Original Research
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Heat-treated NiTi instruments and final irrigation protocols for biomechanical preparation of flattened canals

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Abstract: This study evaluate shaping ability of heat-treated NiTi-alloy instruments associated with different final irrigation protocols in flattened root canals. Thirty human mandibular incisors with flattened root canals were divided into 5 groups (n = 10): (XP) Original Protocol XP-endo Shaper; (XP-WT) Original Protocol XP-endo Shaper with working time variation; (XP-K) XP-endo Shaper with kinematics variation; (XP-WTK) XP-endo Shaper with kinematics and working time variations; (Hyflex) Hyflex CM. For the variation in working time protocols the same sample of the XP-endo Shaper groups with and without kinematic variation were used. To evaluate final irrigation protocols, groups 1, 3 and 5 were submitted to 3 protocols: (NI) No irrigation (n = 2); (CI) conventional irrigation (n = 4), and (EndoVac) irrigation (n = 4). The samples were scanned by microcomputed tomography and prepared for scanning electron microscopy evaluation. Quantitative data were evaluated using the parametric ANOVA test, with statistical significance level set at 5%, and qualitative data obtained were compared to establish the agreement between examiners through the Kappa test. It was observed that in the analysis of XP-endo Shaper protocols, the additional working time did not cause difference in any of parameters evaluated ($p > 0.05$) in relation to time recommended by manufacturer. Compared to Hyflex, XP-K showed highest mean volume increase ($p < 0.05$) and lowest percentage of untouched walls ($p < 0.05$). In the qualitative evaluation, final irrigation protocol with EndoVac provided the best cleaning results when associated with XP-K and with Hyflex. Thus, supplementary techniques are effective tools to enhance cleaning and to promote higher touch of walls during root canal preparation.

Keywords: Endodontics; Root Canal Preparation; Molar; X-Ray Microtomography; Microscopy, Electron, Scanning

Introduction

The root canal system (RCS) may have circular, oval, long oval, or flattened cross-sectional shapes, depending on buccolingual and mesiodistal dimensions.[1] These variations can result in 59.6% to 79.9% of untouched root canal walls during biomechanical preparation,[2,3] hindering the removal of dentin debris and necrotic tissues from the

RCS, especially in polar areas,[2,4] leading to endodontic treatment failure.[5,6] Thus, in these cases, irrigating solutions become essential because the chemical action of tissue dissolution of pulp and necrotic tissue,[7] combined with irrigation and aspiration to remove debris along the root canal, can reach areas that were not prepared by mechanical instruments.[8]

Note that root canals can be irrigated by insertion of solutions into the RCS by means of syringes and needles,[9] or ultrasonic inserts[10,11] and mechanized systems, in line with the concept of apical negative pressure.[12-14] Studies have demonstrated increased efficacy of irrigating solutions with the use of ultrasonic inserts.[11,12] Apical negative pressure has also shown promising outcomes when compared to conventional irrigation.[12-14]

The scientific literature highlights that the preparation of oval and flattened canals can be influenced by some characteristics of the instruments, such as design, composition, kinematics, and taper.[15] Heat-treatment of NiTi alloys gives the instruments greater resistance to cyclic fatigue and flexibility.[16,17] On the other hand, instruments with larger tapers have higher cutting ability with a tendency towards presenting centering ability.[18,19] Therefore, XP-endo Shaper was designed using rotary kinematics, with expansion capacity, for the heat treatment of NiTi alloys, allowing the "whipping" of root canal walls.[20] This instrument provides similar outcomes to those of rotary and reciprocating instruments with respect to two- and three-dimensional changes, as demonstrated in studies using microcomputed tomography.[3,21-25]

Instrumentation of flattened canals with XP-endo Shaper significantly changed the overall geometry of the root canal to a more conical shape.[20-22] Based on that, it was proposed that working time should be increased, which, according to De-Deus et al.[3], resulted in preparation with greater volume and larger removal of dentin surface area and volume from mesial roots of moderately curved mandibular molars. In flattened canals, Veloso et al.[25] observed that there was no complete preparation of the root canals of mandibular incisors, even when XP-endo Shaper was used for longer working time according to the kinematics recommended by the manufacturer.

In addition to increased working time, proposals to vary the kinematics of the instrument through brush motion have been described in the literature, and the use of rotary and reciprocating instruments in brush motion has demonstrated larger contact with the root canal wall and better cleaning.[27,28]

Thus, given the difficulty in the preparation of oval and flattened canals[2,4,29] and the presence of oval-shaped canals in practically all tooth groups and root thirds,[30] it is necessary to verify the effect of changing the working time and kinematics of XP-endo Shaper, to determine whether there is greater three-dimensional adaptation to the canal and, consequently, larger contact with the root canal walls. Accordingly, the aim of the present study was to evaluate, by means of micro-CT and scanning electron microscopy (SEM), the biomechanical preparation of flattened root canals with heat-treated instruments, varying the working time and instrument kinematics, as well as the cleaning capacity of different final irrigation protocols.

Methodology

Specimen selection

After approval by the local Research Ethics Committee (CAAE no. 0072.0.138.000-09), the sample size was calculated using SigmaPlot 11.0 (Systat Software Inc., San Jose, USA), based on parameters determined in a pilot study, considering a probability level of a = 0.05 and statistical power of 0.8. The estimated minimum sample size was eight specimens per group. Thus, 30 mandibular incisors with flattened canals, with mean ratio between the largest and smallest diameters (mean aspect ratio) at 10 mm apical equal to or greater than 4,[1, 21] were selected and randomly divided into five groups according to the instrumentation protocol. Of note, the same specimen from XP-endo Shaper groups with and without kinematic variation were used for assessing the variation in working time protocols.

The selected specimens were scanned with isotropic resolution of 26.7 μm on a high-resolution micro-CT scanner (SkyScan1174 v.2; Bruker-microCT, Kontich, Belgium) at 50 kVp, 800 µA, 180° rotation around the vertical axis, and 0.7° rotation step, using 0.5 mm thick aluminum filter. Two-dimensional projections of the generated images were reconstructed (NRecon v.1.7.4.2; Bruker-microCT) by applying algorithms for ring artifact reduction at a value of 5, beam hardening at a percentage of 40%, smoothing at a value of 7, and contrast histogram ranging from 0.003 to 0.15.

Two-dimensional morphometric data (area, perimeter, roundness, major and minor diameter) of the cervical, middle, and apical thirds, and three-dimensional parameters of volume (mm^3), surface area (mm^2), and 3D geometry (structure model index – SMI) of the root canals, from the cementoenamel junction to the apical foramen,[4,7] were obtained using CTAn v.1.18 software (Bruker-microCT).

Specimen preparation

Conventional endodontic access surgery was performed using a spherical diamond bur (801L Jota AG, Rüthi, Switzerland) and Endo ZK bur (Beavers Jet Burs, Morrisburg, Canada). Stainless steel K-type hand files #08 and #10 (FKG-Dentaire, La Chaux-de-Fonds, Switzerland) were employed for canal patency and the working length (WL) was established when the tip of the hand file was 0.5 mm short of the apical foramen.

Root canal preparation

The specimens were gripped onto a vise (Mini Articulated Vise; EDA, São Paulo, Brazil) and immersed in water (Water Bath Model 102; Fanem, São Paulo, Brazil) at 37ºC monitored by a digital thermometer (HG Brazil, São Paulo, Brazil), keeping the root below the water level throughout. The root canal was prepared according to the protocol for each experimental group. The teeth were distributed into five experimental groups (n = 10):

Group 1 – XP (Original Protocol XP-endo Shaper)

XP-endo Shaper was used according to the manufacturer's recommendations (FKG-Dentaire, La Chaux de Fonds, Switzerland). The canal was initially irrigated with 2 mL of 2.5% NaOCl and the instrument was activated in continuous rotation (800 rpm and 1 N.cm) using a Rooter Universal motor (FKG-Dentaire, La Chaux-de-Fonds, Switzerland). As soon as the WL was reached, the instrument was removed and the canal was irrigated with 2 mL of 2.5% NaOCl. Long and smooth linear in-and-out movements were performed for 15 s until the WL was reached. At the end of the preparation, the canals were irrigated with 2 mL of 2.5% NaOCl. To standardize the volume of irrigation, this procedure was performed up to the final volume of 10 mL.

Group 2 - XP-WT (Original XP-endo Shaper Protocol with Working Time Variation)

The same instrumentation protocol described for group 1 was performed and, complementarily, the instrument was activated for an additional working time of 30 s, divided into two interventions of 15 s each, alternating with irrigation with 2 mL of 2.5% NaOCl. At the end of the preparation, the canals were irrigated with 2 mL of 2.5% NaOCl. To standardize the volume of irrigation, this procedure was performed up to the final volume of 10 mL.

Group 3 - XP-K (XP-endo Shaper protocol with variation in kinematics)

The same instrumentation protocol described for group 1 was applied, and after reaching the WL, long and smooth in-and-out movements were performed, with each outward movement of the instrument acting on the buccal and lingual walls of the root canal for 15 s. At the end of the preparation, the canals were irrigated with 2 mL of 2.5% NaOCl. To standardize the volume of irrigation, this procedure was performed up to the final volume of 10 mL.

Group 4 – XP-WTK (XP-endo Shaper protocol with variation in working time and kinematics)

The same instrumentation protocol described for group 3 was applied, and complementarily, the instrument was activated for an additional working time of 30 s, divided into two interventions of 15 s each, alternating them with irrigation of 2 mL of 2.5% NaOCl. At the end of the preparation, the canals were irrigated with 2 mL of 2.5% NaOCl. To standardize the volume of irrigation, this procedure was performed up to the final volume of 10 mL.

Group 5 - Hyflex (Hyflex CM System)

After irrigation of the canal with 2 mL of 2.5% NaOCl, the 25/.08 instrument was adjusted to 2/3 of the WL and inserted in the canal in continuous rotation (500 rpm and 2.5 N.cm), coupled to the Rooter Universal motor (FKG Dentaire). The following sequence of instruments was then used along the WL: 20/.04, 25/.04, 20/.06, and 30/.04. The irrigating solution (2 mL of 2.5% NaOCl) was renewed after the use of each instrument. To standardize the volume of irrigation, this procedure was performed up to the final volume of 10 mL.

Final irrigation protocols

After that, the specimens from groups 1, 3, and 5 were randomly distributed into three subgroups according to the final irrigation protocol:

Subgroup 1 – NI (No final irrigation) (n = 2)

The canals were not irrigated, only aspirated with a Capillary Tip (Ultradent Products Inc.) with subsequent drying with absorbent paper points.

Subgroup 2 – CI (Conventional irrigation) (n = 4)

The canals were irrigated with 3 mL of 2.5% NaOCl using a disposable plastic syringe and a 30G NaviTip needle positioned 1 mm behind the WL, allowing continuous flow of the solution during aspiration with an endodontic cannula. Next, 3 mL of 17% EDTA (5 min) was used, followed by 3 mL of 2.5% NaOCl (5 min), and 2 mL of distilled water. After final aspiration with a Capillary Tip (Ultradent Products Inc.), the canals were dried with absorbent paper points.

Subgroup 3 – EndoVac (Negative pressure irrigation - EndoVac System) (n = 4)

The canals were irrigated with 3 mL of 17% EDTA (5 min) using the master delivery tip while simultaneous aspiration was performed with the microcannula inserted 2 mm from the WL. A new irrigation cycle was then performed with 3 mL of NaOCl 2.5% (5 min). The canals were then irrigated with 2 mL of distilled water and dried by aspiration (Capillary Tip) and absorbent paper points.

Micro-CT analysis

After biomechanical preparation, the canals were dried with aborbent paper points, and the specimens were scanned and reconstructed in accordance with the initial parameters. The datasets obtained before and after preparation were co-registered using DataViewer v.1.5.6.2 (Bruker-microCT) and the two-dimensional and three-dimensional morphometric parameters were analyzed. The combined three-dimensional models were then identified by distinct colors for qualitative evaluation in the CTVol v.2.3.2 program (Bruker-microCT).

SEM analysis

The ultrastructural morphological analysis of the specimens was performed under a scanning electron microscope (JSM JEOL, model 6610, Tokyo, Japan), operating at 25 kV. The specimens were initially analyzed in panoramic view to locate the areas, and later at 100× magnification to evaluate the inner surface of the canal for the presence of dentin debris.

The obtained photomicrographs were evaluated blindly by experienced and previously calibrated examiners. The root dentin surface patterns regarding the presence of debris layer after biomechanical preparation under different final irrigation protocols were classified according to the evaluation proposed by Hülsmann.[31] The root canal walls were evaluated for the presence of debris, organization (sparse or agglomerated), and degree of wall coverage.

During specimen preparation, the roots were cleaved longitudinally in the lingual-buccal direction, and the hemi-sections obtained may thus include areas of mesiodistal flattening, characteristic of mandibular incisors.

Statistical analysis

The two-dimensional quantitative data (area, perimeter, roundness, major and minor diameters), three-dimensional data (volume, surface area, and SMI) were initially subjected to normality (Shapiro-

Wilk) and homogeneity of variance (Levene) tests. Once normal distribution was verified, parametric ANOVA was selected. To detect statistical differences between groups, the Tukey-Kramer test was used with statistical significance level set at 5%. The Kappa inter-observer test (0.87) was performed to establish the agreement between the observers regarding the qualitative data of dentin debris evaluation obtained on SEM images. The analyses were performed using SPSS 15.0 (SPSS Inc., Chicago, USA).

Results

2D analysis

The values for the two-dimensional parameters (area, perimeter, roundness, and major and minor diameter) are shown in Table 1 and represented in Figure 1.

The analysis of XP-endo Shaper showed that adding 30 s to the working time, regardless of the kinematics used, did not significantly change any of the parameters evaluated ($p > 0.05$), at any of the root thirds.

Regarding area and roundness, there was no statistically significant difference between XP-endo Shaper instrumentation protocols at the cervical, middle, and apical thirds when compared to the Hyflex protocol ($p > 0.05$). Regarding perimeter, the results showed that the original XP-endo Shaper protocols with working time variation and XP-endo Shaper with kinematic variation showed the highest mean increase at the middle third ($p < 0.05$) compared to the Hyflex protocol. For major diameter, instrumentation with the original XP-endo Shaper protocols with and without variation in working time showed the highest mean increase ($p < 0.05$) at the middle third only when compared to the Hyflex protocol. However, in relation to the smallest diameter, the original XP-endo Shaper, XP-endo Shaper with variation in working time, and Hyflex protocols showed the smallest mean increases ($p < 0.05$) at the apical third when compared to the XP Endo Shaper protocols with kinematic variation. Regarding the middle third, the original XP-endo Shaper, XP-endo Shaper with variation in working time, XP-endo Shaper with kinematic variation, and Hyflex protocols presented the lowest mean increments compared to the XP-endo Shaper protocol with variation in kinematics and working time ($p < 0.05$).

3D analysis

The values of the Tukey-Kramer complementary test for the three-dimensional parameters (volume, surface area, SMI, and number of untouched walls) are displayed in Table 2. The ANOVA for volume data showed that the original XP-endo Shaper protocol with variation in working time and XP-endo Shaper protocol with kinematic variation with and without variation in working presented the highest mean increases, with significant difference ($p < 0.05$) in relation to the original XP-endo Shaper and Hyflex protocols. Regarding root canal surface area and SMI, there was no difference between the groups ($p > 0.05$). Regarding the percentage of untouched walls, the XP-endo Shaper protocols, regardless of kinematics and working time, resulted in fewer untouched walls compared to Hyflex ($p < 0.05$) (Figure 2).

SEM qualitative analysis

The ultrastructural morphological analysis of the canals prepared with XP-endo Shaper using the kinematics recommended by the manufacturer showed, in general, clean walls for all final irrigation protocols (Figure 3A). Less than 50% of debris was observed on the surface, both in specimens without final irrigation and in those irrigated with the conventional protocol. In relation to the EndoVac protocol, cleaner root canal walls with fewer agglomerated debris were observed.

When the canals were prepared with XP-endo Shaper in a brushing motion along the root canal walls (Figure 3B), more than 50% of the debris were observed on the surface of the specimens without a final irrigation protocol. In the specimens with conventional final irrigation and prepared with the EndoVac system, less than 50% of debris was observed on the root canal walls.

The canals prepared with Hyflex showed (Figure 3C) more than 50% of debris covering the dentin walls in specimens without final irrigation. However, in specimens in which the conventional

Table 1. Morphometric two-dimensional data (mean + standard deviation) for parameters evaluated at the apical, middle, and cervical thirds of root canals of mesial mandibular molars before and after root canal preparation.

Variable	XP	XP-WT	XP-K	XP-WTK	Hyflex
Area (mm^2)					
Before					
Cervical	0.82 + 0.2	1.6 + 0.74	0.8 + 0.2	1.60 + 0.7	0.64 + 0.17
Middle	0.36 + 0.13	0.57 + 0.18	0.36 + 0.09	0.5 + 0.18	0.24 + 0.05
Apical	0.076 + 0.03	0.11 + 0.5	0.07 + 0.05	0.11 + 0.05	0.09 + 0.06
After					
Cervical	1.6 + 0.74	1.79 + 0.6	1.60 + 0.7	1.79 + 0.6	1.19 + 0.39
Middle	0.57 + 0.18	0.6 + 0.15	0.5 + 0.18	0.6 + 0.15	0.32 + 0.05
Apical	0.11 + 0.5	0.12+ 0.04	0.11 + 0.05	0.12 + 0.04	0.13 + 0.06
Δ					
Cervical	0.96 + 0.6[a]	0.89 + 0.46[a]	0.78 + 0.5[a]	0.91 + 0.47[a]	0.54 + 0.32[a]
Middle	0.2 + 0.28[a]	0.3 + 0.24[a]	0.21 + 0.1[a]	0.30 + 0.09[a]	0.09 + 0.06[a]
Apical	0.04 + 0.05[a]	0.05 + 0.04[a]	0.04 + 0.03[a]	0.05 + 0.03[a]	0.04 + 0.02[a]
Perimeter (mm)					
Before					
Cervical	3.76 + 0.46	3.76 + 0.46	3.87 + 0.67	3.87 + 0.67	3.36 + 0.49
Middle	3.55 + 0.88	3.55 + 0.88	3.40 + 0.79	3.40 + 0.79	2.21 + 0.34
Apical	1.05 + 0.2	1.05 + 0.2	1.06 + 0.38	1.06 + 0.38	0.94 + 0.15
After					
Cervical	4.46 + 0.51	4.56 + 0.48	4.92 + 0.34	5.23 + 0.99	4.21 + 0.73
Middle	3.87 + 0.86	4.00 + 0.8	3.74 + 1	3.72 + 0.73	2.33 + 0.3
Apical	1.12 + 0.21	1.20 + 0.18	1.29 + 0.34	1.36 + 0.24	1.13 + 0.14
Δ					
Cervical	0.68 + 0.4[a]	0.78 + 0.35[a]	1.06 + 0.8[a]	1.33 + 0.69[a]	0.85 + 0.58[a]
Middle	0.33 +0.25[ab]	0.45 + 0.28[a]	0.45 + 0.36[a]	0.26 + 0.3[ab]	0.08 + 0.1[b]
Apical	0.08 + 0.13[a]	0.14 + 0.13[a]	0.24 + 0.26[a]	0.3 + 0.28[a]	0.19 + 0.15[a]
Roundness					
Before					
Cervical	0.49 + 0.07	0.49 + 0.07	0.49 + 0.07	0.49 + 0.07	0.56 + 0.12
Middle	0.23 + 0.11	0.23 + 0.11	0.24 + 0.06	0.24 + 0.06	0.44 + 0.17
Apical	0.69 + 0.08	0.69 + 0.08	0.58 + 0.09	0.58 + 0.09	0.61 + 0.119
After					
Cervical	0.64 + 0.07	0.66 + 0.06	0.59 + 0.11	0.63 + 0.1	0.67 + 0.1
Middle	0.34 + 0.2	0.40 + 0.22	0.36 + 0.1	0.44 + 0.12	0.63 + 0.14
Apical	0.72 + 0.1	0.73 + 0.11	0.66 + 0.08	0.68 + 0.07	0.64 + 0.13
Δ					
Cervical	0.15 + 0.07[a]	0.17 + 0.07[a]	0.1 + 0.06[a]	0.14 + 0.06[a]	0.11 + 0.03[a]
Middle	0.13 + 0.1[a]	0.17 + 0.12[a]	0.13 + 0.07[a]	0.2 + 0.08[a]	0.20 + 0.11[a]
Apical	0.02 + 0.05[a]	0.03 + 0.06[a]	0.09 + 0.07[a]	0.1 + 0.08[a]	0.06 + 0.03[a]

Continue

Continuation

Major diameter (mm)					
Before					
Cervical	1.46 + 0.17	1.46 + 0.17	1.49 + 0.26	1.49 + 0.26	1.21 + 0.18
Middle	1.44 + 0.42	1.46 + 0.42	1.41 + 0.34	1.42 + 0.34	0.87 + 0.18
Apical	0.37 + 0.07	0.37 + 0.07	0.40 + 0.14	0.40 + 0.14	0.35 + 0.07
After					
Cervical	1.61 + 0.2	1.63 + 0.19	1.82 + 0.49	1.91 + 0.43	1.49 + 0.29
Middle	1.55 + 0.43	1.57 + 0.41	1.43 + 0.33	1.45 + 0.34	0.87 + 0.18
Apical	0.4 + 0.09	0.42 + 0.09	0.46 + 0.12	0.49 + 0.09	0.40 + 0.07
Δ					
Cervical	0.14 + 0.14^{a}	0.16 + 0.14^{a}	0.33 + 0.3^{a}	0.4 + 0.2^{a}	0.28 + 0.2^{a}
Middle	0.11 + 0.15^{b}	0.11 + 0.15^{b}	0.02 +0.04^{b}	0.01 + 0.02^{b}	0.002 +0.04^{a}
Apical	0.01 + 0.12^{a}	0.11 + 0.1^{a}	0.06 + 0.09^{a}	0.08 + 0.1^{a}	0.03 + 0.08^{a}
Minor diameter (mm)					
Before					
Cervical	0.74 + 0.14	0.74 + 0.14	0.76 + 0.14	0.76 + 0.14	0.71 + 0.15
Middle	0.40 + 0.15	0.40 + 0.15	0.35 + 0.08	0.35 + 0.08	0.36 + 0.1
Apical	0.28 + 0.06	0.28 + 0.06	0.24 + 0.07	0.24 + 0.07	0.28 + 0.16
After					
Cervical	1.07 + 0.12	1.12 + 0.12	1.08 + 0.25	1.20 + 0.11	1.03 + 0.13
Middle	0.66 + 0.09	0.77 + 0.12	0.69 + 0.15	0.81 + 0.09	0.56 + 0.06
Apical	0.30 + 0.05	0.32 + 0.03	0.33 + 0.07	0.35 + 0.04	0.28 + 0.06
Δ					
Cervical	0.33 + 0.12^{a}	0.38 + 0.09^{a}	0.33 + 0.16^{a}	0.44 + 0.11^{a}	0.32 + 0.15^{a}
Middle	0.26 + 0.14^{a}	0.37 + 0.18^{a}	0.35 + 0.14^{a}	0.45 + 0.11^{b}	0.19 + 0.11^{a}
Apical	0.02 + 0.02^{a}	0.04 + 0.04^{a}	0.09 +0.07^{b}	0.11 + 0.08^{b}	0.02 + 0.1^{a}

Different letters in the rows indicate statistically significant difference. Δ, mean increase (± standard deviation).

and EndoVac final irrigation protocols were used, clean walls were observed, with less than 50% of debris on the surface.

It should be emphasized that debris accumulated in polar areas in all of the groups.

Discussion

The biomechanical preparation of root canals involves mechanical action of the instruments and chemical and physical action of the irrigating solutions. Instrumentation is aimed at the shaping and modeling of the canal by accessing and abrading as many walls as possible, whereas the chemical action of auxiliary solutions, along with the physical action of irrigation/flooding/aspiration, consists in introducing one or more solutions into the root canals, reaching areas that could not be prepared by the mechanical instruments in an attempt to clean them and disinfect them by reducing the bacterial count and by removing pulp tissue, necrotic debris, and debris.[15,25] Thus, it was important to verify the action of mechanized instruments with different kinematics and at different working time intervals and to assess different final irrigation protocols in flattened canals, considering that 25% of human teeth present flattening, a rate that increases to 50% in mandibular incisors and maxillary second premolars.[25,32]

In the present study, we carefully selected the specimens by means of micro-CT for standardization

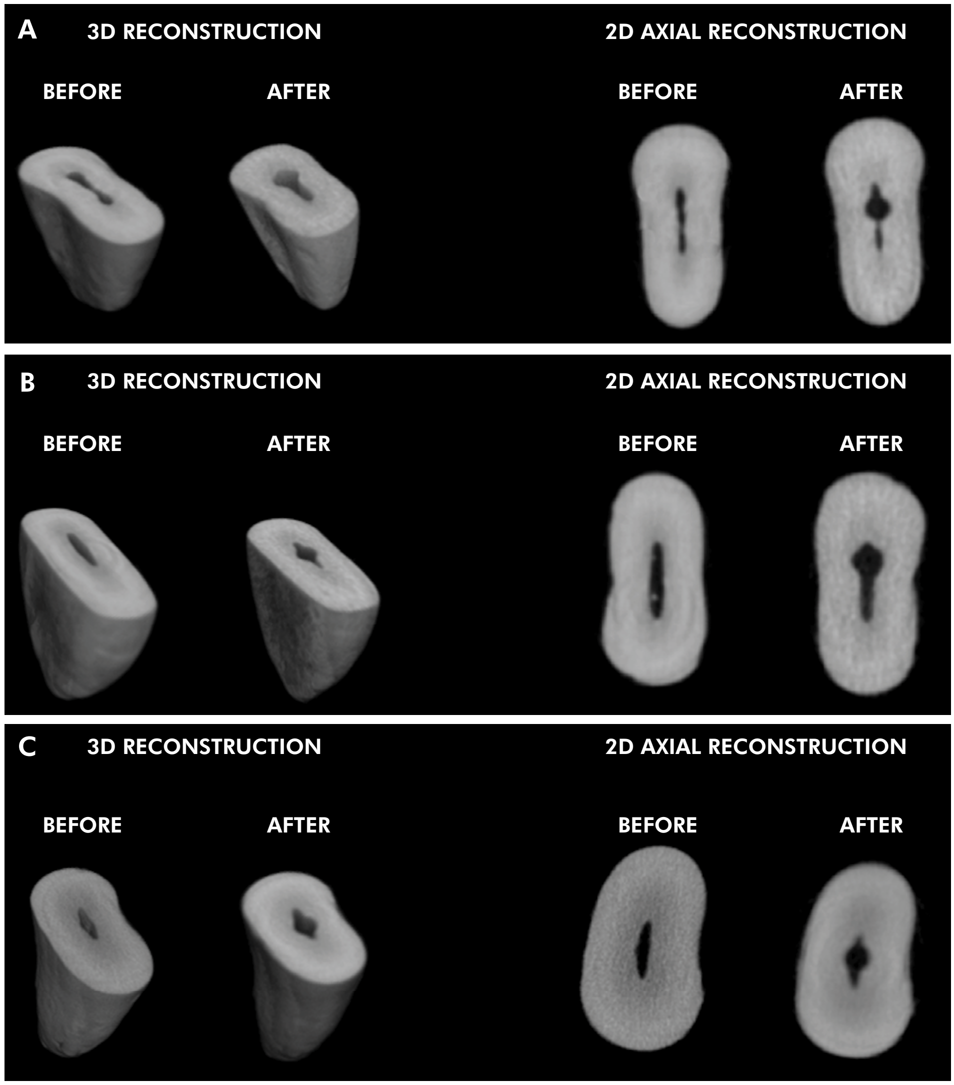

Figure 1. 3D reconstructions of representative root of mandibular incisors before and after instrumentation; and 2D image of axial reconstruction at 3 mm from the cementoenamel junction before and after biomechanical preparation: (A) XP; (B) XP-K; (C) Hyflex.

and anatomically balanced experimental groups, thereby reducing the risk of bias.[33,34] Those canals with a ratio ≥4[1] were considered flat. Micro-CT was selected because it is a non-invasive and non-destructive method that provides high-resolution images and allows the analysis of two-dimensional and three-dimensional parameters through the combination of images before and after preparation.[2,15,21]

Regarding the evaluated instruments, it should be noted that XP-endo shaper (XPS; FKG Dentaire, Switzerland) was developed as an instrument composed of MaxWire alloy for operation in continuous rotation when subjected to temperature variations, expanding or contracting according to the canal morphology.[20,21] The Hyflex system is composed of a sequence of multiple instruments with tapers of .02, .04, and .06,[35] made of a specific NiTi alloy that has a lower weight percentage of nickel (52.1% WT) than do conventional NiTi alloys.[36] Therefore, considering the purpose of our study, we included Hyflex instruments in order to evaluate if the behavior of XP-endo Finisher, which expands and contracts inside the canal, at the speed and torque recommended by the manufacturers, at different working time intervals and kinematics, could improve the shaping ability

Table 2. Morphometric three-dimensional data (mean + standard deviation) values and percentage of untouched walls of root canals of mesial mandibular molars according to the root canal preparation protocols.

Variable	XP	XP-WT	XP-K	XP-WTK	Hyflex
Volume (mm3)	1.71 + 0.85[b]	2.62 + 1.2[a]	2.51 + 1.23[a]	3.51 + 1.07[a]	1.57 + 1.24[b]
Surface area (mm^2)	3.95 + 1.5[a]	5.7 + 2.69[a]	5.15 + 2.79[a]	6.99 + 2.5[a]	2.73 + 2.45[a]
SMI	0.33 + 0.2[a]	0.45 + 0.22[a]	0.42 + 0.27[a]	0.53 + 0.2[a]	0.51 + 0.29[a]
Untouched walls (%)	22 + 8[a]	24 + 11[a]	20 + 8[a]	21 + 7[a]	43 + 13[b]

Different letters in the rows indicate statistically significant difference. Numbers in bold, mean increase (± standard deviation) of the analyzed parameter. SMI: structure model index.

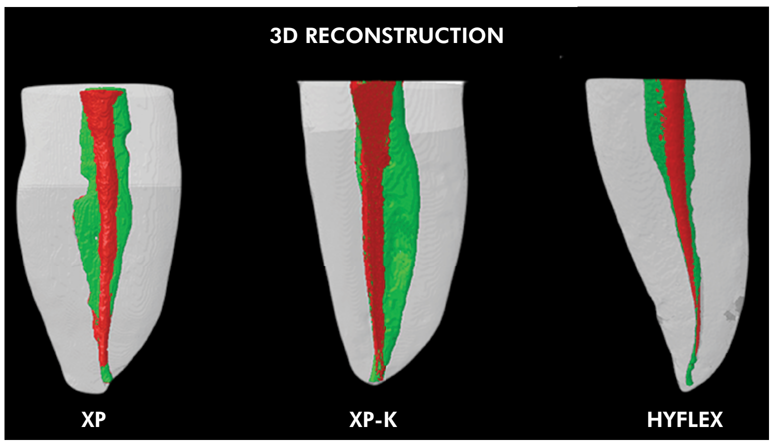

Figure 2. 3D reconstructions of representative root of mandibular incisors in buccal view. Green areas represent the original root canal anatomy, which remained untouched by instruments (XP; XP-K; Hyflex). Areas in red represent the instrumented root canal after preparation (XP; XP-K; Hyflex).

of flattened canals compared to a rotary instrument, without this capacity of expansion.

Concerning working time, increasing it in XP-endo Shaper, either according to the kinematics recommended by the manufacturer or with brushing, did not have an impact on any of the morphometric parameters evaluated ($p > 0.05$). This can be attributed to the characteristics of the instrument which, despite its capacity to expand and "whip" the canal walls, presents a tendency towards wearing away the central region of the flat canal, as shown in Figure 1, and as it expands, even when working time is increased, it loses its abrasion capacity in polar areas, thus having no impact on the geometry of flat root canals. This finding is in agreement with Veloso *et al*.,[25] who observed no difference in the geometry of flattened canals of mandibular incisors when using XP-endo Shaper with additional working time. Conversely, De-Deus et al.[3] observed that increasing XP-endo Shaper working time caused an increase in volume and surface area in the mesial roots of molars. In curved canals, however, the instrument touches the anticurvature and procurvature regions irregularly, which can explain the higher values found in these cases.

Regarding kinematic variation, in the comparison of XP-endo Shaper protocols with and without brushing motion with the Hyflex protocol, instrumentation with XP-endo Shaper with brushing motion presented the highest mean increase in perimeter at the middle third ($p < 0.05$), as well as the greatest increase in volume ($p < 0.05$) compared to XP-endo Shaper without brushing motion and Hyflex protocols, in addition to the lowest percentage of untouched walls in relation to the Hyflex protocol ($p < 0.05$). These findings can be attributed to the design, taper, and kinematics of the instruments, given that XP-endo Shaper features expansion of its area of operation, allowing root canal preparation to be performed with a .04 taper, even though it is a single rotary instrument of .01 taper.[3,20] In addition, the

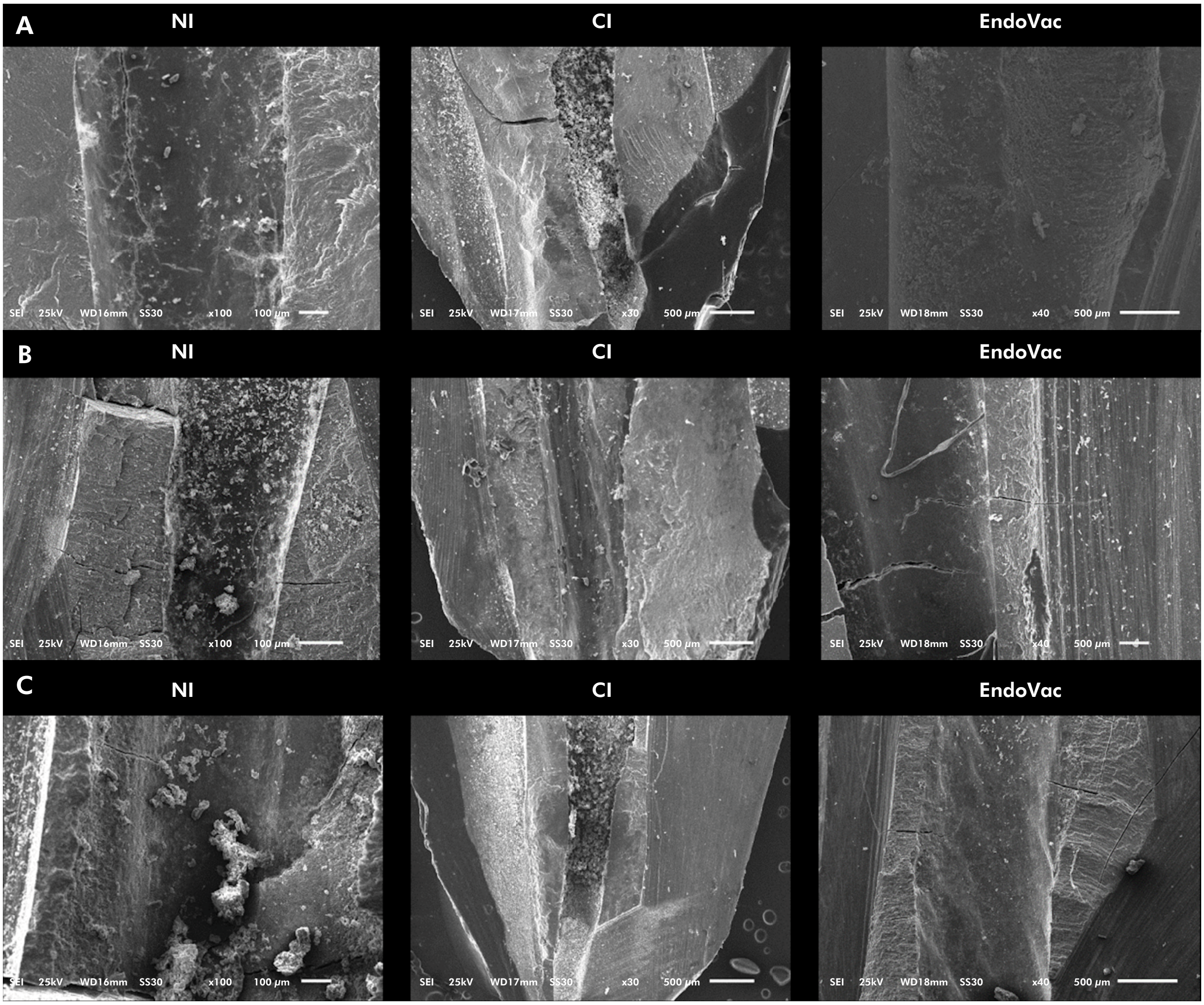

Figure 3. Representative scanning electron microscopy images of the ultrastructural morphological analysis of root canal after biomechanical preparation associated with different final irrigation protocols (no final irrigation, conventional protocol, and EndoVac protocol). (A) Original XP-endo Shaper protocol according to the manufacturer's instructions, in general, with clean walls for all final irrigation protocols. EndoVac provided better cleaning of root canal walls with less debris accumulation. (B) XP-endo Shaper in brushing motion, with more than 50% of debris on the surface of the specimens without final irrigation, and root canal walls with less than 50% debris in specimens with conventional final irrigation and the EndoVac system. (C) Hyflex instrument images showing more than 50% of debris covering the dentin walls in specimens without final irrigation and clean walls with less than 50% of debris on the surface in specimens prepared with the conventional and EndoVac final irrigation protocols.

brushing motion allows greater contact with the canal wall, producing changes in root canal geometry mostly similar to those promoted by the Hyflex multi-instrument rotary system, as observed in the analysis of the other parameters and as also observed by Perez et al.[23]

In order to understand the impact of final irrigation protocols on the cleaning of flattened canals, the volume of irrigation was standardized at the final volume of 10 mL. SEM was used after the procedures for qualitative evaluation of dentin debris.[12,36,37] Thus, the present study demonstrated the importance of complementary tools for cleaning uninstrumented regions. EndoVac had less accumulation of debris, regardless of the instrument used, probably due to the greater circulation of the irrigating solution within the root canals thanks to the negative pressure generated by the system. This larger circulation allows continuous renewal of the solution inside the canal, facilitating the removal of debris through fast and efficient vacuum aspiration of the irrigating solution,[12,13] which does not occur in the conventional irrigation protocol.[10,38]

In the comparison of instrumentation protocols, the use of XP-endo Shaper in a brushing motion resulted in greater accumulation of debris on the root canal walls, especially when no irrigation or the conventional irrigation protocol was used. These findings can be attributed to the fact that that the instrument reaches the walls and causes greater debris disorganization,[39-42] but the conventional irrigation protocol does not allow sufficient circulation of the irrigating solution for removal of the debris.[10,38]

We may conclude that in flattened canals, the cleaning and shaping of the root canal is closely linked to the preparation protocol, instrument design and kinematics, and irrigation protocol. XP-endo Shaper showed similar performance to that of the Hyflex multiple rotary instrument system, with a greater number of instrumented walls when brushing motion was used. Additionally, the importance of using final irrigation protocols, such as the negative apical pressure protocol, became evident because cleaning was enhanced in uninstrumented regions, with larger debris removal, resulting in effective biomechanical preparation, especially in flattened areas.

Conclusions

Overall, it may be concluded that supplementary techniques such as the use of final irrigation protocols and instruments employed in brushing motion are effective in improving cleaning and promoting higher contact with the walls during root canal preparation.

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