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ORIGINAL RESEARCH

Evaluation of the mechanical properties of different nickel–titanium retreatment instruments

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Abstract

This study investigated the cyclic fatigue, bending, torsional resistance and angular deflection of Pro-R 25.08, Logic RT 25.08, MK Retreatment 25.08 (MK RT) and ProTaper Retreatment D2 instruments. Cyclic fatigue test was performed until fracture in a custom stainless-steel device with water bath equipment to simulate body temperature. Fracture time was recorded. A number of cycles were calculated. Resistance to bending at 45°, torsional resistance and angular deflection were evaluated. The fracture surfaces were examined by scanning electron microscopy. Statistical analysis was performed with one-way ANOVA and Tukey and Kruskal–Wallis and Dunn tests. Pro-R and Logic RT presented the highest cyclic fatigue ($P < 0.05$). D2 had higher strength to bend than Pro-R and Logic RT ($P < 0.05$). Logic RT showed the highest torque and angular deflection ($P < 0.05$), without differences when compared to D2 ($P > 0.05$). Instrument performances were dependent on their geometrical features and heat treatments.

Introduction

The need for endodontic retreatment is mainly due to the presence of persistent or secondary bacterial infection (1). Several techniques have been proposed for the removal of the filling material. However, none can completely remove gutta-percha and the endodontic sealer from the root canal system (2). Studies have already shown the effectiveness of nickel–titanium (NiTi) instruments specifically designed for these situations (3,4).

The NiTi alloy can be presented in 3 microstructural phases (austenite, martensite and R-phase). Conventional NiTi alloy instruments present a high level of elasticity, mainly containing austenite phase, and when induced to temperature drops or mechanical stress, a martensite transformation occurs, presenting a shape memory effect, increasing its flexural resistance (5,6). However, these instruments are also subject to failure due to torsional fracture or cyclic fatigue (7).

Therefore, the technologies such as different geometries, kinematics and thermal treatments, modifying the temperature required to obtain the austenite–martensite transformation, have been proposed to improve the performance of NiTi instruments (8–16). Pro-R #25.08 (Pro-R – MK Life, Porto Alegre, Brazil) is a 25-mm-length reciprocating instrument that presents an alloy with M-Wire treatment and a double-helix cross section. ProDesign Logic RT #25.08 (Logic RT – Easy Equipamentos Odontológicos, Belo Horizonte, Brazil), a 25-mm-length rotary instrument, presents CM-Wire treatment on its alloy with a triple-helix cross section. MK Retreatment #25.08 (MK RT – MK Life, Porto Alegre, Brazil), an 18-mm-length rotary instrument without heat treatment, presents a rhomboidal cross section. And ProTaper Retreatment D2 #25.08 (D2 – Dentsply/Tulsa Dental Specialties, Tulsa, OK, USA), also an 18-mm-length rotary conventional NiTi instrument, presents with a convex triangular cross section.

NiTi retreatment instruments move with their tip in close contact with the filling material, being frequently subject to locking, requiring a specific resistance to torsion (17). These instruments must also present enough flexibility to reduce the potential risk of canal transportation (18). Several studies evaluated the mechanical performance of retreatment NiTi instruments (17–20), but recent data have shown that different temperatures at which NiTi instruments are subjected can alter the properties of their alloy, affecting their flexural strength (21-23), without any effect on their torsional behaviour, regardless of heat treatment (24).

For these reasons, due to the need for studies evaluating the performance of instruments at body temperature, this study aimed to evaluate the mechanical properties of four NiTi retreatment instruments: Pro-R #25.08, ProDesign Logic RT #25.08, MK Retreatment #25.08 and ProTaper Retreatment D2 #25.08. The null hypotheses of the study are as follows: (i) there are no differences in the cyclic fatigue resistance of the tested instruments; (ii) there are no differences in the bending capacity of the instruments; (iii) there are no differences in the torsional strength of the tested instruments.

Materials and methods

Sample size calculation was performed before the mechanical testing using G*Power v.3.1 for Mac (Heinrich Heine, University of Düsseldorf, Düsseldorf, Germany) and by selecting the Wilcoxon–Mann–Whitney test. The alpha-type error of 0.05, beta power of 0.95 and N2/N1 ratio of 1 were also stipulated. The test calculated eight samples for each group as the ideal size for noting significant differences. However, an additional 20% of the real instruments were used to compensate for atypical values that might lead to sample loss.

A total of 80 NiTi instruments were selected for this study. The samples were divided into four groups ($n = 20$) as follows: Pro-R #25.08 (Pro-R), MK Retreatment #25.08 (MK RT), ProTaper Retreatment D2 #25.08 (D2) and ProDesign Logic RT #25.08 (Logic RT).

Pro-R is a 25-mm-length reciprocating NiTi instrument that presents an alloy with M-Wire treatment, a #25 mm tip, and .08 taper on its first 3 mm with a double-helix cross section. Logic RT is a 25-mm-length rotary NiTi instrument presenting CM-Wire treatment on its alloy, #25-mm tip, and .08 taper on its first 3 mm with a triple-helix cross section. MK RT is an 18-mm-length rotary conventional NiTi instrument, with a #25 mm tip and 0.08 taper presenting a rhomboidal cross section, and D2 is also an 18-mm-length rotary conventional NiTi instrument, presenting a #25-mm tip and .08 taper on its first 3 mm with a convex triangular cross section.

Pro-R and MK RT instruments are commercialised in sterile blisters packs. Since Logic RT and D2 instruments are not commercialised in sterile blister packs, these instruments were subjected to the sterilisation process in an autoclave (Bioclave 12L, Saevo, Ribeirão Preto, São Paulo, Brazil) for 16 minutes at a temperature of $128° \pm 1°C$ and a pressure of 1,7kgf $cm^{-2} \pm 0,4$, in order to simulate clinical conditions. Previously to the mechanical tests, all files were inspected under a stereomicroscope (Carls Zeiss, LLC, EUA) at 16× magnification to detect possible defects or deformities; none were discarded.

Cyclic fatigue test

The cyclic fatigue test was performed using a custom-made device that simulated an artificial canal made of stainless steel, with a 60° angle of curvature and a 5-mm radius of curvature reproducing the size and taper of the instruments. The curvature of the artificial canal was fitted onto a cylindrical guide made of the same material. An outer arch had a 1-mm-deep groove that served as a guide path for the instruments, which kept the instruments on the curvature, allowing them to rotate or reciprocate freely during the test. The device allowed an accurate and reproducible position of the curvature to be established for all the instruments. The same device was used in previous studies (25–27).

This test was performed at body temperatures ($36° \pm 1°C$) using a histology water bath equipment (Leica HI 1210), which allowed to control the temperature (28). A total of 600 mL of water was used to fill the equipment container to the desired level, allowing the simulated canal to be submerged on the water. The temperature was controlled using a digital thermometer of the equipment and infrared thermometer during all the test.

The instruments were coupled to a VDW Silver Motor (VDW, Munich, Germany), and speed and torque were programmed according to the manufacturer's recommendations: Pro-R instruments were operated with the 'Reciproc ALL' program (300 rpm) in reciprocating motion and Logic RT (900 rpm and 4 Ncm), MK RT (350 rpm and 2 Ncm) and D2 (500 rpm and 4 Ncm) in rotary motion.

All instruments were activated until a fracture occurs. A digital chronometer measured the time to fracture, and video recordings were made during all the tests. The time to fracture was multiplied by the number of rotations per minute (rpm) to obtain the number of cycles to fracture (NCF) for each instrument.

Bending and torsional tests

Previously to the torsional test, ten instruments of each system were subjected to the bending test. The bending test was performed using a torsion machine (Analógica, Belo Horizonte, Brazil), adapted to the ISO 3630-1 specifications to verify the flexibility and the maximum force required to bend the files at 45° angular deflection, as previously reported (18).

Instruments were fixed at 3 mm from the tip and perpendicularly to the motor axis. The bending angle (45°) was measured and controlled by a resistive angular transducer connected to a process controller. The force required to bend the instruments was automatically measured by the load cell and recorded by a machine's specific programme (MicroTorque; Analógica).

After the bending tests, the torsional test was performed, following the ISO 3630-1 specifications, as previously described (18). Torque and angular rotation were measured throughout the entire test. The values of ultimate load and angular rotation (°) were provided by the same torsion machine and programme previously described. Before testing, the handle of all instruments was removed when they attached to the torsion shaft. The 3 mm of the instrument tip was clamped to a geared motor and then started in the counter-clockwise motion (2 rpm) for all groups.

Scanning electron microscopy evaluation

All instruments were examined under a scanning electron microscopy (SEM) to verify the topographic features of the fragment fractures. Before SEM, the instruments were cleaned in an ultrasonic device (L100, Schuster, Santa Maria, RS, Brazil) in distilled water for 3 minutes. The instruments' fracture surface was examined at 100× magnification in the cross-sectional direction and transversally at 50× magnification after cyclic fatigue testing, and at 150× and 250× magnification in the instruments cross section after torsional testing.

Statistical analysis

Shapiro–Wilk test was performed to verify the presence or absence of normality. One-way analysis of variance and Tukey's post hoc tests were used for multiple and individual comparisons on the cyclic fatigue and torsional results. Kruskal–Wallis and Dunn post hoc tests were used for multiple and individual comparisons on the bending and angular deflection results. 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

The values (mean and standard deviation) of cyclic fatigue, bending and torsional resistance (torque maximum load and angle of rotation) tests are presented in Table 1. Pro-R and Logic RT presented higher cyclic fatigue values than MK RT and D2 ($P < 0.05$).

D2 had higher strength to bend when compared to Pro-R and Logic RT ($P < 0.05$), but similar to MK RT ($P > 0.05$). Logic RT presented the lowest values ($P < 0.05$), except when compared to Pro-R ($P > 0.05$).

After the torsional test, Logic RT presented the highest torque and angular deflection values ($P < 0.05$), but without differences only when compared to D2 ($P > 0.05$). MK RT showed the lowest torque ($P < 0.05$), except when compared with Pro-R ($P > 0.05$).

SEM evaluation of the fragment surfaces showed typical cyclic fatigue and torsional failure for all the instruments analysed. Instruments subjected to the cyclic fatigue test showed ductile morphologic characteristics and did not present plastic deformation on their helical shafts (Figure 1). Following the torsional test, the instruments showed abrasion marks and fibrous dimples near the centre of the rotation (Figure 2).

Discussion

NiTi instruments can be presented in three microstructural phases. The austenitic phase provides super elastic properties to the NiTi alloy, making the instruments harder and stiffer. The R-phase is a rhombohedral distorted phase before the martensitic transformation. Finally, the martensitic phase provides the alloy more ductility, making it easier to be deformed and possessing a shape memory effect (5,6,13). These transformations are temperature and stress-induced (5,13). Therefore, to increase the instruments' flexibility by altering the austenite–martensite transformation temperature, several heat treatments of the NiTi alloys have been proposed (6).

Table 1 Mean (and standard deviation) of the cyclic fatigue (NCF), bending (°), torque (N.cm) and angular deflection (°) of the tested instruments

Instruments	Cyclic fatigue (NCF)	Bending (°)	Torque (N.cm)	Angular deflection (°)
Pro-R	953.1^{a} (155)	1.27^{bc} (0.42)	1.80^{bc} (0.41)	319.7^{b} (67.93)
Logic RT	867.2^{a} (289.6)	0.86^{c} (0.21)	2.51^{a} (0.49)	455.5^{a} (122.9)
MK RT	265.1^{b} (125.7)	2.04^{ab} (0.29)	1.40^{c} (0.44)	336.5^{b} (41.66)
D2	255.8^{b} (63.24)	2.51^{a} (0.28)	2.08^{ab} (0.48)	360.4^{ab} (50.65)

Different lowercase letters denote statistically significant differences in each column ($P < 0.05$).

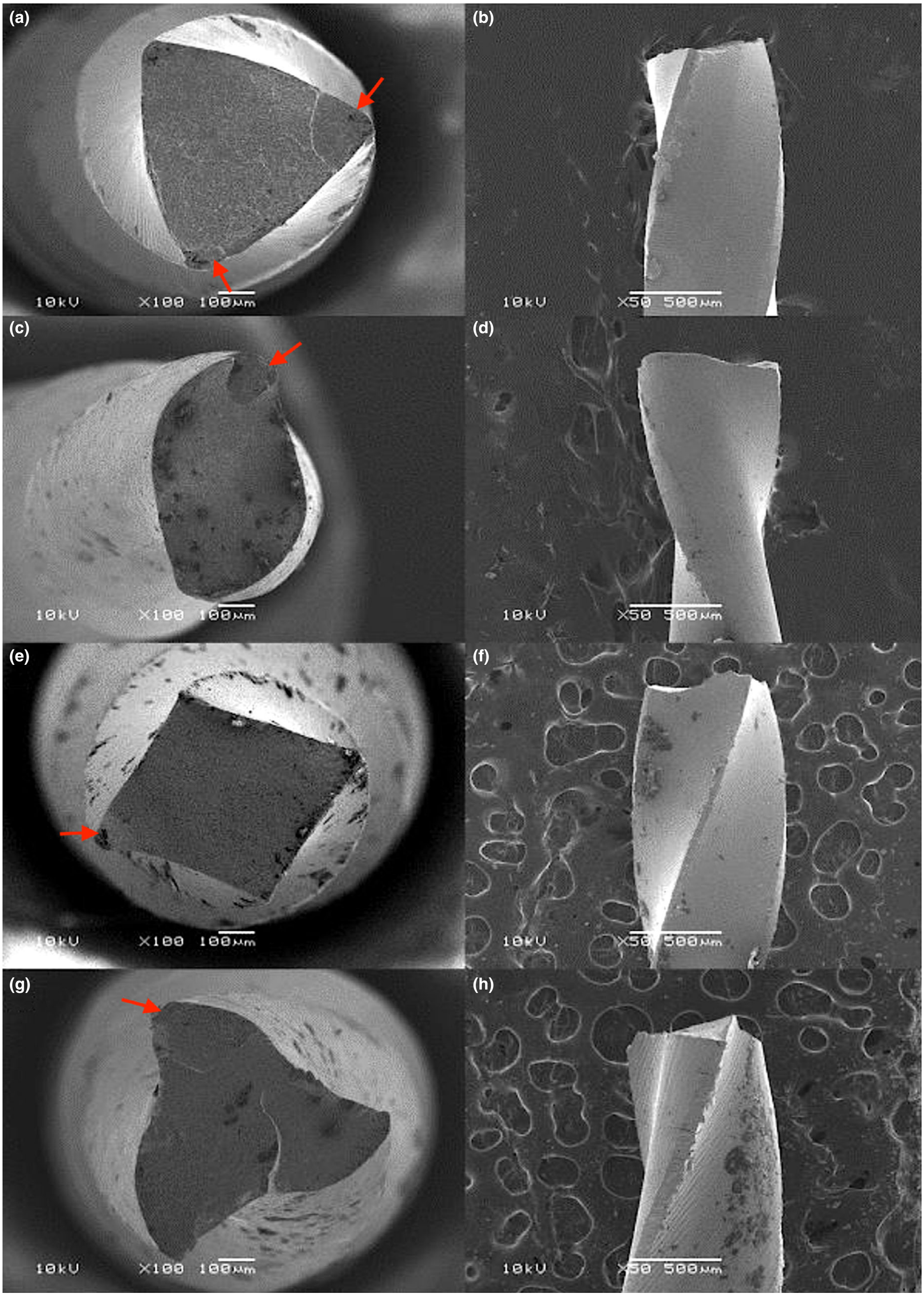

(a)
10kV
×100
100μm
(b)
10kV
×50
500μm
(c)
10kV
×100
100μm
(d)
10kV
×50
500μm
(e)
10kV
×100
100μm
(f)
10kV
×50
500μm
(g)
10kV
×100
100μm
(h)
10kV
×50
500μm

Figure 1 Scanning electron microscopy images of the fracture surfaces of D2 (a and b), Pro-R (c and d), MK RT (e and f) and Logic RT (G and H) instruments after cyclic fatigue test.

Knowing that temperature influences the microstructural phase transformation and, consequently, the performance of the instruments regarding cyclic fatigue resistance (21-23), and that, when in clinical conditions, these instruments are subjected to temperatures ranging those presented by the patient's body ($36° \pm 1°C$), it is necessary to verify the resistance to cyclic fatigue of instruments with different alloys when subjected to this conditions.

It is also necessary that the instruments are mounted in a stabilised handpiece and made to rotate or reciprocate freely in an artificial canal with predefined characteristics and under specific conditions (27), characterising the static cyclic fatigue model. Using this method, it is possible to increase the internal validity and reproducibility test, allowing a better comprehension of the resistance behaviour of the instrument and minimising biases like speed and amplitude movements that, although possible to reproduce in the dynamic model, are, in clinical situations, operator-dependent (27). Therefore, although some editorials (29,30) present conclusions that criticise such tests' performance, they are still valid and allow the verification of several factors associated with the instruments' performance, such as changes caused by temperature and factors associated with the instrument's geometrical features.

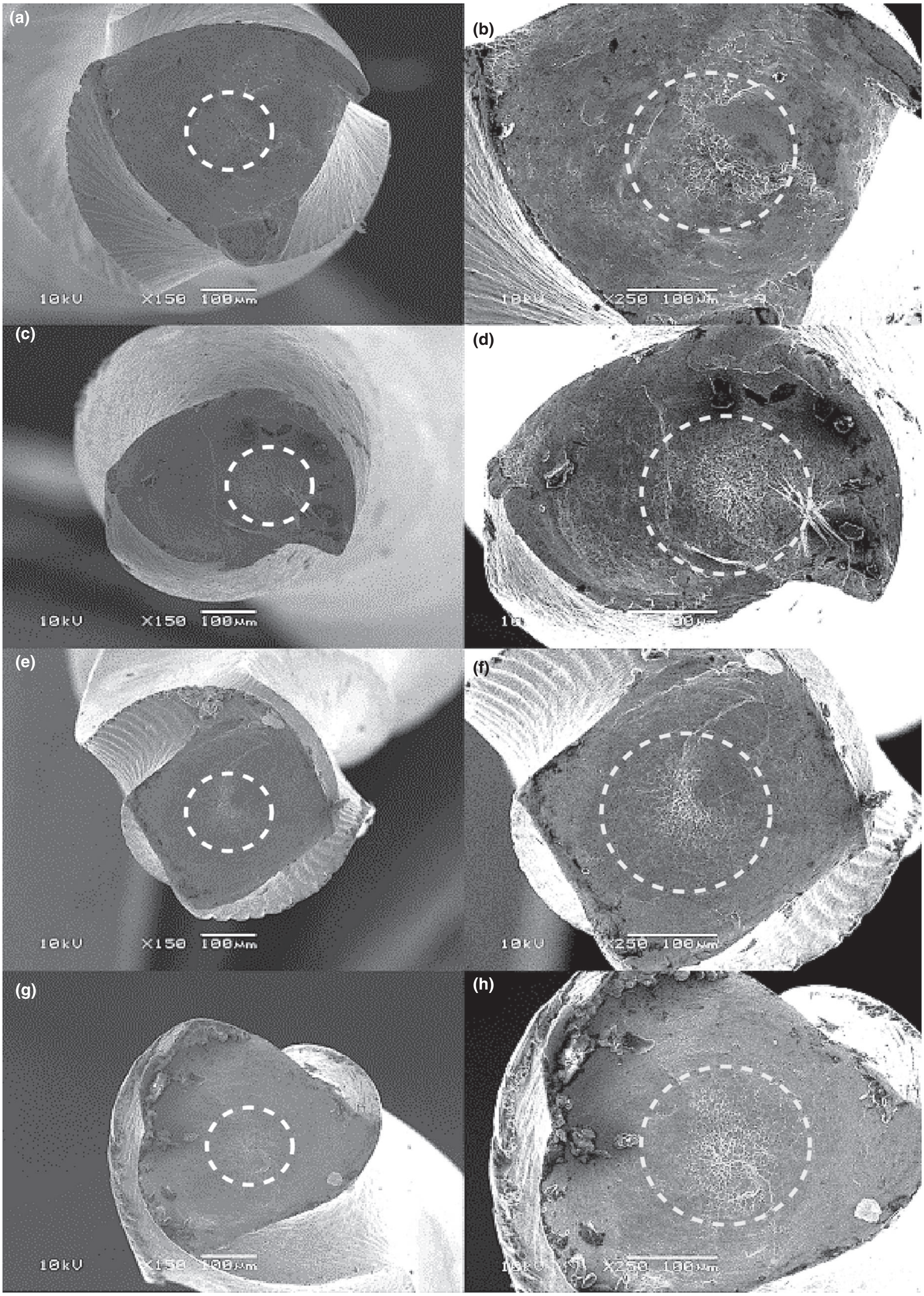
In this study, four different instruments designed explicitly for retreatment situations were tested, and the first null hypothesis was rejected. Pro-R and Logic RT present a heat-treated alloy, M-Wire and CM-Wire, respectively. The temperature of the complete austenitic transformation of M-Wire instruments is around 43–50°C (6,13), which is below the temperature found inside the root canal. Thus, when inserted into body temperature, M-Wire instruments contain austenite phase with small amounts of R-phase and martensite (6,11,15), increasing its cyclic fatigue resistance compared to the conventional NiTi (6), presented by MK RT and D2. Regarding CM-Wire instruments, they are presented mainly in the martensitic phase with an austenite finish temperature around 47–55°C (6), and differently from the M-Wire instruments, it does not possess superelastic properties (10). The literature shows that CM-Wire instruments are more flexible and resistant to cyclic fatigue compared to M-Wire instruments (6,13). This study did not find differences between Pro-R (M-Wire) and Logic RT (CM-Wire) ($P > 0.05$). This result can probably be explained by the kinematics and rotational speed of both instruments. Pro-R is an instrument, which is operated in reciprocating motion with speed set at 300rpm and Logic RT in rotary motion at 900rpm. Studies have shown that reciprocating motion can improve the cyclic fatigue resistance of the instruments (9) and that in higher rotational speeds, the instrument is subjected to more rubbing within the canal. Thus, more cycles of tension and compression are created, leading to decreased resistance in curved canals (7,16).

MK RT and D2 are presented in conventional NiTi alloy. Thus, according to previous studies, when in body temperature, these instruments are mainly in austenitic phase, reducing its flexibility and resistance to cyclic fatigue (6,13). This can be the probable explanation for MK RT and D2 instruments' lower results after cyclic fatigue ($P < 0.05$). Also, both instruments were designed to work only in the coronal and middle third. This study used them in a 60° angle of curvature and a 5 mm radius of curvature, located 5mm from their tips. According to a previous study (18), instruments specifically projected to these root thirds are less flexible due to their larger diameter and, since both presents reduced lengths when inserted into curved canals, there is a tendency for the larger diameter of the instrument to suffer higher stress, resulting in less resistance (19).

Bending stiffness is related to the instrument's capacity to follow the curvature of the root canal and reduce the risk of canal transportation (13). Due to the results found in this study, the second null hypothesis was also rejected. Logic RT presented the lower results ($P < 0.05$), probably due to its CM-Wire, that present lower ultimate tensile strength than the other instruments tested (19). Although it is reported that M-Wire instruments present greater flexibility than conventional NiTi instruments (10), in this study, Pro-R and MK RT did not differ ($P > 0.05$), probably because of their geometrical features.

In retreatments situations, the instruments work with intimate contact with the filling material and the dentin walls. Therefore, some resistance to torsion is necessary

Figure 2 Scanning electron microscopy images of the fracture surfaces of D2 (a and b), Pro-R (c and d), MK RT (e and f) and Logic RT (g and h) instruments after torsional resistance test.


(a)
10kV X150 100μm
(b)
(c)
10kV X150 100μm
(d)
(e)
10kV X150 100μm
(f)
10kV X250 100μm
(g)
10kV X150 100μm
(h)

t-
o

avoid complications due to fracture of the instrument (17). Torsional resistance is mainly related to the instrument's cross section and mass volume of metal. Thus, instruments with larger diameters may present higher torsional resistance (12,14). According to the results, the third null hypothesis was rejected.

In this study, all instruments had the same tip and taper diameters to reduce bias. Therefore, they only differ in their cross-sectional geometries and length. Logic RT presented the highest values regarding torsional resistance and angular deflection ($P < 0.05$), but without differences when compared to D2 ($P > 0.05$). Logic RT and D2 present a triple-helix and convex triangular cross section, respectively. These results corroborate with other studies in which already had concluded that instruments presenting these cross-sectional geometries are more torque resistance (12,14).

D2 and Pro-R also presented similar torsional resistance and angular deflection results ($P > 0.05$), probably because of their cross section. Although these instruments have the same taper, Pro-R has a double-helix, S-shaped cross section. According to a previous study (14), this cross section is asymmetrical and has a smaller area. Therefore, the stress is poorly distributed, being more prone to fracture. However, it is necessary to emphasise that, due to the kinematics, reciprocating instruments are less susceptible to torsional fracture (20). MK RT presented the lowest values to torsional fracture ($P < 0.05$), but with no differences when compared to Pro-R ($P > 0.05$). This finding agrees with a previous study (8), which concluded that rhombus-shaped instruments are less resistant to torsional loadings.

Regarding angular deflection, this characteristic is associated with the plastic and elastic deformation of the instrument before it reaches the torsional failure, functioning as a safety factor in clinical situations (17). It has been reported that CM-Wire instruments exhibit a more significant angular deflection compared to M-Wire and conventional NiTi instruments (6). Therefore, the results of this study are partially following this sentence because Logic RT presented the greater angular deflection among the instruments tested ($P < 0.05$), except when compared to the D2 instrument ($P > 0.05$).

The SEM analysis of the instruments subjected to the cyclic fatigue test showed crack initiation areas that propagated over a single or in multiple planes and the presence of numerous dimples with varied forms. Also, no plastic deformation of the helical shafts was observed, agreeing with other studies (16,19). The SEM analysis showed concentric abrasion marks and fibrous dimples at the centre of rotation for torsional failure, also agreeing with other studies (17,24).

Based on this study's results, it is possible to infer that clinically, Pro-R and Logic RT may present a more significant safety when used in curved canals. It is also possible to infer that all the tested instruments present some safety regarding torsion and angular deflection. Although generating relevant knowledge about these instruments, this study did not evaluate all their mechanical properties. Therefore, other aspects, such as their efficiency in removing filling material, centring ability, canal transportation, dentin removal and debris formation, were not assessed. Other studies must be performed to evaluate these outcomes.

With this study, it is possible to conclude that Pro-R and Logic RT presented higher resistance to cyclic fatigue, probably related to their cross-sectional designs and heat treatments. The results were dependent on the instruments' geometrical features and heat treatment regarding bending, torque to fracture and angular deflection.

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Disclosure statement

The authors declare that they have no conflict of interest.

Authorship declaration

All authors have contributed significantly and are in agreement with this article.

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