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ORIGINAL ARTICLE

Micro-CT Analysis of an Abrasive-expanding System of Oval Canal Debridement Capacity: A Laboratory Study

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ABSTRACT

Objective: Biomechanical root canal preparation involves both mechanical instrumentation and endodontic irrigation, aiming to reduce bacterial levels to promote periradicular healing. However, complete removal of biofilm and debris, especially in complex canal morphologies, remains difficult. This study aimed to evaluate, through microcomputed tomography (micro-CT), the use of the XP-Endo Finisher and Tornado Disinfection Kit (TDK) systems during the final agitation of the irrigating solution for the final debridement of oval-shaped canals of lower incisors.

Methods: Thirty-nine extracted human mandibular incisors were instrumented up to size #25/.05 and divided into three groups (n=13) based on the final irrigation system: Conventional irrigation with syringe and needle (CI), XP-Endo Finisher (XPF), and TDK. 40 mL of 2.5% NaOCl was used for each group. Teeth were scanned ex vivo using a micro-CT before instrumentation, after instrumentation, and after irrigation. Three-dimensional root canal models were evaluated for volume, untouched surfaces, and dentine removal. Data were analyzed using repeated-measures ANOVA, t-test, and Tukey tests ($p<0.05$).

Results: TDK showed a significant difference in total and cervical third compared to CI and XPF regarding volume and dentine removal analysis ($p<0.05$), with no significant difference in the apical third compared to XPF ($p>0.05$). TDK had a lower percentage of untouched volume compared to the other systems in the overall analysis ($p<0.05$) and at all thirds compared to CI ($p<0.05$).

Conclusion: Supplementary instruments improve root canal debridement compared to conventional irrigation, particularly in smaller apical diameters and oval-shaped canals of lower incisors. TDK offers enhanced wall contact after root canal preparation and is a viable alternative for complementing debridement.

Keywords: Root canal irrigants, root canal preparation, X-ray microtomography

HIGHLIGHTS

- This study reference whether using supplementary instrument during irrigating solution agitation improves final debridement of oval-shaped canals.
- The Tornado Disinfection Kit removed more dentine with less untouched volume than conventional irrigation.
- The Tornado Disinfection Kit can be considered an alternative for enhancing debridement in these canals.

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INTRODUCTION

Biomechanical root canal preparation involves mechanical instrumentation and endodontic irrigation (1), seeking to eradicate or reduce bacteria to levels considered compatible with periradicular tissue healing (2). However, it has been difficult to combine the preservation of the original dentine structure with proper cleaning of the canal system (3). However, current mechanical instrumentation methods, incompletely eradicate the biofilm, dentinal debris, and/or microorganisms, mainly in complex root canal areas (4). Therefore, endodontic irrigation is crucial for better cleaning and disinfection of those areas (5).

Conventional irrigation with syringes and needles has some flaws, such as the irrigant being confined around the needle tip (6) and the "vapor lock" effect (7). To improve irrigation efficiency, various tools have been developed over the years to optimize the cleaning of root canals, including advanced technologies such as laser, sonic, and ultrasonic activation (8, 9). However, to mechanically enhance the removal of debris and biofilm from complex canal anatomies, instruments like the XP-Endo Finisher (25/.00) (XPF) (FKG, La Chaux-de-Fonds, Canton of Neuchâtel, Switzerland) have been developed. This file is designed for use after root canal preparation in canals with diameters of 25 or greater (10). Made from MaxWire alloy, it remains straight when cooled and transforms into a "spoon-shaped" design at body temperature (37°C), allowing it to adapt to irregular canal morphologies and improve cleaning efficiency.

An alternative is the Tornado Disinfection Kit–TDK (MedicNRG, Kibbutz Afikim, Jordan Valley, Israel), consisting of two instruments: the GentleFile Red (23/.04), an abrasive stainless-steel instrument with three wires in the middle and cervical thirds, and two wires in the apical third, based on the concept of centrifugal force, and GentleFile Brush, an instrument with seven fine stainless steel wires in the apical part and, when activated, generating a rotational flow of the irrigant within the root canal. They are driven by an automated and non-programmable handpiece at 6,500 rpm (11) with quick and short in-and-out motion.

The high percentage of areas unprepared by mechanical instrumentation (12) can facilitate microbial retention and cause post-treatment endodontic disease (13). This study aimed to assess whether the XPF and TDK systems alter volume, reduce untouched areas, and eliminate dentine post minimally invasive root canal preparation of single-rooted mandibular incisors, using computed microtomography (micro-CT). The null hypothesis stated that there would be no difference in the volume, untouched areas, and eliminate dentine between the groups.

MATERIALS AND METHODS

Sample Size Calculation

G * Power v3.1 (Heinrich Heine, Universität Düsseldorf, Dusseldorf, Bundesland, Germany) was used for sample size calculation, selecting the Wilcoxon-Mann-Whitney test from the t test family. Based on data from a previous study on mandibular incisor root canal preparation (14), an effect size of 1.20 was established for this study. With an alpha error of 0.05, beta power of 0.80, and N2/N1 ratio of 1, a group size of 10 specimens per group was determined to detect significant differences, resulting in 39 teeth (n=13/group) to account for a 30% sample loss risk.

Specimen Selection

This study was approved by the Research Ethics Committee (protocol: 42281921.3.0000.5417, February 17th, 2021) and conducted in accordance with Declaration of Helsinki.

Eighty-six mandibular incisors extracted for periodontal or orthodontic reasons were initially selected based on the following inclusion criteria: presence of a single canal, an intact crown, and a complete apex, as confirmed by buccolingual and mesiodistal radiographs (Microimaging, Indaiatuba, São Paulo, Brazil). Teeth with cracks, restorations, caries, root resorption, or calcifications were excluded. The selected teeth were stored in 0.1% thymol solution at 4°C to preserve their structure.

Each tooth was mounted in a wax block and scanned *ex vivo* using a SkyScan1174v2 micro-CT system (Bruker-micro-CT, Kontich, Antwerp, Belgium), with the following parameters: 22.9µm pixel size, 50kV, 800mA, 180-degree rotation (0.8° angular step), and a resolution of 1024x1304. A 1-mm aluminum filter was used to minimize the beam hardening effect. Thirty-nine standardized teeth were selected based on their length, volume, and anatomical configuration of the canal. Oval canals were identified using micro-CT analysis, where canal shape was assessed in cross-sectional images at different levels (cervical, middle, and apical thirds). Canals were considered oval when the ratio between the major and minor diameters (major-to-minor diameter ratio) was equal to or greater than 2, as established in previous studies (15).

Chemomechanical Preparation

A specialist in Endodontics with more than 5 years of experience accessed the root canals using high-speed spherical diamond burs under water cooling. #10 and 15 K-files (Dentsply Maillefer, Baillaigues, Switzerland) were introduced into the canal until their tips were visible through the apical foramen, observed under 30x magnification with a stereomicroscope (Carl Zeiss Vision GmbH, Hallbergmoos, Germany). The actual tooth size was determined using a silicone cursor at the incisal edge, subtracting 1 mm to establish the working length.

The canal was then filled with 2.5% sodium hypochlorite (NaOCl) solution. A BassiLogic 25/.05 file (BassiEndo, Belo Horizonte, Minas Gerais, Brazil) was used, moving in-and-out with a 3 mm amplitude, rotating at 400 rpm with 2 N·cm^2 torque, reaching the canal's first third. The canal was irrigated with a 5 mL plastic syringe and a 30-gauge NaviTip needle (Ultradent Products Inc., South Jordan, UT, USA). After cleaning the file with alcohol-soaked gauze, the process was repeated until instrumentation was complete. After irrigation with 40 mL of irrigating solution, the canal was rinsed with 10 mL of distilled water. Each instrument was used for three teeth before disposal.

Post-instrumentation specimens underwent micro-CT scanning using a SkyScan1174v2 (Bruker-micro-CT), maintaining the previously set parameters.

Group Distribution

Specimens were paired based on pre- and post-instrumentation canal length, volume, and flatness at the cervical, middle, and apical thirds, as determined by micro-CT imaging. To confirm homogeneity, a statistical analysis was performed (Shapiro-Wilk test; p>0.05).

The 39 teeth were divided into three groups (n=13) according to the irrigation protocol:

Conventional irrigation (CI): The root canal was irrigated with 40 mL of 2.5% NaOCl with a 5 mL disposable syringe (Ultradent Products Inc.) and a 30-gauge NaviTip needle (Ultradent Products Inc.), positioned 1 mm short of the working length.

Tornado Disinfection Kit (TDK): The root canal was irrigated with 5 mL of 2.5% NaOCl. GentleFile Red (MedicNRG) was inserted into the canal, rotated at 6,500 rpm with proper contra-angle until resistance was obtained, and then activated using a smooth in-and-out movement with light apical pressure for 5 seconds. This was repeated until reaching the working length, irrigating with 2.5% NaOCl between activations, resulting in 40mL of the irrigation solution. GentleFile Brush (MedicNRG) was then activated for 30 seconds after filling the canal with irrigant. Each instrument was used once and discarded.

XP-Endo Finisher (XPF): The root canal was irrigated with 5 mL of 2.5% NaOCl, agitated with XPF (FKG Dentaire). The instrument was placed at a contra-angle (VDW Silver; VDW, Munich, Bavaria, Germany) and inserted into the canal without rotation. After that, rotation was started (800 rpm and 1 N·cm^2) and the instrument was activated for 1 minute using slow, smooth movements of 8 mm along the long axis of the tooth to the working length. Each instrument was used on one tooth and then discarded. 40mL of 2.5% NaOCl were used for each sample.

At the end, the root canal was irrigated with 5 mL of 17% EDTA, being inundated in the solution for 3 minutes and rinsed with 5 mL distilled water (16). Each group was irrigated with a total of 40 mL of irrigating solution, with agitation protocols conducted in a closed system using individualized silicone molds. These molds were placed inside a muffle submerged in a 37ºC distilled water bath (Lupetec, São Carlos, São Paulo, Brazil) at 37°C.

Post-agitation, specimens underwent a third micro-CT scan using SkyScan-1174v2 (Bruker-micro-CT), maintaining prior parameters.

Micro-CT Analysis

The specimen images from all three scans were reconstructed (NRecon-v.1.6.9.16; Bruker-micro-CT), with post-alignment corrections and optimized ring-artifact corrections as necessary. Smoothing and beam-hardening adjustments were set at 5% and 45%, respectively. DataViewer software (Bruker-micro-CT) was used to co-register the 3D models of the pre- and postoperative images with custom combination of a rigid registration model based on image intensity similarities with accuracy greater than 1 voxel.

After precise registration, scans were segmented using CTAn-v.1.14.4 software (Bruker-micro-CT) to allow root canal quantification. From the resulting binary images, individual three-dimensional (3D-models) of the teeth and canal for each treatment period were made using 3-Matic (Materialise, Leuven, Belgium). The total volume (mm^3), untouched volume (mm^3), and dentine removal (in mm^3) were calculated in all three-dimensions using the 3D-models created in the CTan program, from the cementoenamel junction to the apical foramen. Subsequently, the same analyses were performed on the cervical, middle, and apical thirds, determined individually in the CTan program. These same models were imported into the 3-Matic program, which enabled the models to be superimposed and, based on the voxel difference between them, the results are obtained.

The regions of the non-instrumented canal were determined by calculating static voxels (present in the same position on pre- and post-operative canal surfaces) expressed as a percentage of total surface voxels using the formula (17):

$$\frac{Number\ of\ Static\ voxels}{Total\ \ number\ of\ voxels}\times 100$$

The analysis of the percentage increase in volume was used to identify the alteration of the initial root canal volume after the instrumentation and agitation steps. For this analysis, overlays of the 3D models (initial and post-instrumentation; post-instrumentation and post-agitation) were performed, and the volume difference (in voxels) between them was identified using the 3-Matic program.

The volume of removed dentine post-agitation was calculated by subtracting the post-instrumentation model from the segmented 3D post-agitation model (3-Matic, Materialise).

The 3D models of each treatment period were overlaid on each other and the surfaces were colour-coded to estimate the structural discrepancy between the root canals, allowing visualization and qualitative assessment of the root canal system configuration. For this analysis, a color-coding pattern was established: green for the volume of the initial root canal, red for the volume post-instrumentation, and blue for the volume post-agitation (Fig. 1).

Statistical Analysis

The volume percentage (mm^3) and dentine removal (mm^3) were compared post-instrumentation and post-agitation to confirm the hypotheses of similar anatomical conditions between groups (Shapiro-Wilk, p<0.05). A repeated-measures analysis of variance (ANOVA) was used to examine the effects of treatment stage (initial, post-instrumentation, post-agitation) and group (CI, XPF, TDK) on volume and surface changes. Post-hoc Tukey's test corrected t-tests were used to explore significant interaction effects, with significance set at 5% (SPSS v25, IBM Corp, Armonk, NY).

RESULTS

Group homogeneity was confirmed by the Shapiro-Wilk test for baseline volume and post-instrumentation (p=0.821) (Period I-PI, Table 1, 2).

Analysis of final canal volume revealed that the TDK group had better greater increase in volume compared to CI and XPF groups (p<0.05). In the analysis of thirds, TDK group showed a larger volume increase at the cervical than the other groups,

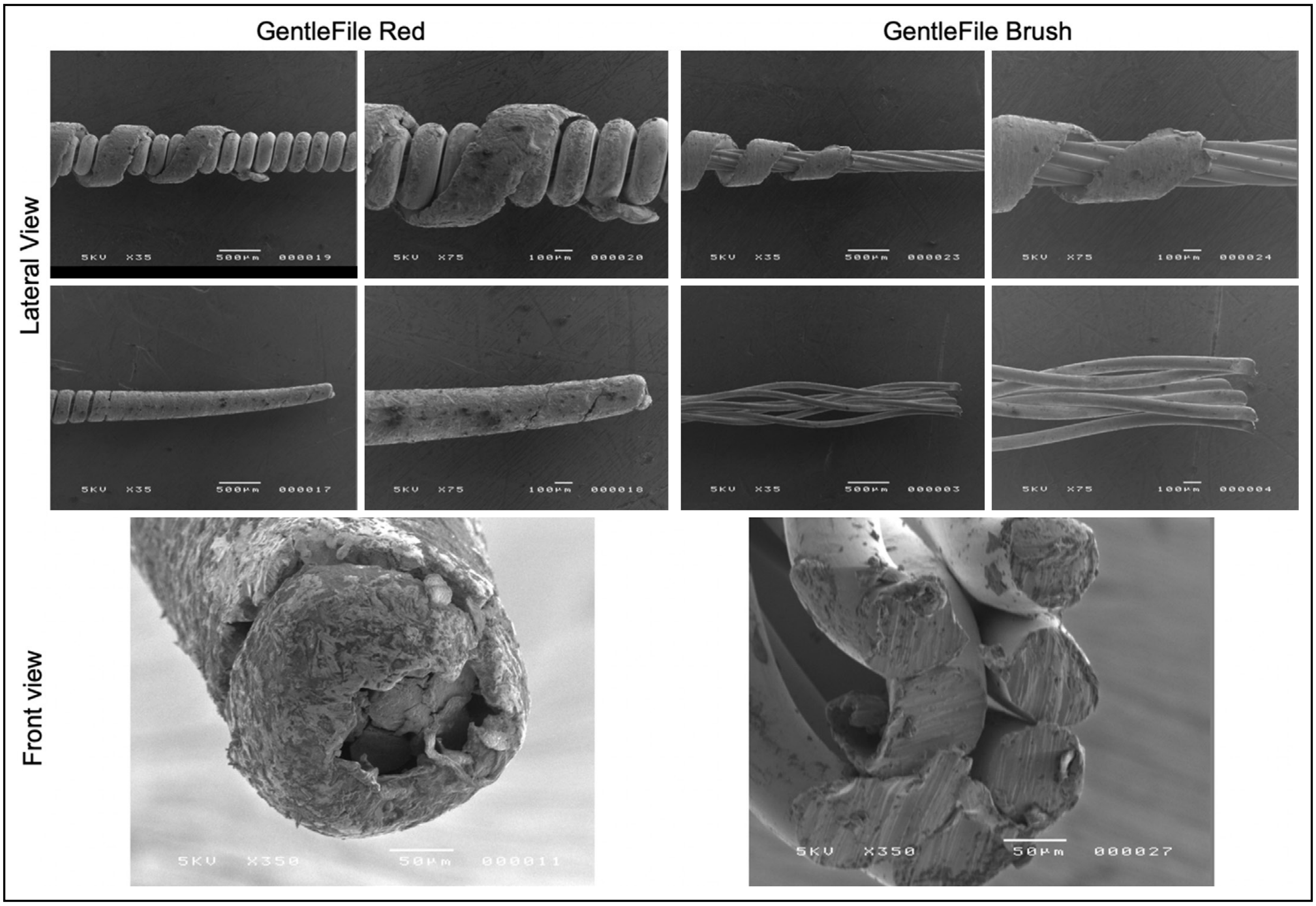

Figure 1. High vacuum laser scanning electron microscope (SEM) image of the GentleFile Red and GentleFile Brush in a lateral view (35x magnification on the top row and 75x on the bottom row) and in a front view (350x magnification)

and at the apical third whereas the TDK group had a larger volume than that of the CI group and similar to that of XPF at the apical third ($p<0.05$) (Table 1).

Regarding dentine removal percentage, TDK showed greater removal compared to CI and XPF groups in total canal analysis and at the cervical third ($p<0.05$). No significant difference was observed at apical and middle third between the groups ($p>0.05$) (Table 1).

In Figure 2, it is possible to observe the areas of the root canal that were more modified (red), the areas that did not show any changes (green), and those where there was debris deposition (blue).

Table 2 shows the means and standard deviations (in parentheses) of the percentage of non-instrumented volume post-instrumentation with BassiLogic 25/.05 and post-agitation. TDK group showed lower percentages overall and at the cervical third compared to other groups ($p<0.05$). At the middle and apical thirds, TDK and XPF groups presented a lower percentage than CI group and were similar to each other ($p<0.05$).

Figure 3 illustrate the root canal anatomy initially (green), post-instrumentation (red), post-irrigation (blue), and remaining untouched volume after irrigation protocols.

DISCUSSION

This study aimed to evaluate the effects of the XPF and TDK systems on the volume, untouched areas, and dentine removal after minimally invasive root canal preparation of single-rooted mandibular incisors, using micro-CT for analysis. The null hypothesis stated that there would be no difference in volume, untouched areas, and dentine removal between the groups. However, TDK increased the total and cervical third volume compared to CI and XPF, and similarly to XPF at the apical third ($p<0.05$). Initially, GentleFile Red was designated for canal shaping, while GentleFile Brush for agitating the irrigant (18, 19). Neelakantan et al. (11) found that using GentleFile Red alone for root canal instrumentation resulted in irregular removal of pulp tissue compared to the previous use of 25-diameter NiTi files, which tended to concentrate pulp tissue in polar areas.

Based on this study, TDK exhibited a more favorable performance in oval-shaped mandibular incisors with apical preparations up to 25-diameter compared to CI. This could be attributed to TDK's abrasion of dentinal walls, facilitated after initial canal path creation (20).

Human mandibular incisors were chosen for this study based on previous research (21), which found mesiodistal apical di-

TABLE 1. Means and standard deviations (in parentheses) of the percentage of volume increase and dentin removed (mm^3) in the evaluated periods

Period	Area evaluated	% Volume increased			% Dentine removed		
		CI Mean (SD)	TDK Mean (SD)	XPF Mean (SD)	CI Mean (SD)	TDK Mean (SD)	XPF Mean (SD)
I-PI	Total	35.8 (±26.2)[a]	40.0 (±20.5)[a]	42.6 (±21.8)[a]	20.3 (±17.9)[a]	23.4 (±16.9)[a]	25.1 (±20.2)[a]
PI-PA	Total	0.00 (±0.94)[a]	15.86 (±7.26)[b]	3.16 (±9.88)[ab]	0.00 (±0.38)[a]	6.63 (±5.03)[b]	0.07 (±3.34)[a]
	C	0.00 (±0.29)[a]	16.59 (±7.87)[b]	2.39 (±8.00)[a]	0.00 (±0.30)[a]	7.33 (±4.84)[b]	0.11 (±1.18)[a]
	M	0.00 (±0.80)[a]	9.70 (±10.30)[a]	8.20 (±9.51)[a]	0.00 (±0.60)[a]	1.10 (±6.51)[a]	0.02 (±6.92)[a]
	A	0.00 (±0.60)[a]	25.44 (±15.1)[b]	22.74 (±15.4)[b]	0.00 (±0.05)[a]	11.83 (±9.97)[b]	9.83 (±9.03)[a]

Different letters indicate a statistically significant difference between the percentages of volume increase and dentine removal between the groups in each region analyzed (ANOVA, t-test and Tuckey tests; p<0.05). CI: Conventional irrigation, TDK: Tornado Disinfection Kit, XPF: XP-Endo Finisher, SD: Standard deviation, I: Initial samples, PI: Post instrumentation, PA: Post agitation, C: Cervical third, M: Middle third, A: Apical third

TABLE 2. Means and standard deviations (in parentheses) of the percentage of the non-instrumented volume (mm^3) in the evaluated periods

Period	Area evaluated	% Non-instrumented volume		
		Conventional irrigation Mean (SD)	Tornado Disinfection Kit Mean (SD)	XP-Endo Finisher Mean (SD)
I-PI	Total	46.50 (±18.50)[a]	45.00 (±23.30)[a]	52.50 (±19.00)[a]
PI-PA	Total	56.25 (±26.07)[a]	16.01 (±13.54)[b]	48.42 (±20.94)[a]
	C	41.29 (±24.29)[a]	12.15 (±12.19)[b]	36.24 (±20.83)[a]
	M	47.52 (±21.10)[a]	15.64 (±29.58)[b]	35.10 (±20.63)[ab]
	A	55.14 (±26.61)[a]	38.47 (±28.42)[b]	43.16 (±26.92)[ab]

Different letters indicate a statistically significant difference between the percentages of non-instrumented volume between the groups in each region analyzed (ANOVA, t-test and Tuckey tests; p<0.05). SD: Standard deviation, I: Initial samples, PI: Post instrumentation, PA: Post agitation, C: Cervical third, M: Middle third, A: apical third

ameters averaging 0.20 mm and 0.25 mm in the initial 3 mm, with diameters exceeding 0.40 mm often observed in the buccolingual direction at 1 mm level. Teeth with these anatomical characteristics would require larger-gauge instruments for effective canal cleaning, potentially increasing root structure wear and susceptibility to fractures or perforation (22). No study has demonstrated instruments capable of fully preparing all oval-shaped canal walls (4).

Regarding the effects of the XPF, despite not designed for dentine cutting, showed a difference in volume at the apical third when compared to CI (p<0.05). This possible debridement capacity can be explained by its kinematics and expansive design, promoting greater contact with the walls, especially when the apical third is dilated to smaller diameters, resulting in the removal of dentinal debris (23).

The volume change analysis is fully associated with the percentage of dentine removal (16), which contributes to decontamination during root canal preparation (24). However, such removal can weaken the tooth if excessive, making it more susceptible to fracture (25). Therefore, minimal damage to the tooth, without compromising root canal decontamination, is crucial.

In this study, we observed no difference in the percentage of dentine removal at the apical and middle third between the groups (p>0.05). This can be explained by the greater flattened area found in the middle third and a smaller expansion capacity of instruments in the apical third due to a smaller diameter, which limits debridement by endodontic instruments (18).

The activation of the irrigating solution is essential for successful endodontic treatment and can be achieved using devices such as lasers, ultrasound, and rotary instruments like the XP-Endo Finisher. However, the percentage of unprepared volume also plays an important role in reducing the uninstrumented surfaces of root canals (16), improving the performance of the irrigating solution and enhancing microbial contro (13, 16). Therefore, the TDK system is proposed as it combines an abrasive instrument (GentleFile Red) to improve debridement, followed by the GentleFile Brush to agitate the irrigating solution and access complex areas.

This is demonstrated by the findings of this study, which indicate that the TDK presented fewer untouched walls compared to the XPF and CI groups (p<0.05). When comparing the canal thirds, TDK showed the lowest untouched values in the apical third compared to CI and similar values to XPF. The apical third is considered the most challenging region to clean due to its complex anatomy (26) and reduced space (27). Therefore, the use of instruments with larger apical diameters is often recommended to improve cleaning and debridement in this critical region.

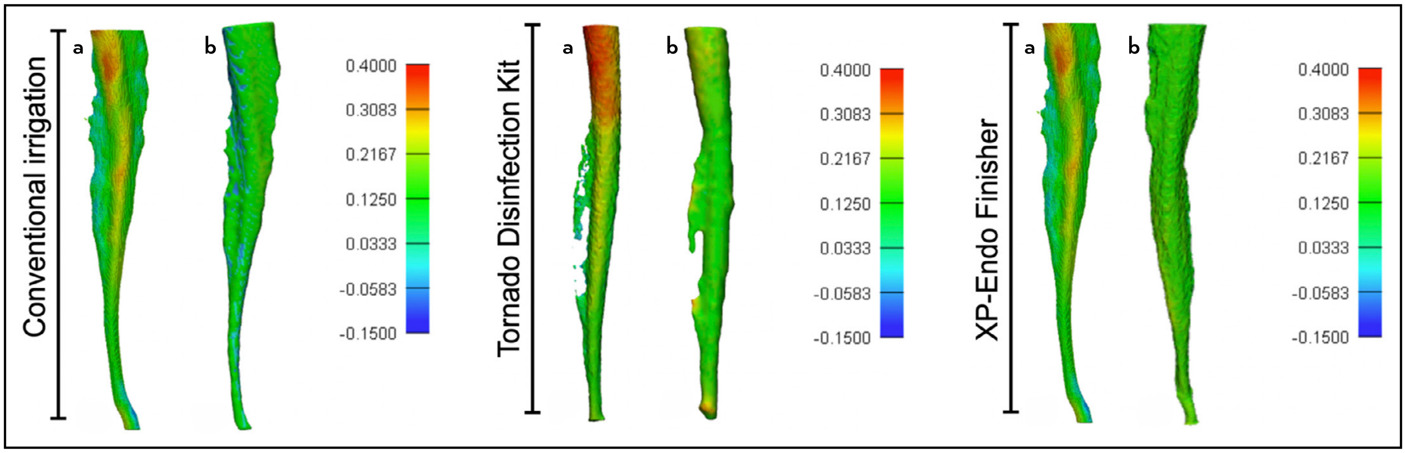

Figure 2. Representative 3D models from computerized microtomography after instrumentation with BassiLogic 25/.05 (a) and after irrigation protocols (b). The closer to red, the greater the alteration of the root canal; regions with little or no changes are represented in green, and areas where dental debris deposition occurred are represented in blue

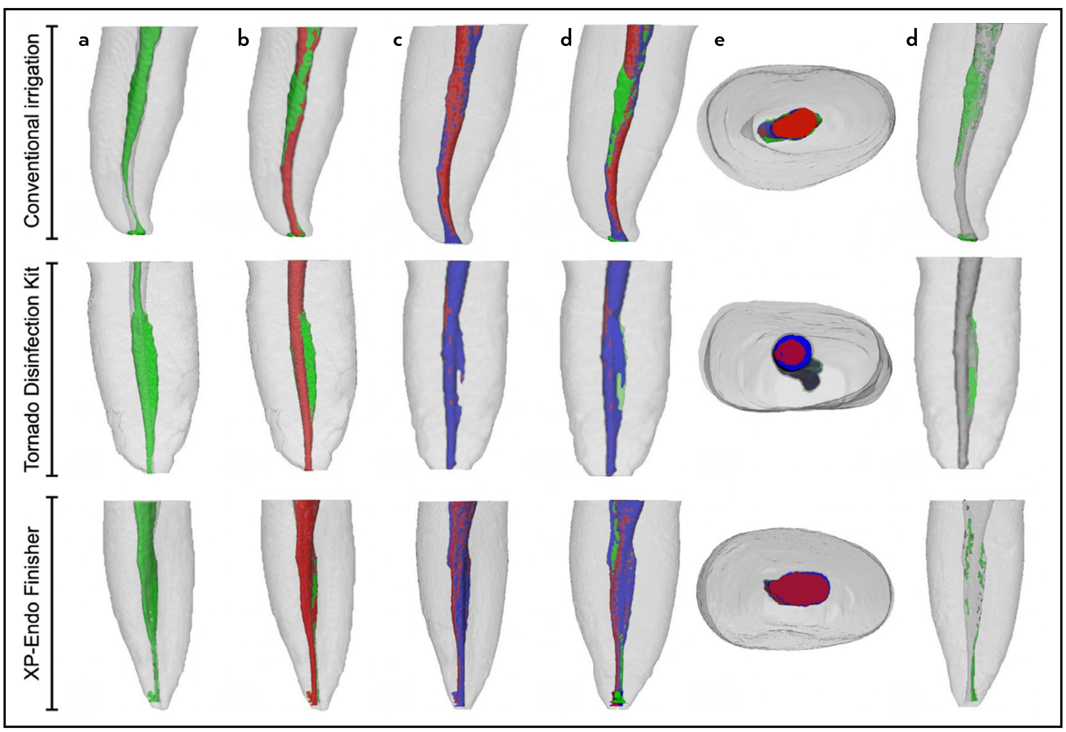

Figure 3. Representative 3D models of micro-CT scans illustrating the initial configuration (a) of the root canal in green; post-instrumentation with BassiLogic 25/.05 (b) in red; after irrigation protocols (c) in blue; comparison among the three analysis periods with a lateral view (d) and a superior view (e) and the areas that remained untouched in the end (f)

Micro-CT: Microcomputed tomography

Nevertheless, a greater magnitude and change in force distribution occur as the instrument diameter increases (28). Removal of apical dentine when larger apical dilation is performed can result in a larger number of dentinal defects with worse severity (29). Most of these defects occur in the apical region in a coronal direction30 and can result in tooth fractures (30).

Additionally, studies on the difference in the percentage of unprepared volume with different apical magnification powers showed conventional irrigation becomes more significant at larger magnification (31). The findings herein show a percentage volume not prepared after the use of TDK similar to those findings obtained after the preparation of root canals with larger apical diameters (32), which may be explained by the expansion and cutting capacities of TDK.

This study suggest root canal debridement might be possible to perform with smaller apical sizes under specific anatomical conditions, instrumentation, and activation of the irrigating solution. This challenges the paradigm of needing to remove dentine for canal cleaning (11), necessitating randomized clinical studies for confirmation.

This laboratory-based study is limited to oval-shaped canals with relatively straight roots. Micro-CT was chosen for analyzing irrigation efficacy because it provides detailed, nondestructive 3D imaging that allows for precise visualization and measurement of the root canal's internal structure (12, 33). It can reveal intricate details of canal morphology, including its complexity and any remaining debris or dentine after irrigation, offering a comprehensive assessment of irrigation effectiveness (14, 17, 21, 23, 33, 34). However, other methods could provide complementary perspectives. Future studies should explore additional analytical approaches and investigate different tooth types, such as those with curved roots and isthmuses. Additionally, while the sample size was statistically justified, it was limited to a controlled laboratory setting and may not capture the full variability seen in clinical cases. The *ex vivo* nature of the study also excludes the influence of dynamic biological factors, such as blood flow, tissue healing, and patient variability, which could affect the outcomes of root canal procedures.

While *in vitro* studies are valuable in the absence of randomized clinical trials, caution is advised when applying these findings clinically. Further research is required to validate these results under *in vivo* conditions and across a broader range of clinical scenarios.

CONCLUSION

Based on the findings and methodology, supplementary instruments are more effective in debriding root canal than conventional irrigation, particularly in smaller apical sizes of oval-shaped canals of lower incisors. TDK allowed greater dentine removal and less volume untouched compared to conventional irrigation, becoming an alternative for enhancing debridement in these canals.

Disclosures

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