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RESEARCH

Influence of brushing motions on the shaping of oval canals by rotary and reciprocating instruments

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Abstract

Objective The effects of brushing on shaping with three different instruments were assessed in oval canals.

Design Mandibular incisors were assigned to 6 groups ($n = 12$/group) according to the system, each one with or without brushing: Reciproc Blue, VDW.Rotate, and Race EVO. Micro-computed tomography was performed before and after preparation.

Results Brushing strokes caused no increase in canal volume, surface area, and structure model index independently of the system ($p > 0.05$), except for RaCe EVO in the full canal surface area ($p < 0.05$). Brushing did not increase the prepared areas ($p > 0.05$), except for Reciproc in the apical canal ($p < 0.05$). Reciproc with no brushing exhibited less pericervical dentin than with brushing ($p < 0.05$), while RaCe EVO with brushing resulted in less remaining dentin ($p < 0.05$).

Conclusions The brushing motion had no effects on the overall shaping performance of the 3 instruments tested. An exception was the increase in prepared surface area in the apical canal segment when the Reciproc instrument was used with brushing strokes.

Keywords Brushing motion · Oval canal · Unprepared root canal area · Dentin thickness

Introduction

Cleaning, disinfection, and shaping of the root canals of teeth with apical periodontitis are the main objectives of root canal preparation and play a crucial role in the long-term treatment outcome [1]. However, the anatomical complexity of the root canal system poses challenges to achieve these goals during treatment [2]. For instance, the buccal and lingual recess areas of oval and flattened canals usually remain not affected by instruments and irrigants and may harbor residual bacteria and pulp tissue remnants [3–5]. Studies have demonstrated that the amount of unprepared surface areas in oval/flattened canals after instrumentation ranges from 10 to 80%, depending on the type of tooth and instrument evaluated [6–10].

Because conventional rotary instruments are used in either continuous rotation or reciprocation, they carve round preparations, which are rather inadequate for most oval/flattened canals, leaving recesses unaffected [11]. In addition, teeth with oval/flattened canals may become unnecessarily weakened if a pronounced cross-sectional roundness is prepared in the middle and coronal thirds. Many strategies have been devised to circumvent these limitations, including preparation considering the oval canal as two separate entities [6], Hedstrom files in circumferential filing [12], special conforming instruments [3], ultrasonic activation of irrigants or special tips [12, 13], and application of lateral brushing strokes to the instruments [11, 14].

Although nickel-titanium (NiTi) instruments were initially recommended to be used with no lateral action, some manufacturers now indicate that their instruments be also operated not only with pecking motions but also in lateral brushing movements. This strategy has been used and

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adopted in many studies [7, 10, 13, 15]. In the brushing action, the instrument can be displaced circumferentially along the canal perimeter or concentrated on some specific areas, such as the polar recesses of oval/flattened canals. Studies have demonstrated that the brushing motion requires less torque [16] and does not affect the cyclic fatigue resistance of NiTi instruments [17, 18]. A study showed that an increase in the number of brushing strokes applied to 3 instruments (WaveOne, Reciproc, and a prototype) resulted in more dentinal cutting in the direction of the strokes [19]. Even though it has been suggested that the brushing motion can increase the canal flaring and possibly cleaning [16], to the best of our knowledge, there are no studies showing the effects of brushing in root canal shaping of oval canals. It remains unknown whether the lateral brushing movement applied coronally to highly flexible instruments can be successfully transferred to the apical part of these instruments in the canal, while the same are operated in reciprocating or rotary mode. The cutting effect of the instrument in brushing motion (which is similar to the filing motion) also depends on the cross-sectional design and disposition of the cutting edges of the instrument.

Therefore, the present study aimed at evaluating the effects of the lateral brushing motion on the shaping ability of 3 different instruments in oval canals. A comparison was also made between instruments that were recently introduced and for which there is limited information on the shaping ability. The test instruments have either an S-shaped (Reciproc Blue and VDW.Rotate, VDW, Munich, Germany) or triangular cross-section (Race EVO, FKG Dentaire, La Chaux-de-Fonds, Switzerland) and are operated in either reciprocating (Reciproc Blue) or continuous rotary motion (VDW.Rotate and RaCe EVO).

Materials and methods

Sample selection

The sample size was calculated using the G*Power 3.1 software (Heinrich Heine Universität, Düsseldorf, Germany) and was based on a previous study [20]. It was performed with the alpha-type error set at 0.05 and power at 80%, resulting in 10 specimens per group. Twelve specimens were used in each group to compensate for possible losses.

The study protocol was approved by the Institutional Ethics Committee. Tooth specimens were selected from a collection of 146 human mandibular incisors extracted for reasons not related to this study. Teeth were disinfected in 0.1% thymol solution for 24 h and kept in purified filtered water for 30 days. For selection, each tooth was initially examined under a dental operating microscope at 10× magnification (Alliance, São Paulo, SP, Brazil) and radiographed in both mesiodistal and buccolingual projections. Teeth with roots showing caries, cracks, resorption, immature apices, moderate to severe apical curvature, two or more canals, or that were <8 mm-long were excluded.

The inclusion criteria were as follows: teeth with a single canal, which was oval-shaped at 5 mm and 8 mm short of the apex based on the buccolingual and mesiodistal radiographs; the presence of the single oval canal was later confirmed by micro-CT imaging. To be considered oval, the canal had to present a buccolingual distance at least twice as large as the mesiodistal distance [21]. Therefore, 72 mandibular incisors with long oval root canals were finally selected. To minimize anatomic discrepancies, the teeth were anatomically matched in sextets, based on the canal volume measurement and anatomical appearance as determined by micro-CT analysis (see below). One specimen from each sextet was randomly manually allocated to each of the 6 experimental groups.

Micro-CT scanning

The specimens were scanned in a micro-CT SkyScan 1174v2 device (SkyScan; Bruker microCT, Kontich, Belgium) using the following parameters: isotropic resolution of 19.16 mm, 50 kV, 800 mA, 180° rotation around the vertical axis, and rotation step of 1.0 using a 0.5-mm-thick aluminum filter. After scanning, the images were reconstructed using the NRecon 1.6.9 software (Bruker microCT), producing 700–750 images per tooth and using the following parameters: ring artifact correction of 10, beam hardening correction of 41%, and smoothing of 7.

Root canal preparation

Coronal access cavities were prepared and a K-file size 15 (FKG Dentaire) was introduced in the canal until it was visible at the apical foramen under the operating microscope. The working length (WL) was established at 1 mm short of this length.

The instrument types and sizes were as follows. Reciproc Blue (25/.08); VDW.Rotate (15/.04, 25/.04, 30/.04); and RaCe EVO (15/.04, 25/.04, 30/.04). They were powered by the VDW Silver electric motor (VDW) in the settings recommended by the respective manufacturers. The former was used in reciprocating mode, while the two others were used in continuous clockwise rotation mode. One experienced endodontist previously trained with all the test systems performed all the preparations. Each set of instruments was used to prepare two root canals.

For each instrument system, the canals were prepared using or not the brushing motion (total = 6 groups). For preparation in all groups, each instrument was used in in-and-out pecking motions of approximately 3 mm amplitude.

After 3 pecking movements, the instrument was removed from the canal and cleaned, and apical patency was confirmed with a hand K-file size 15. The canal was irrigated with 2.5% NaOCl and the instrument reutilized with the same motions until it reached the WL. In the groups using brushing, after every penetration of the instrument in the canal by pecking motions, the instrument was withdrawn 1–2 mm so that it could be slightly loosened, and then lateral brushing strokes were directed to the areas of buccal and lingual recesses of the oval canal. Three brushing strokes were applied per recess area.

During canal preparation, the same irrigation protocol was used in all groups. The irrigant solution (2.5% NaOCl) was delivered by a 30-G needle between each instrument change (2 mL). A total of 10 mL NaOCl was used per canal. Patency of the apical foramen was maintained throughout the preparation procedures with a K-file size 15.

Micro-CT analysis

Image datasets (same specimen before and after instrumentation) were registered using the 3D Slicer 5.0.2 software (http://www.slicer.org), ensuring the exact spatial positioning. The volume of the sound canal (initial dataset) was considered the reference volume, and an "Affine"' algorithm with 12 degrees of freedom was used.

After registration, the surface area (mm^2) and volume (mm^3) of the apical canal segment (from the WL to 4 mm short) and the full canal length (standardized as up to 8 mm short of the WL) were calculated using the ImageJ 1.50d software (National Institutes of Health, Bethesda, MD, USA). The same software was used to assess the area of unprepared canal surface by calculating the number of static voxels. Values were obtained by subtracting the scores for the prepared canals from those recorded for their unprepared counterparts and then converted into percentages. The reconstruction of the 3-dimensional models was performed using the CTvol v.2.2.1 software (Bruker-microCT). The green color was used for the preoperative and red for the postoperative surfaces.

In addition, the CTAn v.14.4.1 software (Bruker micro-CT) was used to evaluate the dentin thickness on the mesial and distal root walls at the cementoenamel junction (CEJ) and 4 mm apically to this point, before and after preparation. The Structure Model Index (SMI), which is a measure of surface convexity, and therefore a suitable parameter in evaluating oval canals, was also evaluated. SMI values range from 0 to 4 and represent the shape of the root canal (0 corresponds to parallel flat planes and 4 corresponds to a perfect ball) [22]. Canal transportation was assessed from centers of gravity calculated for each slice before and after preparation [8].

Statistical analysis

Data distribution was analyzed by the Shapiro-Wilk normality test and graphical analysis. For intragroup comparisons (before and after preparation) on the full canal length, the Wilcoxon test was applied to the volume, surface area, and SMI data analyses. The percent increase in volume, surface area, SMI, and centroid between each instrument system with and without brushing was compared using the Mann-Whitney *U* test. In addition, these same parameters were analyzed by the Kruskal-Wallis test to compare the six groups. The unpaired-*T*-test was used to compare dentin thickness when the instrument system was used with or without brushing. One-way analysis of variance (ANOVA) and the Tukey's test were applied to compare the six groups for dentin thickness values.

When the apical 4-mm segment of the canal was evaluated separately for increased volume and surface area, the Mann-Whitney *U* test was used for pairwise intergroup (with or without brushing) analyses and the Wilcoxon test for intragroup (before and after) comparisons. Also, the Kruskal-Wallis test was applied to compare the six groups. The Mann-Whitney *U* test compared the unprepared surface area between the paired groups (with or without brushing) at full canal length and the apical segment. The same test was used for pairwise comparison between the 6 groups. The SPSS statistical software (Statistical Package for the Social Sciences 21.0; IBM Brasil, SP, Brazil) was used for all analyses, with the significance level set at 5%.

Results

Volume, surface area, SMI, and centroid

The data relating to root canal volume, surface area, SMI, and centroid showed preoperative homogeneity between groups with no statistically significant differences ($p > 0.05$). Table 1 depicts the values for volume increase, surface area, unprepared areas, and SMI at the full length (8 mm) and the apical portion (4 mm) of the oval root canals before and after preparation. No instrument breakage occurred during root canal preparation.

Canal volume, surface area, and SMI significantly increased after preparation with all systems, with or without brushing ($p < 0.001$). However, pairwise comparisons for each instrument type used with or without brushing for the percent increase in these same parameters showed no significant differences ($p > 0.05$). The only exception was for percent increase in the full canal surface area with RaCe EVO, with brushing showing superior results than no brushing ($p = 0.03$).

Table 1 Micro-computed tomographic analyses before and after root canal preparation with three different systems with and without brushing. Data for the full root canal length and the 4-mm apical segment expressed as mean (median; range)

Data	Reciproc Blue	Reciproc Blue (Brushing)	Rotate	Rotate (Brushing)	RaceEvo	RaceEvo (Brushing)
Full canal length						
Volume (mm^3)						
Initial	1.8^{A} (1.7; 1–2.7)	2^{B} (1.9; 1.3–4)	2.2^{C} (1.7; 1.2–5)	1.9^{D} (1.7; 1.1–3.3)	1.9^{E} (1.9; 0.9–2.9)	1.9^{F} (1.8; 0.9–2.8)
After preparation	2.9^{A} (3; 1.9–3.8)	3.1^{B} (2.9; 2.1–4.8)	2.8^{C} (2.6; 1.8–5.5)	2.5^{D} (2.5; 1.7–3.7)	2.5^{E} (2.6; 1.6–3.3)	2.8^{F} (2.7; 2.2–3.7)
Δ% after preparation	70.1 (59.1; 18.2–185.3)	62.7 (47.6; 17.5–204.4)	36.6 (32; 0.8–135.1)	38.7 (43.4; 10.8–67.7)	39.3 (26.5; 12.5–149.1)	54.8 (47.9; 15.5–161.8)
Surface area (mm^2)						
Initial	23.3^{G} (22.3; 16.2–36.7)	24.8^{H} (22.3; 17–47.8)	26.6^{I} (24.1; 18–47.2)	26.3^{J} (24; 17.8–43.3)	24.4^{K} (24.5; 15.6–33.6)	26^{L} (24.4; 20.6–39.1)
After preparation	26.3^{G} (25.4; 20.7–40.9)	28.2^{H} (25.6; 20.6–48.6)	28.5^{I} (25.5; 20.4–48.7)	28.8^{J} (26.4; 20.8–45.1)	26.9^{K} (26.2; 18.8–36.1)	29.9^{L} (28.5; 23.6–43)
Δ% after preparation	14.3 (11.3; 1.4–37.8)	14.3 (14.8; 1.7–22.8)	8.3 (5.9; 0.5–16.8)	10.5 (10.9; 1.7–22)	11.3^{a} (7.2; 3.2–42.3)	15.5^{a} (14.2; 5.1–33.4)
Unprepared areas (%)						
After preparation	43 (44; 9–85.2)	35.1 (28.4; 9.7–94.7)	33.6 (35.6; 1.2–72.5)	30.8 (30; 4.4–70.9)	26.9 (21.8; 6.5–78.9)	27.4 (23.1; 7.6–61.9)
SMI						
Initial	1.9^{M} (2; 1–2.5)	2^{N} (2.2; 1.2–2.5)	1.6^{O} (1.6; 0.4–2.5)	1.7^{P} (1.8; 0.9–2.6)	1.8^{Q} (1.9; 1.2–2.3)	1.7^{R} (1.6; 1.3–2.4)
After preparation	2.7^{M} (2.8; 1.2–3.4)	2.5^{N} (2.6; 1.3–3.2)	2.3^{O} (2.2; 1.4–3.3)	2.1^{P} (2.3; 1.2–2.8)	2.1^{Q} (2.2; 1.6–2.5)	2^{R} (1.9; 1.3–2.6)
Δ% after preparation	42.5 (40.6; 0.6–102.8)	33 (14.9; 6.5–150.4)	71.7 (29.3; 0.3–418.5)	22 (19.6; 0.4–63.6)	16.2 (11.6; 2.6–35.4)	15 (15.4; 3.2–27.5)
4-mm apical segment						
Volume (mm^3)						
Initial	0.5^{A1} (0.5; 0.3–0.9)	0.5^{B1} (0.4; 0.3–1.3)	0.6^{C1} (0.5; 0.3–1.5)	0.5^{D1} (0.4; 0.2–1)	0.6^{E1} (0.6; 0.3–0.8)	0.5^{F1} (0.5; 0.2–0.8)
After preparation	0.9^{A1} (0.8; 0.5–1.6)	0.8^{B1} (0.8; 0.5–1.5)	1^{C1} (0.8; 0.5–1.7)	0.8^{D1} (0.7; 0.5–1.3)	0.8^{E1} (0.8; 0.5–0.9)	0.8^{F1} (0.8; 0.7–1.4)
Δ% after preparation	84 (47.1; 12.1–344.2)	67.2 (62.9; 11–145.7)	73.7 (47.7; 3.6–329)	73.1 (48.8; 13.7–191.4)	51.8 (41.1; 16.2–149.8)	70.7 (62.93; 12.4–195.8)
Surface area (mm^2)						
Initial	8.7^{G1} (8.4; 5.3–12.8)	8.86^{H1} (7.6; 5.2–20.5)	9.6^{I1} (9.4; 5.7–17.9)	9.2^{J1} (8; 4.6–15.6)	8.8^{K1} (8.9; 5.9–12.4)	8.9^{L1} (8.3; 5.6–13.7)
After preparation	9.8^{G1} (9.7; 7.1–14.6)	10.5^{H1} (9.2; 6.9–21.4)	10.6^{I1} (10.2; 7.3–18.4)	10.7^{J1} (9.5; 7.3–16.5)	10.1^{K1} (10.5; 7.5–13)	10.8^{L1} (9.8; 9–16)
Δ% after preparation	14.9 (10.2; 1.4–62.9)	20.2 (19.7; 2.8–38.1)	12 (11.2; 0.4–28.1)	20.2 (15.2; 5.9–59.8)	16.8 (13.3; 5.1–51.6)	23.6 (22.3; 6–61.9)
Unprepared areas (%)						
After preparation	55.9^{b} (56.2; 11.6–99.5)	34.2^{b} (34.9; 10.5–82.6)	39.7 (32.2; 1.3–99.7)	27 (19; 0.6–91.9)	31 (20.4; 3.4–83.9)	28 (16.5; 0–81.5)

For each row, pre- and postoperative values that share the same superscript upper-case letter (A-R) were significantly different ($p < 0.05$). The same superscript lower-case letter (a/b) represents significant difference between groups at the 5% level

For centroid shift, a statistically significant difference could be observed only in preparations with Reciproc Blue, with brushing showing lower deviation than no brushing ($p < 0.05$). No differences were observed for the other instruments ($p > 0.05$) (Table 2).

Unprepared surface areas

Data on unprepared surface areas for all groups are shown in Table 1. Except for RaCe EVO in the full canal, the brushing motion resulted in an increase in prepared areas for all instruments in both apical and full canal (Fig. 1). The mean unprepared surface areas for Reciproc Blue with and without brushing in the full canal length were 35.1% and 43%, respectively. Corresponding figures for VDW. Rotate were 30.8% and 33.6%; and 27.4% and 26.9% for Race EVO. In the apical 4-mm segment, unprepared areas with and without brushing were respectively 34.2% and 55.9% for Reciproc Blue, 27% and 39.7% for VDW.Rotate, and 28% and 31% for RaCe EVO. However, differences were only statistically significant for the Reciproc Blue instrument in the apical canal, with brushing showing more prepared areas than no brushing ($p = 0.03$). No other significant differences for unprepared areas were observed ($p > 0.05$) (Table 1).

Pairwise comparisons of unprepared areas were also made involving all combinations from the 6 groups. In the full canal, significant results were found only when comparing RaCe EVO (no brushing) and Reciproc Blue (no brushing), with the former preparing more areas ($p = 0.04$). In the apical 4 mm segment, differences were found for the following comparisons of unprepared areas: Rotate (brushing) < Reciproc Blue (no brushing) ($p = 0.01$); RaceEvo (no brushing) < Reciproc Blue (no brushing) ($p = 0.03$); RaceEvo (brushing) < Reciproc Blue (no brushing) ($p = 0.02$).

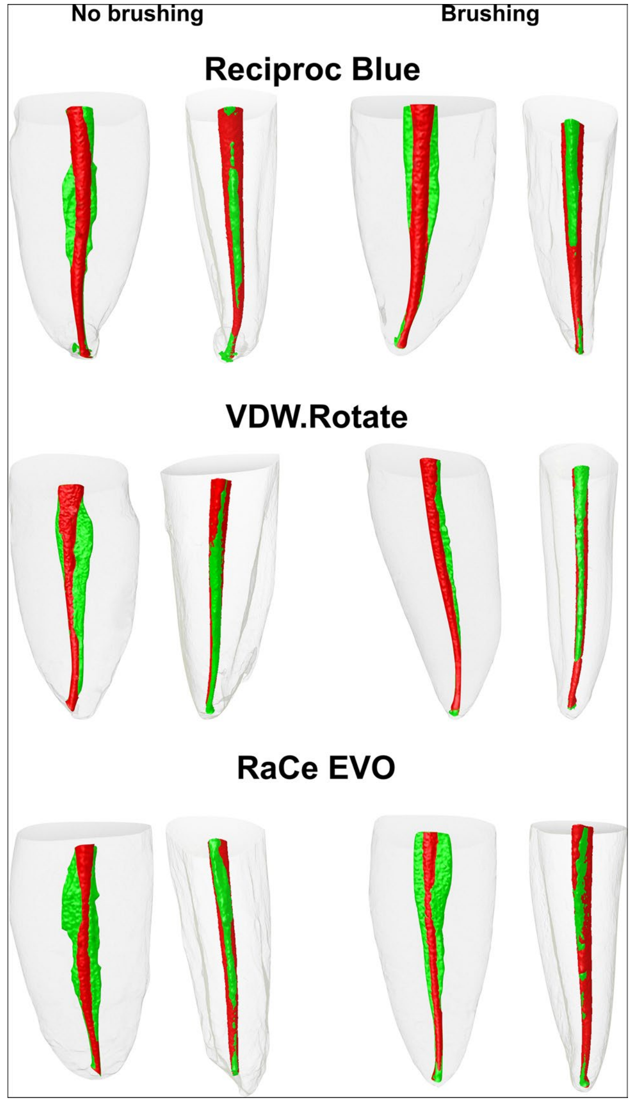

Fig. 1 Representative 3D reconstructions of micro-CT scans taken before (green) and after preparation using three instruments with or without brushing motion. Superimposed views show unprepared root canal areas in green from mesiodistal and buccolingual views

Table 2 Center of gravity shift (mm) in the root canals after preparation with three systems with and without brushing

Group	Mean	Median	Range
Reciproc Blue	0.099	0.001[a]	−0.022-1.19
Reciproc Blue (Brushing)	0.001	0.001[a]	-0.025-0.045
Rotate	−0.226	−0.009	-2.669-0.029
Rotate (Brushing)	0.010	0.009	-0.013-0.027
Race Evo	0.005	0.003	-0.015-0.024
Race Evo (Brushing)	0.004	0.005	-0.060-0.030

*Negative values means deviation to the buccal aspect; positive values to lingual

Values that share the same superscript lower-case letter (a) showed significantly different between groups ($p < 0.05$)

Dentinal thickness

Data on the remaining dentin thickness are depicted in Table 3. In all groups, the dentinal thickness in mesial and distal walls was reduced in CEJ and 4 mm apical to this point. The pairwise comparison revealed that in the mesial dentin at the CEJ level, Reciproc Blue with no brushing exhibited significantly less remaining dentin than with brushing ($p = 0.03$). At this same level in distal dentin, a significant difference was observed for RaCe EVO, with brushing resulting in less remaining dentin ($p = 0.03$). At 4 mm apical to the CEJ, RaCe EVO with brushing also resulted in smaller dentin thickness than RaCe EVO with no brushing ($p < 0.01$).

Table 3 Dentin thickness (mm) before and after preparation with three systems with and without brushing. Data for the cementoenamel junction and 4 mm apically to this point expressed as mean (median; range)

Data	Mesial			Distal		
	Initial	After	**Δ**	Initial	After	**Δ**
Cementoenamel junction						
Reciproc Blue	1.2 (1.2; 1–1.3)	1[a] (1; 0.9–1.2)	0.17	1.2 (1.2; 1–1.3)	1 (1.1; 0.7–1.2)	0.16
Reciproc Blue (Brushing)	1.3 (1.3; 1–1.5)	1.1[a] (1.1; 0.9–1.4)	0.16	1.2 (1.2; 1–1.4)	1.1 (1.1; 1–1.3)	0.14
Rotate	1.2 (1.2; 1–1.6)	1.2 (1.1; 0.9–1.6)	0.07	1.3 (1.3; 1–1.6)	1.2 (1.2; 0.9–1.6)	0.07
Rotate (Brushing)	1.2 (1.2; 0.9–1.4)	1.2 (1.2; 0.8–1.4)	0.05	1.3 (1.3; 1.1–1.5)	1.1 (1.2; 0.7–1.3)	0.13
Race Evo	1.2 (1.2; 0.9–1.4)	1.1 (1.1; 0.9–1.4)	0.07	1.2 (1.3; 1–1.5)	1.1[b] (1.1; 0.9–1.4)	0.09
Race Evo (Brushing)	1.2 (1.2; 0.9–1.4)	1.1 (1.1; 0.8–1.3)	0.11	1.2 (1.2; 0.9–1.3)	1[b] (1.1; 0.8–1.2)	0.12
4 mm apical to canal opening						
Reciproc Blue	0.9 (1; 0.8–1.2)	0.8 (0.9; 0.5–1.0)	0.14	0.9 (0.9; 0.7–1.2)	0.8 (0.8; 0.5–1)	0.14
Reciproc Blue (Brushing)	1 (1; 0.9–1)	0.9 (0.9; 0.7–1.1)	0.16	1 (1; 0.8–1.1)	0.9 (0.8; 0.6–1.1)	0.18
Rotate	1 (1; 0.8–1.3)	0.9 (0.9; 0.7–1.2)	0.08	1 (1; 0.9–1.2)	1 (1; 0.7–1.2)	0.06
Rotate (Brushing)	0.9 (1; 0.2–1.2)	0.9 (0.9; 0.3–1.2)	0.03	1 (1.1; 0.8–1.2)	1 (1; 0.7–1.2)	0.08
Race Evo	0.9 (0.8; 0.7–1.1)	0.8 (0.8; 0.6–1.1)	0.10	1.1 (1.1; 0.9–1.3)	1[c] (1; 0.8–1.2)	0.08
Race Evo (Brushing)	1 (1; 0.7–1.2)	0.9 (0.9; 0.6–1.2)	0.10	0.9 (0.9; 0.7–1)	0.8[c] (0.8; 0.5–1)	0.12

Pre- and postoperative values that share the same superscript lower-case letter (a–c) showed significant difference between groups ($p < 0.05$)

Discussion

The present micro-CT study evaluated and compared the shaping ability of 3 recent NiTi instruments with or without lateral brushing motion in oval canals. As expected, the canal volume, surface area, and SMI were significantly increased after canal preparation with the 3 tested systems, with or without brushing. The effects of brushing on oval canal shaping were observed only in a few parameters evaluated and depending on the instrument tested.

One of the most important parameters evaluated in micro-CT studies is the canal preparation performance in terms of the amount of prepared surface areas. This is because unprepared areas can exhibit residual bacterial biofilm and/or pulp tissue remnants [23, 24], which may negatively affect the treatment outcome [25]. Regardless of the different instrument types, alloys, geometrical designs, operation modes and the use of brushing strokes, no specimen showed all surfaces prepared. At full canal length, the amount of unprepared areas ranged from 26.9 (RaCe EVO) to 43% (Reciproc Blue), while in the apical canal the range was from 27 (VDW.Rotate/brushing) to 55.9% (Reciproc Blue). These figures are within the range previously reported in the literature [26]. Although the lateral brushing motion was proposed to improve root canal shaping by incorporating more areas in the final preparation shape, the present findings in oval canals revealed that it had no significant impact on the tested systems, either in the full canal or in the isolated analysis of the apical canal. The only exception was the Reciproc Blue instrument in the apical canal segment, for which lateral brushing strokes significantly increased the amount of prepared areas.

The Reciproc Blue R25 instrument is geometrically similar to the previous Reciproc instrument but comprises advanced technology, with increased flexibility and cyclic fatigue resistance, resulting from its manufacturing from a new heat treatment approach with the formation of a blue titanium oxide layer on its surface. The instrument has an S-shaped cross-section and studies have reported satisfactory results in its shaping ability [24, 27, 28]. In addition to improving apical preparation, the brushing motion affected other shaping parameters when Reciproc Blue was used. For instance, centroid shift evaluation revealed that brushing with Reciproc Blue caused less canal deviation than no brushing. When the remaining dentin thickness in the pericervical area was examined, Reciproc with no brushing led to more dentin removal on the mesial side. This may possibly be explained by the brushing motion possibly balancing the distribution of the cutting effect in the canal.

The VDW.Rotate instrument (VDW) has manufacturing similarities to Reciproc Blue. However, contrary to what was observed for Reciproc Blue, the use of brushing strokes resulted in no significant shaping effects in comparison with no brushing for the VDW.Rotate instruments. The main differences between VDW.Rotate and Reciproc Blue that may help explain the different results are related to the number of instruments used for preparation (Reciproc Blue is a single-file system), the direction of the cutting blades, and operation mode (VDW.Rotate is used in continuous clockwise rotation and Reciproc Blue in reciprocation). However, when compared to the other instruments, VDW.Rotate with brushing prepared significantly more surface areas in the apical 4 mm segment than Reciproc Blue with no brushing. Another possible reason for differences between VDW.Rotate and Reciproc Blue performances may be the fact that VDW. Rotate 30/.04 presents larger diameters over the first 3 mm from the instrument tip when compared with Reciproc Blue 25/.08.

The RaCe EVO instrument is made from a heat-treated Max-Wire NiTi alloy, with a triangular cross-section design, electropolished surface, and alternate cutting edges. It is recommended for use in continuous clockwise rotation. Application of the brushing motion significantly increased the canal surface area in the full canal length compared with no brushing. Brushing with RaCe EVO also resulted in significantly less remaining dentin at the region of pericervical dentin when compared with no brushing. Compared with the other instruments for unprepared surfaces, RaCe EVO with no brushing performed significantly better than Reciproc Blue with no brushing in both the full canal length and the apical canal segment. RaCe EVO with brushing was also significantly better than Reciproc Blue with no brushing in the apical canal. These findings may be possibly explained by the triangular cross-section with alternating cutting edges, the instrument dimensions, and the higher rotation speed applied to RaCe EVO.

All instruments seemed to produce conservative and safe preparations. Despite differences in geometry, surface treatment, and flexibility, the tested systems showed similar performance in dentin removal, with no difference in the root canal volume increase between groups. An increase in total canal surface area from only 8 to 15.5% was observed for the 3 instruments tested, with or without brushing. Moreover, no instrument fracture was observed in this study, which is in agreement with other studies [16–18] that showed that brushing may be a safe procedure in terms of risk of instrument breakage. The brushing motion may allow stresses to be distributed along the instrument axis, preventing stress concentration on the same areas.

Another factor related to the safety of canal preparation is the remaining dentinal thickness, especially at the pericervical area, which is the area located between 4 mm coronal and 4 mm apical to the bone crest and believed to play a crucial role in transferring occlusal forces across the root [29]. As expected, the dentin thickness in the mesial and distal walls was significantly reduced in both the CEJ and 4 mm apically in all groups. It has been recommended that, ideally, 1 mm of coronal root dentin thickness be preserved around the prepared canal [30–33]. However, the literature also reports an arbitrary value of 0.3 mm as the minimum dentin thickness that should remain after instrumentation to avoid perforation and prevent root fracture [34, 35]. In the present study, even in specimens showing preoperative pericervical dentin thickness less than 1-mm thick in the mesial or distal aspects, the mean postinstrumentation figure was always greater than 0.8 mm, with only one specimen showing 0.3 mm (minimum value). It was also found that brushing did not substantially affect the thickness of the pericervical dentin. These findings suggest that preparations with the test instruments and sizes, with or without brushing, did not significantly compromise the root structure and possibly the fracture resistance.

An important strength of this study was that the tooth specimens were paired based on their anatomic features as evaluated by micro-CT imaging. The absence of statistically significant differences in the canal volume, surface area, and SMI between groups confirmed that pairing effectively provided a homogeneous sample, helping to reduce potential anatomical biases that might interfere with the results [36]. Limitations of this study include its ex vivo nature and the fact that it was limited to only oval canals of mandibular incisors.

In conclusion, the present study revealed that the brushing motion had minor effects on the overall shaping performance of the 3 instruments tested. One exception was the increase in prepared surface area in the apical canal segment when applied to the Reciproc Blue instrument. Further studies should evaluate the impact of the lateral brushing motion in enhancing root canal disinfection, especially in recess and isthmus areas of oval/flattened root canals.

Author contribution Renata Pérez, Alejandro R. Pérez, and Flávio R. F. Alves: formal analysis (lead). Kaline Romeiro, Thaís M. Souza, Luciana F. Gominho, and Sabrina C. Brasil: formal analysis (supporting). José F. Siqueira Jr, Isabela N. Rôças, and Flávio R. F. Alves: writing—review and editing (supporting). José F. Siqueira Jr and Isabela N. Rôças: Conceptualization (lead).

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Data availability All data can be accessed directly in the manuscript and supplementary table.

Declarations

Ethics approval The study protocol was approved by the Institutional Ethics Committee.

Competing interests The authors declare no competing interests.

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