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ORIGINAL ARTICLE

Dynamic Cyclic Fatigue Resistance of Heat-treated Nickel Titanium Instruments in Reciprocating Motion

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ABSTRACT

Objective: To compare the fatigue resistance of different heat-treated reciprocating instruments tested in a dynamic cyclic fatigue model.

Methods: Forty-eight new instruments were inspected under magnification and selected for this study, and then divided as follows (n=12): X1 Blue (MK Life, Porto Alegre, RS, Brazil), Pro-R (MK Life), Reciproc (VDW, Munich, Germany), and Reciproc Blue (VDW). Artificial canals presenting a curvature of 60o angle and 5 mm radius were milled in zirconia. The block containing the artificial canals was mounted in a container filled with water kept at 37oC. A specially designed device was used to perform controlled axial movements while the instruments were activated inside the canals. Time to failure was recorded in seconds, and fragment lengths were measured (mm). Data were analyzed statistically with the significance level set at 5% (One-Way ANOVA and Tukey test).

Results: Pro-R and Reciproc Blue instruments presented the highest fatigue resistance, being significantly different from the other tested files ($p<0.05$). Reciproc presented intermediate results, significantly different X1 Blue ($p<0.05$). The fractographic analysis showed typical features of cyclic fatigue for all instruments.

Conclusion: Pro-R and Reciproc Blue instruments are more resistant to dynamic cyclic fatigue than the Reciproc and X1 Blue.

Keywords: Dental instruments, dynamic cyclic fatigue, endodontics, nickel-titanium, reciprocation

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HIGHLIGHTS

- Differences in the fatigue resistance were found among the reciprocating instruments.
- Pro-R and Reciproc Blue were more resistant to dynamic cyclic fatigue compared to Reciproc and X1 Blue.
- Pro-R presented the smallest mean fragment length, being statistically different from the other groups.

INTRODUCTION

Mechanized nickel-titanium (NiTi) instruments have been widely used to prepare root canals due to their high flexibility and centering ability (1–4). However, despite their favorable mechanical properties, unexpected fractures can occur without visible signs of deformation (1, 4–8).

Fracture of NiTi rotary instruments is mainly related to cyclic or torsional fatigue, or the combination of both. Cyclic fatigue occurs when a section is alternately subjected to tensile and compressive stresses, usually in the curvatures of the root canal (1, 7–9). Torsion fracture occurs when a small part of the instrument, usually the apical end, is trapped in the canal's walls while the rest of the instrument continues its motion (9, 10). Thus, to improve NiTi instruments' mechanical properties, manufacturers have used different strategies, such as modifications in instrument design, different alloys, heat treatment, manufacturing process, and instrument kinematics (3, 4, 9–14).

Reciprocating motion has improved the safety of endodontic instruments by increasing their resistance to cyclic fatigue compared to continuous rotation and allowing the development of single-file systems (12, 14). Reciproc (VDW, Munich, Germany) and WaveOne (Dentsply Sirona, Ballaigues, Switzerland) were the first commercially available brands using the contemporary concept of reciprocating motion. While these two brands have been widely studied (10–15), the literature lacks regarding many different instruments introduced into the market recently. X1 Blue and Pro-R (MK Life, Porto Alegre, RS, Brazil) are two new reciprocating files presenting respectively convex triangular and double helix cross-sections. Another difference is the type of heat treatment; however, the manufacturer does not disclose further information. To date, there are no reports in the literature evaluating the Pro-R system, and a few have assessed the cyclic fatigue resistance of the X1 Blue (16, 17).

Thermal treatment is one of the most fundamental approaches to adjust the transition temperature in the NiTi alloy; the results obtained using heat treatments are directly influenced by factors such as time, temperature, moment, and manufacturing process, promoting different mechanical properties for NiTi instruments (18–21). Studies have shown that heat-treated instruments present improved fatigue resistance, torsional strength, and flexibility cvompared to their non-treated counterparts (18, 20), including Reciproc and its thermally treated version, Reciproc Blue (13). However, controversial results exist in the literature when comparing the resistance to cyclic fatigue among instruments manufactured with different types of heat treatments (16, 17, 19, 22, 23).

The discrepancy among cyclic fatigue studies is also related to the diversity in methodology and study designs, such as environmental temperature, the trajectory of the artificial canal, fit of the instrument, and use of static or dynamic models (1, 9, 14, 16, 21, 23, 24). The main difference between static and dynamic models for cyclic fatigue tests is that the latter also includes an intermittent axial movement up and down while the instrument is activated within the artificial canal (1, 23–26). Compared to the static model, a dynamic model allows for stress distribution during instrument insertion and removal, which better translates the clinical use of endodontic instruments (23–25).

In this context, it is necessary to evaluate the mechanical properties of new instruments using a methodology that simulates their clinical use. In order to test the cyclic fatigue resistance of the X1 Blue and Pro-R, similar instruments regarding the characteristics of the metallic alloy and that have already been extensively researched, were chosen. Thus, Reciproc Blue and Reciproc, respectively, were elected for comparisons.

This study aimed to compare the resistance to cyclic fatigue of four heat-treated reciprocating instruments using a dynamic model at body temperature. The null hypothesis is that there is no difference in the resistance to cyclic fatigue between Pro-R 25.08, X1 Blue 25.06, Reciproc Blue R25, and Reciproc R25 instruments.

MATERIALS AND METHODS

The sample calculation was performed using G * Power v3.1 for Mac (Heinrich Heine, University of Düsseldorf) with alpha error set at 0.05, beta power at 0.95, and an N2/N1 ratio of 1. The test showed 12 samples for each group as the ideal size to identify significant differences.

Twelve new nickel-titanium endodontic instruments of each tested brand were selected for the study: X1 Blue (25.06) (MK Life), Pro-R (25.08) (MK Life), Reciproc R25 (25.08) (VDW), and Reciproc Blue R25 (25.08) (VDW). All instruments were 25 mm long and were initially observed under 20× magnification to discard those with visible deformations or defects.

Dynamic Cyclic Fatigue Test

A customized device (Fig. 1) and artificial canals (Fig. 2) were fabricated to perform the dynamic cyclic fatigue tests. The artificial canals were 3D modelled (Autodesk Inventor 2017 / Autodesk, San Rafael, CA, USA) to fit an instrument size 30.08, then milled in a block of zirconia dioxide (InCoris ZI, Dentsply Sirona, Bensheim, Germany). The canal used in this study was 18 mm in length with a curvature of 60o angle and 5 mm radius, located 8 mm from the apical end.

The zirconia block containing the artificial canals was mounted in a container (15×10×4 cm) filled with distilled water; the temperature was kept at 37°C in water bath, controlled with a digital infrared thermometer (Lasergrip 774 Etekcity, Anaheim, CA, USA). The water-filled container and the endodontic handpiece were connected to a mainframe which allowed precise and reproducible positioning of the instruments, as well as to operate the axial movement of the instruments (pecking motion) at a speed of 8 mm/sec to simulate clinical use. The instruments were attached to the handpiece and adequately fitted into the artificial canals. The endodontic motor X Smart IQ motor (Dentsply Sirona) was used to activate the instruments using the “Reciproc” setting, until the fracture was observed. Time to fracture was recorded in seconds (s) using a digital stopwatch and video recording simultaneously.

The number of cycles to fracture (NCF) of each instrument was calculated using the formula: NCF=300 (instrument rpm) × time (in seconds until fracture) / 60 (15, 16, 25). The fractured instruments' fragment length was measured with a digital caliper (Mcaliper, Montreal, Canada).

Figure 1. Customized device

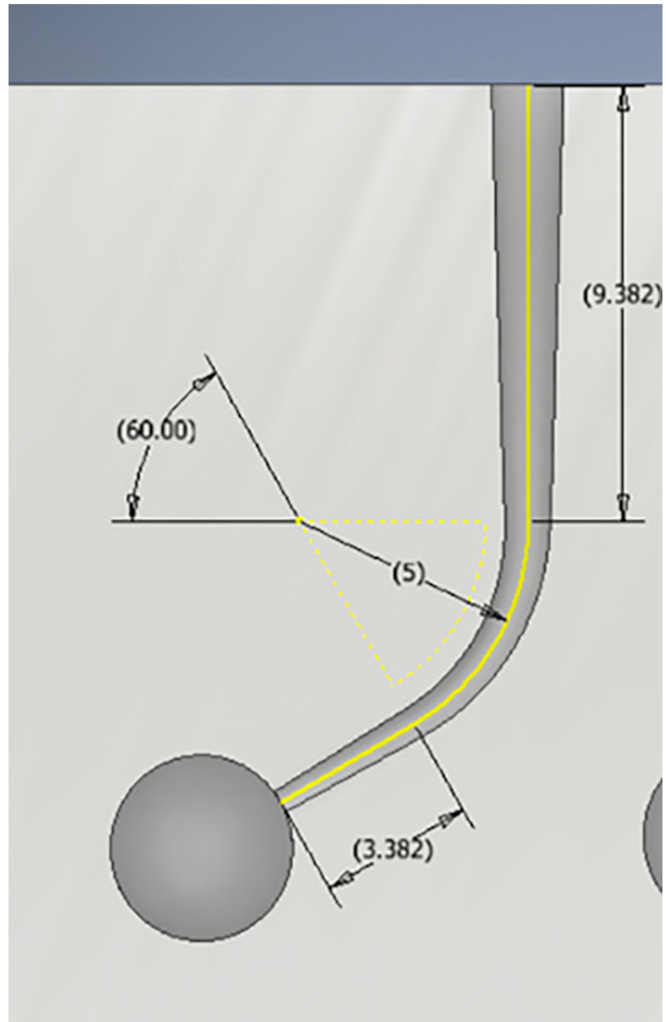

Figure 2. Schematic drawing of the artificial canal

The fractured ends of the files were examined (Fig. 3), just for illustrative purpose with scanning electron microscopy (SEM) using a Hitachi SU 70 Field Emission SEM (Hitachi High-Technologies Corporation, Tokyo, Japan) operated at 20 kV. The surfaces were inspected at a magnification of 150× and 2500× to look for the topographic the topographic features of the fractured surface.

A single operator performed all cyclic fatigue testing procedures. The video was analyzed in slow motion by the operator and the moment of the fracture was confirmed by a second researcher.

Statistical Analysis

Initially the Shapiro-Wilk was performed. Then, One-Way ANOVA and Tukey tests were used. The tests were performed using Jamovi statistical program (The Jamovi Project 2020, Version 1.2) with the significance level set at 5%.

RESULTS

A normal data distribution ($p>0.05$) occurred. Descriptive of the results are shown in Table 1.

Pro-R and Reciproc Blue instruments presented significantly higher fracture time than the other instruments ($p<0.05$). Mean time to fracture and NCF of Reciproc instruments were statistically different from X1 Blue File ($p<0.05$). Pro-R presented the smallest mean fragment length, being statistically different from the other groups ($p<0.05$).

DISCUSSION

Automated NiTi instruments undergo constant evolution in the manufacturing processes, alloys, design, and kinematic, aiming to improve flexibility and resistance to deliver effective and safe preparation of root canals. The results of the present study showed that both design and type of heat treatment were the factors that influenced the fatigue resistance of reciprocating instruments at body temperature.

It has been shown that one of the most critical factors for improving the mechanical properties of endodontic instruments is the manufacturing processes, including heat treatments (3, 13, 18–20, 22). Previous studies have indicated that a high percentage of the martensitic phase increases the flexibility of heat-treated NiTi instruments and improves the performance of such instruments when evaluated for cyclic fatigue resistance (3, 18). Here, the tested null hypothesis was rejected because significant differences were found among the evaluated instruments. Pro-R and Reciproc Blue presented higher fatigue resistance than the other tested instruments.

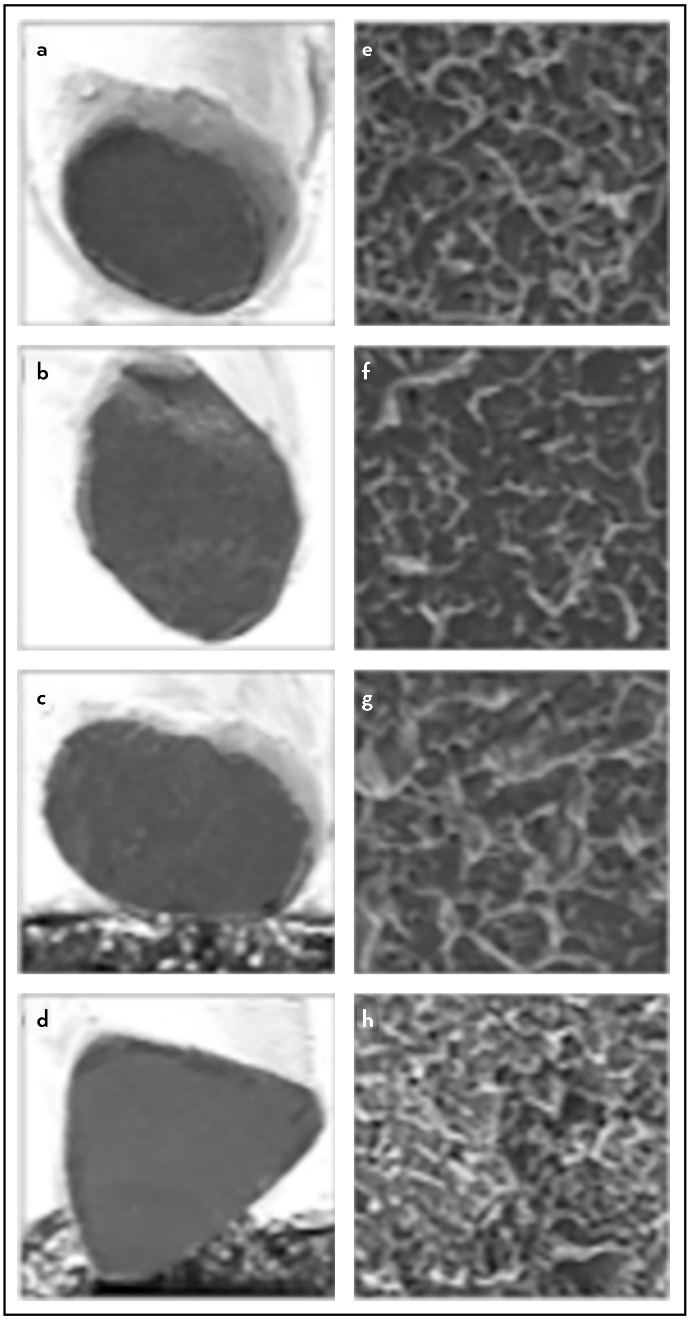

Figure 3. SEM images showing the cross-section of the fractured instruments at 150× (a–d) and 2500× (e–h) magnification: (a, e) Pro-R; (b, f) Reciproc; (c, g) Reciproc Blue; (d, h) X1 Blue. Higher magnification of images of the fracture surface of the instruments displays specific patterns indicating cyclic fatigue failure

SEM: Scanning electron microscopy

Cyclic fatigue has been considered an important cause of fracture of NiTi endodontic instruments, even when used in reciprocating motion (5, 11, 12, 27). It is important to note that, in clinical situations, the instrument is also subjected to torsional and bending stresses depending on the anatomy of the canals and how the instruments are being used by the clinician (1–6). However, for the purposes of evaluating the mechanical properties of instruments, it is not possible yet to obtain many samples of natural teeth that are anatomically fully standardized (1, 21, 28). On the other hand, it is possible to improve the reliability of cyclic fatigue tests by using features such as artificial canals that allow the perfect fit and trajectory of the instrument (1, 14, 28), dynamic models which allow simulating better the axial movements of a clinical situation (17, 21, 25), as well performing the tests at body temperature (37°C) (16, 23, 29–31).

TABLE 1. Mean and standard deviation of time (s) and number of cycles until fracture (NCF) of tested instruments

Instrument	Time (s)	NCF	Fragment length
Pro-R	342±88.1[a]	1710±441[a]	4.75±1.05[a]
Reciproc	238±40.4[b]	1189±202[b]	6.83±0.37[b]
Reciproc Blue	319±35.6[a]	1597±178[a]	6.19±0.40[b]
X1 Blue File	116±46.4[c]	582±232[c]	6.29±0.91[b]

Different superscript letters in the same column indicate statistical difference (Tukey test, $p<0.05$)

It has been shown that increasing temperature decreases the lifespan of endodontic instruments; thus, laboratory tests should preferably be performed simulating body temperature (16, 29–31). In the present study, the instruments were submerged in water throughout the experiment maintaining the temperature at 37°C (±1°C). Moreover, using an aqueous medium simulates the irrigating solution, lubricates, and avoids the increase in temperature due to friction between the instrument and the simulated canal (32).

In the present study, the artificial canals were designed in CAD software and milled to allow the precise fit and trajectory for the evaluated instruments (1, 28, 30, 33). The use of zirconium dioxide facilitates the visualization of the instruments inside them while presenting high resistance to wear and abrasion (30, 33). It is important to consider the taper chosen for the tube (30.08) and the fact that the instruments selected presented size 25 and .08 taper, except for X1 Blue File (.06 taper).The standardization of the canal diameters is necessary for the instrument to work passively in the canals, where the evaluation will be of the fatigue in the curvature and not in the canal walls. Although it has been shown that smaller tapers might improve the resistance to breakage (3, 26), in the present results, X1 Blue had the smallest lifespan. Present results could be partially related to the convex triangular cross-section of the X1 Blue instrument, different from the other tested instruments, which present an "S" shaped cross-section. Different design features, such as the cross-section, core diameter, and flute pitch, might also impact the total mass at the maximum stress point and lower the resistance to cyclic fatigue stress of the instruments (1, 3–5, 10, 32, 34). One should note that most of these previous studies were performed using static models for cyclic fatigue testing, which hinders further comparison.

Dynamic models for cyclic fatigue are considered more realistic because they better simulate axial movements of a clinical situation (21, 23–25). However, to the best of our knowledge, no previous studies assessed the resistance to dynamic cyclic fatigue of the X1 Blue File and Pro-R instruments, while controversial results are found regarding the comparison between Reciproc and Reciproc Blue (19, 23). In the present investigation, the Pro-R and Reciproc Blue were significantly more resistant than Reciproc, and X1 Blue presented the shortest lifespan.

When files are tested for cyclic fatigue in a static model, the compressive and tensile stresses accumulate in a restricted area, usually at the maximum point of the curvature might underestimate the resistance to fracture (1, 21, 24). Differently, in the dynamic model, the up and down motion of the file distribute the stress along a larger area of the instruments, increasing the resistance to cyclic fatigue (23–25). This fact might partially explain the differences observed for the fragment length of Pro-R files, which were on mean shorter and with a higher standard deviation compared to the other instruments. In the literature, some studies did not report the results for fragment length (21, 24), while others reported similar fragment length while testing different instruments in dynamic cyclic fatigue (19, 23, 25). Thus, the results for the fragment length of Pro-R suggest that the stresses were more distributed, which is also is correlated to the increased resistance to fracture of this file.

In addition to the methodology used to perform the cyclic fatigue tests, the resistance of NiTi endodontic instruments can be influenced by several factors such as diameter, kinematics, taper, cross-section, and type of alloy (1, 3, 5, 11, 12, 21, 32, 34). Little information is available in the literature regarding X1 Blue (16, 17). A study showed that X1 Blue File presented similar cyclic fatigue resistance compared to Reciproc Blue in a static model at both room and body temperature (16). Differently, in the present study, Reciproc Blue was statistically more resistant than X1 Blue File in a dynamic model at body temperature. Another study (17) showed that X1 Blue was more resistant to static cyclic fatigue at body temperature compared to another heat-treated reciprocating file, W File (TDKa File, Shenzhen, China).

As a limitation of this study, *in vitro* studies evaluating cyclic fatigue do not accurately simulate clinical situations of stress generated to the instrument, because cyclic fatigue is accompanied by torsional stress. Future studies are suggested with the inclusion of the location and type of fracture, including SEM analyses.

CONCLUSION

Pro-R and Reciproc Blue are more resistant to dynamic cyclic fatigue compared to Reciproc and X1 Blue instruments.

Disclosures

Conflict of interest: The authors deny any conflict of interest.

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REFERENCES

1. Plotino G, Grande NM, Cordaro M, Testarelli L, Gambarini G. A review of cyclic fatigue testing of nickel-titanium rotary instruments. J Endod 2009; 35(11):1469–76.
2. Serene TP, Adams JD, Saxena A. Nickel-titanium Instruments: Applications in Endodontics. St Louis: Ishiyaku EuroAmerica; 1995.
3. Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment of nickel-titanium instruments. J Endod 2013; 39(2):163–72.
4. Sattapan B, Nervo GJ, Palamara JE, Messer HH. Defects in rotary nickel-titanium files after clinical use. J Endod 2000; 26(3):161–5.
5. Gambarini G, Piasecki L, Di Nardo D, Miccoli G, Di Giorgio G, Carneiro E, et al. Incidence of deformation and fracture of twisted file adaptive instruments after repeated clinical use. J Oral Maxillofac Res 2016; 7(4):1–7.
6. Ferreira M, Ferreira H, Oliveiras B, Carrilho E. Defects in ProFile rotary nickel-titanium files after clinical use. ENDO 2012; 6(2):113–7.
7. Pruett JP, Clement DJ, Carnes DL Jr. Cyclic fatigue testing of nickel-titanium endodontic instruments. J Endod 1997; 23(2):77–85.
8. Ullmann CJ, Peters OA. Effect of cyclic fatigue on static fracture loads in ProTaper nickel-titanium rotary instruments. J Endod 2005; 31(3):183–6.
9. Zhang EW, Cheung GS, Zheng YF. A mathematical model for describing the mechanical behaviour of root canal instruments. Int Endod J 2011; 44(1):72–6.
10. Kim HC, Kwak SW, Cheung GS, Ko DH, Chung SM, Lee W. Cyclic fatigue and torsional resistance of two new nickel-titanium instruments used in reciprocation motion: Reciproc versus WaveOne. J Endod 2012; 38(4):541–4.
11. Zupanc J, Vahdat-Pajouh N, Schafer E. New thermomechanically treated NiTi alloys - a review. Int Endod J 2018; 51(10):1088–103.
12. Plotino G, Ahmed HM, Grande NM, Cohen S, Bukiet F. Current assessment of reciprocation in endodontic preparation: a comprehensive review - part II: properties and effectiveness. J Endod 2015; 41(12):1939–50.
13. De-Deus G, Silva EJ, Vieira VT, Belladonna FG, Elias CN, Plotino G, et al. Blue thermomechanical treatment optimizes fatigue resistance and flexibility of the Reciproc files. J Endod 2017; 43(3):462–6.
14. Gambarini G, Piasecki L, Miccoli G, Gaimari G, De Giorgio R, Di Nardo D, et al. Classification and cyclic fatigue evaluation of new kinematics for endodontic instruments. Aust Endod J 2019; 45(2):154–62.
15. Plotino G, Grande NM, Testarelli L, Gambarini G. Cyclic fatigue of Reciproc and WaveOne reciprocating instruments. Int Endod J 2012; 45(7):614–8.
16. Klymus ME, Alcalde MP, Vivan RR, Só MVR, de Vasconselos BC, Duarte MAH. Effect of temperature on the cyclic fatigue resistance of thermally treated reciprocating instruments. Clin Oral Investig 2019; 23(7):3047–52.
17. Calefi PHS, Osaki RB, Evedove NFD, Cruz VM, Andrade FB, Alcalde MP. Cyclic and torsional fatigue resistance of W File and X1 Blue file reciprocating instruments. Dental Press Endod 2020; 10(2):60–6.
18. Hieawy A, Haapasalo M, Zhou H, Wang ZJ, Shen Y. Phase transformation behavior and resistance to bending and cyclic fatigue of ProTaper Gold and ProTaper Universal instruments. J Endod 2015; 41(7):1134–8.
19. Keskin C, Inan U, Demiral M, Keleş A. Cyclic fatigue resistance of Reciproc Blue, Reciproc, and WaveOne Gold reciprocating instruments. J Endod 2017; 43(8):1360–3.
20. Gao Y, Gutmann JL, Wilkinson K, Maxwell R, Ammon D. Evaluation of the impact of raw materials on the fatigue and mechanical properties of ProFile Vortex rotary instruments. J Endod 2012; 38(3):398–401.
21. Yao JH, Schwartz SA, Beeson TJ. Cyclic fatigue of three types of rotary nickel-titanium files in a dynamics model. J Endod 2006; 32(1):55–7.
22. Gundogar M, Ozyurek T. Cyclic fatigue resistance of OneShape, HyFlex EDM, WaveOne Gold, and Reciproc Blue nickel-titanium instruments. J Endod 2017; 43(7):1192–6.
23. Keleş A, Eymirli A, Uyanık O, Nagas E. Influence of static and dynamic cyclic fatigue tests on the lifespan of four reciprocating systems at different temperatures. Int Endod J 2019; 52(6):880–6.
24. Li UM, Lee BS, Shih CT, Lan WH, Lin CP. Cyclic fatigue of endodontic nickel-titanium Rotary instruments: static and dynamic tests. J Endod 2002; 28(6):448–51.
25. Uslu G, Özyürek T, İnan U. Comparison of cyclic fatigue resistance of ProGlider and One G glide path files. J Endod 2016; 42(10):1555–8.

26. Drexel M, Selvaduray G, Pelton A. The effects of cold work and heat treatment on the properties of nitinol wire. In: Medical Device Materials IV: Proceedings from the Materials and Processes for Medical Devices Conference. Ohio: ASM International, Materials Park; 2007. p.144–9.
27. Plotino G, Grande NM, Porciani PF. Deformation and fracture incidence of Reciproc instruments: a clinical evaluation. Int Endod J 2015; 48(2):199–205.
28. Piasecki L, Makowka SR, Gambarini G. Anatomic two-dimensional and three-dimensional models for cyclic fatigue testing of endodontic instruments. Iran Endod J 2020; 15(2):100–5.
29. de Vasconcelos RA, Murphy S, Carvalho CA, Govindjee RG, Govindjee S, Peters OA. Evidence for reduced fatigue resistance of contemporary rotary instruments exposed to body temperature. J Endod 2016; 42(5):782–7.
30. Shen Y, Huang X, Wang Z, Wei X, Haapasalo M. Low environmental temperature influences the fatigue resistance of nickel-titanium files. J Endod 2018; 44(4):626–9.
31. Dosangh AD, Paurazas SS, Askar MZ. The effect of temperature on cyclic fatigue of nickel-titanium rotary endodontic instruments. J Endod 2017; 43(5):823–6.
32. Cheung GS, Darvell BW. Fatigue testing of a NiTi rotary instrument. Part 1: strain-life relationship. J Endod 2007; 40(8):612–8.
33. Huang X, Shen Y, Wei X, Haapasalo M. Fatigue resistance of nickel-titanium instruments exposed to high-concentration hypochlorite. J Endod 2017; 43(11):1847–51.
34. Grande NM, Plotino G, Pecci R, Bedini R, Malagnino VA, Somma F. Cyclic fatigue resistance and three-dimensional analysis of instruments from two nickel-titanium rotary systems. Int Endod J 2006; 39(10):755–63.