Zhao et al. BMC Oral Health (2025) 25:319
https://doi.org/10.1186/s12903-025-05696-x

BMC Oral Health

RESEARCH

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Evaluation of two instrumentation techniques and obturation methods in mandibular first premolar C-shaped canals by Micro-CT

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Abstract

Objectives To investigate the effectiveness of instrumentation using Protaper Next (PN; Dentsply Sirona, Maillefer, Ballaigues, Switzerland) and Waveone Gold (WG; Dentsply Sirona, Maillefer, Ballaigues, Switzerland) systems on the area of untouched surface (US), accumulated hard tissue debris (AHTD), and the filling ability of two obturation techniques on the volume percentage (vol%) of voids within C-shaped root canals of mandibular first premolars.

Methods A total of 64 mandibular first premolars with C-shaped canals were scanned, matched, and subsequently assigned to two shaping groups ($n = 32$): PN and WG. After instrumentation, the specimens were randomly allocated into two obturation subgroups ($n = 16$): continuous wave compaction (CWC) and single-cone (SC) techniques. The US% and AHTD% post- instrumentation, as well as the vol% of voids after obturation, were calculated from micro-computed tomography. Data were analyzed using comparisons for two groups (PN vs. WG) or two subgroups (CWC vs. SC) at $\alpha = 0.05$.

Results The untouched canal wall area was 18.75% and 22.69% in the PN and WG groups ($p > 0.05$), respectively. The apical third had higher US% than the coronal third ($p < 0.05$) in the two shaping groups. Instrumentation with WG left more debris (26.48%) than PN (8.36%) in the apical 1–3 mm ($p < 0.05$). In PN and WG group, the vol% of voids had no significant difference between the CWC and SC subgroups ($p > 0.05$). The apical region had significantly more voids than the coronal region of canal space in the two obturation subgroups regardless of which system was applied ($p < 0.05$).

Conclusions Both PN and WG systems showed similar performance on US after instrumenting C-shaped canals of the mandibular first premolar. WG left significantly more AHTD compared with PN in the apical region. In PN or WG

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group, SC yielded similar obturation quality when compared with CWC. Both CWC and SC obturation techniques provided inferior filling quality in the apical region than that observed in the coronal region.

Keywords C-shaped Canal, Instrumentation, Obturation, Mandibular first premolar, micro-CT

Introduction

The C-shaped root canal system is a complex anatomical variation of mandibular first premolars [1, 2], with an incidence ranging from 12.5 to 67.47% in Chinese population [3, 4]. The mandibular first premolars with this special morphology characterized by a deep and narrow radicular groove [5]. The buccal and lingual canals are fully or partially connected via an isthmus, forming a C-shaped or semicolon-like configuration in cross-section. This feature is predominantly observed in the middle and apical segments of the root canal, often accompanied by varying degrees of curvature [4]. The anatomical complex configuration, along with apical variation (e.g. accessory canals, lateral canals, intercanal communications, and apical deltas) significantly complicates the debridement of the C-shaped canal system rather difficult to accomplish. Furthermore, in infected C-shaped canals, hard tissue debris as the by-product during instrumentation tends to accumulate in the irregular areas, potentially harboring bacteria and impeding effective disinfection and obturation by compromising the irrigating efficacy [6, 7].

It has been demonstrated that micro–computed tomography (micro-CT) serve as a valuable tool for evaluating the morphologic changes of root canal before and after instrumentation. The method allows the assessment of the three-dimensional configuration of the original root canal, instrumentation, and filling procedures, without handling of the specimens [8–11].

There exists a diverse array of nickel-titanium (NiTi) machine files on the market, each employing different mechanisms such as rotation, reciprocating, central motion or eccentric motion [12]. Protaper Next (PN; Dentsply Sirona, Maillefer, Ballaigues, Switzerland) features a distinctive eccentric rectangular design along with a progressive and decreasing percentage taper. This design facilitates optimal debris removal from the root canal [13]. The offset mass during rotation is particularly advantageous for preparing irregular canals. Numerous studies have found that Protaper Next exhibits superior shaping and centering capabilities [14, 15]. Furthermore, the Protaper Next system shows comparable shaping ability in long-oval canals when compared to XP-endo Shaper system (FKG Dentaire, La Chaux-de-Fonds, Switzerland) [16].

Waveone Gold (WG; Dentsply Sirona, Maillefer, Ballaigues, Switzerland) systems have been introduced that utilize the same reciprocating motion as Waveone (WO; Dentsply Sirona, Maillefer, Ballaigues, Switzerland). WG files feature an off-center, parallelogram design. The cross sections of these parallelogram-shaped are spatially ordered in a discontinuous manner, which allows variation of the instrument's contact [17]. WG files are produced using advanced heat treatment technology [18, 19]. The manufacturer claims that this innovative heat treatment method enhances the flexibility of WG files.

Based on the complexity and variability of C-shaped canal anatomy in mandibular first premolars, thoroughly removal of microorganisms is not always achievable. The surviving microorganisms must be sealed within root canal filling material to block microorganisms and toxins from the oral cavity into the root canal system [20]. Three-dimensional filling of the prepared canal is of critical importance for the success of root canal therapy. There are several techniques available for obturating root canals, including the lateral compaction, thermo-plasticized gutta-percha obturation, continuous wave obturation, core-carrier technique, single cone technique, among others. Despite numerous accessory gutta-percha cones being inserted in C-shaped canals, radiographic assessments often reveal a less dense appearance compared to normal root canals. Previous studies have indicated that the quality of filling using lateral compaction in oval canals [21] was less reliable. The MicroSeal system represents a thermomechanical filling technique that employs lateral compaction combined with α-gutta-percha placement to backfill the canal. Ordinola-Zapata et al. found that this technique was unable to achieve complete sealing of C-shaped canals, especially in the apical third [22]. Although earlier studies have suggested that thermo-plasticized gutta-percha was more suitable for filling abnormal canal [23], in the work of Soo et al., this technique to fill C-shaped canal resulted in poor apical sealing but excellent adaptation in the coronal two-thirds of the canal [24]. With regard to the filling efficacy of core-carrier technique in obturating C-shaped canals, data published in the literature are contradictory. While some studies have indicated that core-carrier technique was superior, as assessed by gutta-percha area, when compared to lateral compaction and thermo-plasticized gutta-percha obturation in simulated C-shaped canal [24], the conclusion is not corroborated by two more recent investigations using a similar experimental design [25, 26].

The continuous wave compaction and single-cone technique are commonly used in clinical practice. The thermal gutta-percha softened in vertical compression is considered beneficial for filling complex root canals

[27]. The single-cone technique has gained popularity with the advent of bioceramic sealer. iRoot SP (Innovative BioCeramix Inc., Vancouver, Canada) is a premixed bioceramic endodontic sealer which contains zirconium oxide, tricalcium silicate, dicalcium silicate, colloidal silica, calcium silicates, calcium phosphate monobasic, and calcium hydroxide, filler and thickener [28]. As an endodontic sealer, iRoot SP possesses many desirable properties, including biocompatibility, chemical stability, hydrophilicity, flowability, radiopacity, and slight expansive tendencies [29–32]. These characteristics of iRoot SP have been anticipated to enhance the effectiveness of root canal obturation and may allow for an enhanced seal within otherwise inaccessible canal anatomies.

Recent research found that the SC technique was effective in filling mandibular molar canals, resulting in fewer voids [33, 34]. A retrospective survey further suggested that the SC technique combined with bioceramic sealer achieved a success rate of 90.9% in initial treatment and retreatment [35]. Nevertheless, there remains a lack of comprehensive knowledge on the shaping outcomes of the two aforementioned off-center design nickel-titanium systems and the sealing quality of continuous wave compaction and single cone techniques within complex canal systems- such as those found in C-shaped canals of mandibular first premolars.

Accordingly, the present study was designed to quantitatively evaluate the shaping properties of PN and WG instruments and the sealing ability using two obturation approaches in mandibular first premolars C-shaped canal. The null hypotheses tested were: (1) that the PN system and the WG system yield similar morphological features after instrumentation of C-shaped canals; and (2) that there is no significant difference between the two obturation techniques regarding the volume percentage of voids.

Materials and methods

Sample size estimation

An a priori Wilcoxon signed-rank test (matched pairs) was selected from the t-tests family using G*Power 3.1.7 software for Windows (Heinrich Heine Universität, Düsseldorf, Germany). The effect size for this study was established (= 0.5). An alpha-type error of 0.05 and power beta of 0.95 were also specified. A total of 64 samples were indicated as the ideal size required for observing significant differences.

Specimen selection

The protocol of the current study was approved by the Ethics Committee of School and Stomatology Wenzhou Medical University (WYKQ2021007).

The selected human mandibular first premolars with C-shaped canal had mature apices, no fractures or cracks, no caries or calcification, and no signs of endodontically treatment. The specimens were scanned using a high-resolution micro-computed tomographic system (SkyScan 1176; Bruker-micro-CT, Kontich, Belgium) with an isotropic resolution of 17.54 μm at 90 kV, 270 μA, 0.1 mm Cu filter, and 360° rotation with a rotation step of 0.5°. The acquired projection images were reconstructed into cross-sectional slices with NRecon (v 1.6.10.4; Bruker micro-CT, Kontich, Belgium) using standardized parameters for beam hardening correction of 30%, ring artifact correction of 7, and a smoothing of 2. The two-dimensional images were saved in Tagged Image File format (.tiff). The volume of interest was selected extending from the above CEJ (Cemento-enamel junction) level to the apex of the root, resulting in the acquisition of 700 to 900 transverse cross sections per tooth. After 3D reconstruction from the scanned data using CTAn software (v 1.20.3.0; Bruker-micro-CT, Kontich, Belgium), a total of 64 mandibular first premolars, each with a C-shaped canal system according to previously reported definition [36], were selected and paired into 2 groups ($n = 32$); each pair was matched with respect to 3D configuration, and the initial volume and surface area of the root canals. One tooth from each pair was randomly allocated to one of the 2 experimental groups, whereas the other tooth was assigned to the other group. A coin toss was used to determine which group would receive treatment with either Protaper Next rotary files or Waveone Gold reciprocating files.

Canal instrumentation

Access cavity preparation was performed using a high-speed diamond bur. Apical patency was established by passively inserting a size 10 K-file (Dentsply Sirona, Maillefer, Ballaigues, Switzerland) until the tip was visible at the apical foramen. The working length (WL) was 1 mm shorter than the measurement. Glide path preparation was performed in both groups to WL with a size 15 K-file. Two coats of nail polish were applied to seal the apex [37]. Subsequent instrumentation was performed by a single operator with experience of PN and WG systems. A set of the files (PN and WG) was discarded after instrumenting one specimen (containing 2 to 3 canals).

Protaper next (PN) group The X1 (size 17/0.04 taper) and X2 (size 25/0.06 taper) files were serially powered by the motor X-smart plus (Dentsply Sirona, Maillefer, Ballaigues, Switzerland) with parameters set at 300 rpm and torque 2.5 N /cm^2. The instruments were used in a slow in-and-out motion of approximately 3 mm in amplitude in the apical direction, using a gentle brushing motion against the canal wall. The procedure was repeated twice until the WL was reached.

Waveone gold (WG) group Small (size 20/0.07 taper) and Primary (size 25/0.07 taper) files were utilized in the canals with an in-and-out motion by the reciprocating "Waveone ALL" setup of the same motor. Following 3 movements with a maximum amplitude of 3 mm in the apical direction, using a gentle brushing motion against the canal wall, the instruments were removed and cleaned with gauze. The WL was reached after 3 cycles of instrumentation used in the same manner.

The same irrigation protocol was employed during instrumentation for both groups. For all specimens, a total of 5 mL of 1% NaOCl solution was used for glide path preparation and 15 mL for shaping within each canal. During the shaping process, each root canal was irrigated with 2.5 mL 1% NaOCl solution after the instrument was removed from the canal and cleaned. Once instrumentation was completed, final irrigation was performed with 5 mL 17% EDTA to remove the smear layer. The EDTA was subsequently removed with 1 mL of deionized water. Then the canals were dried with size 25/0.06 taper paper points (Dentsply Sirona, Maillefer, Ballaigues, Switzerland). The access cavities were sealed with Cavition (GC Corporation, Tokyo, Japan). The irrigant was delivered with a 30-gauge needle attached to a disposable syringe. The needle tip was positioned as close as possible to the apex of the root canal without binding and up to 1 mm short of WL. The flow rate for delivering the irrigant was 5 mL per minute.

Micro-CT analysis

All postoperative specimens were scanned with the preoperative parameter settings. The scanning data sets after preparation were rendered and co-registered with their respective preoperative data sets using the Data Viewer (v 1.5.6.2; Bruker-micro-CT, Kontich, Belgium).

The canals were segmented in the CTAn software (v 1.20.3.0; Bruker-micro-CT, Kontich, Belgium) using the 2-dimensional Otsu method [38]. Morphologic parameters of the pre- and post-instrumentation root canal system (volume and surface area) were calculated. Information including increasement of root canal surface area (mm^2) and volume (mm^3), accumulated hard tissue debris (AHTD, in mm^3), area of untouched surface (US, in mm^2) and the volume of voids (vV, in mm^3) was evaluated and analyzed by CTAn, and 3D models were exported in STL format by the same software. The minimum mesial wall thickness (MT, in mm) was measured according to the method described in a previous study [39]. A radiopaque shadow with a density similar to dentin appeared in the radiolucent pre-operative canal images, and the percentage of this radiopaque shadow with respect to the volume of the root canal before preparation was defined as AHTD [37, 40, 41]. Those surface voxels remaining in the same position preoperatively and postoperatively represented the untreated surface (US) of the canal wall. This parameter was expressed as a percentage of the static voxels to the total surface voxels [42, 43]. All analyses about US and AHTD were conducted separately for the cervical (6–9 mm), middle (3–6 mm), and apical (1–3 mm) thirds of the canal. The percentage of MT thinning was calculated according to the formula: $(MT_B\text{-}MT_A)/MT_B \times 100\%$, where MT_B and MT_A are the thickness of minimum mesial wall before and after instrumentation, respectively.

Canal obturation

The specimens, after instrumentation, were pair-matched within each group with respect to the 3D morphology of root canal. One tooth from each pair was randomly assigned to one of the two subgroups ($n = 16$) according to the obturation technique employed:

1. **Continuous wave compaction subgroup (CWC)**: Each canal was filled with a gutta-percha cone (25/0.06) (Dentsply DeTrey GmbH, Konstanz, Germany) and AH plus sealer (Dentsply DeTrey GmbH, Konstanz, Germany). An EQ-V Pack Tip (Meta Biomed Co, Cheongju-si, Chungbuk, Korea) was used to remove excess cone material in the upper segment, leaving only 4–6 mm within the WL, and an EQ-V thermal gun (Meta Biomed Co, Cheongju-si, Chungbuk, Korea) was used to backfill.
2. **Single-cone subgroup (SC)**: Each canal was filled with a gutta-percha cone (25/0.06) and iRoot SP sealer (Innovative BioCeramix Inc, Vancouver, Canada). The upper segment was removed with the EQ-V heat source, and 1 mm lower the canal orifice level was retained.

Each specimen was subjected to a post-obturation scan, and the scanned data were used for reconstruction following the aforementioned parameters. The volume percentage of voids (vol%) was calculated according to the formula: V_v $/(V_v+V_F) \times 100\%$, where V_v represents the volume of the voids after obturation and V_F denotes the volume of the filling material, respectively. The vol% of voids in the entire canal and its different regions (i.e. coronal-third, middle-third, and apical-third) were recorded.

Statistical analyses

The normality of all data was tested using the Shapiro-Wilk test. Analyses were conducted on the changes in surface area and volume, AHTD, US, MT and vol% of voids. Even after applying multiple nonlinear transformations, the data failed to meet the normality assumption. Therefore, the statistical analyses were performed using the Wilcoxon signed-rank test. Each dataset was expressed as a median and confidence interval (CI).

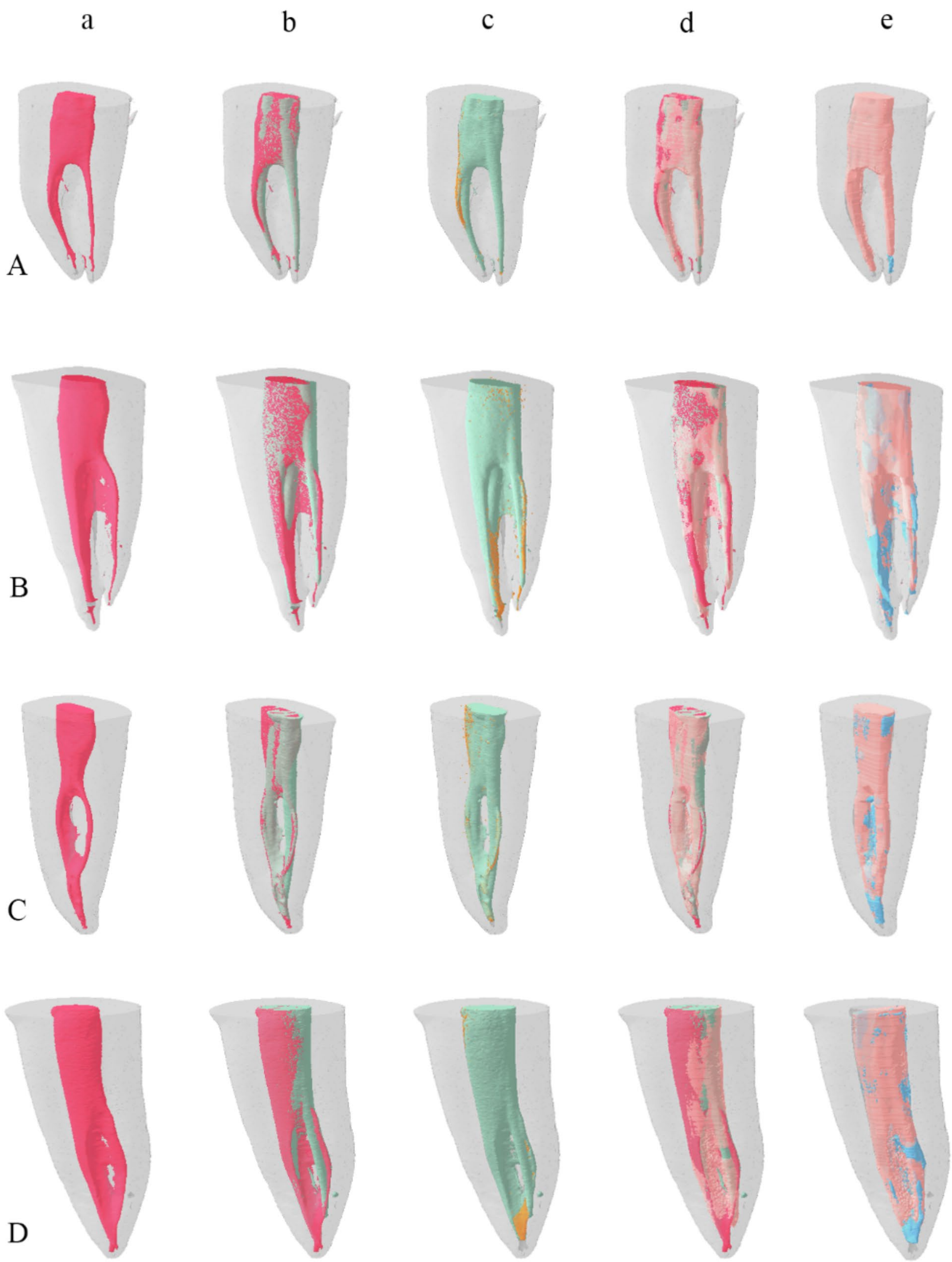

Fig. 1 (See legend on next page.)

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Fig. 1 Representative examples of micro-CT reconstructions illustrating the changes in C-shaped canals of mandibular first premolars after instrumentation and after obturation. **(a)** Pre-instrumentation reconstructions. **(b)** Superimpositions of pre-instrumentation (red) and post-instrumentation (green) reconstructions. Red regions were untouched by instruments. **(c)** Volume of accumulated hard tissue debris (AHTD) after instrumentation (orange). **(d)** Superimpositions of post-obturation (pink) in C-shaped canal systems. **(e)** Volume of void after obturation (blue). **Row A**: canal shaped by the PN system and obturated by CWC. **Row B**: canal shaped by the PN system and obturated by SP. **Row C**: canal shaped by the WG system and obturated by CWC. **Row D**: canal shaped by the WG system and obturated by SP)

Intergroups comparison was performed using Kruskal-Wallis analysis. ALL statistical analyses were performed using IBM SPSS v23.0 (SPSS Inc., Chicago, IL, USA). The significance level was pre-set at $\alpha = 0.05$.

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Results

Reconstructed 3D images of C-shaped canals of mandibular first premolars, after instrumentation with the PN or WG system and subsequent obturation with CWC and SP, are shown in Fig. 1. Representative cross sections of hard tissue debris accumulation in post-instrumented C-shaped canals (the coronal-third, middle-third, and apical-third regions) are illustrated in Fig. 2.

The median initial surface areas (mm^2) and volumes (mm^3) for the two groups were as follows: PN group had 88.68 mm^2 and 18.14 mm^3, while WG group exhibited 88.57 mm^2 and 18.73 mm^3, respectively. There was no significant difference between the two groups before instrumentation ($p > 0.05$). After instrumentation, the difference on the increasement of surface areas and volumes was not significant between the two groups ($p > 0.05$) (Table 1).

The percentage of US of the entire canal was 18.75% in the PN group and 22.69% in the WG group, respectively (as shown in Table 2). No significant difference was observed in the percentage area of US between the two groups ($p > 0.05$). The distributions of US from different regions within the canal space are collectively represented in Table 2. In the PN group, the apical region (1–3 mm) had significantly higher US% when compared to coronal region (6–9 mm) ($p < 0.05$); however, no significant differences were found between the apical and middle regions or between the middle and coronal regions of the canal wall. For the WG group, a significantly higher US% was noted in the apical region compared to the middle region, which had a significantly higher US% than the coronal region ($p < 0.05$). Canal perforation was not observed in any specimens.

Instrumentation of the C-shaped canals in mandibular first premolars using WG left 2.15% of the initial canal volume filled by dentin debris. In contrast, only 1.39% of the original canal volume was filled by debris in the PN group; the differences between the two groups were not statistically significant in the entire canal ($p > 0.05$). For comparisons of different regions of the canal space, significant differences between the PN and WG groups could only be identified in the apical region of the canal space ($p < 0.05$). For canals instrumented with the two systems, the coronal region of the canal space had significantly less debris than the middle region, which, in turn, had significantly less debris than the apical region ($p < 0.05$ for all pairwise comparisons) (Table 2).

After instrumentation, the MT was less than 0.5 mm in 65.63% of the samples (42 out of 64), with a minimum value of 0.14 mm. The MT in the cross-section containing the C-shaped canal exhibited varying degrees of thinning, with the most significant reduction at M-1 and M levels (as detailed in Table 3). No significant differences were identified on the percentage of MT thinning between the PN and WG groups.

The vol% of voids after obturation in two instrumentation groups is collectively presented in Table 4. Irrespective of the type of file system utilized for canal shaping, the two obturation protocols both produced voids in C-shaped canals. In PN and WG group, there was no significant difference in the vol% of voids between the CWC and SC subgroups ($p > 0.05$). The findings regarding comparisons of different regions of the canal space in two instrumentation groups were similar. The apical region had significantly more voids than the coronal region of the canal space ($p < 0.05$); there was no significant difference between the middle and apical region, as well as between the coronal and middle region ($p > 0.05$).

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Discussion

Difficulties in evaluating instrumentation and obturation arise from the morphological irregularities of C-shaped canal. In this study, the selected 64 mandibular first premolars were pre-screened using micro-CT prior to preparation. Based on root canal volume, surface area, and 3D anatomy of C-shaped canals, the specimens were paired and randomly allocated into two groups: PN and WG instrumentation. This approach ensured a uniform distribution of samples across the two groups, while minimizing potential bias associated with anatomical structures. There was no significant difference in the canal volume and surface area before and after preparation in the two instrumentation groups ($p > 0.05$). After the preparation, the teeth were divided into two obturation subgroups ($n = 16$) in each experimental group. Statistical analysis confirmed the homogeneity of baseline parameters between the groups, thereby enhancing the

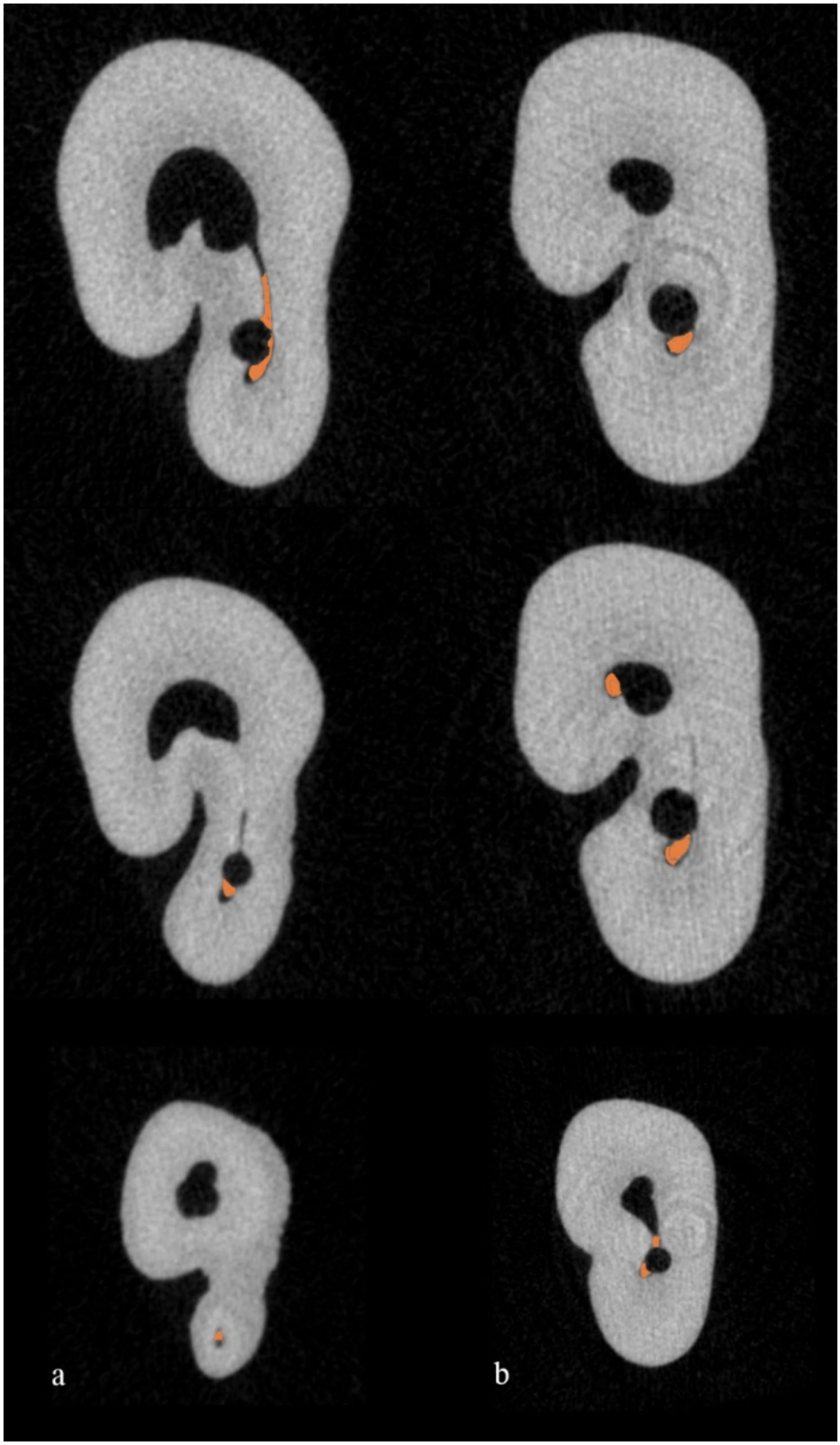

Fig. 2 Representative cross sections of hard tissue debris accumulation (orange) in post-instrumented C-shaped canals of mandibular first premolars. **(a)** Canal shaped by the PN system. **(b)** Canal shaped by the WG system. Top row: sections derived from the coronal-third region of the canal space. Middle row: sections derived from the middle-third region of the canal space. Bottom row: sections derived from the apical-third region of the canal space

Table 1 Canal volume (mm^3) and surface area (mm^2) before and after instrumentation using protaper next (PN) and Waveone gold (WG) systems as well as the increased percentages (%) (median and confidence interval)

	PN	WG
Canal Volume		
Before (mm^3)	18.14 (15.50-20.82)	18.73 (14.67–20.45)
After (mm^3)	20.76 (19.52–24.91)	22.56 (18.63–22.95)
Increasement of Canal Volume (%)	10.10 (2.64–20.78)	13.65 (3.24–21.15)
Canal Surface Area		
Before (mm^2)	88.68 (78.27–93.38)	88.57 (77.81–99.88)
After (mm^2)	96.42 (90.03-107.62)	94.77 (84.84-106.85)
Increasement of Canal Surface Area (%)	10.33 (6.05-14.00)	9.55 (4.13–12.33)

There were no significant differences in any of the parameters between the Protaper Next and Waveone Gold groups ($p > 0.05$)

Table 2 US (%) and AHTD (vol%) after instrumentation using protaper next (PN) and Waveone gold (WG) systems in mandibular first premolars with C-shaped root canals (median and confidence interval)

	US(%)		AHTD(%)	
	PN	WG	PN	WG
Entire canal	18.75 (13.09–23.96)	22.69 (14.01–28.41)	1.39 (0.99–2.16)	2.15 (1.35–2.79)
Apical region (1–3 mm)	35.25 (24.22–51.76) ^{A}	64.34 (39.84–74.78) ^{A}	8.36 (5.25–15.63) ^{A*}	26.48 (13.15–47.42) ^{A*}
Middle region (3–6 mm)	24.97 (19.53–37.25) ^{AB}	33.63 (20.25–42.95) ^{B}	4.83 (3.36–8.46) ^{B}	5.74 (3.23–9.72) ^{B}
Coronal region (6–9 mm)	16.15 (11.45–24.47) ^{B}	15.21 (6.96-22.00) ^{C}	1.64 (1.27–2.71) ^{C}	1.26 (0.72–3.41) ^{C}

Asterisk (*) indicates significant difference between different instruments ($p < 0.05$)

Different uppercase superscripts in a single column represent significant differences among the different regions ($p < 0.05$)

Table 3 Minimum mesial wall thickness (MT) before and after Preparation and the percentage of MT thinning after instrumentation using protaper next (PN) and Waveone gold (WG) systems in mandibular first premolars with C-shaped root canals (median and confidence interval)

Group/level	*n*	Before (mm)	After (mm)	Thinning (%)
PN				
M + 1	19	0.86(0.62–1.13)	0.81(0.48–1.05)	12.0(9.5–15.8)
M	23	0.68(0.60–0.88)	0.52(0.42–0.87)	22.6(10.7–33.7)
M-1	29	0.68(0.60–0.78)	0.51(0.39–0.69)	21.0(7.2–35.2)
AM	18	0.61(0.56–0.72)	0.52(0.45–0.57)	16.2(6.5–23.4)
WG				
M + 1	17	0.86(0.72–1.03)	0.73(0.51–0.96)	12.3(5.0-24.1)
M	22	0.71(0.62–0.86)	0.60(0.48–0.65)	15.2(5.9–23.1)
M-1	23	0.61(0.59–0.71)	0.49(0.42–0.58)	19.3(6.3–30.6)
AM	18	0.61(0.54–0.71)	0.50(0.48–0.64)	6.6(4.9–13.0)

There was no significant difference on the degree of MT thinning in M + 1, M, M-1, AM levels after preparation between PN and WG ($p > 0.05$)

M + 1, 1 mm above the middle of the root; M, the middle of the root; M-1, 1 mm below the middle of the root; AM, the junction of apical third and middle third of root

internal validity of this study [44, 45]. Some previous studies on mandibular molars with C-shaped canals have used simulated resin 3D-printed replicas [46–48], which minimized the anatomic variability and its impact on the shaping effects of different tested files. Nevertheless, one limitation of studies using 3D-printed replicas is that the difference in hardness between dentin and resin replicas may affect the evaluation outcomes regarding the shaping ability of endodontic instruments. Additionally, the variations in the physicochemical properties of resin replicas render the assessment about remained debris unattainable.

The present study found no significant difference in the increase of canal surface area and volume between the two experimental groups. The X2 file in the PN system created a 0.06 taper in the apical 3 mm with an ISO #25 diameter, whereas the Primary file in the WG system produced a larger taper of 0.07 and an equal diameter of 0.25 mm during canal instrumentation. The minor difference in taper design is not enough to result in any significant variations observed in canal volume and surface area within the present study.

Previous studies on mandibular second molars have suggested that the wall of the C-shaped root canal is thinner on the side adjacent to the radicular groove than other sides [49–51]. Cheung & Cheung [52] reported that after instrumentation to size 30/06, the shortest average thickness of dentine in C-shaped canal molars at different root levels (0.71–0.96 mm) consistently originated from the mesio-lingual canals. Gu et al. [53] measured the canal wall thickness at various levels in C-shaped root canals of mandibular first premolars and confirmed that these findings were also applicable in mandibular first premolar teeth.

Table 4 Volume percentage (vol%) of voids after obturation using continuous wave compaction (CWC) and single cone (SC) techniques in mandibular first premolars with C-shaped root canals (median and confidence interval)

	PN		WG	
	CWC (%)	**SC (%)**	**CWC (%)**	**SC (%)**
Entire canal	5.37 (3.00-8.13)	5.46 (2.29–12.77)	4.44 (1.85–14.62)	6.57 (2.25–13.25)
Apical region (1–3 mm)	18.65 (3.73–32.55) [A]	26.38 (3.25–30.26) [A]	12.11 (5.58–28.83) [A]	27.73 (10.46-62.00) [A]
Middle region (3–6 mm)	7.15 (0.62–12.37) [AB]	5.56 (2.15–28.04) [AB]	3.63 (1.35–16.99) [AB]	10.95 (3.38–18.59) [AB]
Coronal region (6–9 mm)	2.46 (0.81–3.76) [B]	1.75 (0.75–5.92) [B]	4.64 (0.98–9.19) [B]	4.26 (1.86–8.66) [B]

No significant difference between the two filling methods when the same shaping instruments were applied ($p > 0.05$)

Different uppercase superscripts in a single column represent significant differences among the various regions ($p < 0.05$)

The canal in mandibular first premolar characteristically bifurcates in the apical and middle regions to form C-shaped root canal structures [4]. The irregular morphology of C-shaped root canals increases the likelihood of stripping perforation during endodontic preparation [36, 54]. Our previous study revealed that the further the distance from the cemento-enamel junction, the deeper root radicular groove, the smaller the radicular groove angle, and the thinner the mesial wall. Consequently, mechanical preparation of the root canal -particularly for the lingual root canal and its lower segment- should be conducted with utmost care to avoid unexpected deviations and perforations.

There is currently no universal consensus on critical dentine thickness, below which break down of the canal wall is likely to occur. It is generally recommended to maintain 0.2–0.3 mm thickness dentin to resist fracture due to pressure during the placement and compaction of root fillings [55]. A previous study found that the minimum dentine thickness from the instrumented canal with Waveone Gold Primary file to the lingual groove ranged from 0.27 mm to 0.41 mm in 12 mandibular second molars with 3 types C-shaped canal. This finding aligns with our results [56]. In this study, following treatment with two systems, the remaining MT was less than 0.5 mm in 65.63% of the samples examined.

The results supported the above-mentioned statements. Although C-shaped morphology may occur at various levels along the root canal of mandibular first premolars, the distribution of sample size at each level is uneven. The present study further demonstrated that C-shaped morphology was more prevalent in the middle regions of the canal. In light of this observation, a comparison was made regarding the degree of MT thinning between the two groups at the M + 1, M, M-1, and AM levels.

There was no significant difference between the two files on the degree of MT thinning, which may be attributed to the similar cross-sectional design of the two instruments. It has been recommended that the isthmus of C-shaped canals should not be instrumented by files larger than ISO #25 to avoid perforating the canals [57]. In the present study, no perforation was observed using either X2 or Primary file in two experimental groups. However, it is noteworthy that the extreme value of MT after instrumentation was 0.14 mm, indicating a considerable risk of perforation during canal cleaning.

The two experimental groups left a similar percentage of untouched surface area in the C-shaped canals of mandibular first premolars. In the PN and WG group, the untouched surface areas were 18.75% and 22.69%, respectively. The results are less than those reported in previous studies about the instrumentation of C-shaped canals in mandibular molars using different NiTi systems [38, 58–60]. Although the two tooth types both exhibit C-shaped canal systems, the quantitative divergence between the previously reported data and the present findings may be attributed to the difference in root canal volume of different tooth types. The C-shaped canal in mandibular first premolar is relatively narrower and smaller; consequently, a larger proportion of canal wall is treated by the instruments during the shaping process.

Despite the innovations in designs, metallurgies, kinematics and thermal treatments, neither of the two NiTi systems were capable of fully touching the root canal walls. There were no significant differences between the mechanized preparation systems regarding the percentages of US. One disadvantage of continuous rotary motion instruments when employed in complex anatomies is that they tend to centralize preparation, leaving more unprepared root canal walls. The improvements in instrument designs of PTN created files that rotate eccentrically or asymmetrically inside the root canal. The movement of these files contacts more surfaces in non-circular canals [48]. Several previous studies reported that the untreated surface varied from 19.9 to 41.5% in curved mesial root canals of mandibular molars, 55.3% in distal root canals of mandibular molars, and 65.1% in C1 type canals of plastic model of mandibular molar after using Protaper Next [47, 61–63]. The difference in the percentage of untreated areas in various canals is mainly attributed to the anatomical variations. A previous study has reported the results of shaping various types of C-shaped canal systems in mandibular second molars using Waveone Gold. The percentages of canal wall surface area touched in Type I, II, and III C-shaped canals were 10%, 32%, and 36%, respectively [56]. Furthermore, two recent studies on Waveone Gold shaping in oval-shaped canals indicated that the percentages of unprepared area ranged from 18.9 to 50.9% [63, 64]. Although it has been reported that larger taper files can touch more canal wall [65], the statement was not confirmed in the present study.

The percentage of US in the apical regions of the canal space was 35.25% in PN group and 64.34% in WG group, respectively. The percentages of US in apical region were larger than those in coronal region for both groups. The similar results regarding the instrumentation of C-shaped canal in mandibular molars have been reported by Zhao et al. [38]. High percentages of US in the apical regions may be attributed to the complexity of apical anatomy of C-shaped canals, which complicates the debridement of the apical region [52, 66, 67]. These findings further reinforce the viewpoint that irrigation and intracanal medicament play a crucial role in chemo-mechanical preparation to compensate for the deficiencies of mechanical debridement [65, 68].

Hard tissue debris, an undesirable by-product of dentin removal during mechanical preparation [69], is often packed into the irregular regions of the root canal system. Many studies have confirmed that the debris can interfere with irrigation, medication [70], and obturation [71], thereby diminishing the success rate of root canal treatment. Paqué et al. [70] established a method to qualitatively and quantitatively analyze the remained dentine debris in the root canal system during instrumentation.

In the present study, no significant difference on AHTD was observed in the total canal using two file systems. However, the PN system produced a comparatively lower percentage of AHTD in the apical regions of the canal space when compared to the WG system. The result may be explained by the differences in movement kinematics and taper designs of the respective file systems.

Some studies have suggested that the kinematics of a NiTi file system may significantly impact the efficacy of debris removal [38, 41, 72]. Zhao et al.. found that rotary systems produced less debris than reciprocating systems in the C-shaped canals of mandibular molars [38]. The continuous forward motion of the rotary file facilitates a constant exit of debris up the flute of the file, while reciprocating motion may push debris into recesses and isthmus areas [73]. The PN rotary file features an off-centered rectangular cross-section with progressive and decreasing taper design, superior strength and novel asymmetric rotational motion [74, 75] for maximum debris removal [13]. These design features of PN files provide a wider chip space and a smaller tip taper (X1: size 17/0.04 taper and X2: size 25/0.06 taper), and when accompanied by rotary movement, improve debris removal from the canal system. In the present study, the amount of debris remaining in C-shaped canals of mandibular premolars shaped by the WG system was found to be less than that reported in previous studies [41, 72]. The primary causes contributing to this difference may include variations in canal morphology and differences in irrigation protocols.

The AHTD vol% was highest in apical region and lowest in coronal region in the two groups. The findings of the present study are consistent with those reported by Zhao et al. [38] who compared reciprocating versus rotary techniques used in C-shaped canal of mandibular molars instrumentation. The anatomical variations and limited space in the apical regions of C-shaped canals may diminish the efficacy of instrumentation and irrigation, thereby contributing to the aforementioned results.

According to the previous findings and the results presented in this study, no instrumentation protocol has successfully achieved debris-free conditions in the complex regions of C-shaped canals [38, 72, 73]. Therefore, a three-dimensional sealing of root canal system is of critical importance for successful endodontic treatment.

Several methodologies are applied to evaluate the quality of root canal filling, including: two-dimensional radiographs [76], dye or alternative tracer leakage models [7], stereomicroscopic evaluation of root cross-Sects. [21, 25], and micro-CT scanning [77, 78]. The dye penetration dose not adequately replicate true clinical conditions. The air entrapment in voids along the root canal filling can hinder fluid dye infiltration [79]. The loss of material during sectioning and discontinuous cross sections may affect the accurate evaluation on the percentage of voids [11]. Reconstructing 3D model by micro-CT scanning and imaging allows accurate assessment of canal filling outcomes. Micro-CT possesses the potential to differentiate filling materials, voids, and tooth structures [80]. The methodology provides clear information about the distribution of the root filling materials, as well as the location and volume measurements of internal voids along the entire root canal system.

The majority of published studies on the filling quality of C-shaped canals have primarily focused on mandibular molars. Due to the diversity in research methodologies, sample selection, and filling techniques, findings on the effectiveness of C-shaped root canal filling are not entirely consistent. Previous studies have demonstrated that the filling quality of C-shaped canals is often unsatisfactory when employing techniques such as cold lateral compaction, the MicroSeal system, thermo-plasticized gutta-percha obturation, and core-carrier technique. Given the significant callenges associated with sample collection, the present study only evaluated the quality of obturation by calculating the volume percentage of voids after the application of SC and CWC in C-shaped canals of mandibular first premolars.

The present results showed that more voids were observed in the apical 1–3 mm regions across all subgroups. The present and previous studies have consistently indicated that the apical third of C-shaped canals is less completely filled when using techniques such as cold lateral compaction, MicroSeal, core carrier, continuous wave compaction (CWC), and single cne (SC) technique [22, 24, 25]. The poor filling quality in the apical region may be attributed to the irregular anatomy of C-shaped canal. The divergent areas in the apical region of C-shaped canals are commonly unshaped, which hinders the flow of obturating materials-such as gutta-perch and sealer- into these abnormalities. Although softened warm gutta-percha has excellent adaptation in the coronal two-thirds of the canal, insufficient extension remains a main factor contributing to unsatisfactory apical filling [81]. Moreover, the dentine plug in the canals also serves as a barrier to achieving the high-quality apical obturation [82].

The CW technique may provide superior filling in canal irregularities and lateral canals [23], especially within the coronal regions [34]. The findings align closely with those of the present study. The results may be attributed to the fact that heated gutta-percha conforms more readily to the irregularities of the root canal during the backfilling procedure [83]. Moreover, since coronal gutta-percha is subjected to forces more directly, this enhances the adaptation of filling material in this region.

iRoot SP exhibits superior flowability and the capacity for slight expansion during setting [84]. As a bioceramic material, the sealer is capable of producing hydroxyapatite, which precipitates within the calcium silicate hydrate phase and reinforces a bond between the dentinal wall and the sealer [85]. In addition, iRoot SP displayed a potent antibacterial effect against *E. faecalis* [86], which might be a combination of high pH, hydrophilicity, and active calcium hydroxide release. The above-mentioned characteristics make iRoot SP a good choice as the sealer for use in a SC technique. Regarding the obturation quality of SC in various types of canals, studies have shown mixed results. Inan et al. [87] found that the apical sealing ability of SC was comparable to that of lateral condensation and Thermafil techniques in lower premolars. Holmes et al. [26]. found that the filling quality achieved with SC was inferior to that obtained using cold lateral technique but superior to that achieved with core carrier technique in C-shaped canals. In the present study, SC combined with iRoot SP sealer did not produce a superior filling quality than CWC utilizing `AH plus sealer in the C-shaped canal of mandibular first premolars. Other studies also suggested that SC technique yielded similar obturation quality when compared to CWC technique in curved mesial canals of mandibular molars and the canals of 3D–printed replicas of maxillary left central incisor [26, 34, 88].

One significant limitation of this study is the use of human teeth as experimental samples. Even though the study pair-matched the group samples based on volume, surface area, and 3D imaging, it is essential to acknowledge the potential bias stemming from anatomical variability and its influence on the evaluation results related to the instrument shaping effects or filling quality. Within the limitations of the present in vitro study, both tested instruments were associated with larger percentages of untouched canal wall and more hard tissue debris in the apical region of C-shaped canals within mandibular first premolars. Therefore, it is crucial to emphasize that implementing a supplementary irrigation protocol following canal preparation can help eliminate debris and improve instrumentation efficacy within the complexities of root canal system. The present study suggested that the SC technique yielded similar obturation quality when compared to the CWC technique. The primary advantage of the SC technique lies in its simplicity. Therefore, utilizing SC combined with iRoot SP sealer remains a viable option for obturating C-shaped canal in mandibular first premolars.

Conclusion

The Protaper Next and Waveone Gold systems were associated with considerable percentages of untouched canal wall after the shaping of C-shaped canals in mandibular first premolars. The Protaper Next system produced less hard tissue debris in the apical regions during instrumentation when compared to the Waveone Gold system. After instrumentation, the remaining MT was found be less than 0.5 mm in almost two-thirds of the specimens. Neither of the tested techniques was capable of achieving a thorough seal in the C-shaped canals. Regardless of the system selected for preparation or the technique employed for obturation, more voids were remained in the apical region. The SC technique combined with iRoot SP yielded similar obturation quality when compared to the CWC technique. Further studies are necessary to investigate the prognosis of treatments conducted with this technique, especially in the premolars with complex C-shaped canal anatomy.

Acknowledgements

All data generated or analyzed in this study are included in this published article.

Author contributions

YZ, YZ, DZ and YP conceived the study and designed the experiments. YZ, JS, GZ and YC collected the samples. YZ, YZ and JS performed the experiments, analyzed the data and wrote the manuscript. DZ and YP edited and approved the final manuscript. All authors contributed to the article and approved the submitted version.

Funding
This study was supported by the National Natural Science Foundation of China (80218095).

Data availability
All data generated or analyzed in this study are included in this published article.

Declarations

Ethics approval and consent to participate
All procedures performed in studies involving human participants were in accordance with relevant guidelines and regulations and the ethics approval was provided by the ethical standards of the Ethics Committee of School and Stomatology Wenzhou Medical University (WYKQ2021007). The requirement for informed consent was waived by the Ethics Committee of School and Stomatology Wenzhou Medical University because of the retrospective nature of the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 3 October 2024 / Accepted: 19 February 2025
Published online: 28 February 2025

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