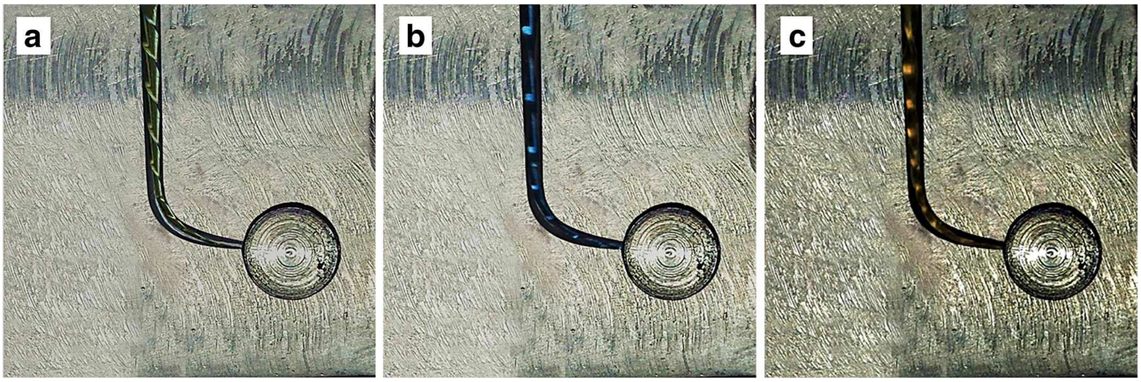

Fig. 1 The trajectory of ProDesign R (**a**), Reciproc Blue (**b**), and WaveOne Gold (**c**) in the artificial canal used in the present study

rotation at failure were provided by a specifically designed computed program (ODEME Analysis TT; ODEME).

Scanning electron microscopic evaluation

A scanning electron microscope (SEM) (JSM 5800; JEOL, Tokyo, Japan) was used to analyze the fracture surfaces of all the tested instruments in order to observe the fracture mode. Different magnifications were used (× 250, × 900, and × 1500).

Statistical analysis

Because the preliminary analysis of the raw pooled and isolated data revealed a bell-shaped distribution (Shapiro-Wilk normality test), statistical analysis was performed by using parametric methods (one-way ANOVA). Post hoc pair-wise comparisons were performed by using Tukey's test for multiple comparisons. The alpha-type error was set at 0.05. Biostat (Instituto Mamirauá, Tefé, Brazil) was used as analytical tool.

Results

ProDesign R instruments showed a significantly longer cyclic fatigue life than the other tested instruments ($p < 0.05$). Reciproc Blue showed longer cyclic life than WaveOne Gold ($p < 0.05$). Reciproc Blue showed the higher torsional strength, followed by WaveOne Gold and ProDesign R instruments ($p < 0.05$). Moreover, Reciproc Blue showed significantly higher angular rotation to fracture than ProDesign R ($p < 0.05$). WaveOne Gold showed intermediary results with no differences when compared to Reciproc Blue or ProDesign R instruments ($p < 0.05$). The mean and standard deviations of the cyclic fatigue resistance, torque maximum load, and angle of rotation until fracture for each instrument are presented in Table 1.

Scanning electron microscopy of the fracture surface showed similar and typical features of cyclic fatigue and torsional failure for the three types of instruments. The crack initiation area and overload fast fracture zone for cyclic fatigue (Fig. 2) and concentric abrasion marks and the micro voids at the center of rotation for torsional failure (Fig. 3) could be observed.

Discussion

NiTi instrument fracture during clinical use has been a problem ever since the introduction of NiTi alloys [1]. The unexpected fracture of these instruments might occur via two different mechanisms: cyclic fatigue or torsional stress [10]. In the first scenario, fracture is produced by repetitive compressive and tensile stress on the area of maximum root canal curvature. Torsional fracture occurs when the tip of the instrument binds into the canal whereas the base of the instrument continues to rotate and, consequently, the torque exceeds the elastic limit of the metal [10]. Reciprocating kinematics can reduce torsional stress around the instrument, decreasing the rate of torsional failure. Moreover, this kinematics also increases the cyclic fatigue of NiTi instruments [2].

Although it might be difficult to correlate the findings of laboratory tests with a clinical situation due to the amount of variables acting together to result in the fracture of the instrument, it is important to access mechanical properties of endodontic instruments in order to present valid information for the clinician [11]. In a comprehensive literature review, there was no study evaluating the cyclic and the torsional fatigue resistance of Reciproc Blue, WaveOne Gold, and ProDesign R instruments, all thermally treated reciprocating instruments.

In this study, the methodology used to evaluate cyclic fatigue was already validated and used in numerous articles published in peer-reviewed journals [3–6, 8, 12]. It is important to highlight that there are no specifications or international standards for the evaluation of this propriety in NiTi endodontic instruments. The development of thermally treated NiTi, with higher flexibility when compared to conventional NiTi alloys, enabled the better preservation of internal anatomy of

Table 1 Mean and standard deviation of time to failure (s), number of cycles to fracture (NCF), torque (Ncm), and angle of rotation (°) of the tested instruments

Instrument	Time to failure (s)	NCF	Torque (Ncm)	Angle of rotation (°)
ProDesign R	306 ± 26^{A}	1532 ± 131^{A}	1.0 ± 0.2^{C}	412 ± 46^{B}
Reciproc Blue	211 ± 30^{B}	1057 ± 150^{B}	1.9 ± 0.1^{A}	474 ± 31^{A}
WaveOne Gold	149 ± 15^{C}	869 ± 87^{C}	1.4 ± 0.1^{B}	456 ± 21^{AB}

Different superscript letters in the same column indicate statistic differences among groups ($p < 0.05$)

curved root canals [13–15]. In addition, these new NiTi alloys allowed root canal preparation of curved canals with a lower risk of instrument fracture by cyclic fatigue [4, 5, 8]. In this study, we have decided to test then in severely curved simulated canals (80°).

ProDesign R instruments showed significantly longer cyclic fatigue life when compared to Reciproc Blue or WaveOne Gold instruments ($p < 0.05$). Therefore, the first null hypothesis was rejected. Resistance to cyclic fatigue depends on several factors such as diameter, metal mass, flexibility, cross-sectional section, and NiTi alloy. The controlled memory NiTi alloy of the ProDesign R instruments might explain these findings. It has been previously reported that CM wire instruments have greater flexibility and cyclic fatigue resistance than other thermal-treated NiTi instruments [16]. ProDesign R also demonstrated better results in cyclic fatigue test when compared to Reciproc and Unicone [17] and when compared to M-wire Reciproc and WaveOne systems [8]. The

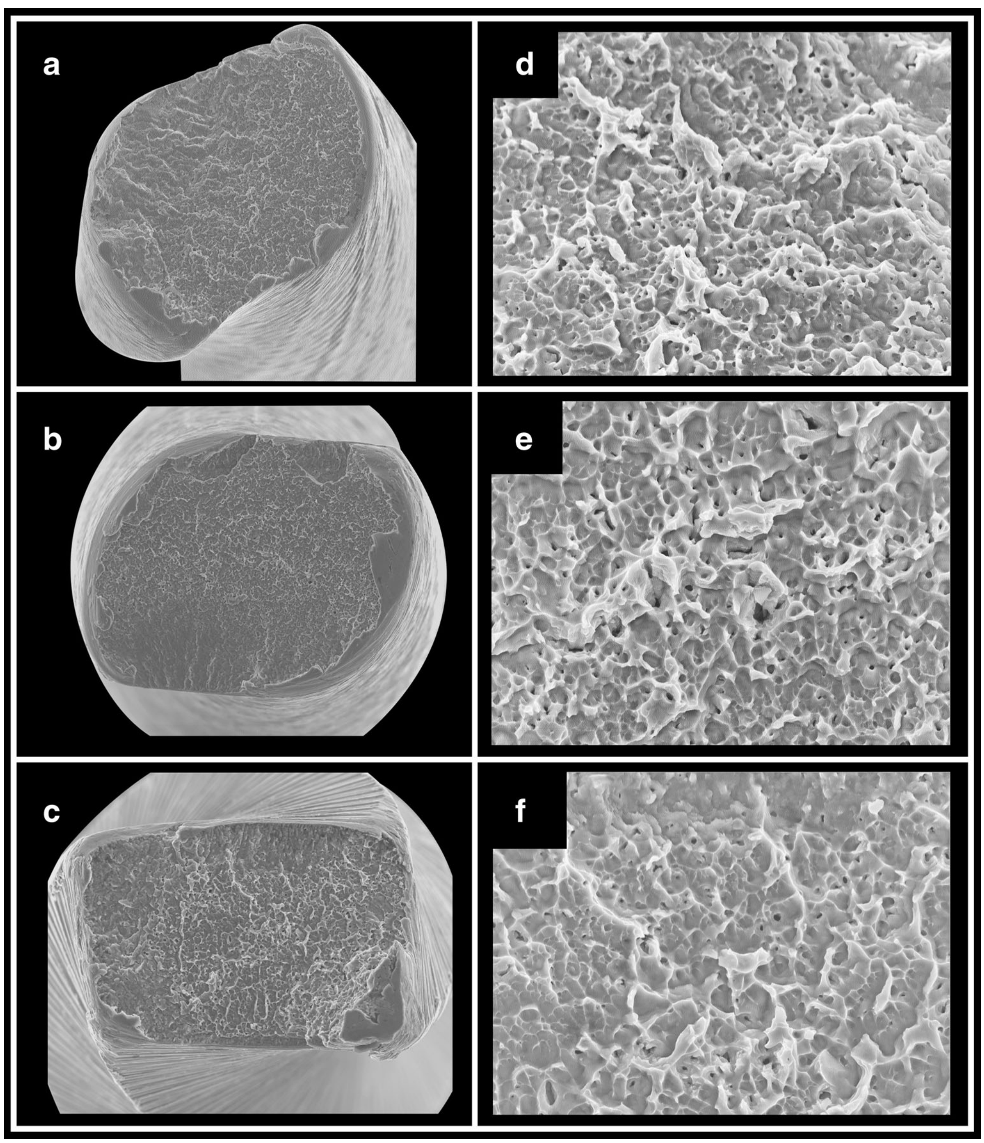

Fig. 2 Surface fracture after the cyclic fatigue test of ProDesign R (**a**), Reciproc Blue (**b**), and WaveOne Gold (**c**) with original magnification of × 250. The ductile aspect of the dimples of ProDesign R (**d**), Reciproc Blue (**e**), and WaveOne Gold (**f**) with original magnification of × 1500

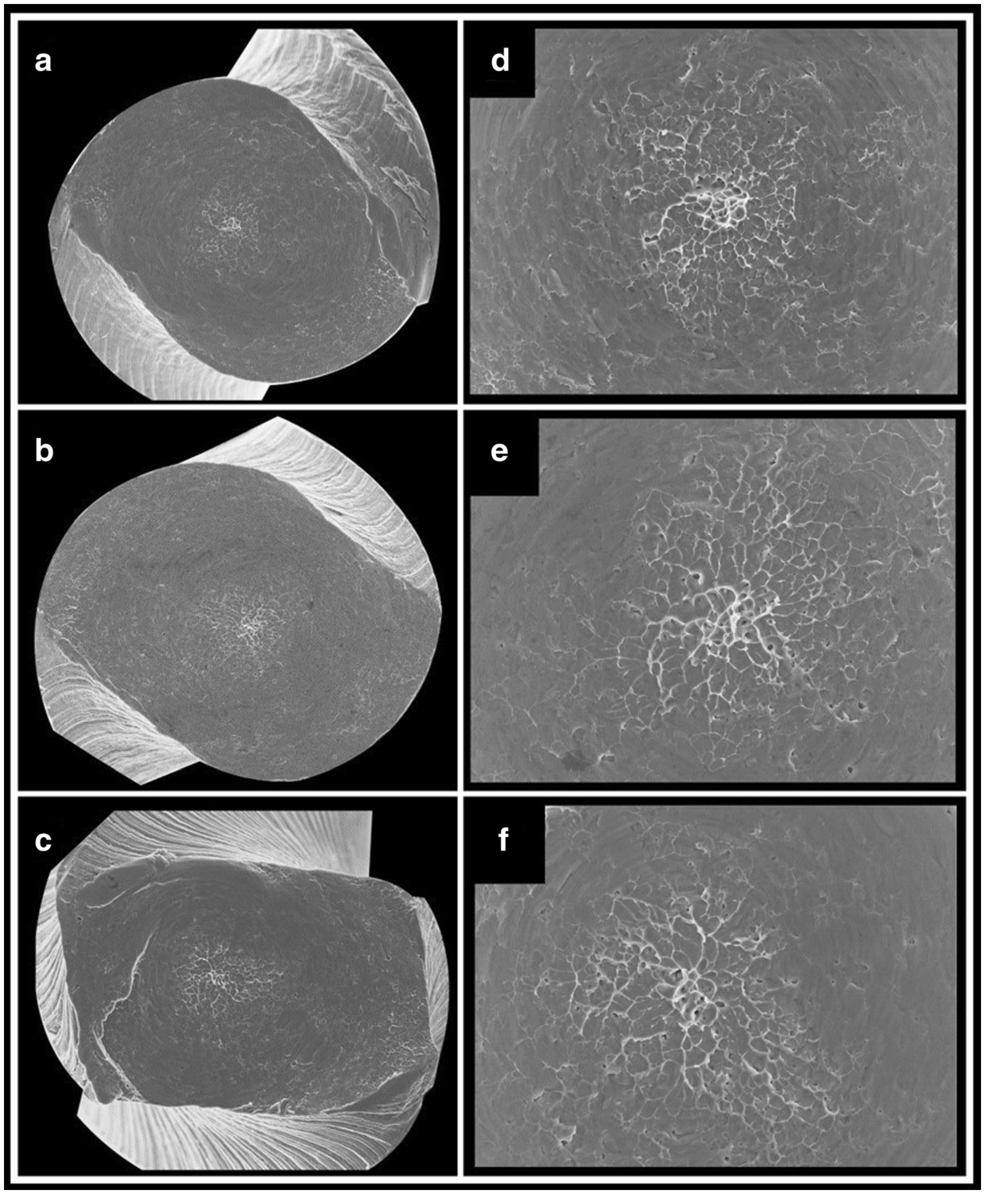

Fig. 3 Surface fracture after the torsion test of ProDesign R (**a**), Reciproc Blue (**b**), and WaveOne Gold (**c**) with original magnification of × 250. At the core, the files displayed ductile aspect, and around this area, plastic deformation was observed in ProDesign R (**d**), Reciproc Blue (**e**), and WaveOne Gold (**f**) files (original magnification of × 900)

smaller taper of ProDesign R (0.06) when compared to Reciproc Blue (0.08v) and WaveOne Gold (0.07v) associated with a small cross-sectional area could also be related to the results. Reciproc Blue showed longer cyclic fatigue life when compared to WaveOne Gold instruments ($p < 0.05$). These results are in accordance with a recently published study that demonstrated that Reciproc Blue instruments had significantly higher cyclic fatigue resistance when compared to WaveOne Gold and M-Wire Reciproc instruments [18]. Apart from the thermal treatment differences of these files, the cross-section design should be taken into account for the outcomes of this result. WaveOne Gold has a parallelogram-shaped cross-section, whereas both Reciproc Blue have S-shaped cross-sections. WaveOne Gold cross-section is higher than Reciproc Blue and it has been reported that instruments with a greater metal core mass had reduced cyclic fatigue resistance [19]. Moreover, the crack initiation mainly occurs at the leading edge of the file. Reciproc Blue has only two leading edges in comparison with the four leading edges of WaveOne Gold instruments.

The methodology used in the torsional test was also reported and validated in previous studies [17, 20]. The results of the torsional fatigue test demonstrated that the maximum torsional strength of Reciproc Blue was higher than ProDesign R and WaveOne Gold instruments ($p < 0.05$). Therefore, the second null hypothesis was also rejected. These findings indicate that Reciproc Blue is more resistant to torsional fracture than the other tested instruments and requires a higher strength to fracture. This might implicate in a lower chance of breakage in a clinical situation when the tip of the instrument binds to the canal. The other outcome of torsional test demonstrated that Reciproc Blue showed significantly higher angular rotation to fracture than ProDesign R ($p < 0.05$). WaveOne Gold showed intermediary results with no differences when compared to Reciproc Blue or ProDesign R instruments. These results could be explained by Reciproc Blue higher taper (0.08 at the first 3 mm), which ensures a higher cross-sectional area at the binding place for torsional test. Also, the type of NiTi alloy used in its manufacture could explain these results.

Conclusions

Within the results of the present study, it can be concluded that ProDesign R presented the highest cyclic fatigue resistance when compared with Reciproc Blue and WaveOne Gold. However, Reciproc Blue showed the higher torsional strength and higher angular rotation to fracture when compared to the other tested instruments.

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Compliance with ethical standards

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

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

References

1. Peters OA, de Azevedo Bahia MG, Pereira ES (2017) Contemporary root canal preparation: innovations in biomechanics. Dent Clin North Am 61(1):37–58. https://doi.org/10.1016/j.cden.2016.08.002
2. Ferreira F, Adeobato C, Barbosa I, Aboud L, Scelza P, Zaccaro Scelza M (2017) Movement kinematics and cyclic fatigue of NiTi rotary instruments: a systematic review. Int Endod J 50(2):143–152. https://doi.org/10.1111/iej.12613
3. Pérez-Higueras JJ, Arias A, de la Macorra JC (2013) Cyclic fatigue resistance of K3, K3XF, and twisted file nickel-titanium files under continuous rotation or reciprocating motion. J Endod 39:1585–1588
4. Lopes HP, Gambarra-Soares T, Elias CN, Siqueira JF Jr, Inojosa IF, Lopes WS et al (2013) Comparison of the mechanical properties of rotary instruments made of conventional nickel-titanium, M-wire, or nickel-titanium alloy in R-phase. J Endod 39:516–520
5. De-Deus G, Silva EJ, Vieira VT, Belladonna FG, Elias CN, Plotino G et al (2017) Blue thermomechanical treatment optimizes fatigue resistance and flexibility of the Reciproc files. J Endod 43(3):462–466. https://doi.org/10.1016/j.joen.2016.10.039
6. Adıgüzel M, Capar ID (2017) Comparison of cyclic fatigue resistance of WaveOne and WaveOne Gold small, primary, and large instruments. J Endod 43(4):623–627. https://doi.org/10.1016/j.joen.2016.11.021
7. Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M (2013) Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. J Endod 39(2):163–172. https://doi.org/10.1016/j.joen.2012.11.005
8. Silva EJ, Rodrigues C, Vieira VT, Belladona FD, De-Deus G, Lopes HP (2016) Bending resistance and cyclic fatigue of a new heat-treated reciprocating instrument. Scanning 38(6):837–841. https://doi.org/10.1002/sca.21333
9. International Organization for Standardization ISO 3630-1 (1992) Dental root canal instruments: part 1—files, reamers, barbed broaches, rasps, paste carriers, explorers and cotton broaches. International Organization for Standardization, Geneva, Switzerland
10. Sattapan B, Nervo GJ, Palamara JE, Messer HH (2000) Defects in rotary nickel-titanium files after clinical use. J Endod 26(3):161–165. https://doi.org/10.1097/00004770-200003000-00008
11. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G (2009) A review of cyclic fatigue testing of nickel titanium rotary instruments. J Endod 35(11):1469–1476. https://doi.org/10.1016/j.joen.2009.06.015
12. Silva EJ, Villarino LS, Vieira VT, Accorsi-Mendonça T, Antunes HD, De-Deus G et al (2016) Bending resistance and cyclic fatigue life of Reciproc, Unicone, and WaveOne reciprocating instruments. J Endod 42(12):1789–1793. https://doi.org/10.1016/j.joen.2016.08.026
13. Gabliardi J, Versiani MA, de Sousa-Neto MD, Plazas-Garzon A, Basrani B (2015) Evaluation of the shaping characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in curved canals. J Endod 41(10):1718–1724. https://doi.org/10.1016/j.joen.2015.07.009
14. Duque JA, Vivan RR, Cavenago BC, Amoroso-Silva PA, Bernardes RA, Vasconcelos BC et al (2017) Influence of NiTi alloy on the root canal shaping capabilities of the ProTaper Universal and ProTaper Gold rotary instrument systems. J Appl Oral Sci 25(1):27–33. https://doi.org/10.1590/1678-77572016-0230
15. Özyürek T, Yilmaz K, Uslu G (2017) Shaping ability of Reciproc, WaveOne GOLD, and Hyflex EDM single-file systems in simulated S-shaped canals. J Endod 43:805–809
16. de Vasconcelos RA, Murphy S, Carvalho CA, Govindjee RG, Govindjee S, Peters A (2016) Evidence for reduced fatigue resistance of contemporary rotary instruments exposed to body temperature. J Endod 42(5):782–787. https://doi.org/10.1016/j.joen.2016.01.025
17. Alcalde MP, Tanomaru-Filho M, Bramante CM, Duarte MAH, Guerreiro-Tanomaru J, Camilo-Pinto J et al (2017) Cyclic and torsional fatigue resistance of reciprocating single files manufactured by different nickel-titanium alloys. J Endod 43(7):1186–1191. https://doi.org/10.1016/j.joen.2017.03.008
18. Keskin C, Inan U, Demiral M, Keles A (2017) Cyclic fatigue resistance of Reciproc Blue, Reciproc, and WaveOne Gold reciprocating instruments. J Endod 43(8):1360–1363. https://doi.org/10.1016/j.joen.2017.03.036
19. De-Deus G, Vieira VT, Silva EJ, Lopes H, Elias CN, Moreira EJ (2014) Bending resistance and dynamic and static cyclic fatigue life of Reciproc and WaveOne large instruments. J Endod 40(4):575–579. https://doi.org/10.1016/j.joen.2013.10.013
20. Pedullà E, Lo Savio F, Boninelli S, Plotino G, Grande NM, La Rosa G, Rapisarda E (2016) Torsional and cyclic fatigue resistance of a new nickel-titanium instrument manufactured by electrical discharge machining. J Endod 42(1):156–159. https://doi.org/10.1016/j.joen.2015.10.004