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Original Article

The Efficacy of Brush File Used for Irrigation Activation Versus Passive Ultrasonic Irrigation in Terms of Smear Layer Removal and Canal Cleanliness in Single Rooted Teeth: A Comparative In-Vitro Study

Omnia Ibrahim El-Halaby, Alaa Diab, Dina A. Morsy

[1]Department of Endodontics, Faculty of Dentistry, Cairo University.

Email: omnia.halaby@dentistry.cu.edu.eg

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Abstract

Aim: The present study aimed to evaluate the cleaning efficacy of Brush File as an irrigation activation tool compared to Passive Ultrasonic Irrigation and conventional syringe and needle irrigation without activation in terms of smear layer and debris removal in single-rooted teeth.

Subjects and methods: 36 single-rooted premolars with single root-canal system were used, Root apices were sealed to simulate the in-vivo conditions. Instrumentation was done using Wave-one gold reciprocating system, then teeth were assigned randomly into three groups (n=12) according to the final irrigation protocol, group (1): Brush File (BF), group (2): Passive ultrasonic irrigation (PUI), group (3): Conventional irrigation with no activation (CI). Longitudinal splitting of teeth for Scanning Electron Microscope (SEM) imaging, Parente's scoring system was used for evaluation. Data were analyzed using Kruskal-Wallis and Mann-Whitney tests, with significance level set at ($p < 0.05$).

Results: The inter-group comparison showed that both BF and PUI groups removed smear layer and debris better than CI group at all root-canal thirds, with no significant difference between them ($p > 0.05$). For the intra-group comparison, no significant difference between the three root thirds in both BF group and CI group ($P > 0.05$). Regarding PUI, apical third showed the highest smear layer scores ($P = 0.013$), while the coronal third showed higher debris scores than middle third ($P = 0.05$).

Conclusion: No activation protocol completely removed smear layer and debris, Brush file showed great cleaning efficacy for both smear layer and debris at all root-canal thirds that were comparable to PUI.

Keywords: smear layer removal, canal cleanliness, Brush File, Passive ultrasonic activation (PUI), irrigation activation, Scanning electron microscope.

Introduction

The key elements for successful and predictable root canal treatment are both Cleaning and shaping[1]. Over the years, many advances were developed to obtain faster, safer and predictable preparation in the field of instrumentation, however, no single instrument alone can prepare the root canal space [2]. Since not all root canal systems are just round straight tunnels, instead they have complex anatomy varying from being oval, and irregular to having isthmuses, ramifications, lateral and accessory canals which hinder the irrigant penetration to these difficult-to-reach areas [3]. Together with the resulting organic and inorganic debris from mechanical preparation attached to the walls and packed into the dentinal tubules the role of irrigation is essential, beneficial and critical in root canal treatment success [4].

These irrigation solutions need to be in direct contact with the canal walls for effective action. It was claimed that irrigation with conventional needle showed ineffective results since fluid exchange occurs only just beyond the needle tip [5]. Besides, the vapor-lock effect present apically in closed tunnels hinders irrigant replenishment and efficacy in the apical part [6]. Consequently, different techniques and delivery devices were proposed aiming to enhance irrigant flow, exchange, distribution and efficacy in the root canal treatment [7,8].

Among the different agitation techniques proposed, Passive ultrasonic irrigation (PUI) being the most used technique. A non-cutting irrigation agitation protocol that depends on acoustic stream transmitted to the irrigant with its cavitation effect resulted from oscillation of a file or smooth wire in the root canal using ultrasonic waves which will disrupt the vapor lock [9].

Recently, a new tool called “Brush File Max” was introduced to enhance the efficacy of the irrigation. It is designed by twisting 6 strands of stainless-steel wires, these bristles will open as brushes when the instrument rotates in the canal activating the irrigation solution. This technique -according to the manufacturer- enhances cleaning hard-to-reach areas and improves debris/smear layer removal. It is 25 mm in length, with a 0.27 mm tip size and works with speed range 600 to 4000 rpm and torque value 0.05 to1 N.cm.

Up to the date, no studies were found assessing the Brush File as irrigation activation tool and its effectiveness on smear layer removal and canal cleanliness.

Thus, the aim of this study was to evaluate the efficiency of the Brush File (BF) compared to passive ultrasonic irrigation (PUI) as irrigation activation techniques on smear layer removal and canal cleanliness in single rooted teeth.

Subjects and Methods

Sample size

Based on the previous study of ***Caron et al., 2010*** [10] and using 80% power and 5% significance level thirty-six single rooted mandibular premolars were utilized in this study and divided into three groups each containing twelve samples.

Sample preparation

Pre-operative radiographs were taken from buccolingual and mesiodistal aspects to assess the presence of a single patent canal and the absence of internal resorption and confirm fulfilling eligibility criteria without any complexities or defects. The external root surfaces of the teeth were cleaned with a curette to remove calculus and periodontal tissues and then placed in 5.25% NaOCl for 30 minutes to remove soft tissue debris. Then, the teeth were stored in sterile saline till use. The teeth were decoronated using a low-speed diamond disc (Dental Fix, Canada) to obtain 16 mm uniform root lengths. Access cavity was refined using Endo-z bur (Dentsply Maillefer, Ballaigues, Switzerland) with High-speed handpiece under copious irrigation. K-file size #10 was inserted in the canal to check patency then working length was adjusted using K-file #15 to a

standardized working length of 15 mm. The apices were sealed by pink wax and embedded in Gypsum blocks by two-thirds of their lengths to prevent extrusion of the irrigation solution and simulate in-vivo conditions. The root canals were instrumented by Wave One Gold reciprocating system (DENTSPLY Sirona, U.S.). The small file (20.07) was used to the full W.L. to facilitate the progression of the primary file (26.07). Then, completing the canal preparation up to the medium file (35.06) using the E-connect S wireless endo-motor (Eighteeth, China) with counter-clockwise angle of 150o and clockwise one of 30o. In all groups, the canals were irrigated with 3 ml of freshly prepared 2.6% sodium hypochlorite solution as an irrigation solution after each file using a 30-gauge side vented needle (Rayblue, India) with the tip placed 1 mm shorter from the working length. Canal patency was retained by using #10 K-file between each rotary file. According to the final irrigation agitation regimen, specimens were randomly divided into three main groups (n=12).

Experimental groups distribution

❖Brush File group (BF): the canals were irrigated with 3 mL 2.6% NaOCl that was activated for one minute using Brush File (NPP "SOVA", RUSSIA) in an intermittent way activating each 1 mL of solution for 20 seconds. A single use file of 25 mm length and 0.27 tip size with zero taper, designed by counterclockwise twisting of 6 strands of stainless-steel wires. These bristles will open as brushes when the instrument rotates in the canal activating the irrigation solution achieving an un-paralleled cleaning and scrubbing action. Insertion of the BF to the WL followed by gentle and slow lengthwise movements at rotation speed of 1000 rpm in clockwise direction and torque value 1 N.cm. according to manufacturer's instructions. Then, the canals were flushed with 2.5 mL of saline and irrigated with 3 mL of 17% EDTA (Prevest DenPro, India) that was activated with BF for 1 min. as mentioned. Finally, the canals were rinsed with 2.5 mL saline and dried with paper points (META BIOMED, Korea) Size 35/06.

❖Passive ultrasonic irrigation group (PUI): the canals were irrigated with 3 mL 2.6% NaOCl where PUI was used to activate it with the woodpecker ultrasonic system and a U-file (Woodpecker, China) size #25. A Niti ultrasonic activation tip with K-file design, 33 mm in length and 0.02 taper. The tip was inserted into the canal 1 mm short of the WL, set at medium power setting (3W-20W) and the irrigant was ultrasonically activated for one minute in an intermittent way activating each 1 mL of solution for 20 seconds. The file was kept as centered as possible to minimize contact with the canal walls, as any contact with the canal wall could dampen the oscillatory motion of the file. Then the canal was flushed with 2.5 mL of saline and irrigated with 3 mL of 17% EDTA that was activated for 1 minute with PUI as mentioned. Finally, the canals were rinsed with 2.5 mL saline and dried with paper points Size 35/06.

❖Conventional irrigation with no activation (CI) group: it is the control group in which the canal was irrigated with 3 mL 2.6% NaOCl left in situ for one minute then flushed with 2.5 mL saline and filled again with 3 mL of 17% EDTA for one minute. Finally, the canals were rinsed with 2.5 mL saline and dried with paper points Size 35/06.

Outcome assessment

A Moist cotton pellet was placed in the canal opening before cutting off the grooves to prevent entrance of any debris formed during sectioning. Gypsum molds were then divided into two halves via chisel and mallet to facilitate preparation of the specimens for longitudinal splitting. Two longitudinal grooves were prepared on the buccal and lingual surfaces with a diamond disk to facilitate splitting of the roots. The grooves stopped just before the canal, then, chisel and mallet were used to complete the longitudinal splitting of the specimens into two halves. The split tooth was

then removed from the gypsum mold by a tweezer for subsequent examination of the two halves of each specimen under dental operating microscope (DOM) under 16x magnification for selection of the most representative half for SEM evaluation. The selected halves were then dehydrated and stored in sealed Eppendorf tubes. The root splits were then observed for residual debris and smear layer using SEM analysis (FEI Company, Hillsboro, Oregon, USA). The coronal, middle, and apical thirds of the root canal were examined individually in each specimen. **Parente et al.**[11] scoring system was used for assessment of the resultant photo-micrographs.

Scoring system for assessment of smear layer removal (*Parente et al., 2010*)

• Score 1: Smear layer is completely absent. Most tubules are patent and debris-free (coronal third and middle third) or occluded with sclerotic casts (apical third).

• Score 2: Smear layer covering <25% of the canal wall. Dentinal tubule orifices, when identified, may be reduced in dimensions owing to partial or complete occlusion by debris.

• Score 3: Smear layer is evident in 25–50% of the canal surface. Dentinal tubule orifices, when identified, may be reduced in dimensions owing to partial or complete occlusion by debris.

• Score 4: Smear layer is evident in 50–75% of the canal surface. Dentinal tubule orifices, when identified, may be reduced in dimensions owing to partial or complete occlusion by debris.

• Score 5: Smear layer covering 75–100% of the canal surface. Dentinal tubule orifices, when identified, may be reduced in dimensions owing to partial or complete occlusion by debris.

Scoring system for assessment of canal cleanliness (*Parente et al., 2010*)

• Score 1: clean canal wall, only very few debris particles.

• Score 2: few small conglomerations.

• Score 3: many conglomerations, <50% of the canal wall covered.

• Score 4: >50% of the canal wall covered with conglomerations.

• Score 5: complete cover of the canal walls with conglomerations.

Statistical analysis

Data were presented as mean, standard deviation, median and range. Between-group comparisons were conducted using Kruskal Wallis test followed by Mann Whitney U test for pairwise comparisons. Within-group comparisons were conducted using Friedman's test followed by Wilcoxon's signed rank test for pairwise comparisons. Significance level for statistical tests was set at $p < 0.05$. Statistical analysis was performed using SPSS software.

Results

Inter-groups comparison in the current study revealed that CI group had significantly higher smear layer and debris scores than BF and PUI at all root thirds, with no significant difference between BF and PUI groups ($P > 0.05$) (tables 1&2) (Fig. 1&3).

Table (1): descriptive statistics and the results of Kruskal Wallis test and Mann – Whitney U post hoc test for comparison of the Smear layer scores between the three groups:

		BF	PUI	CI	*p*-value
Coronal	Mean (SD)	1.58^{b} (0.67)	$1.75^{b\ B}$ (0.45)	2.75^{a} (0.62)	**<0.001***
	Median (Range)	1.5 (1 - 3)	2 (1 - 2)	2 (2 - 4)	
Middle	Mean (SD)	1.67^{b} (0.49)	$1.92^{b\ B}$ (0.51)	2.67^{a} (0.49)	**<0.001***
	Median (Range)	2 (1 - 2)	2 (1 - 3)	2 (2 - 3)	
Apical	Mean (SD)	2.0^{b} (0.6)	$2.33^{b\ A}$ (0.49)	3.08^{a} (0.67)	**0.001***
	Median (Range)	2 (1 - 3)	2 (2 - 3)	2 (2 - 4)	
p-value		0.331	**0.013***	0.223	

**Significant at p<0.05*

***Different small letters in the same row indicate significant difference between groups*

**** Different capital letters in the same column indicate significant difference between three root-canal thirds within same group*

Table (2): descriptive statistics and the results of Kruskal Wallis test and Mann – Whitney U post hoc test for comparison of the debris scores between the three groups:

		BF	PUI	CI	*p*-value
Coronal	Mean (SD)	1.75^{b} (0.75)	$1.67^{b\ B}$ (0.65)	3.0^{a} (0.6)	**<0.001***
	Median (Range)	2 (1 - 3)	2 (1 - 3)	2 (2 - 4)	
Middle	Mean (SD)	1.33^{b} (0.49)	$1.17^{b\ A}$ (0.39)	3.0^{a} (0.85)	**<0.001***
	Median (Range)	1 (1 - 2)	1 (1 - 2)	1 (2 - 5)	
Apical	Mean (SD)	1.33^{b} (0.49)	$1.42^{b\ BA}$ (0.51)	3.25^{a} (1.06)	**<0.001***
	Median (Range)	1 (1 - 2)	1 (1 - 2)	1 (2 - 5)	
p-value		0.228	**0.05***	0.999	

**Significant at p<0.05*

***Different small letters in the same row indicate significant difference between groups*

**** Different capital letters in the same column indicate significant difference between three root-canal thirds within same group*

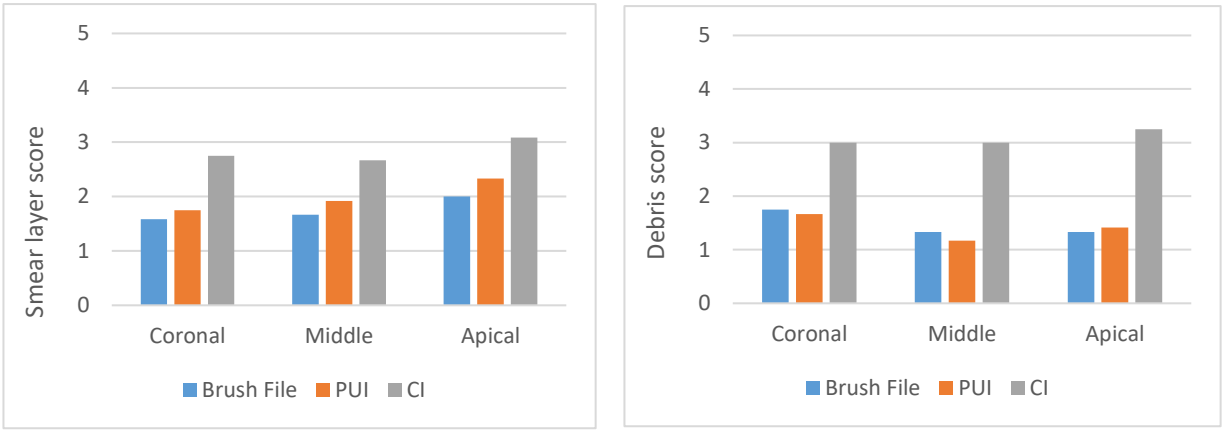

Fig. (1): Bar charts representing the mean smear layer and debris scores between the three groups

Intra-groups comparison showed no significant difference in the smear layer and debris scores between the three root-canal thirds for both BF and CI groups. While for PUI intra-group comparison, revealed a significantly higher smear layer score in the apical third than that of the middle third and the coronal third, with no significant difference between the coronal and the middle thirds (Table 1). Regarding the debris scores, it revealed a significantly higher debris score in the coronal third than the middle third, with no significant difference between the apical third and both the middle and coronal thirds (Table 2) (Fig. 2&3)

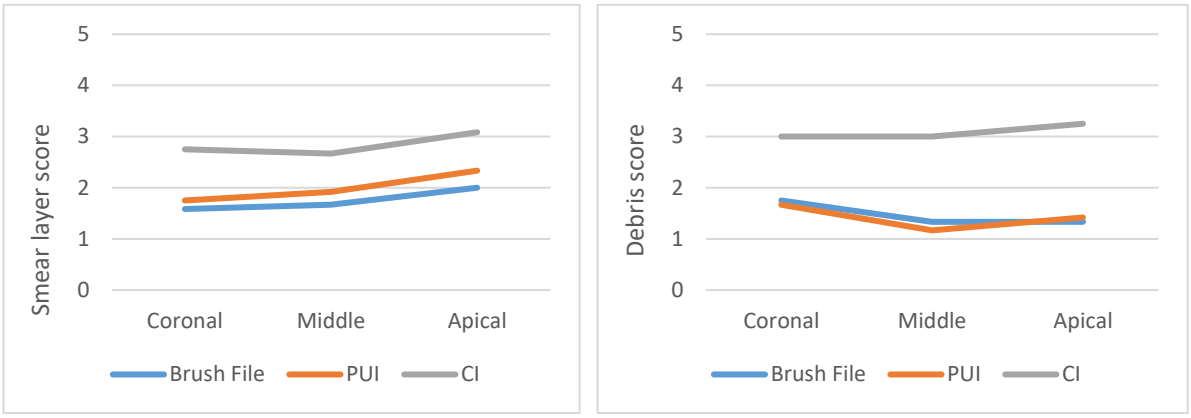

Fig. (2) Line charts representing the change in smear layer and debris scores within each group

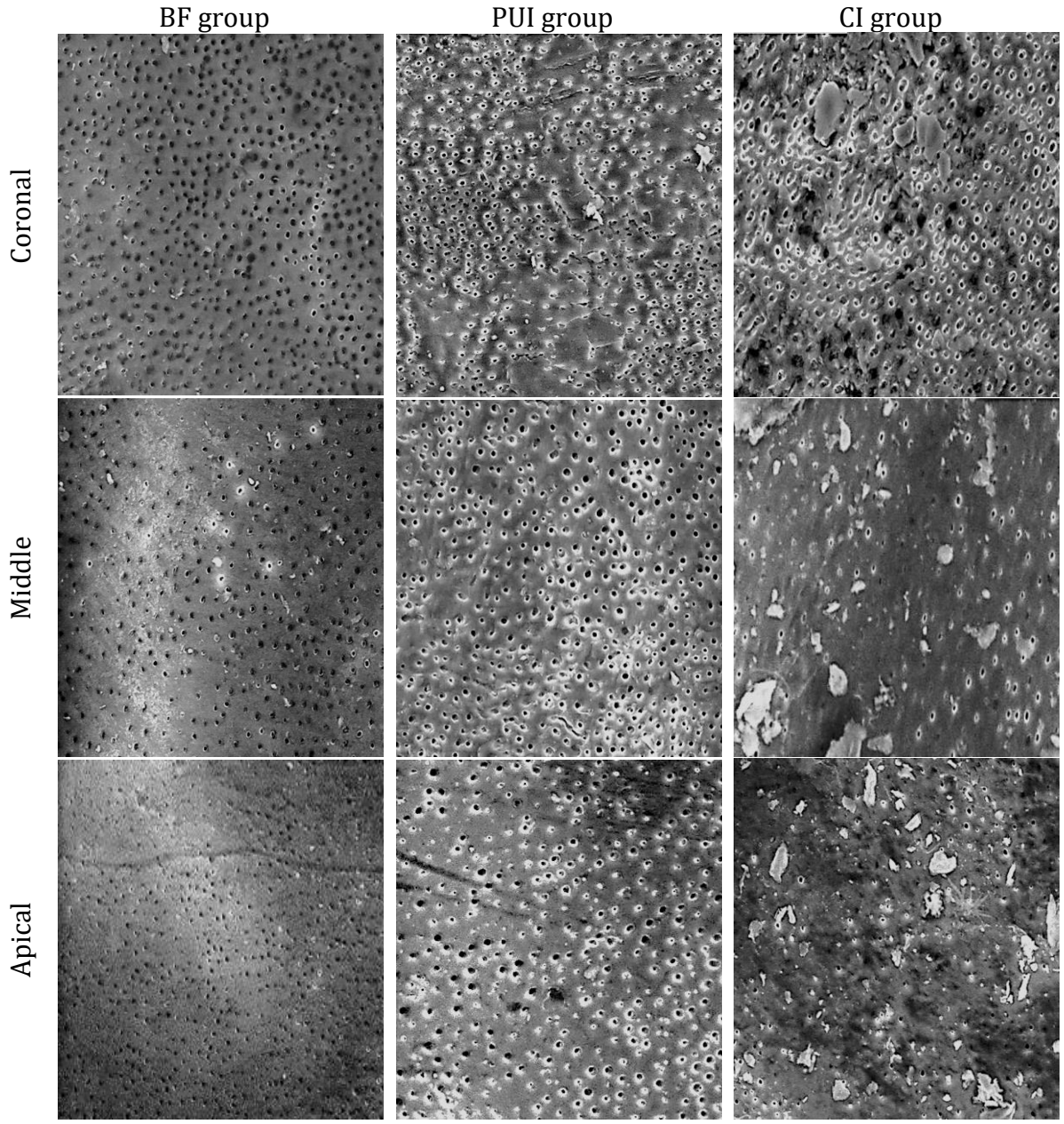

Figure (3): SEM photomicrographs representing the three groups at coronal, middle and apical thirds under 1000x magnification power showing residual smear layer and debris after final irrigation protocol

Discussion

Chemo-mechanical preparation involving both cleaning and shaping of the root canal system to receive a 3D-obturation and achieving a fluid-tight seal is the key element for successful and predictable endodontic treatment [1–3]. However, many challenges resulted in a shift in the role of "shaping" from being mainly a debridement function to a concept of being more as a radicular access for the irrigation to the complex root canal system [12–21]. Unfortunately, Conventional irrigation technique using syringe and needle can only deliver the irrigants to just beyond the needle tip [5,22]. So, different irrigant delivery devices and activation techniques were introduced to overcome these limitations and increase the efficacy of endodontic irrigation [8,23–25].

The aim of this in-vitro study was to evaluate the efficacy of brush file as an irrigation activation tool compared to passive ultrasonic irrigation and conventional irrigation with no activation in terms of Smear layer removal and canal cleanliness in single-rooted premolars with single oval canals.

To ensure standardization, Single-rooted mandibular premolars with oval straight canals showing type I Vertucci's canal configuration were chosen [26–29] and then decoronated to a uniform length of 16 mm [30–32].

The root apices were sealed with soft modeling wax and embedded into gypsum molds creating the fluid-tight seal of closed canal system in order to simulate the in-vivo clinical conditions [6,11,33,34].

The canals were prepared using Wave One Gold single file reciprocating system that showed better cyclic fatigue resistance, better centering ability and less transportation compared to multi-file continuous rotation systems [35–37]. However, they resulted in more debris and smear layer formation and more apical packing of debris along the dentinal tubules presenting a beneficial point to assess in our study by different irrigation activation regimens [38–40]. Canals were prepared up to the medium file size #35 taper 6%, which was proven to be the adequate apical preparation size and canal taper to facilitate deeper insertion of irrigation needle, more efficient irrigant replacement apically and effective reverse flow of irrigant coronally [22,41–45].

For irrigant delivery, 30-Gauge Side-vented needle was used and placed 1 mm from the working length, being the most efficient diameter for apical cleaning and allowing safe irrigant exchange apically compared to open-ended needles [46–48].

NaOCl irrigation is known for its excellent antimicrobial action, effectiveness against bacterial biofilms and organic tissue dissolving ability [49,50]. However, in the final irrigation protocol, A chelating agent such as EDTA was used for its inorganic tissue removal ability in order to effectively eradicate the smear layer [51,52]. So, Alternate application of 2.6% NaOCl followed by 17% EDTA [7,53–56] for 1 minute whether activated or not, which was proven to be the most effective time regarding debris removal and dentinal tubules exposure [57], and to avoid the erosive effect of EDTA on dentinal walls [58–60]. Normal saline was used between NaOCl and EDTA to prevent interactions between irrigants and was the last irrigation solution in all groups [61].

PUI is the mostly used supplementary irrigation agitation method [62]. Its action is based on acoustic microstreaming and subsequent cavitation effect by formation and implosion of vapor bubbles [24,63,64], that does not occur only at the file tip but along the length of the file and up to 2mm beyond the tip and at the entrance of lateral canals and isthmi [65,66].

U-file Niti ultrasonic tip of K-file design with size #25 and 0.02 taper was used in this study and inserted into the canal 1 mm short of the W.L. [63,64,67]. The ultrasonic tip was kept as centered as possible to minimize contact with the canal walls, as any contact of the oscillating tip with the canal wall will not only results in damping effect on oscillation, streaming and resultant cavitation but also, lead to debris and smear layer production during this final activation step as concluded by *Rius et al., 2020* [68].

Activation was performed in an intermittent activation technique with the delivery of fresh irrigants in between, allowing repeated start-up of oscillation and microstreaming, and permits continuous irrigant replenishment compared to the uninterrupted techniques [61].

The ultrasonic tip was used in dynamic motion with up and down movements to enhance its efficacy specially apically compared to the static protocol either

apically or per third as concluded by *Vivan et al., 2016* [69].

Sixty seconds application time was proven by *Plazza et al., 2022* [57] to be adequative and the most effective in removing debris and opening dentinal tubules compared to longer cycles which was explained by the absence of solution renovation and new debris formation.

For outcome assessment, Environmental SEM was used due to its capacity to offer indiscriminate view of surface topography [70] and the ability to take images of the specimens without the need for prior sample preparation with conductive coating, which allows easier procedural steps and avoids the samples distortion preserving the original state of the material eliminating any artifacts [71]. The 1000x magnification was chosen as it provides wide surface area together with fine details [72].

Parente's scoring system was preferred for being clear, detailed, easy to apply and provides two separate 5-point scoring systems for each smear layer and debris and for being more reproducible [11].

The result of our study showed that, regarding the inter-group comparison, BF and PUI groups significantly decreased smear layer and resulted in significant canal cleanliness at all root-canal thirds when compared to CI. These results came in accordance with previous studies that concluded that PUI and other mechanical activation techniques improved the canal cleanliness by increasing the irrigant movement inside the canal and the accompanied shear stresses on the canal [62,73–80].

No significant difference regarding the smear layer and debris score at all examined thirds was found between the BF group and the PUI group. Up to the date of this research, no studies were found evaluating the efficacy of Brush file as irrigant activation tool. However, the results came comparable to previous results found by *Neelakantan et al., 2018* [81] which showed that Finisher Gentlefile Brush (File with the same design as Brush File Max) was effective in improving canal cleanliness compared to CI. And also by *Nguyen et al., 2019* [82] who concluded that Gentlefile Brush was equivalent to PUI in the coronal and middle thirds, and superior to PUI in the apical third regarding root-canal filling material removal .

The results of intra-group comparison of BF group showed no significant difference between the three root-canal thirds regarding both smear layer and debris scores. From the obtained results of our study together with the previously conducted studies assessing efficacy of Files of similar design, BF is proven to be an efficient adjunctive agitation tool in improving canal cleanliness and smear layer removal at all root-canal thirds even apically which is the most challenging part in the root canal treatment.

The intra-group comparison results of PUI regarding smear layer removal showed that PUI significantly removed smear layer in coronal and middle thirds better than the apical. These results came confirmatory to previous studies that evaluated the efficacy of PUI at different root canal thirds [76,83–85]. However, our results are different from *Ahmad Ali et al., 2023* [86] that found no significant difference between the three root canal thirds after using 5.25% NaOCl with 31-gauge irrigation needle.

While for the PUI debris scores, the coronal third showed significantly higher debris score compared to the middle third, with no significant difference between apical third and both the middle and the coronal thirds. These results were also concluded by *Haupt et al., 2020* [44] and *Plazza et al., 2022* are in disagreement with what was concluded by *Titato et al., 2018* and *Urban et al., 2017* [78,87] that canal cleanliness and debris removal

increased significantly from apical to coronal.

Regarding the apical third, the decrease in canal diameter from coronal to apical supposedly increases and augments the shear stresses from the acoustic streaming and cavitation applied on the walls [63]. However, this decrease in diameter puts more risks on the ultrasonic tip to contact the canal walls accidently [68] and also limits the volume and the exchange of the irrigant [78]. Added to these factors, the vapor-lock effect presents apically limiting fluid exchange apically. These challenges caused the variability in apical third results, which was inferior to coronal and middle thirds regarding smear layer score but equivalent to them in the debris scores.

Conclusion:

1- No irrigation activation technique was capable of complete elimination of the smear layer and debris.
2- Regardless the final irrigation agitation technique, the effectiveness of smear layer removal and canal cleanliness decreases while moving from the coronal to the apical thirds of the root canal.
3- Brush File and PUI irrigation activation protocols were more efficient than conventional irrigation technique without activation regarding smear layer removal and canal cleanliness.
4- Brush File as irrigation agitation tool was an effective irrigant activation technique at all root-canal thirds, it was as efficient as PUI regarding smear layer removal and canal cleanliness.

Conflict of Interest:

The authors deny any conflicts of interest in this study.

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Ethics:

This study protocol was approved by the ethical committee of the faculty of dentistry- Cairo university on: 28/12/2021, approval number: 11221

References

1. **Hulsmann M, Peters OA, Dummer PMH.** Mechanical preparation of root canals: shaping goals, techniques and means. *Endod Top*.**2005**;10(1):30-76. doi:10.1111/j.1601-1546.2005.00152.x

2. **McComb D, Smith DC.** A preliminary scanning electron microscopic study of root canals after endodontic procedures. *J Endod*. **1975**;1(7):238-242. doi:10.1016/S0099-2399(75)80226-3

3. **Gulabivala K, Patel B, Evans G, Ng YL.** Effects of mechanical and chemical procedures on root canal surfaces. *Endod Top*. **2005**;10(1):103-122. doi:10.1111/j.1601-1546.2005.00133.x

4. **Violich DR, Chandler NP.** The smear layer in endodontics - A review. *Int Endod J*. **2010**;43(1):2-15. doi:10.1111/j.1365-2591.2009.01627.x

5. **Boutsioukis C, Lambrianidis T, Kastrinakis E.** Irrigant flow within a prepared root canal using various flow rates: A Computational Fluid Dynamics study. *Int Endod.J*.**2009**;42(2):144155. doi:10.1111/j.1365-2591.2008.01503.x

6. **Tay FR, Gu L sha, Schoeffel GJ, et al**. Effect of Vapor Lock on Root Canal Debridement by Using a Side-vented Needle for Positive-pressure Irrigant Delivery. *J Endod*.**2010**;36(4):745-750. doi:10.1016/j.joen.2009.11.022

7. **Kuah HG, Lui JN, Tseng PSK, Chen NN.** The Effect of EDTA with and without Ultrasonics on Removal of the Smear Layer. *J Endod*.**2009**;35(3):393-396. doi:10.1016/j.joen.2008.12.007

8. **Plotino G, Cortese T, Grande NM, et al**. New technologies to improve root canal disinfection. *Braz Dent J*. **2016**;27(1):3-8. doi:10.1590/0103-6440201600726

9. **De-Deus G, Belladonna FG, de Siqueira Zuolo A, et al.** Micro-CT comparison of XP-endo Finisher and passive ultrasonic irrigation as final irrigation protocols on the removal of accumulated hard-tissue debris from oval shaped-canals. *Clin Oral Investig*. **2019**;23(7):3087-3093. doi:10.1007/s00784-018-2729-y

10. **Caron G, Nham K, Bronnec F, MacHtou P.** Effectiveness of different final irrigant activation protocols on smear layer removal in curved canals. *J Endod*. **2010**;36(8):1361-1366. doi:10.1016/j.joen.2010.03.037

11. **Parente JM, Loushine RJ, Susin L, et al.** Root canal debridement using manual dynamic agitation or the EndoVac for final irrigation in a closed system and an open system. *Int Endod J*. **2010**;43(11):1001-1012. doi:10.1111/j.1365-2591.2010.01755.x

12. **Peters OA, Laib A, Göhring TN, Barbakow F.** Changes in root canal geometry after preparation assessed by high-resolution computed tomography. *J Endod*. **2001**;27(1):1-6. doi:10.1097/00004770-200101000-00001

13. **Peters OA, Peters CI, Scho K.** ProTaper rotary root canal preparation_ effects of canal anatomy on final shape analysed by micro CT I DeepDyve' - www_deepdyve_com_lp_wiley_prot-053.pdf. Published online **2003**:86-92.

14. **Eick JD, Wilko ROYA, Anderson CH, Sorensen SE.** Scanning Microscopy by Microprobe. *J Dent Res*. **1969**;49:1359-1369, 1970.

15. **Michelich VJ, Schuster GS, Pashley DH.** Bacterial Penetration of Human Dentin in vitro. *J Dent Res*. **1980**;59(8):1398-1403. doi:10.1177/00220345800590080701

16. **Pashley DH, Michelich V, Kehl T.** Dentin permeability: Effects of smear layer removal. *J Prosthet Dent*. **1981**;46(5):531-537. doi:10.1016/0022-3913(81)90243-2

17. **CERGNEUX M, CIUCCHI B, DIETSCHI JM, HOLZ J.** The influence of the smear layer on the sealing ability of canal obturation. *Int Endod J*. **1987**;20(5):228-232. doi:10.1111/j.1365-2591.1987.tb00619.x

18. **Williams S, Goldman M.** Penetrability of the Smeared Layer by a Strain of Proteus vulgaris Permeabilidad de la Capa de Barro Dentinario por una Cepa de Proteus vulgaris. *J Enbodontics*. **1985**;11(9):9-12.

19. **Baumgartner JC, Mader CL.** A scanning electron microscopic evaluation of four root canal irrigation systems. *J Endod*. **1987**;13(4):147-157.

20. **Goldman LB, Goldman M, Kronman JH, Lin PS.** The efficacy of several irrigating solutions for endodontics: A scanning electron microscopic study. *Oral Surgery, Oral Med Oral Pathol*. **1981**;52(2):197-204. doi:10.1016/0030-4220(81)90319-4

21. **Yang SE, Bae KS.** Scanning electron microscopy study of the adhesion of prevotella nigrescens to the dentin of prepared root canals. *J.Endod*.**2002**;28(6):433-437. doi:10.1097/00004770-200206000-00004

22. **Boutsioukis C, Gogos C, Verhaagen B, Versluis M, Kastrinakis E, van der Sluis LWM.** The effect of apical preparation size on irrigant flow in root canals evaluated using an unsteady Computational Fluid Dynamics model. *Int Endod J*. **2010**;43(10):874-881. doi:10.1111/j.1365-2591.2010.01761.x

23. **Gu L sha, Kim JR, Ling J, Choi KK, Pashley DH, Tay FR.** Review of Contemporary Irrigant Agitation Techniques

and Devices. *J Endod*. **2009**;35(6):791-804. doi:10.1016/j.joen.2009.03.010

24. **Tashkandi N, Alghamdi F.** Effect of Chemical Debridement and Irrigant Activation on Endodontic Treatment Outcomes: An Updated Overview. *Cureus*. **2022**;(January). doi:10.7759/cureus.21525

25. **van der Sluis L, Boutsioukis C, Jiang LM, Macedo R, Verhaagen B, Versluis M.** Root Canal Irrigation. **2015**;7(2):259-301. doi:10.1007/978-3-662-47415-0_9

26. **Siqueira Junior JF, Rôças I das N, Marceliano-Alves MF, Pérez AR, Ricucci D.** Unprepared root canal surface areas: Causes, clinical implications, and therapeutic strategies. *Braz.Oral.Res*.**2018**;32:1-19. doi:10.1590/1807-3107bor-2018.vol32.0065

27. **Versiani MA, Leoni GB, Steier L, et al.** Micro-computed tomography study of oval-shaped canals prepared with the self-adjusting file, reciproc, waveone, and protaper universal systems. *J Endod*. **2013**;39(8):1060-1066. doi:10.1016/j.joen.2013.04.009

28. **Weiger R, El Ayouti A, Löst C.** Efficiency of hand and rotary instruments in shaping oval root canals. *J Endod*. **2002**;28(8):580-583. doi:10.1097/00004770-200208000-00004

29. **Schneider SW.** A comparison of canal preparations in straight and curved root canals. *Oral Surgery, Oral Med Oral Pathol*. **1971**;32(2):271-275. doi:10.1016/0030-4220(71)90230-1

30. **Darrag AM**. Effectiveness of different final irrigation solutions on smear layer removal in intraradicular dentin. *Tanta Dent J*. **2014**;11(2):93-99. doi:10.1016/j.tdj.2014.06.002

31. **De Gregorio C, Estevez R, Cisneros R, Paranjpe A, Cohenca N.** Efficacy of different irrigation and activation systems on the penetration of sodium hypochlorite into simulated lateral canals and up to working length: An in vitro study. *J Endod*. **2010**;36(7):1216-1221. doi:10.1016/j.joen.2010.02.019

32. **Kour S, P.R P, R VK, Chaudhury T, Syam A.** Effect of Final Irrigating Solutions on Smear Layer Removal and Penetrability of an Epoxy Resin based Sealer into Dentinal Tubules. *Int J Contemp Med Res [IJCMR]*. **2019**;6(2):1-6. doi:10.21276/ijcmr.2019.6.2.22

33. **Sabet NE, Lutfy RA.** Ultrastructural morphologic evaluation of root canal walls prepared by two rotary nickel-titanium systems: a comparative study. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology*. **2008**;106(3):59-66. doi:10.1016/j.tripleo.2008.05.005

34. **Sáinz-Pardo M, Estevez R, de Pablo ÓV, Rossi-Fedele G, Cisneros R.** Root canal penetration of a sodium hypochlorite mixture using sonic or ultrasonic activation. *Braz Dent J*. **2014**;25(6):489-493. doi:10.1590/0103-6440201300209

35. **Poly A, Marques F, Moura Sassone L, Karabucak B.** The shaping ability of WaveOne Gold, TRUShape and XP-endo Shaper systems in oval-shaped distal canals of mandibular molars: A microcomputed tomographic analysis. *Int Endod J*. **2021**;54(12):2300-2306. doi:10.1111/iej.13625

36. **Shubhashini N, Sahu GK, Consul S, Nandakishore K, Idris M.** Rotary Endodontics or Reciprocating Endodontics: Which is New and Which is True? *J Heal Sci Res*. **2016**;7(2):51-57. doi:10.5005/jp-journals-10042-1035

37. **Thomas JP, Lynch M, Paurazas S, Askar M.** Micro–computed Tomographic Evaluation of the Shaping Ability of WaveOne Gold, TRUShape, EdgeCoil, and XP-3D Shaper Endodontic Files in Single, Oval-shaped Canals: An in Vitro Study. *J Endod*. **2020**;46(2):244-251.e1. doi:10.1016/j.joen.2019.11.001

38. **Ali M.** Comparative Evaluation of Smear Layer Formation of WaveOne Gold, Protaper Gold and Manual files: An in vitro

SEM Study. *Curr Sci Int*. Published online **2020**:381-386. doi:10.36632/csi/2020.9.2.33

39. **Dagna A, Gastaldo G, Beltrami R, Poggio C.** Debris Evaluation after Root Canal Shaping with Rotating and Reciprocating Single-File Systems. *J Funct Biomater*. **2016**;7(4):28. doi:10.3390/jfb7040028

40. **Poggio C, Dagna A, Chiesa M, Scribante A, Beltrami R, Colombo M.** Effects of NiTi rotary and reciprocating instruments on debris and smear layer scores: An SEM evaluation. *J Appl Biomater Funct Mater*. **2014**;12(3):256-262. doi:10.5301/jabfm.5000161

41. **Khademi A, Yazdizadeh M, Feizianfard M.** Determination of the Minimum Instrumentation Size for Penetration of Irrigants to the Apical Third of Root Canal Systems. *J Endod*. **2006**;32(5):417-420. doi:10.1016/j.joen.2005.11.008

42. **Tziafas D, Alraeesi D, Hormoodi R Al, Ataya M, Fezai H, Aga N.** Preparation prerequisites for effective irrigation of apical root canal: A critical review. *J Clin Exp Dent*. **2017**;9(10):e1256-e1263. doi:10.4317/jced.54117

43. **Vinel A, Sinan A, Dedieu M, Laurencin-Dalicieux S, Diemer F, Georgelin-Gurgel M.** Effect of apical preparation on different needle depth penetration. *G Ital Endod*. **2016**;30(2):96-100. doi:10.1016/j.gien.2016.09.004

44. **Haupt F, Meinel M, Gunawardana A, Hülsmann M**. Effectiveness of different activated irrigation techniques on debris and smear layer removal from curved root canals: a SEM evaluation. *Aust Endod J*. **2020**;46(1):40-46. doi:10.1111/aej.12342

45. **Rödig T, Sedghi M, Konietschke F, Lange K, Ziebolz D, Hülsmann M.** Efficacy of syringe irrigation, RinsEndo® and passive ultrasonic irrigation in removing debris from irregularities in root canals with different apical sizes. *Int Endod J*. **2010**;43(7):581-589. doi:10.1111/j.1365-2591.2010.01721.x

46. **Boutsioukis C, Verhaagen B, Versluis M, Kastrinakis E, Wesselink PR, van der Sluis LWM.** Evaluation of Irrigant Flow in the Root Canal Using Different Needle Types by an Unsteady Computational Fluid Dynamics Model. *J Endod*. **2010**;36(5):875-879. doi:10.1016/j.joen.2009.12.026

47. **Boutsioukis C, Gutierrez Nova P.** Syringe Irrigation in Minimally Shaped Root Canals Using 3 Endodontic Needles: A Computational Fluid Dynamics Study. *J Endod*. **2021**;47(9):1487-1495. doi:10.1016/j.joen.2021.06.001

48. **Guerreiro-Tanomaru JM, Loiola LE, Morgental RD, Leonardo R de T, Tanomaru-Filho M.** Efficacy of four irrigation needles in cleaning the apical third of root canals. *Braz Dent J*. **2013**;24(1):21-24. doi:10.1590/0103-6440201302153

49. **E Nuzzolese, M M Lepore, I Cukovic-Bagic FM, Vella and G Di.** Forensic sciences and forensic odontology. *Int Dent J*. **2008;**58(2009):342-348. doi:10.1922/IDJ

50. **Marion JJC, Manhães FC, Bajo H, Duque TM.** Efficiency of different concentrations of sodium hypochlorite during endodontic treatment. Literature review. *Dent Press Endod*. **2012**;2(4):32-37.

51. **Hülsmann M, Heckendorff M, Lennon Á.** Chelating agents in root canal treatment: Mode of action and indications for their use. *Int Endod J*. **2003**;36(12):810-830. doi:10.1111/j.1365-2591.2003.00754.x

52. **Mohammadi Z, Shalavi S, Jafarzadeh H.** Ethylenediaminetetraacetic acid in endodontics. *Eur J Dent*. **2013**;7(5 SUPPL.). doi:10.4103/1305-7456.119091

53. **Demirel A, Yüksel BN, Ziya M, Gümüş H, Doğan S, Sari Ş.** The effect of different irrigation protocols on smear layer removal in root canals of primary teeth: a SEM study. *Acta Odontol Scand*. **2019**;77(5):380-385. doi:10.1080/00016357.2019.1577491

54. **Menezes ACSC de, Zanet CG, Valera MC.** Smear layer removal capacity of disinfectant solutions used with and without EDTA for the irrigation of canals: a SEM study. *Pesqui Odontol Bras*. **2003**;17(4):349-355. doi:10.1590/S1517-74912003000400010

55. **Wang HH, Sanabria-Liviac D, Sleiman P, Dorn SO, Jaramillo DE.** Smear layer and debris removal from dentinal tubules using different irrigation protocols: scanning electron microscopic evaluation, an in vitro study. *Evidence-Based Endod*. **2017**;2(1):4-9. doi:10.1186/s41121-017-0011-4

56. **Wilkoński W, Jamróz-Wilkońska L, Zapotoczny S, Opiła J, Krupiński J, Pytko-Polończyk J.** The effects of alternate irrigation of root canals with chelating agents and sodium hypochlorite on the effectiveness of smear layer removal. *Adv Clin Exp Med*. **2020**;29(2):209-213. doi:10.17219/acem/112603

57. **Plazza FA, Dal-Fabbro R, Cosme-Silva L, et al.** Effectiveness of Passive Ultrasonic Irrigation Protocols in Simulated Complex Root Canal Cavities. *Oral*. **2022**;3(1):1-10. doi:10.3390/oral3010001

58. **Çalt S, Serper A.** Time-dependent effects of EDTA on dentin structures. *J Endod*. **2002**;28(1):17-19. doi:10.1097/00004770-200201000-00004

59. **De-Deus G, Paciornik S, Mauricio MHP.** Evaluation of the effect of EDTA, EDTAC and citric acid on the microhardness of root dentine. *Int Endod J*. **2006**;39(5):401-407. doi:10.1111/j.1365-2591.2006.01094.x

60. **Şen BH, Ertürk Ö, Pişkin B.** The effect of different concentrations of EDTA on instrumented root canal walls. *Oral Surgery, Oral Med Oral Pathol Oral Radiol Endodontology*. **2009**;108(4):622-627. doi:10.1016/j.tripleo.2009.04.042

61. **Boutsioukis C, Arias-Moliz MT**. Present status and future directions – irrigants and irrigation methods. *Int Endod J*. **2022**;55(S3):588-612. doi:10.1111/iej.13739

62. **Miguéns-Vila R, Martín-Biedma B, Aboy-Pazos S, et al.** Effectiveness of Different Irrigant Activation Systems on Smear Layer Removal: A Scanning Electron Microscopic Study. *J Clin Med*. **2022**;11(4). doi:10.3390/jcm11041003

63. **Ahmad M, Pitt Ford TR, Crum LA, Walton AJ.** Ultrasonic debridement of root canals: Acoustic cavitation and its relevance. *Int Endod J*. **2009**;42(5):391-398. doi:10.1111/j.1365-2591.2009.01560.x

64. **Boutsioukis C, Verhaagen B, van der Sluis LWM, Versluis M.** Irrigant flow in the root canal during ultrasonic activation: A numerical fluid–structure interaction model and its validation. *Int Endod J*. **2022**;55(9):938-949. doi:10.1111/iej.13791

65. **Macedo RG, Verhaagen B, Rivas DF, Versluis M, Wesselink P, Van Der Sluis L.** Cavitation measurement during sonic and ultrasonic activated irrigation. *J Endod*. **2014**;40(4):580-583. doi:10.1016/j.joen.2013.09.018

66. **Plotino G, Grande NM, Mercade M, et al.** Efficacy of sonic and ultrasonic irrigation devices in the removal of debris from canal irregularities in artificial root canals. *J Appl Oral Sci*. **2019**;27:1-6. doi:10.1590/1678-7757-2018-0045

67. **Van Der Sluis LWM, Versluis M, Wu MK, Wesselink PR.** Passive ultrasonic irrigation of the root canal: A review of the literature. *Int Endod J*. **2007**;40(6):415-426. doi:10.1111/j.1365-2591.2007.01243.x

68. **Rius L, Arias A, Aranguren JM, Romero M, de Gregorio C.** Analysis of the smear layer generated by different activation systems: an in vitro study. *Clin Oral Investig*. Published online **2020**. doi:10.1007/s00784-020-03355-9

69. **Vivan RR, Duque JA, Alcalde MP, Só MVR, Bramante CM, Duarte MAH.** Evaluation of different passive ultrasonic irrigation protocols on the removal of dentinal debris from artificial grooves. *Braz Dent J*.

2016;27(5):568-572. doi:10.1590/0103-6440201600725

70. **Kanodia S, Matta MS, Parmar GJ.** Original article: Stereomicroscopic and scanning electron microscopic evaluation of glyde file prep tm in smear layer removal Abstract: *Int J Healthc Biomed Res*. **2014**;2(2):170-177.

71. **Mancini M, Cerroni L, Iorio L, Armellin E, Conte G, Cianconi L.** Smear layer removal and canal cleanliness using different irrigation systems (EndoActivator, EndoVac, and passive ultrasonic irrigation): Field emission scanning electron microscopic evaluation in an in vitro study. *J Endod*. **2013**;39(11):1456-1460. doi:10.1016/j.joen.2013.07.028

72. **Mancini M, Cerroni L, Palopoli P, et al.** FESEM evaluation of smear layer removal from conservatively shaped canals: laser activated irrigation (PIPS and SWEEPS) compared to sonic and passive ultrasonic activation—an ex vivo study. *BMC Oral Health.* **2021**;21(1):1-10. doi:10.1186/s12903-021-01427-0

73. **Dioguardi M, Di Gioia G, Illuzzi G, et al.** Passive Ultrasonic Irrigation Efficacy in the Vapor Lock Removal: Systematic Review and Meta-Analysis. *Sci World J*. **2019**;2019. doi:10.1155/2019/6765349

74. **Justo AM, Da Rosa RA, Santini MF, et al.** Effectiveness of final irrigant protocols for debris removal from simulated canal irregularities. *J Endod*. **2014**;40(12):2009-2014. doi:10.1016/j.joen.2014.08.006

75. **Mozo S, Llena C, Chieffi N, Forner L, Ferrari M.** Effectiveness of passive ultrasonic irrigation in improving elimination of smear layer and opening dentinal tubules. *J Clin Exp Dent*. **2014**;6(1). doi:10.4317/jced.51297

76. **Orlowski NB, Schimdt TF, Teixeira C da S, et al.** Smear Layer Removal Using Passive Ultrasonic Irrigation and Different Concentrations of Sodium Hypochlorite. *J Endod*.**2020**;46(11):1738-1744. doi:10.1016/j.joen.2020.07.020

77. **Swimberghe RCD, Buyse R, Meire MA, De Moor RJG.** Efficacy of different irrigation technique in simulated curved root canals. *Lasers Med Sci***. 2021**;36(6):1317-1322. doi:10.1007/s10103-021-03263-8

78. **Urban K, Donnermeyer D, Schäfer E, Bürklein S.** Canal cleanliness using different irrigation activation systems: a SEM evaluation. *Clin Oral Investig*. **2017**;21(9):2681-2687. doi:10.1007/s00784-017-2070-x

79. **Kumar RS, Ankola A, Peerzade M, et al.** Comparative Efficacy of Different Irrigant Activation Techniques for Irrigant Delivery Up to the Working Length of Mature Permanent Teeth: A Systematic Review and Meta-Analysis. *Eur Endod J*. **2023**;8(1):1-19. doi:10.14744/eej.2022.87587

80. **Kumar RS, Ankola A, Peerzade M, et al.** Comparative Efficacy of Different Irrigant Activation Techniques for Irrigant Delivery Up to the Working Length of Mature Permanent Teeth: A Systematic Review and Meta-Analysis. *Eur Endod J*. **2023;**8(1):1-19. doi:10.14744/eej.2022.87587

81. **Neelakantan P, Khan K, Li KY, Shetty H, Xi W.** Effectiveness of supplementary irrigant agitation with the Finisher GF Brush on the debridement of oval root canals instrumented with the Gentlefile or nickel titanium rotary instruments. *Int Endod J*. **2018**;51(7):800-807. doi:10.1111/iej.12892

82. **Nguyen TA, Kim Y, Kim E, Shin SJ, Kim S.** Comparison of the efficacy of different techniques for the removal of root canal filling material in artificial teeth: A micro-computed tomography study. *J Clin Med*. **2019**;8(7). doi:10.3390/jcm8070984

83. **Blank-Gonalves LM, Nabeshima CK, Martins GHR, MacHado MEDL.** Qualitative analysis of the removal of the smear layer in the apical third of curved roots: Conventional irrigation versus activation

systems. *J Endod*. **2011**;37(9):1268-1271. doi:10.1016/j.joen.2011.06.009

84. **Kato AS, Cunha RS, Da Silveira Bueno CE, Pelegrine RA, Fontana CE, De Martin AS.** Investigation of the efficacy of passive ultrasonic irrigation versus irrigation with reciprocating activation: An environmental scanning electron microscopic study. *J Endod*. **2016;**42(4):659-663. doi:10.1016/j.joen.2016.01.016

85. **Machado R, da Silva I, Comparin D, de Mattos BAM, Alberton LR, da Silva Neto UX.** Smear layer removal by passive ultrasonic irrigation and 2 new mechanical methods for activation of the chelating solution. *Restor Dent Endod*.**2021**;46(1). doi:10.5395/rde.2021.46.e11

86. **Ahmad Ali I, Layous K, Alzoubi H.** Evaluating the Effectiveness of Different Irrigant Activation Techniques in Removing the Smear Layer and Opening the Dentinal Canals: A Scanning Electron Microscopic Study.*Cureus*.**2023**;15(1):1-10. doi:10.7759/cureus.33961

87. **Titato PCG, Canali LCF, Du-Que JA, Vivan RR, Duarte MAH.** Effect of the irrigation protocols on the elimination of dentin debris from simu-lated lateral canals. *Brazilian Dent.Sci*.**2018**;21(4):437-444. doi:10.14295/bds.2018.v21i4.1644