Research Square

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Comparative Efficacy of Sequential Chelation, Continuous Chelation, and Triton® All-In-One Irrigation Protocols for Removing Accumulated Hard-Tissue Debris: A Micro-CT Study

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Abstract

Objectives

To use micro-computed tomography (micro-CT) to evaluate residual accumulated hard-tissue debris (AHTD) and changes in root canal volume after three irrigation protocols: NaOCl followed by EDTA, Triton® All-In-One, and NaOCl combined with Dual Rinse® HEDP.

Materials and Methods

Thirty-six extracted single-rooted human teeth with a single canal were allocated equally to three groups (n = 12). Canals were prepared with ProTaper Ultimate to FX (35/.12) and irrigated with 5.25% NaOCl followed by 17% EDTA (group A), Triton® All-In-One (group B), or 5.25% NaOCl/HEDP® (group C). Pre- and post-treatment micro-CT scans were acquired at an isotropic resolution of 8.92 µm. AHTD was quantified as absolute volume and as a percentage of canal volume. Groups were compared using Kruskal-Wallis tests and ANCOVA.

Results

Median residual AHTD volumes were 0.38 mm³ in group A, 0.41 mm³ in group B, and 0.31 mm³ in group C ($p = 0.370$). AHTD normalized to post-treatment canal volume was 7.23%, 6.67%, and 5.00%, respectively ($p = 0.559$). No significant differences were found in adjusted post-treatment canal volume ($p = 0.599$) or in absolute or percentage changes in canal volume.

Conclusions

No statistically significant differences were detected among the protocols, and none completely prevented AHTD accumulation. The favorable trend observed with NaOCl/HEDP requires confirmation in larger studies.

Clinical Relevance

Under the conditions tested, none of the three irrigation protocols provided a statistically demonstrable advantage in reducing AHTD.

Introduction

Successful endodontic treatment depends on reducing microbial load and removing organic and inorganic material from the root canal system. Instrumentation creates space for irrigation and obturation but cannot uniformly debride isthmuses, recesses, oval extensions, and other anatomical irregularities [1–3]. It may also compact dentin fragments in areas untouched by instruments. This mineralized accumulated hard-tissue debris (AHTD) is distinct from the smear layer, although both partly share the same origin, and may hinder irrigant penetration and retain organic remnants and microorganisms [4–6].

Sodium hypochlorite (NaOCl) remains the most widely used root canal irrigant due to its antibiofilm activity and ability to dissolve organic tissue [7]. However, NaOCl has insufficient chelating activity and does not effectively remove the inorganic component of the smear layer or mineralized dentinal debris. Therefore, the conventional protocol combines NaOCl used during instrumentation with a final rinse of a chelating agent like 17% ethylenediaminetetraacetic acid (EDTA). EDTA chelates calcium ions and facilitates removal of the inorganic component, but its effect is exposure-time dependent and, when prolonged or followed by further contact with NaOCl, may cause demineralization and erosion of root dentin [8–10].

Sequential NaOCl and EDTA provide complementary functions but have limitations. Direct contact rapidly reduces free available chlorine in NaOCl, requiring an intermediate rinse [8]. Moreover, chelation occurs mainly after shaping, when debris may already have been compacted into canal irregularities. Continuous chelation instead uses a weak NaOCl-compatible chelator throughout chemomechanical preparation to limit hard-tissue debris accumulation as it occurs.

Etidronic acid, or 1-hydroxyethylidene-1,1-bisphosphonate (HEDP), is a bisphosphonate with milder chelating activity than EDTA [8, 10]. Dual Rinse® HEDP is a predosed formulation mixed with NaOCl immediately before use; when prepared and used as directed, the mixture remains stable in the short term for a period compatible with clinical treatment [11]. The presence of a chelator during instrumentation may limit debris accumulation as it is generated rather than acting only at the end of preparation. Consistent with this rationale, adding etidronate to NaOCl reduced AHTD formation compared with NaOCl alone in a previous micro-CT study [12]. However, studies comparing continuous chelation with sequential protocols have not yielded entirely consistent results, partly because of differences in formulations and assessment methods [13–15].

A different approach to combining action against organic and inorganic components is provided by Triton® All-In-One Irrigation Solution (Inter-Med, Inc./Vista Dental Products, Racine, WI, USA; distributed by Brasseler U.S.A. Dental, LLC, Savannah, GA, USA). Supplied as a self-mixing two-component system, the solution contains approximately 4% NaOCl combined with a proprietary mixture of chelating agents, surfactants, pH modifiers, and stabilizers. The simultaneous presence of NaOCl and chelators is intended to act on organic and inorganic components without a separate final EDTA rinse. Surfactants also reduce surface tension and contact angle, properties that may improve contact of the solution with canal walls and irregularities [16]. These features provide a rationale for a possible effect on debris but do not in themselves demonstrate greater volumetric removal of AHTD.

Evidence on Triton smear-layer and superficial-debris removal derives mainly from scanning electron microscopy (SEM) and is inconsistent [17–21]. Castagnola et al. reported better superficial-debris removal with Triton than with NaOCl/HEDP and NaOCl-EDTA in most canal thirds [15]. However, SEM assesses selected wall areas and cannot determine whether the same difference exists in total AHTD volume. Contact time, irrigant volume, anatomy, and scoring criteria may also explain variability.

The smear layer, superficial debris, and AHTD do not represent the same outcome. SEM provides high-resolution images of selected portions of the canal surface but requires sectioning of the specimen and yields a two-dimensional assessment, often based on ordinal scores. Consequently, the observed area may not represent the entire root canal system and does not permit longitudinal comparison of the same volume [22]. In contrast, micro-computed tomography (micro-CT) enables nondestructive registration and comparison of pre- and post-treatment datasets, segmentation of mineralized material, and three-dimensional quantification of AHTD throughout the volume of interest [23].

Three-dimensional data directly comparing sequential NaOCl-EDTA, Triton, and continuous NaOCl/HEDP chelation within one experimental design are lacking. This micro-CT study, therefore, evaluated residual AHTD and canal-volume changes after these three protocols. The null hypothesis was that the protocols would not differ in absolute or normalized residual AHTD or in post-treatment canal-volume changes.

Materials and methods

Ethics approval

The study protocol was reviewed and approved by the Comitato Etico Area Vasta Emilia Nord (CE AVEN; approval no. 204/2026/TESS/AOUMO; SMITH26 study; favorable opinion issued on 14 July 2026). Extracted human teeth were handled according to the approved protocol and irreversibly anonymized before allocation. Root surfaces were cleaned with a curette, and specimens were stored in 0.2% sodium azide (MilliporeSigma, St Louis, MO, USA) at 4°C until use.

Sample size calculation

Sample size was determined a priori with G*Power 3.1.9.7 (Heinrich Heine University, Düsseldorf, Germany), using AHTD volume as the primary outcome. An effect size of f = 0.91 from Giardino et al. [14], three groups, α = 0.05, and 95% power yielded a minimum of 22 specimens for a fixed-effects one-way ANOVA omnibus test. Because G*Power has no direct Kruskal-Wallis procedure, ANOVA was used as an approximation. A supporting calculation based on Perez et al. [24] (Wilcoxon-Mann-Whitney; effect size = 1.87; α = 0.05; 95% power; 1:1 allocation) required nine specimens per group. Thirty-six maxillary incisors with straight roots and a single relatively round canal confirmed by micro-CT were therefore allocated equally (n = 12), exceeding both estimates and allowing for variability or exclusions.

Specimen preparation and preoperative scanning

Before preoperative micro-CT scanning, the teeth were evaluated using two-dimensional radiography to select single-rooted specimens with macroscopically comparable anatomy, mature apices, and no evidence of marked calcification, resorption, fracture, or previous endodontic treatment. Only a standardized coronal access cavity was prepared in each collected tooth to permit access to the root

canal system while preserving the coronal and radicular anatomy as much as possible. This approach was intended to maintain an anatomical configuration closer to the ex vivo clinical condition, reduce geometric changes caused by crown removal, and preserve an irrigant access pathway more similar to that present in vivo.

After access cavity preparation, the specimens were embedded in groups of four teeth in epoxy resin blocks. Only the apical third of each tooth was embedded, leaving the coronal portion and middle third of the root exposed. This configuration stabilized the specimens during scanning and allowed reproducible repositioning while maintaining a closed-end ex vivo model. This feature is particularly important in endodontic irrigation studies because open-canal models may artificially facilitate irrigant flow and underestimate phenomena such as apical vapor lock, whereas closed-end models more realistically reproduce the fluid-dynamic limitations encountered clinically [25].

Each resin block was identified using radiopaque gutta-percha markers positioned to indicate the scanning orientation and uniquely identify the block. The blocks were labeled sequentially from A to I. This marking system maintained a consistent specimen orientation during repeated micro-CT acquisitions and enabled each tooth to be linked to its corresponding experimental block.

The blocks were then placed in custom 3D-printed containers designed to facilitate specimen orientation, transport, and storage between the experimental phases (Fig. S1).

Throughout the procedures, the teeth were kept under controlled moisture conditions to prevent specimen desiccation. This precaution was taken to minimize dehydration-related changes in the dentin substrate, which may affect the physical and structural properties of dentin and introduce uncontrolled experimental variability [26, 27].

Before chemomechanical preparation, all specimens underwent preoperative micro-CT scanning with a SkyScan 1176 scanner (Bruker, Kontich, Belgium). The scans were used to confirm a single relatively round root canal in cross-section, a closed apex, similar root length, absence of pre-existing fractures or cracks, and absence of relevant canal calcifications in each tooth. Micro-CT also provided a nondestructive three-dimensional assessment of the initial canal anatomy and allowed the same specimen to be compared across the experimental phases [2, 5].

As described previously, the specimens were scanned at an isotropic resolution of 8.92 µm. Acquisition parameters were set at 90 kV and 280 µA, with a rotation step of 0.5° and a 0.1-mm copper filter [14]. The volume of interest included the entire root canal system, from the accessible coronal portion to the root apex. The reconstructed images were then analyzed to assess the preoperative anatomical parameters.

Before allocation to the experimental groups, all specimens underwent preliminary morphometric assessment using ImageJ/Fiji. Total tooth volume, root canal length, and mean canal width were

measured for each tooth. Mean canal width was calculated by averaging measurements obtained at standardized points along the canal.

The specimens were then assigned to the three experimental groups using a balanced allocation procedure based on the preoperative morphometric parameters. Allocation was completed before the irrigation protocols were applied and was intended to reduce the influence of baseline anatomical variability on the study outcomes by avoiding clustering of specimens with similar dimensions within the same group.

Allocation was not based on the complete three-dimensional canal volume but on preliminary morphometric parameters representative of the overall tooth dimensions and main canal geometry. Statistical analysis of the balancing variables was performed only after allocation had been completed, to verify baseline comparability among the groups and not as an iterative selection criterion.

Groups A, B, and C received sequential NaOCl-EDTA, Triton® All-In-One, and NaOCl/HEDP, respectively. No negative control was included because the study compared active protocols; saline or distilled water lacks chelating activity and is not a clinically relevant comparator for mineralized-debris removal.

Table 1
Preoperative morphometric parameters and baseline comparability among the experimental groups. No statistically significant differences were found among groups in total tooth volume, canal length, or mean canal width ($p > 0.05$).

Parameter	Group A	Group B	Group C	Kruskal–Wallis *H*	*p*-value
Total tooth volume (mm^3)	342.5 ± 133.9	350.2 ± 130.5	359.1 ± 163.2	0.097	0.953
Root canal length (µm)	13,847.8 ± 1,999.4	13,095.4 ± 2,214.2	13,158.3 ± 1,768.0	0.410	0.815
Mean canal width (µm)	753.3 ± 328.6	870.9 ± 210.9	853.2 ± 282.9	0.956	0.620

Root canal preparation

Working length was established by advancing a size 10 K-file (Dentsply Sirona, Charlotte, NC, USA) until visible at the apical foramen under magnification and subtracting 1 mm [14]. Canals were prepared with ProTaper Ultimate NiTi instruments (Dentsply Sirona) to FX (35/.12). At each instrument change, 1 mL of the assigned irrigant was delivered through a 30-gauge side-vented needle (Max-i-Probe; Dentsply Rinn, Elgin, IL, USA) positioned 2 mm short of working length. Group A received 5.25% NaOCl (Ogna Laboratori Farmaceutici, Muggiò, Italy) for 6 min, followed by 2 mL of 17% EDTA (Ogna Laboratori Farmaceutici) for 2 min [14]. Group B received Triton for 6 min. Group C received 5.25% NaOCl mixed with Dual Rinse HEDP according to the manufacturer's instructions for 6 min. Canals were finally rinsed with 5 mL sterile saline and dried with size 35 paper points.

Postoperative scanning

After root canal preparation, all specimens were rescanned by micro-CT to quantify the accumulation of hard-tissue debris within the canal system. Pre- and post-preparation datasets were imported into Dragonfly 3D World (Comet Technologies Canada Inc., Montreal, QC, Canada) and subjected to three-dimensional registration [14]. Root canal space, dentin, and accumulated hard-tissue debris were subsequently identified using semiautomated segmentation and dedicated thresholds.

Accumulated hard-tissue debris (AHTD) volume was calculated by intersecting the segmented volumes from the pre- and post-preparation datasets to identify areas of the canal space that were initially empty but occupied by mineralized material after instrumentation. Total AHTD volume was expressed both as an absolute value in cubic millimeters (mm^3) and as a percentage of the total root canal system volume [23].

Statistical analysis

Statistical analyses were performed using R software (version 4.5.1; R Foundation for Statistical Computing, Vienna, Austria). The dataset comprised 36 specimens equally distributed among the three experimental irrigation groups, with 12 specimens per group. For each specimen, accumulated hard-tissue debris volume (mm^3), pre-treatment canal volume, and post-treatment canal volume were recorded. Absolute change in canal volume, defined as post-treatment minus pre-treatment volume, percentage change from baseline, and two normalized debris indices, calculated by dividing debris volume by pre- and post-treatment canal volume, were also derived.

Quantitative variables were summarized as mean and standard deviation or median and interquartile range, according to their distribution. Normality of continuous variables within each group was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated using Levene's test. Because debris volume did not fully meet the normality assumption, groups were compared for this outcome using the nonparametric Kruskal-Wallis test. The same approach was used to compare normalized debris indices and absolute and percentage changes in canal volume among the groups.

The effect of the experimental protocol on post-treatment root canal volume was assessed by analysis of covariance (ANCOVA), with post-treatment volume as the dependent variable, experimental group as a fixed factor, and pre-treatment volume as the covariate (Table 2). This approach was used to compare groups while accounting for baseline anatomical differences among canals. Homogeneity of regression slopes was assessed by comparing the standard ANCOVA model with a model including the interaction between experimental group and pre-treatment volume. Residual normality was assessed using a Q-Q plot and the Shapiro-Wilk test, whereas homoscedasticity was evaluated using a residuals-versus-fitted plot and the Breusch-Pagan test. Influential observations were assessed using Cook's distance, with 4/n used as a reference threshold; when values exceeded this threshold, a sensitivity analysis was performed. Effect sizes for the ANCOVA model were expressed as partial eta squared (η^2p). Estimated

marginal means of post-treatment volumes were calculated for each group and compared using Tukey-adjusted post hoc tests.

Potential associations among debris volume, pre-treatment canal volume, post-treatment canal volume, and change in canal volume were assessed using Pearson and Spearman correlation analyses. Statistical significance was set at $p < 0.05$.

Results

Sample characteristics and baseline comparability

All 36 specimens were analyzed (n = 12 per group). Table 2 reports the main volumetric and AHTD outcomes.

Table 2
Volumetric parameters and AHTD in the three experimental groups. *ANCOVA adjusted for pre-treatment volume; Kruskal-Wallis tests are reported for all other outcomes. AHTD, accumulated hard-tissue debris; IQR, interquartile range.

Outcome	Group A	Group B	Group C	*p*-value
Pre-treatment canal volume (mm^3), mean ± SD	4.25 ± 1.54	3.42 ± 1.58	4.00 ± 2.11	0.527
Post-treatment canal volume (mm^3), mean ± SD	7.06 ± 2.55	6.14 ± 2.37	6.27 ± 2.02	0.599*
AHTD (mm^3), median (IQR)	0.38 (0.32–0.75)	0.41 (0.23–0.64)	0.31 (0.23–0.41)	0.370
AHTD/pre-treatment volume (%), median (IQR)	12.45 (7.27–20.28)	10.30 (6.52–17.77)	8.87 (4.84–15.61)	0.624
AHTD/post-treatment volume (%), median (IQR)	7.23 (4.10–11.57)	6.67 (4.73–9.46)	5.00 (3.35–7.48)	0.559
Δ volume (mm^3), median (IQR)	2.95 (1.87–3.53)	2.47 (1.66–4.10)	1.89 (1.48–3.13)	0.653
Δ volume/pre-treatment volume (%), median (IQR)	71.20 (44.24–91.71)	81.92 (55.74–131.30)	52.30 (28.82–113.49)	0.756

Accumulated hard-tissue debris

Micro-CT reconstructions revealed residual AHTD in specimens from all three groups, with variable spatial distribution among root canal systems (Fig. 1). Absolute AHTD volume was not normally distributed in groups A and C and was therefore compared using the Kruskal-Wallis test. Median residual volume was 0.38 mm^3 (IQR, 0.32–0.75) in group A, 0.41 mm^3 (IQR, 0.23–0.64) in group B, and 0.31 mm^3 (IQR, 0.23–0.41) in group C. No statistically significant differences were found among the protocols (H =

1.99; p = 0.370). Descriptively, group C had the lowest mean residual AHTD volume (0.363 ± 0.307 mm^3), followed by group B (0.449 ± 0.331 mm^3) and group A (0.583 ± 0.423 mm^3) (Fig. 2A).

Median post-treatment-normalized AHTD was 7.23% (IQR, 4.10-11.57), 6.67% (IQR, 4.73–9.46), and 5.00% (IQR, 3.35–7.48) in groups A-C, respectively (H = 1.16; p = 0.559; Fig. 2B). Pre-treatment-normalized AHTD also did not differ (p = 0.624).

Changes in root canal volume

Post-treatment canal volume was 7.06 ± 2.55 mm^3 in group A, 6.14 ± 2.37 mm^3 in group B, and 6.27 ± 2.02 mm^3 in group C. In the ANCOVA adjusted for pre-treatment canal volume, the irrigation protocol had no significant effect on final canal volume ($F(2,32) = 0.52$; $p = 0.599$; $\eta^2p = 0.032$). Conversely, pre-treatment volume was strongly associated with post-treatment volume ($F(1,32) = 61.01$; $p < 0.001$; $\eta^2p = 0.656$), with a regression coefficient of $\beta = 1.07$ (95% CI, 0.79–1.35). The model explained 66.7% of the variability in final volume ($R^2 = 0.667$; adjusted $R^2 = 0.636$), and the interaction between group and pre-treatment volume was not significant (p = 0.271), supporting homogeneity of regression slopes. Model residuals were compatible with normality (Shapiro-Wilk, p = 0.428) and showed no evidence of heteroscedasticity (Breusch-Pagan, p = 0.351). One specimen had a Cook's distance above the 4/n reference threshold (D = 0.231); excluding it in the sensitivity analysis did not change the interpretation of the group effect ($F(2,31) = 0.33$; $p = 0.721$).

Adjusted marginal means were 6.67 mm^3 (95% CI, 5.85–7.49), 6.64 mm^3 (95% CI, 5.81–7.46), and 6.16 mm^3 (95% CI, 5.34–6.97) in groups A-C; no Tukey-adjusted comparison was significant (Fig. 2E). Absolute and percentage canal-volume changes also did not differ (p = 0.653 and p = 0.756, respectively; Fig. 2C).

Correlation analyses

Absolute AHTD was not associated with pre-treatment volume (Spearman's rho = 0.307; p = 0.068), post-treatment volume (rho = 0.151; p = 0.380; Fig. 3D), or absolute volume change (rho = -0.048; p = 0.782). Post-treatment-normalized AHTD was also unrelated to volume change (rho = -0.273; p = 0.107). Pearson analyses were consistent.

Discussion

No significant differences were found among sequential NaOCl-EDTA, Triton® All-In-One, and continuous NaOCl/HEDP chelation in absolute or normalized AHTD or canal-volume changes. The null hypothesis was therefore not rejected.

Nonsignificance does not establish equivalence. Group C had the lowest descriptive absolute and normalized AHTD values, followed by groups B and A. This trend does not demonstrate superiority but warrants evaluation in larger samples and more complex anatomies.

The trend in the NaOCl/HEDP group is consistent with continuous chelation: HEDP is present while instruments generate debris and may progressively chelate calcium ions, limiting compaction in canal irregularities. Adding etidronate to NaOCl previously reduced AHTD formation compared with NaOCl alone [12], whereas sequential NaOCl-EDTA reduced but did not eliminate AHTD [5]. Standardized shaping and irrigation may have attenuated chemistry-related differences in the relatively accessible canals evaluated here.

HEDP has weaker chelating activity than EDTA, but its presence throughout preparation may compensate for a lower instantaneous decalcifying capacity [8, 10]. The NaOCl/HEDP mixture remains sufficiently stable in the short term for clinical use when prepared and used as directed [11]. However, pH influences chelating capacity and the interaction with dentin [28]. Therefore, the behavior observed with Dual Rinse® HEDP cannot be automatically extrapolated to all etidronate-containing formulations.

Triton showed intermediate absolute and normalized AHTD values without significant differences from either comparator. The presence of NaOCl, chelators, pH modifiers, stabilizers, and surfactants in solution should allow simultaneous organic-tissue dissolution and chelation, while reduced surface tension and contact angle may improve canal-wall contact [16, 29–31]. Aranda et al. reported surface tensions of 26.30 mN/m for Triton, compared with 69.97 for NaOCl, 68.45 for NaOCl/HEDP, and 67.58 for 17% EDTA [16]. Despite the presence of these wetting agents in the solution, which can improve its effectiveness, wettability, and diffusion through the root canal [32], Triton did not significantly reduce AHTD more than the other protocols, indicating that surface tension alone is not sufficient to predict the mobilization of compacted mineralized debris [33]. Combining a chelator with NaOCl may instead limit debris as it forms, avoiding a separate final chelation step. Despite its comparatively high surface tension, NaOCl/Dual Rinse HEDP produced lower residual bacterial viability than sequential NaOCl/EDTA [34], and the smear layer did not reduce the antimicrobial activity of NaOCl/HEDP in infected dentin [35]. These findings show that antimicrobial performance may remain favorable despite surface-tension differences, but they concern biological endpoints and cannot be extrapolated directly to volumetric AHTD removal. In the present study, Triton and NaOCl/HEDP produced AHTD amounts comparable to the longer sequential NaOCl-EDTA protocol; this may reflect debris prevention during preparation rather than superior removal of already compacted material.

Using SEM, Castagnola et al. reported better removal of superficial debris with Triton than with NaOCl/HEDP and NaOCl-EDTA in most comparisons [15]. This divergence may reflect the different outcomes: SEM scores selected surface areas, whereas micro-CT quantifies mineralized material throughout the canal system. Superficial debris and three-dimensional AHTD are therefore not directly comparable [22], and protocol differences may further contribute to heterogeneity.

Micro-CT permits three-dimensional, nondestructive, longitudinal assessment of the same specimen [23]. Pre- and post-treatment segmentation quantifies accumulated mineralized material as both an absolute volume and a proportion of canal volume. Agreement between these analyses strengthens the interpretation, although neither demonstrated protocol-related differences.

Final canal volume depended mainly on baseline canal size. Baseline volume was strongly associated with final volume ($\beta = 1.07$; $p < 0.001$), whereas irrigant type had no significant effect ($p = 0.599$). Adjusted final volumes were similar in groups A and B and slightly lower in group C, with no significant pairwise differences. Baseline geometry and standardized mechanical shaping, therefore, influenced final volume more than the irrigation protocol.

Absolute AHTD volume was not significantly associated with pre-treatment volume, post-treatment volume, or canal enlargement. An inverse trend between enlargement and normalized AHTD was nonsignificant in both Pearson and Spearman analyses and should be considered exploratory.

Limitations include the ex vivo model, single-rooted teeth, modest sample size, anatomical variability, and different contact times (8 min for NaOCl-EDTA versus 6 min for the other protocols). The findings cannot be extrapolated to complex molar anatomies. Semiautomated segmentation depends on registration and threshold selection; micro-CT primarily detects mineralized material rather than smear plugs, biofilm, or radiolucent soft tissue [4], and whole-canal analysis may mask regional differences.

Future studies should use larger samples, more complex anatomies, and regional micro-CT analyses. Complementary methods may also distinguish volumetric AHTD removal from dentin-surface cleaning.

Conclusions

All three protocols (NaOCl-EDTA, Triton®, NaOCl/HEDP®) left residual AHTD, and no statistically significant differences were found in absolute or normalized debris volume. Nevertheless, the NaOCl/HEDP group consistently showed the lowest descriptive values for both outcomes, followed by Triton and sequential NaOCl-EDTA. Although this difference does not establish the superiority of etidronate, the observed pattern suggests that continuous chelation may help limit debris accumulation during shaping.

Declarations

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Data availability: The data generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval: The study protocol was approved by the Comitato Etico Area Vasta Emilia Nord (CE AVEN; approval no. 204/2026/TESS/AOUMO; SMITH26 study; favorable opinion issued on 14 July 2026).

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Figures

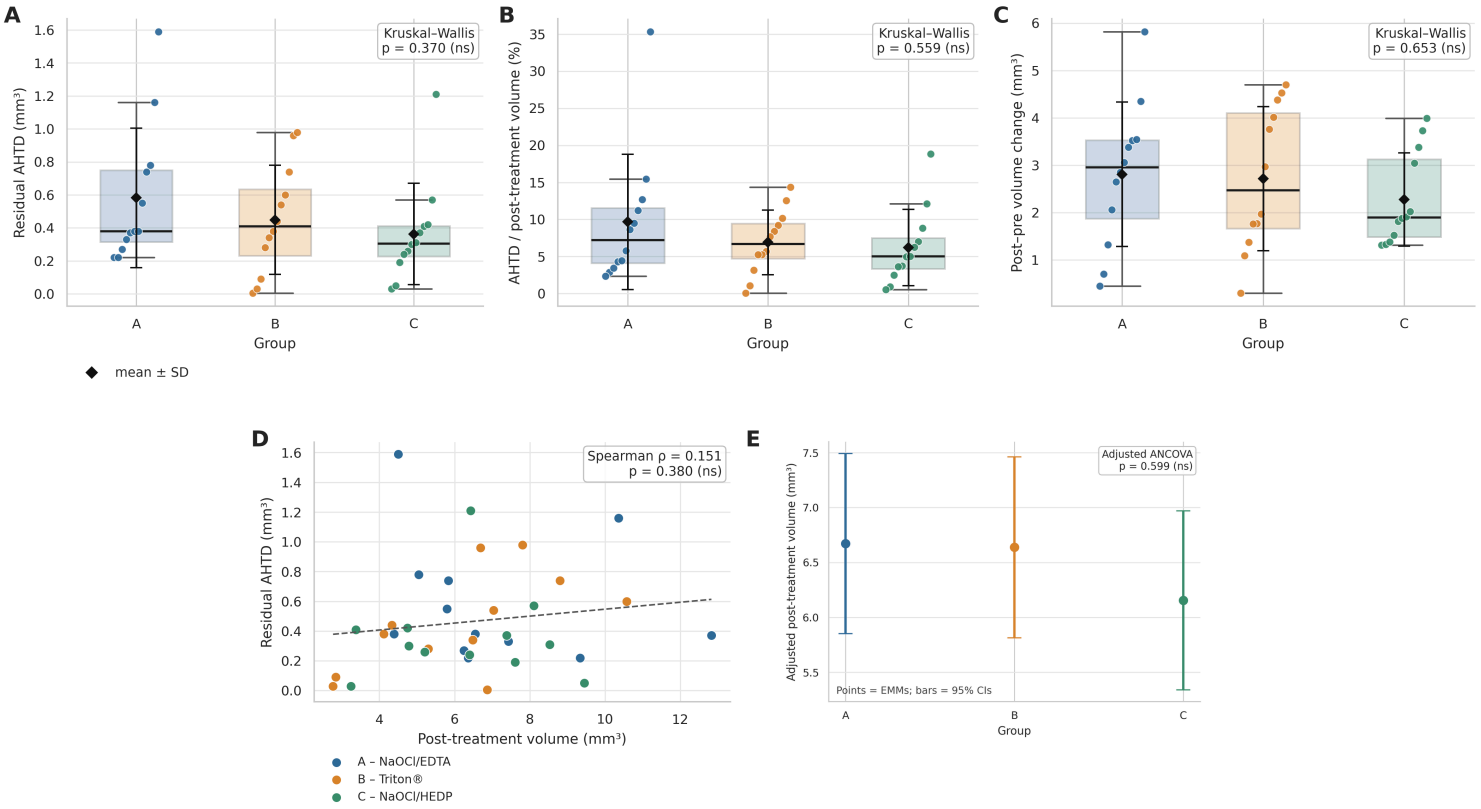


Figure 1

Representative micro-CT reconstructions of specimens assigned to the three experimental protocols: Group A, NaOCl–EDTA (a–e); Group B, Triton® All-in-One (f–j); and Group C, NaOCl/HEDP (k–o). For each group, panels a, f, and k show three-dimensional segmentation of the canal volume before preparation (yellow); panels b, g, and l show transverse sections at the coronal, middle, and apical thirds, respectively, arranged from top to bottom. Panels c, h, and m show three-dimensional superimposition of the pre- and post-preparation canal volumes (yellow and blue, respectively), while panels d, i, and n show the corresponding transverse sections after preparation. Panels e, j, and o show the three-dimensional distribution of residual accumulated hard-tissue debris (AHTD) in red

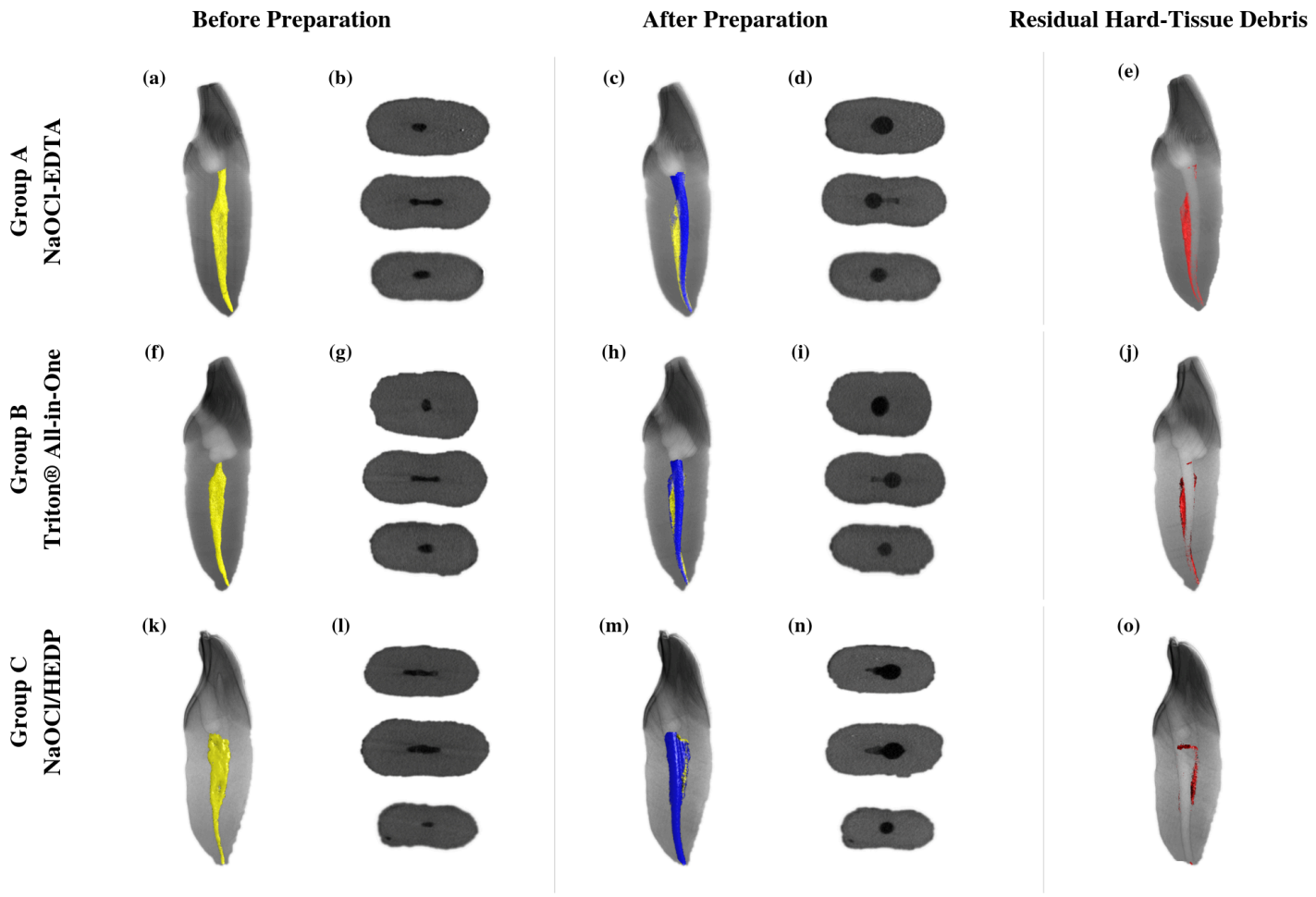


Figure 2

Distribution of volumetric outcomes across the three experimental groups. (A) Absolute residual AHTD volume; (B) AHTD normalized to post-treatment canal volume; (C) absolute change in canal volume; and (D) relationship between post-treatment canal

Supplementary Files

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