ORIGINAL RESEARCH

Influence of Temperature on the Cyclic Fatigue of Nickel–Titanium Instruments with Different Heat Treatments on Severely Curved Canals

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Abstract

Aim: This study aims to investigate the influence of temperatures of 20 °C and 37 °C on the resistance to cyclic fatigue of NiTi instruments with different heat treatments, as tested in severely curved simulated canals.

Materials and methods: Seventy-two instruments were distributed according to the temperature used (20 °C and 37 °C): XP-endo Shaper (30/0.01), ProDesign Logic (30/0.05), and iRaCe (30/0.04). The instruments were rotated freely until the occurrence of fracture inside an artificial severely curved stainless steel canal, which had a 90° angle of curvature and a curvature radius of 5 mm. Kolmogorov–Smirnov, Wilcoxon, ANOVA, and Kruskal–Wallis tests were performed. A p value of <0.05 was considered statistically significant.

Results: XP-endo Shaper instruments presented higher NCF values and time to failure compared with ProDesign Logic and iRaCe instruments at 20 °C and 37 °C ($p < 0.001$).

Conclusion: Within the limitations of this study, the results show that the body temperature (37 °C) significantly lowers the resistance to cyclic fatigue of all instruments compared with 20 °C.

Clinical significance: Body temperature is an important factor in the results of cyclic fatigue tests.

Keywords: Body temperature, Cyclic fatigue, Nickel–titanium alloy, ProDesign Logic, XP-endo Shaper.

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Introduction

Mechanized nickel–titanium (NiTi) instruments are more efficient than those made of stainless steel in the mechanical preparation by virtue of their better ability to respect the original anatomy of the canal through the maintenance of centralization during the preparation.[1,2] However, results vary among instruments concerning the occurrence of iatrogeneses, such as transportation and perforation, particularly in severely curved canals.[3–6] It is more difficult for these instruments to follow this type of anatomy.[7] Moreover, complex anatomies can favor the occurrence of instrument fracture during the preparation; if the fragment impedes or limits the cleaning of the root canal as a whole, it can cause failure in the treatment.[8] Cyclic fatigue has been reported as the main cause of fracture during clinical practice[9] and occurs when the instrument rotates freely in a curvature, generating tension/compression cycles in the region of maximum flexure until fracture.[10]

The performance and the resistance of the instruments appear to be influenced by their dimensions, cross-sections, metallic alloys, and surface treatments.[9,11–13] Thus, the metallic alloys and their manufacturing processes are being improved with the objective of increasing the resistance and reliability of the instruments.[14–16] According to the manufacturer, the rotary instrument XP-endo Shaper (XPS; FKG Dentaire, La Chaux-de-Fonds, Switzerland), recently released to the market, has a triangular cross-section and is manufactured using MaxWire heat treatment of the NiTi alloy (Martensitic-Austenite Electropolish Flex, FKG Dentaire). This treatment would allow changes in the shape of the instrument if its temperature is altered. At lower temperatures, the alloy enters the martensitic phase and presents a straighter conformation, with a #30 tip size and 0.01 taper. At higher temperatures, such as the body temperature, the alloy changes to the austenitic phase and alters its shape, reaching a minimum final preparation of a #30 tip size and 0.04 taper.

Surface heat treatments have been used on NiTi alloys to alter their microstructure, modifying their characteristics of shape memory and their mechanical behavior.[17] This is the case for ProDesign Logic systems (PDL; Easy Equipamentos Odontológicos, Belo Horizonte, MG, Brazil). According to the manufacturer, such instruments present a modified S-shaped cross-section and go through a special thermomechanical treatment, which provides better disposition of the crystalline structure, resulting in greater

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flexibility and controlled shape memory. The higher flexibility of an instrument is a characteristic that makes it more resistant to cyclic fatigue.[9]

The machining process leads to defects in the surface on the endodontic instruments. These defects are stress points that favor the propagation of cracks and this factor can influence the cyclic fatigue resistance of the instruments.[18–20] Electropolishing is a surface finishing method used by manufacturers of NiTi rotary instruments to remove surface defects that may remain after the machining process, increasing the resistance to cyclic fatigue compared to other instruments.[21] The instruments from the iRaCe system (IRC; FKG Dentaire, La Chaux-de-Fonds, Switzerland) have a triangular cross-section and are electropolished. Recent studies indicate that the temperature applied during the use of NiTi instruments is another possible variable that could influence the resistance of the instrument.[22,23] Most studies test the resistance to cyclic fatigue at room temperature, without specific temperature control.[18,24–26] However, endodontic instruments are used inside of root canals, which are surrounded by the periradicular tissue.[27] Body temperature (37 °C) should be taken into consideration as a relevant factor.[28] Thus, the objective of this study was to investigate the influence of temperatures of 20 °C and 37 °C on the resistance to cyclic fatigue of NiTi instruments with different surface treatments (XPS, PDL, and IRC), tested in severely curved simulated canals. After the instrument was fractured, the length of the fragment was measured. The null hypotheses tested were the absence of significant differences in the resistance to cyclic fatigue among the instruments XPS, PDL, and IRC according to the parameters evaluated.

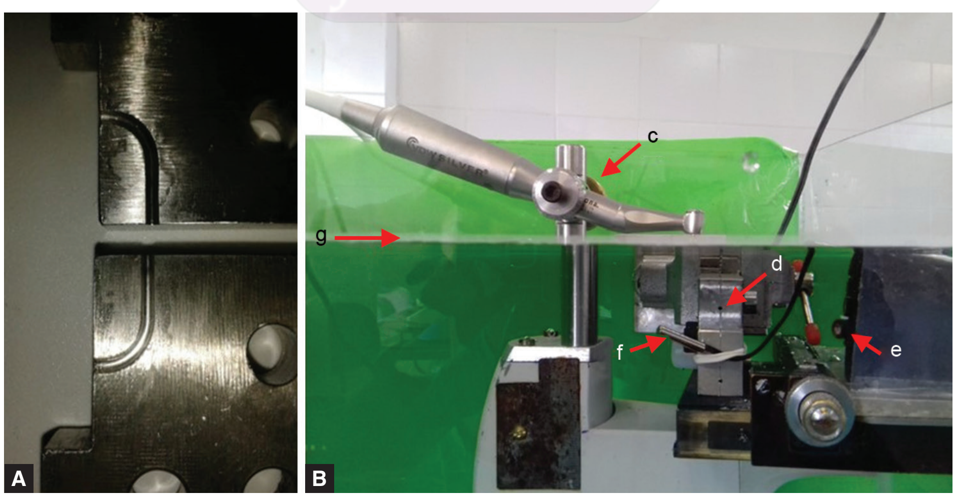
Materials and Methods

Seventy-two new instruments were distributed into six groups ($n = 12$ each group) and tested for cyclic fatigue in a water bath at room temperature (20 °C) and at body temperature (37 °C), based on the previous research,[29,30] XP-endo Shaper 30/0.01, XPS20 and XPS37; ProDesign Logic 30/0.05, PDL20 and PDL37; and iRaCe 30/0.04, IRC20 and IRC37. The inclusion criteria were instruments with the absence of defects or deformations, such as distortions or burrs in the blades. For this, all instruments were checked by a single operator under a stereomicroscope (SteREO Discovery V12; ZEISS, Germany) in 16× augmentation to evaluate the instruments. Consequently, the exclusion criterion was the presence of such changes in the instrument surfaces. No signs of alteration were detected and no instrument was discarded.

Cyclic Fatigue Test

The static cyclic fatigue test was performed by using an artificial severely curved stainless steel canal, which had an angle of curvature of 90° and a curvature radius of 5 mm.[24] The internal diameter was of 1.5 mm, and the center of curvature was at 5 mm from the tip of the instrument (Fig. 1A). All tests were performed by a single operator using a 6:1 reduction handpiece (Sirona Dental Systems GmbH, Bensheim, Germany) coupled to a silver reciproc torque-controlled motor (VDW, Munich, Germany). A personalized support was used to keep the handpiece and the steel canal static during use, allowing only the instrument to rotate freely. The instrument tested was coupled to the handpiece and inserted into the artificial canal, parallel to its vertical portion, following the direction of the tip of the instrument to the base. The device was completely submerged in distilled water, inside a 50 × 20 × 30-cm glass container. The temperature was controlled at 20 °C and 37 °C throughout the working time with the aid of an underwater thermometer and a thermostat (Fig. 1B). To heat and cool the water, an immersion heater and ice were used, respectively. The tip of the thermostat was sufficiently close to the canal to ensure a specific temperature throughout the analysis.

All endodontic instruments were set to operate at the minimal level of torque available in the motor (0.2 N cm) in continuous rotary movement and according to the speed recommendations of the manufacturer. The instrument was rotated freely, in a static position, in the axial direction until a fracture occurred. Time measurement was performed by video recording, initiating when the instrument is triggered and ending when the fracture is visually detected. The time for the fracture to occur was converted to the number of cycles to fracture (NCF) through the formula: NCF = rotation per minute (rpm) × time to failure in seconds (s)/60 s. After the fracture, the length of the fragment was measured with the aid of a digital caliper with a precision of 0.01 mm.



Figs 1A and B: Experimental setup showing (A) artificial curved stainless steel canal. (B) Water bath and electric motor setup and artificial stainless steel canal submerged in water; red arrows: (c) handpiece on the personalized support, (d) instrument inserted into the artificial canal, following the direction of tip of the instrument to the base, (e) video camera, (f) thermostat, and (g) water level.

Statistical Analysis

The data were analyzed using the software STATA/SE 12.0 (StataCorp LLP, College Station, TX) and SPSS 13.0 (SPSS Inc., Chicago, IL) for Windows and Excel 2010. The numerical variables were represented by the measures of central tendency and measures of dispersion, and Kolmogorov–Smirnov, ANOVA, Kruskal–Wallis, and Student's *t* tests were performed. A *p* value of <0.5 was considered statistically significant.

Results

The mean values, standard deviation of NCF, time to failure in seconds, length of the fragment in millimeters of each instrument system, and the tested temperatures are presented in Table 1. XPS instruments showed higher NCF values and time to failure compared with PDL and IRC instruments at 20 °C and 37 °C ($p < 0.001$). With the same parameters, PDL instruments had greater values than IRC instruments ($p < 0.001$). When the length of the fragments is analyzed, PDL instruments present lower lengths, followed by IRC and XPS instruments at 20 °C ($p < 0.001$). At 37 °C, XPS instruments had greater lengths than PDL and IRC instruments ($p < 0.001$), without a significant difference in the length between the groups PDL and IRC ($p > 0.05$). Regarding statistical analysis for the same system, when temperatures are compared, all systems reveal results with a significant statistical difference in time to fracture and NCF ($p < 0.05$).

Discussion

At both temperatures tested, 20 °C and 37 °C, NCF values and time to fracture were statistically higher in the XPS group, followed by the PDL and IRC groups ($p < 0.001$). Parallel to these findings, previous studies report the influence of temperature on the resistance to cyclic fatigue, in which lower temperatures favor greater resistance of the instruments.[29,30] Therefore, the null hypotheses were not accepted for these parameters ($p > 0.05$). However, there are no studies that compare the NCF value of XPS instruments with PDL and IRA instruments in severe curvatures.

Table 1: Mean and standard deviation of time, fragment length, and number of cycles to fracture (NCF) by temperature within the same system

	Temperature		
Variable	*37 °C, mean ± DP*	*20 °C, mean ± DP*	*p value*
ProDesign logic (PDL)			
Time (s)	50.50 ± 22.08	79.92 ± 18.72	0.006*
NCF	799.58 ± 349.54	1265.34 ± 296.40	0.006*
Fragment length (mm)	5.24 ± 0.92	4.70 ± 0.46	0.100
XP-endo shaper (XPS)			
Time (s)	94.83 ± 12.87	329.33 ± 36.09	<0.001*
NCF	1264.44 ± 171.58	4391.11 ± 481.22	<0.001*
Fragment length (mm)	7.50 ± 1.11	7.26 ± 1.08	0.525
iRaCe (IRC)			
Time (s)	18.33 ± 8.19	30.17 ± 9.17	0.003*
NCF	145.83 ± 88.20	301.67 ± 91.73	0.001*
Fragment length (mm)	5.21 ± 0.41	5.20 ± 0.22	0.285

* A *p* value of <0.5 was considered statistically significant

The temperature influences the behavior of the MaxWire surface treatment of the XPS system. At higher temperatures, such as body temperature (37 °C), it changes to its austenitic phase assuming a snake shape that can achieve a final minimum canal preparation of 30/0.04 when using this instrument alone.[23] There is a difference in conicity among the systems tested: 1% for the XPS group, 5% for the PDL group, and 4% for the IRC group. The greater the taper, the shorter is the time for the cyclic fracture of the instrument and, thus, the lower is the NCF.[25] The PDL CM instruments with heat treatment present greater taper and resistance to cyclic fatigue at 4 (20 °C)–5 (37 °C) times higher compared with electropolished NiTi IRC instruments of a smaller taper. And, compared with the XPS, they presented resistance to cyclic fatigue at 3 (20 °C) to 1.5 (37 °C) times lower. Therefore, it can be inferred that the heat treatment performed on the NiTi alloy and taper of the instruments tested seemed to have greater influence on the results.

The properties of the MaxWire NiTi alloy confer to XPS instruments superelasticity and shape memory, and it can reach a canal preparation of 0.04 despite its lower initial taper, favoring lower bending stiffness.[9,11] Studies report the resistance to cyclic fatigue of XPS instruments. Elnaghy and Elsaka[31] compared the cyclic fatigue of XP-endo Shaper (30/0.01), TRUShape (30/0.06), Hyflex CM (30/0.04), iRace (30/0.04), and Vortex Blue (30/0.04) instruments at 37 °C with a 60° angle of curvature and a 3-mm radius of curvature. Silva et al.[23] examined the cyclic fatigue of XP-endo Shaper (30/0.01) and TRUShape (30/0.06) instruments at 37 °C with a 60° angle of curvature and a 5-mm radius of curvature. Keskin et al.[32] evaluated the cyclic fatigue of XP-endo Shaper (30/0.01), K3XF (30/0.04), and ProTaper Gold F3 (30/0.09) instruments at 35 °C with a 60° angle of curvature and a 5-mm radius of curvature. All studies concluded that XPS instruments had a greater resistance to cyclic fatigue. The present study also demonstrates that XPS instruments are more flexible and present a higher NCF value at 20 °C and 37 °C.

On the one hand, PDL instruments possess a modified S-shaped cross-section while XPS and IRC possess a triangular cross-section. The NiTi instruments with larger cross-sectional areas present lower resistance to cyclic fatigue.[33] However, the cross-sectional area does not interfere with resistance to cyclic fatigue.[34] We found that the heat treatment applied to the NiTi alloy of the evaluated instruments seems to have more influence on resistance to cyclic fatigue than the shape of the cross-section of the instrument. This finding is due to the XPS and IRC files, which have the same cross-section and different metallic core sizes but presented different results.

On the other hand, the small central area of the S-shaped cross-section provides a positive effect on the resistance to cyclic fatigue.[35] In this study, the instruments (PDL), even with a larger taper, presented greater resistance to cyclic fatigue compared with those of the IRC group ($p < 0.001$) at both temperatures tested. However, when PDL instruments are compared with XPS instruments, the former presents lower resistance to cyclic fatigue ($p < 0.001$).

As far as the speed is concerned, a higher rpm will consume the lifespan of the instrument much faster than a lower rpm, especially under severe curvature conditions. Although there were no significant results in the investigation of the effect that rpm has in cyclic fatigue,[24] the different rotation speeds between the instruments would produce divergent thermal energy and could temporarily raise the temperature, which would influence the results.[23] In this study, it was observed that the IRC instruments with a lower rpm presented lower NCF values and time to fracture at both temperatures tested. However, these cyclic fatigue results must take into account more than the operating speed of the systems.

Although the instruments tested have the same diameter and kinematics, the fracture site was different between the groups tested. At both temperatures, XPS instruments presented higher length compared to PDL and IRC instruments ($p < 0.001$) in severely curved canals. In a same system, the cooling of the temperature from 37 °C to 20 °C did not influence the length of the fragment. The greater cross-sectional area and the stiffness of the alloy add to the propensity to more coronal fractures of the instruments.[29] In the present study, the instruments with higher flexibility, XPS, presented more coronal fractures with the smallest cross-sectional area. Furthermore, the severe curvature used in this study propitiated a larger fragment length of the XPS files, when compared with the fragments from another study[31] 5.12 ± 0.21 at 37 °C with a 60° angle of curvature and a 3-mm radius of curvature.

The laboratory practices are guiding factors for the choice of instruments and clinical protocols and, in *in vivo* studies, the number of cycles for fatigue is not calculated. The disciplines were applied in the use of simulated stainless steel canals due to their ability to standardize as samples on extracted teeth, the impossibility of testing all instruments at the same level during sampling after instrumentation, and the level of hardness between the blocks stainless steel and dentin.

Conclusion

The results show that body temperature (37°) significantly lowers the resistance to cyclic fatigue of all instruments tested compared with the use at 20 °C. The resistance to cyclic fatigue of the XP-endo Shaper instruments was superior to that of the ProDesign Logic and iRaCe instruments ($p < 0.001$). Future studies should be carried out to identify the impact of low temperatures on the mechanical properties of the instruments, as well as on the dentin and the other surrounding tissues.

Clinical Significance

Body temperature is an important factor in the results of cyclic fatigue tests.

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