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A CONE-BEAM COMPUTED TOMOGRAPHY ASSESSMENT OF THE EFFICACY OF XP-ENDO FINISHER, LASER-ASSISTED AND PASSIVE ULTRASONIC IRRIGATION TECHNIQUES ON REMOVAL OF TWO DIFFERENT INTRACANAL MEDICAMENTS – AN IN-VITRO STUDY

Ashiba K[1], Dr Mohan Thomas Nainan[2], Notu Sai Rama Sri[3], Dr Nirupama Dn[4*], Pragnya Budamagunta[5], Aishwarya Karigoudar[6]

[1]Pg student, University - vydehi institute of dental sciences and research, Nallurhalli, Banglore,
Email: ashiba.k123@gmail.com
[2]HOD And Professor, University - vydehi institute of dental sciences and research, Nallurhalli, Banglore, Email drmohan27tn@yahoo.com
[3]Pg student, University - vydehi institute of dental sciences and research, Nallurhalli, Banglore, Email-sairamasrinotu@gmail.com
[4*]Professor, University - vydehi institute of dental sciences and research, Nallurhalli, Banglore, Mail-dnnirupama@gmail.com
[5]Pg student, University - vydehi institute of dental sciences and research, Nallurhalli , Banglore, Mail-budamagunta9@gmail.com
[6]University - vydehi institute of dental sciences and research, Nallurhalli , Banglore, Mail-abkarigoudar@gmail.com

ABSTRACT:
Objectives: To compare the efficacy of laser-activated irrigation (LAI), passive ultrasonic irrigation (PUI), and XP-Endo Finisher (XPF) in removing Nitrofurantoin and modified triple antibiotic paste (MTAP) from root canals using cone-beam computed tomography (CBCT) volumetric analysis.
Methods: Sixty extracted intact, caries-free, single-rooted mandibular first premolars were prepared and randomly allocated into six experimental groups (n=10), according to the irrigation activation technique and intracanal medicament used. Following medicament placement, removal was performed using LAI, PUI, or XPF. CBCT scans were obtained before and after medicament removal, and the residual medicament volume was assessed separately in the coronal, middle, and apical thirds. Intergroup differences were evaluated using one-way analysis of variance followed by Tukey post-hoc testing, while pre- and post-removal volumes were compared using paired t-tests.
Results: All groups demonstrated a significant reduction in intracanal medicament volume following the removal procedures ($p<0.001$). LAI groups demonstrated significantly lower residual volumes than the PUI and XPF groups in the coronal, middle, and apical thirds ($p<0.001$). In the coronal third, residual volumes were 0.477 ± 0.208 mm³ and 0.493 ± 0.206 mm³ for the two LAI groups, compared with 1.395–1.558 mm³ for the other groups. A similar trend was observed in the middle and apical thirds. The overall reduction in total canal volume was also greater in the LAI groups, with mean reductions of 6.661 mm³ and 6.560 mm³, respectively.
Conclusions:
LAI demonstrated superior intracanal medicament removal compared with PUI and XPF, irrespective of the medicament used. The advantage of LAI was evident throughout the coronal, middle, and apical regions.
Clinical Relevance: Laser-activated irrigation may provide more effective removal of intracanal medicaments before obturation and may enhance canal cleanliness, particularly in anatomically challenging regions such as the apical third.

KEYWORDS: Intracanal medicaments; Laser-activated irrigation; Passive ultrasonic irrigation; XP-Endo Finisher; Nitrofurantoin; Modified triple antibiotic paste; CBCT.

INTRODUCTION

Successful endodontic therapy relies on the thorough elimination of microorganisms from the root canal system and the prevention of reinfection. However, the complex root canal anatomy, including fins, isthmuses, lateral canals, and dentinal tubules, limits the effectiveness of mechanical instrumentation alone, making chemo-mechanical preparation with irrigation essential for adequate disinfection.1,2

Despite advancements in rotary instrumentation and irrigants, significant areas of the canal are used as an adjunct to enhance microbial reduction between appointments. Calcium hydroxide has long been considered the gold standard due to its antimicrobial properties and biocompatibility; however, it shows limited efficacy against resistant microorganisms such as Enterococcus faecalis and Candida albicans, may adversely affect dentin properties, and is difficult to remove completely.3,4

To overcome these limitations, antibiotic-based medicaments such as triple antibiotic paste (TAP) have been introduced, demonstrating broad-spectrum antimicrobial activity. However, their clinical use is restricted due to tooth discolouration, cytotoxicity, and the risk of antibiotic resistance. Modified triple antibiotic paste (MTAP), in which minocycline is replaced with clindamycin, reduces discoloration while maintaining antimicrobial efficacy, but exhibits strong adhesion to dentinal walls, making its removal challenging.5,6

Nitrofurantoin, a nitrofuran antibiotic introduced in the 1950s, has been widely used in medicine for the treatment of urinary tract infections due to its broad-spectrum antibacterial activity and low resistance rates. In dentistry, it has recently been explored as an intracanal medicament because of its effectiveness against resistant endodontic pathogens such as Enterococcus faecalis. Recent studies suggest that nitrofurantoin shows promising antimicrobial efficacy and can be considered a potential alternative to conventional intracanal medicaments .7,8

Complete removal of intracanal medicaments before obturation is critical, as residual remnants can occlude dentinal tubules, impair sealer penetration, and compromise the sealing ability of obturation materials, ultimately affecting treatment outcomes. Conventional methods such as syringe irrigation with sodium hypochlorite and EDTA, combined with manual instrumentation, are often insufficient in complex canal anatomies.9,10

To improve removal efficacy, various techniques have been developed. Agitation and activation methods, including manual dynamic agitation, sonic systems, and passive ultrasonic irrigation, enhance irrigant penetration, with ultrasonics being more effective due to acoustic streaming and cavitation.7,8 Advanced approaches such as the XP-Endo Finisher, laser-activated irrigation, and systems like EndoVac and GentleWave further enhance cleaning through improved mechanical and hydrodynamic action. However, none of these techniques ensures complete removal of intracanal medicaments.11,12,13

Furthermore, no literature exists that directly compares the effectiveness of these techniques in removing newer medicaments such as MTAP and nitrofurantoin using three-dimensional assessment methods. Therefore, the present study aimed to evaluate and compare the efficacy of LAI, PUI, and XP-Endo Finisher in the removal of MTAP and nitrofurantoin using CBCT.

MATERIALS AND METHODS

Study design and sample selection

This in vitro experimental study was conducted in the Department of Conservative Dentistry and Endodontics after approval from the Institutional Ethical Committee (Reference No: VIDS/IEC/PG/APP/2024/135).

Sixty extracted human mandibular first premolars with single roots and single canals were selected. Teeth with fully formed apices and without caries, restorations, fractures, or previous endodontic treatment were included. Teeth with calcified canals, open apices, or morphological defects were excluded.

Specimen preparation

The collected teeth were cleaned of soft tissue debris and stored in 10% buffered formalin (Loba chemie Pvt. Ltd), followed by saline (0.9% w/v; Healthline Pharmaceuticals Pvt. Ltd., India). Radiographs were taken using RVG (Carestream Dental, Atlanta, GA, USA) in buccolingual and mesiodistal directions to confirm single canals. The crowns were decoronated to standardize root length to 15 mm using a diamond disc.

Working length was established using a size #10 K-file (MANI Inc., Tochigi, Japan), 1 mm short of the apical foramen. Root canal preparation was performed using ProTaper Next rotary files up to size F3 (30/.07 taper) (Dentsply Sirona, York, PA, USA). Irrigation was carried out using 3% sodium hypochlorite (Vensons, Bangalore, India) between each file with a 30G side-vented needle (Neoendo, Orikam Healthcare Pvt. Ltd., India). Final irrigation included 17% EDTA (Prime Dental Products Pvt. Ltd., Maharashtra, India) followed by sodium hypochlorite. Canals were dried using paper points (DiaDent Europe B.V., Netherlands).

Preparation and placement of intracanal medicaments

Nitrofurantoin paste was prepared using nitrofurantoin tablets 100mg (Niftas, Intas Pharmaceuticals Ltd., India), mixed with distilled water and methyl cellulose to obtain a homogeneous consistency. Modified triple antibiotic paste (MTAP) was prepared using equal proportions of metronidazole, ciprofloxacin, and clindamycin powders mixed with distilled water and methyl cellulose.

The medicaments were placed into the canals using a lentulospiral (MANI Inc., Tochigi, Japan). Access cavities were sealed with temporary restorative material, and apices were sealed with composite resin. Samples were stored at 37°C for 14 days.

Grouping and Irrigation Protocol

A total of 60 samples were randomly divided into two main groups (n = 30 each) based on the intracanal medicament used:

- **Group 1:** Nitrofurantoin
- **Group 2:** MTAP (Modified Triple Antibiotic Paste)

Each main group was further subdivided into three subgroups (n = 10 each) according to the irrigation activation technique:

Group 1: Nitrofurantoin
Subgroup 1A (Laser-activated irrigation)
Irrigation was performed using 5 mL of 3% sodium hypochlorite activated with an Er:YAG laser at 1.23 W, 30 Hz, and 140 µs pulse duration.

Fig. 1 – Er:YAG laser used for laser-activated irrigation.

Subgroup 1B (Passive ultrasonic irrigation)
Irrigation was performed using 5 mL of 3% sodium hypochlorite activated using a piezoelectric ultrasonic unit for 1 minute.
Subgroup 1C (XP-Endo Finisher)
Irrigation was performed using 5 mL of 3% sodium hypochlorite with XP-Endo Finisher operated at 800 rpm and 1 Ncm torque for 1 minute, repeated three times.
Group 2: MTAP
Subgroup 2A (Laser-activated irrigation)
Same protocol as Subgroup 1A.
Subgroup 2B (Passive ultrasonic irrigation)
Same protocol as Subgroup 1B.
Subgroup 2C (XP-Endo Finisher)
Same protocol as Subgroup 1C.

CBCT analysis and outcome assessment

Fig. 2 – CBCT unit used for three-dimensional volumetric assessment.

Pre- and post-irrigation cone-beam computed tomography scans were obtained using CBCT (Carestream CS 3900, Carestream Dental, Atlanta, GA, USA) to evaluate the volume of intracanal medicament.
Volumetric analysis was performed using ITK-SNAP software (version 4.2.0). 14 Semi-automatic segmentation based on grayscale thresholding was used to assess the medicament volume.
The volume of residual medicament was calculated in cubic millimetres, and the percentage of removal was determined using the formula:15
Removal efficiency = $[(a - b) \times 100 / a]$
where a represents the initial volume and b represents the residual volume after irrigation.

RESULT
The results demonstrated no statistically significant difference in baseline canal volumes among all groups ($p > 0.001$), confirming sample standardization ensuring that subsequent differences could be attributed to the irrigation protocols employed rather than anatomical variability (Table 1a). Following medicament removal, a statistically significant difference was observed across all groups and regions ($p < 0.001$)(Table 1b). Laser-activated irrigation showed the lowest residual canal volumes and highest removal efficiency in coronal, middle, and apical thirds, followed by passive ultrasonic irrigation and XP-Endo Finisher. Although all techniques resulted in significant reduction in intracanal medicament ($p < 0.001$)(Tab, none achieved complete removal, with reduced efficacy noted in the apical third. No significant difference was observed between MTAP and nitrofurantoin within the same groups.

DISCUSSION
The present study aimed to evaluate and compare the efficacy of laser-activated irrigation (LAI), passive ultrasonic irrigation (PUI), and XP-Endo Finisher in the removal of intracanal medicaments— (MTAP) and nitrofurantoin—using CBCT-based volumetric assessment. The use of three-dimensional imaging allowed precise quantification of residual medicament, thereby enhancing the reliability of the findings.
Following medicament removal, all groups demonstrated a statistically significant reduction in canal volume ($p < 0.001$) (Table 1b), indicating that each technique was effective to some extent. However, intergroup comparisons revealed highly significant differences ($p < 0.001$), highlighting variability in the efficiency of the tested irrigation methods. Among them, laser-activated irrigation consistently showed the lowest residual canal volumes and the highest volume of medicament removed across all regions (Table 2).
A statistically significant reduction in canal volume after medicament removal in all groups ($p < 0.001$)(table 3)further demonstrated a significant reduction in total canal volume, with the greatest mean reduction observed in the LAI groups (6.661 and 6.560 mm^3) (Table 4).
The superior performance of LAI can be attributed to its unique mechanism of action. The generation of photoacoustic shockwaves creates rapid fluid movement and secondary cavitation effects, resulting in enhanced irrigant penetration and disruption of medicament remnants adhering to dentinal walls. This hydrodynamic phenomenon allows the irrigant to access complex anatomical areas, including fins, isthmuses, and dentinal tubules, which are otherwise difficult to reach with conventional or mechanically driven systems. These findings are consistent with previous studies that have reported enhanced debridement and smear layer removal with laser activation compared to other techniques.12,16,17
Passive ultrasonic irrigation demonstrated moderate efficacy, with significantly higher residual volumes compared to LAI but comparable performance to XP-Endo Finisher in most regions. The effectiveness of PUI is primarily attributed to acoustic streaming and cavitation, which improve irrigant exchange and generate shear forces along canal walls.

Fig 3: pre irrigation cbct

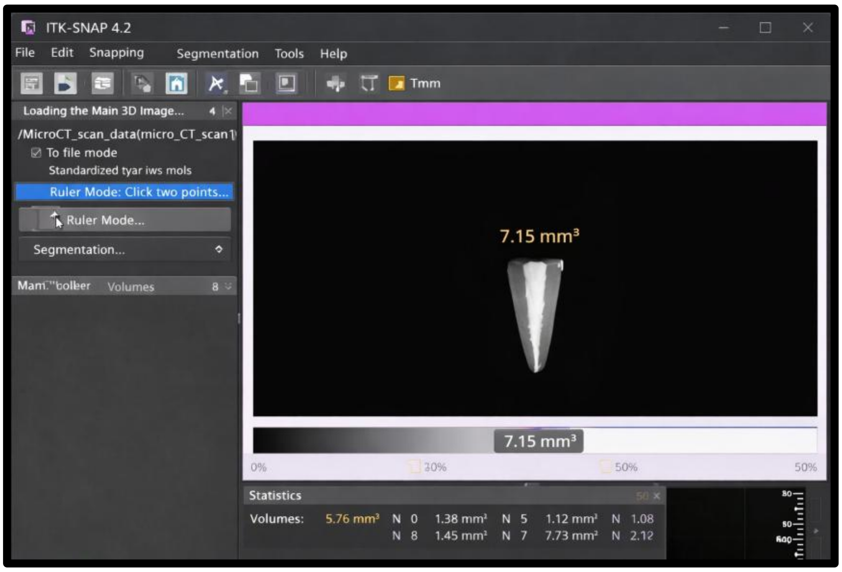

Fig 4 : ITK SNAP SOFTWARE-Pre irrigationa canal

However, its efficacy may be limited by factors such as attenuation of ultrasonic in curved canals, restricted oscillation amplitude, and lack of direct contact with all canal surfaces, particularly in anatomically complex areas.7,18,19

The XP-Endo Finisher, designed with a shape-memory NiTi alloy, expands within the canal to adapt to irregular morphologies and improve mechanical debridement. In the present study, it exhibited comparable results to PUI but remained inferior to LAI. This may be explained by its reliance on mechanical contact rather than fluid dynamics. While it effectively disrupts loosely adherent debris, it may be less efficient in removing medicaments that are firmly bound to dentinal surfaces or deeply penetrated into tubules.20,21,22

An important observation across all groups was the progressive decrease in removal efficiency from coronal to apical regions. The apical third consistently exhibited higher residual volumes and lower removal values, reflecting the inherent difficulty in cleaning this region due to reduced canal diameter, limited irrigant exchange, and complex microanatomy. This finding is in agreement with previous literature, which consistently identifies the apical third as the most challenging region for effective debridement.

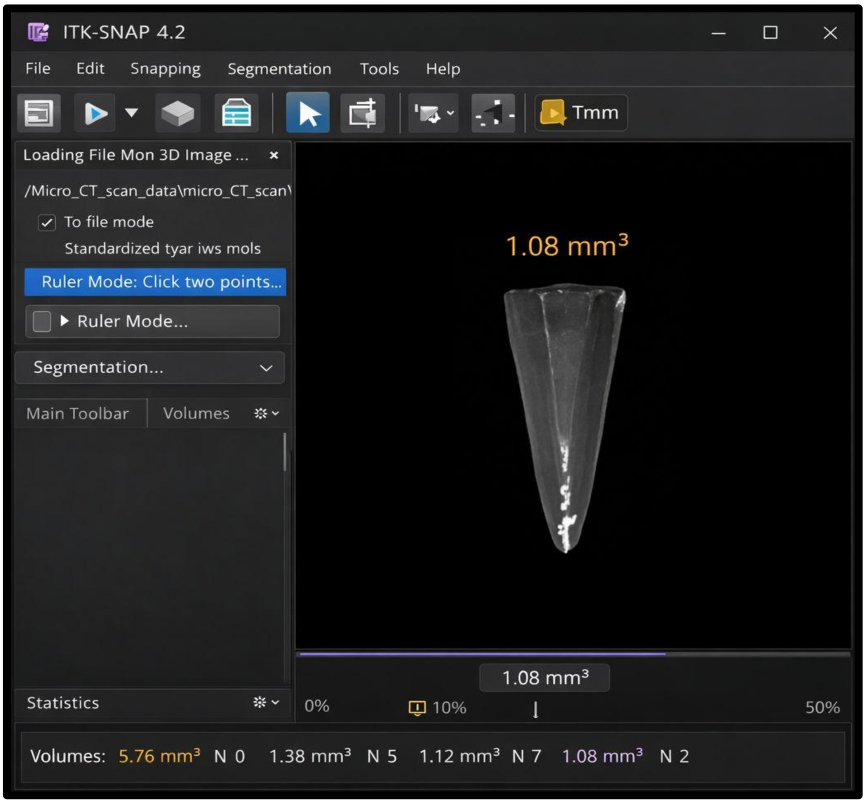

Fig 5 : ITK SNAP SOFTWARE-Post irrigationa canal

With respect to medicament type, no statistically significant difference was observed between MTAP and nitrofurantoin within the same irrigation groups. This suggests that the method of irrigant activation had a greater influence on removal efficacy than the composition of the medicament. However, it is important to consider that antibiotic-based pastes such as MTAP are known to exhibit strong adhesion to dentinal walls and deeper penetration into tubules, which may contribute to their persistence. The comparable behavior observed in this study may indicate that both medicaments present similar challenges in terms of retrievability under the tested conditions.

The findings of the present study also highlight the importance of combining chemical and mechanical strategies for optimal canal cleanliness. While NaOCl and EDTA contribute to dissolution of organic and inorganic components, their effectiveness is significantly enhanced when combined with activation techniques that improve irrigant penetration and distribution.23,24

Despite the superior performance of LAI, none of the techniques achieved complete removal of intracanal medicaments, emphasizing the limitations of current irrigation protocols. This underscores the need for further research focusing on optimizing irrigation parameters, developing novel activation systems, and exploring adjunctive methods to improve medicament retrieval.

Certain limitations of this study must be acknowledged. Being an in vitro study, it does not fully replicate clinical conditions, where factors such as tissue remnants, fluid dynamics, and operator variability may influence outcomes. Additionally, only specific irrigation protocols and activation durations were evaluated.

Table 1.Comparison of mean Canal Volume (in mm3)a) after filling the Intra-canal medicament b) after removing the Intra-canal medicament b/w 6 groups at different regions using One-way ANOVA Test

A

Regions	Groups	N	Mean	SD	Min	Max	p-value
Coronal	Group 1A	10	3.791	0.403	3.21	4.42	0.19
	Group 2A	10	3.783	0.698	3.02	4.76	
	Group 1B	10	3.883	0.733	3.05	4.84	
	Group 2B	10	4.034	0.716	3.15	4.94	
	Group 1C	10	3.478	0.406	3.00	4.21	
	Group 2C	10	4.140	0.416	3.32	4.91	
Middle	Group 1A	10	3.042	0.581	2.13	3.71	0.69
	Group 2A	10	3.103	0.584	2.24	3.79	
	Group 1B	10	2.755	0.495	2.01	3.81	
	Group 2B	10	3.110	0.605	2.19	3.90	
	Group 1C	10	3.108	0.622	2.09	3.97	
	Group 2C	10	3.098	0.479	2.34	3.89	
Apical	Group 1A	10	1.524	0.272	1.09	1.98	0.67
	Group 2A	10	1.491	0.262	1.23	1.93	
	Group 1B	10	1.405	0.275	1.01	1.81	
	Group 2B	10	1.463	0.259	1.09	1.85	
	Group 1C	10	1.555	0.245	1.19	1.94	
	Group 2C	10	1.399	0.172	1.09	1.61	

B

Regions	Groups	N	Mean	SD	Min	Max	p-value
Coronal	Group 1A	10	0.477	0.208	0.19	0.83	<0.001*
	Group 2A	10	0.493	0.206	0.17	0.82	
	Group 1B	10	1.446	0.281	1.07	2.03	
	Group 2B	10	1.486	0.269	1.19	2.13	
	Group 1C	10	1.395	0.228	1.01	1.68	
	Group 2C	10	1.558	0.314	1.11	2.11	
Middle	Group 1A	10	0.616	0.316	0.13	1.09	<0.001*
	Group 2A	10	0.751	0.263	0.39	1.16	
	Group 1B	10	1.450	0.314	1.10	2.13	
	Group 2B	10	1.374	0.120	1.13	1.52	
	Group 1C	10	1.470	0.226	1.20	1.82	
	Group 2C	10	1.593	0.286	1.16	2.11	
Apical	Group 1A	10	0.603	0.233	0.26	0.99	<0.001*
	Group 2A	10	0.573	0.181	0.37	0.86	
	Group 1B	10	0.803	0.139	0.65	1.01	
	Group 2B	10	0.797	0.113	0.67	1.04	
	Group 1C	10	0.899	0.130	0.66	1.16	
	Group 2C	10	0.805	0.131	0.63	1.04	

Table no. 2.Multiple comparison of mean differences in canal volume after removing the Intra-canal medicament b/w 6 groups in a)coronal)middle and c)apical region using Tukey's post hoc Test

A

Region	(I) Group	(J) Groups	Mean Diff. (I-J)	95% CI for the Diff. Lower	95% CI for the Diff. Upper	p-value
Coronal	Group 1A	Group 2A	-0.016	-0.352	0.320	1.00
		Group 1B	-0.969	-1.305	-0.633	<0.001*
		Group 2B	-1.009	-1.345	-0.673	<0.001*
		Group 1C	-0.918	-1.254	-0.582	<0.001*
		Group 2C	-1.081	-1.417	-0.745	<0.001*
	Group 2A	Group 1B	-0.953	-1.289	-0.617	<0.001*
		Group 2B	-0.993	-1.329	-0.657	<0.001*
		Group 1C	-0.902	-1.238	-0.566	<0.001*
		Group 2C	-1.065	-1.401	-0.729	<0.001*
	Group 1B	Group 2B	-0.040	-0.376	0.296	1.00
		Group 1C	0.051	-0.285	0.387	1.00
		Group 2C	-0.112	-0.448	0.224	0.92
	Group 2B	Group 1C	0.091	-0.245	0.427	0.97
		Group 2C	-0.072	-0.408	0.264	0.99
	Group 1C	Group 2C	-0.163	-0.499	0.173	0.71

B

Region	(I) Group	(J) Groups	Mean Diff. (I-J)	95% CI for the Diff. Lower	95% CI for the Diff. Upper	p-value
Middle	Group 1A	Group 2A	-0.135	-0.482	0.212	0.86
		Group 1B	-0.834	-1.181	-0.487	<0.001*
		Group 2B	-0.758	-1.105	-0.411	<0.001*
		Group 1C	-0.854	-1.201	-0.507	<0.001*
		Group 2C	-0.977	-1.324	-0.630	<0.001*
	Group 2A	Group 1B	-0.699	-1.046	-0.352	<0.001*
		Group 2B	-0.623	-0.970	-0.276	<0.001*
		Group 1C	-0.719	-1.066	-0.372	<0.001*
		Group 2C	-0.842	-1.189	-0.495	<0.001*
	Group 1B	Group 2B	0.076	-0.271	0.423	0.99
		Group 1C	-0.020	-0.367	0.327	1.00
		Group 2C	-0.143	-0.490	0.204	0.83
	Group 2B	Group 1C	-0.096	-0.443	0.251	0.96
		Group 2C	-0.219	-0.566	0.128	0.44
	Group 1C	Group 2C	-0.123	-0.470	0.224	0.90

C

Region	(I) Group	(J) Groups	Mean Diff. (I-J)	95% CI for the Diff. Lower	95% CI for the Diff. Upper	p-value
Apical	Group 1A	Group 2A	0.030	-0.181	0.241	1.00
		Group 1B	-0.200	-0.411	0.011	0.04*
		Group 2B	-0.194	-0.405	0.017	0.04*
		Group 1C	-0.296	-0.507	-0.085	<0.001*
		Group 2C	-0.202	-0.413	0.009	0.04*
	Group 2A	Group 1B	-0.230	-0.441	-0.019	0.03*
		Group 2B	-0.224	-0.435	-0.013	0.03*
		Group 1C	-0.326	-0.537	-0.115	<0.001*
		Group 2C	-0.232	-0.443	-0.021	0.02*
	Group 1B	Group 2B	0.006	-0.205	0.217	1.00
		Group 1C	-0.096	-0.307	0.115	0.76
		Group 2C	-0.002	-0.213	0.209	1.00
	Group 2B	Group 1C	-0.102	-0.313	0.109	0.71
		Group 2C	-0.008	-0.219	0.203	1.00
	Group 1C	Group 2C	0.094	-0.117	0.305	0.78

Table 3.Comparison of mean Canal Volume (in mm3) between After filling and Removing the Intracanal medicament in diff. groups a)coronal, b) middle and c) apical using Paired Sample t Test

A

Groups	Irrigation	N	Mean	SD	Mean Diff	p-value
Group 1A	Pre Rx	10	3.791	0.403	3.314	<0.001*
	Post Rx	10	0.477	0.208		
Group 2A	Pre Rx	10	3.783	0.698	3.290	<0.001*
	Post Rx	10	0.493	0.206		
Group 1B	Pre Rx	10	3.883	0.733	2.437	<0.001*
	Post Rx	10	1.446	0.281		
Group 2B	Pre Rx	10	4.034	0.716	2.548	<0.001*
	Post Rx	10	1.486	0.269		
Group 1C	Pre Rx	10	3.478	0.406	2.083	<0.001*
	Post Rx	10	1.395	0.228		
Group 2C	Pre Rx	10	4.140	0.416	2.582	<0.001*
	Post Rx	10	1.558	0.314		

B

Groups	Irrigation	N	Mean	SD	Mean Diff	p-value
Group 1A	Pre Rx	10	3.042	0.581	2.426	<0.001*
	Post Rx	10	0.616	0.316		
Group 2A	Pre Rx	10	3.103	0.584	2.352	<0.001*
	Post Rx	10	0.751	0.263		
Group 1B	Pre Rx	10	2.755	0.495	1.305	<0.001*
	Post Rx	10	1.450	0.314		
Group 2B	Pre Rx	10	3.110	0.605	1.736	<0.001*
	Post Rx	10	1.374	0.120		
Group 1C	Pre Rx	10	3.108	0.622	1.638	<0.001*
	Post Rx	10	1.470	0.226		
Group 2C	Pre Rx	10	3.098	0.479	1.505	<0.001*
	Post Rx	10	1.593	0.286		

C

Groups	Irrigation	N	Mean	SD	Mean Diff	p-value
Group 1A	Pre Rx	10	1.524	0.272	0.921	<0.001*
	Post Rx	10	0.603	0.233		
Group 2A	Pre Rx	10	1.491	0.262	0.918	<0.001*
	Post Rx	10	0.573	0.181		
Group 1B	Pre Rx	10	1.405	0.275	0.602	<0.001*
	Post Rx	10	0.803	0.139		
Group 2B	Pre Rx	10	1.463	0.259	0.666	<0.001*
	Post Rx	10	0.797	0.113		
Group 1C	Pre Rx	10	1.555	0.245	0.656	<0.001*
	Post Rx	10	0.899	0.130		
Group 2C	Pre Rx	10	1.399	0.172	0.594	<0.001*
	Post Rx	10	0.805	0.131		

Table 4. Comparison of mean Total Canal Volume (in mm3) between After filling and Removing the Intracanal medicament in diff. groups using Paired Sample t Test

Groups	Irrigation	N	Mean	SD	Mean Diff	p-value
Group 1A	Pre Rx	10	8.357	0.800	6.661	<0.001*
	Post Rx	10	1.696	0.470		
Group 2A	Pre Rx	10	8.377	1.045	6.560	<0.001*
	Post Rx	10	1.817	0.418		
Group 1B	Pre Rx	10	8.043	0.709	4.344	<0.001*
	Post Rx	10	3.699	0.391		
Group 2B	Pre Rx	10	8.607	1.010	4.950	<0.001*
	Post Rx	10	3.657	0.331		
Group 1C	Pre Rx	10	8.141	0.722	4.377	<0.001*
	Post Rx	10	3.764	0.296		
Group 2C	Pre Rx	10	8.637	0.782	4.681	<0.001*
	Post Rx	10	3.956	0.500		

CONCLUSION

Within the limitations of this study, irrigant activation technique was found to be a critical determinant in the effective retrieval of intracanal medicaments. Laser-assisted activation demonstrated superior cleaning efficiency across all canal regions, indicating the advantage of enhanced fluid dynamics in overcoming anatomical complexities. While all tested methods contributed to significant medicament reduction, residual deposits persisted, particularly in the apical third, emphasizing the inherent limitations of current approaches. These findings highlight the need for optimized and possibly combined irrigation protocols to achieve more predictable and thorough canal debridement, especially when using newer intracanal medicaments.

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