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Evaluation of Root Dentin Erosion Using Different Irrigation Techniques: A Scanning Electron Microscopy Study

[1]Majjari Amruta , [2]C. Sunil Kumar, [3]Vamsee Krishna N,
[4]S. Sunil Kumar , [5]K. S. Chandrababu, [6]R. Bharathi Suma
[2,3,4,5,6]MDS,
[1]Post Graduate ,[2]Professor and Head of the Department,
[3]Associate Professor, [4,5,6]Reader,
Department of Conservative Dentistry and Endodontics,
CKS Theja Institute of Dental Sciences and Research, Tirupati

***Corresponding Author:**
C. Sunil Kumar
Professor and Head of the Departmet, Department of Conservative Dentistry and Endodontics
CKS Theja Institute of Dental Sciences and Research, Tirupati

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Abstract

Background: Irrigant activation techniques improve the penetration and effectiveness of root canal irrigants. However, enhanced irrigant activation may also increase dentin erosion, potentially compromising the structural integrity of root dentin. This study evaluated and compared root dentin erosion produced by Manual Dynamic Agitation (MDA), Sonic Irrigation, and Passive Ultrasonic Irrigation (PUI) using Scanning Electron Microscopy (SEM).

Materials and Methods: Thirty extracted human single-rooted teeth with fully formed apices were decoronated to obtain a standardized root length of 15 mm and randomly allocated into three groups (n = 10): Group I—Manual Dynamic Agitation, Group II—Sonic Irrigation, and Group III—Passive Ultrasonic Irrigation. Root canals were instrumented using a standardized protocol with 3% sodium hypochlorite as the irrigant. Following irrigation activation, roots were longitudinally split and prepared for SEM evaluation. Dentin erosion was assessed at 2, 4, 6, and 8 mm from the apical foramen using a standardized scoring system. Statistical analysis was performed using one-way ANOVA followed by post hoc testing, with the level of significance set at $p < 0.05$.

Results: Passive Ultrasonic Irrigation demonstrated the highest mean erosion scores at all evaluated levels, followed by Sonic Irrigation, while Manual Dynamic Agitation exhibited the lowest erosion scores. The differences among the groups were statistically significant ($p < 0.05$).

Conclusion: Passive Ultrasonic Irrigation produced significantly greater root dentin erosion than Sonic Irrigation and Manual Dynamic Agitation. Manual Dynamic Agitation demonstrated the least erosive effect and may therefore better preserve dentin structure while providing irrigant activation.

Keywords: Dentin erosion; Endodontics; Irrigant activation; Manual Dynamic Agitation; Passive Ultrasonic Irrigation; Scanning Electron Microscopy

Introduction

Root canal treatment is a well-established procedure aimed at preserving teeth affected by pulpal and periapical diseases. The success of endodontic therapy depends on effective chemomechanical preparation, which includes both mechanical instrumentation and chemical irrigation. Although mechanical instrumentation shapes the root canal, it cannot completely eliminate microorganisms and debris from the complex root canal anatomy. Therefore, irrigation plays a crucial role in achieving adequate canal disinfection and improving treatment outcomes.[1]

Sodium hypochlorite (NaOCl) is considered the gold standard root canal irrigant because of its excellent antimicrobial activity and ability to dissolve organic tissues. However, it is ineffective in removing the inorganic component of the smear layer formed during instrumentation. Hence, 17% ethylenediaminetetraacetic acid (EDTA) is commonly used as a final rinse to remove the smear layer and expose dentinal tubules, thereby facilitating better penetration of irrigants and sealers.[2]

Despite the advantages of NaOCl and EDTA, their sequential use may adversely affect the structural integrity of root dentin. Chelating agents can demineralize dentin by removing calcium ions, resulting in erosion of the peritubular and intertubular dentin. Excessive dentin erosion enlarges dentinal tubules, reduces dentin microhardness, and may compromise the fracture resistance and sealing ability of endodontically treated teeth.[3]

Conventional syringe irrigation remains the most commonly employed method for irrigant delivery; however, its effectiveness is limited because the irrigant penetrates only a short distance beyond the needle tip and fails to adequately reach fins, isthmuses, lateral canals, and other anatomical complexities. Consequently, various irrigant activation techniques have been developed to enhance irrigant penetration and improve canal debridement.[4]

Among the currently available activation techniques, Passive Ultrasonic Irrigation (PUI), sonic activation using the EndoActivator, and Manual Dynamic Agitation (MDA) are widely used in clinical practice. Passive Ultrasonic Irrigation enhances irrigant effectiveness through acoustic streaming and cavitation, whereas sonic activation produces hydrodynamic agitation using flexible polymer tips. Manual Dynamic Agitation improves irrigant exchange by repeated push-pull movements of a well-fitting gutta-percha cone within the prepared canal.[5]

Although these activation techniques significantly improve smear layer removal and disinfection, they may also influence the extent of dentin erosion. Qian et al. demonstrated that the sequence of irrigating solutions plays an important role in dentin erosion, with ultrasonic activation producing greater structural changes when chelating agents are used.[6]

Subsequent investigations have also reported differences in the erosive potential of various irrigant activation systems. Kanaan et al. observed that activation techniques capable of producing greater irrigant agitation were associated with increased alterations in dentinal surface morphology.[7] More recently, Mathew et al. compared different activation techniques and reported significantly greater dentin erosion with Passive Ultrasonic Irrigation than with EndoActivator and Manual Dynamic Agitation.[8]

Although several studies have evaluated irrigant activation techniques individually, comparative evidence regarding their effect on root dentin erosion under standardized experimental conditions remains limited. Therefore, the present in vitro study was undertaken to evaluate and compare root dentin erosion produced by Passive Ultrasonic Irrigation, EndoActivator, and Manual Dynamic Agitation using Scanning Electron Microscopy. The null hypothesis tested was that there would be no significant difference in dentin erosion among the three irrigation activation techniques.

Materials And Methods

Study Design

The present in vitro study was conducted to evaluate root dentin erosion produced by different irrigation activation techniques using Scanning Electron Microscopy (SEM).

Sample Selection

A total of 30 extracted human single-rooted permanent teeth with completely formed roots and closed apices were collected from the Department of Oral and Maxillofacial Surgery. Teeth exhibiting cracks, structural defects, open apices, or developmental anomalies were excluded. Soft tissue remnants and calculus were removed, and the teeth were stored in normal saline until use.

Sample Preparation

Standard endodontic access cavities were prepared, and the crowns were decoronated to obtain a standardized root length of 15 mm. Working length was established by introducing a #10 K-file until its tip became visible at the apical foramen and subtracting 1 mm from the measured length. Biomechanical

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preparation was performed using ProTaper rotary files up to F3. During instrumentation, canals were irrigated with 3% sodium hypochlorite using a 30-gauge side-vented needle.

Preparation of Closed Flask Model

Longitudinal grooves were prepared on the mesial and distal root surfaces without penetrating the canal lumen. A gutta-percha point was placed inside the canal, and the apical foramen was sealed with wax. The specimens were embedded in silicone-based impression material within plastic vials to create a closed-flask system. The roots were then split longitudinally, and standardized reference indentations were created at 2 mm, 4 mm, 6 mm, and 8 mm from the apical foramen.

Baseline SEM Evaluation

Pre-irrigation SEM images were obtained at ×2500 magnification to evaluate the baseline morphology of root dentin.

Grouping of Samples

The specimens were randomly divided into three groups (n = 10):

- **Group I:** Passive Ultrasonic Irrigation (PUI)
- **Group II:** EndoActivator
- **Group III:** Manual Dynamic Agitation (MDA)

Irrigation Protocol

All specimens were irrigated using a standardized sequence of 3% sodium hypochlorite and 17% EDTA. Irrigation with sodium hypochlorite was performed in three activation cycles of 20 seconds each with replenishment of fresh irrigant after every cycle. This was followed by activation of 17% EDTA using the same protocol. A final cycle of sodium hypochlorite was then performed, followed by a final flush with double-distilled water.

For Group I, irrigant activation was performed using a Waldent Endo X Ultrasonic Activator with a 20/.02 ultrasonic tip positioned 1 mm short of the working length.

For Group II, sonic activation was carried out using the EndoActivator fitted with a 25/.04 polymer tip positioned 1 mm short of the working length.

For Group III, manual dynamic agitation was performed using a size 30/.09 gutta-percha cone with standardized push-pull strokes to within 1 mm of the working length.

Post-irrigation SEM Evaluation

Following completion of the irrigation protocol, SEM images were again obtained at ×2500 magnification at 2 mm, 4 mm, 6 mm, and 8 mm from the apical foramen. Root dentin erosion was assessed using a three-point ordinal scoring system: Score 1 – No erosion, Score 2 – Moderate erosion, and Score 3 – Severe erosion.

Statistical Analysis

The collected data were analyzed using the Statistical Package for the Social Sciences (SPSS) software. Mean and standard deviation were calculated for each group. Intergroup comparisons were performed using one-way analysis of variance (ANOVA), followed by Tukey's post hoc test for pairwise comparison. A p-value of less than 0.05 was considered statistically significant.

Results

The mean dentin erosion scores for the different irrigation activation techniques at 2 mm, 4 mm, 6 mm, and 8 mm from the apical foramen are presented in Table 1. Passive Ultrasonic Irrigation (PUI) demonstrated the highest dentin erosion scores at all evaluated levels, followed by EndoActivator and Manual Dynamic Agitation (MDA), while the control group showed no evidence of dentin erosion. One-way ANOVA revealed statistically highly significant differences among the study groups at all levels ($p < 0.001$). Tukey's post hoc analysis showed that PUI produced significantly greater dentin erosion than the other irrigation activation techniques at most evaluated levels. SEM examination further confirmed that dentinal erosion was most pronounced in the PUI group, moderate in the EndoActivator group, and least in the MDA group, with greater erosion observed in the apical region than in the coronal region. The detailed statistical analysis and representative SEM images are presented in Tables 1–6 and Figures 1–4.

Discussion

The present **in vitro** study evaluated the effect of Passive Ultrasonic Irrigation (PUI), EndoActivator, and Manual Dynamic Agitation (MDA) on root dentin

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erosion using scanning electron microscopy. The results demonstrated that all irrigation activation techniques produced dentin erosion when used with 3% sodium hypochlorite and 17% EDTA. Among the tested techniques, Passive Ultrasonic Irrigation consistently produced the highest dentin erosion scores at all evaluated levels, followed by EndoActivator, while Manual Dynamic Agitation exhibited the least erosion. Furthermore, dentin erosion was greatest in the apical third and gradually decreased towards the coronal region.

The erosive changes observed in the present study can be explained by the combined action of sodium hypochlorite and EDTA. Sodium hypochlorite degrades the organic component of dentin, whereas EDTA removes the inorganic mineral phase. The sequential use of these irrigants weakens the dentin matrix and increases its susceptibility to surface erosion, particularly when accompanied by irrigation activation. These findings are consistent with those reported by Rath et al., who highlighted that the interaction between sodium hypochlorite and chelating agents contributes to structural alterations of root dentin during endodontic irrigation.[9]

Passive Ultrasonic Irrigation demonstrated the greatest dentin erosion in the present investigation. This finding may be attributed to the generation of acoustic streaming and cavitation, which enhance irrigant penetration and increase contact between the irrigating solution and dentinal walls. Similar findings have been reported by Simezo et al., who observed significantly greater dentinal erosion following passive ultrasonic irrigation compared with other activation techniques.[10] Orlowski et al. also reported that ultrasonic activation improves smear layer removal but is associated with increased dentinal erosion because of enhanced irrigant activity.[11]

The EndoActivator group exhibited moderate dentin erosion, with values consistently lower than those observed with Passive Ultrasonic Irrigation but higher than those produced by Manual Dynamic Agitation. Sonic activation creates hydrodynamic agitation without producing cavitation, resulting in improved irrigant distribution while generating comparatively less mechanical stress on dentin. Abraham et al. reported similar findings and concluded that sonic activation provides effective irrigant agitation with reduced structural alteration when compared with ultrasonic activation.[12] Likewise, Akçay et al. demonstrated that different irrigation activation systems vary in their influence on dentin, with sonic devices producing less erosion than ultrasonic systems.[13]

Manual Dynamic Agitation produced the lowest dentin erosion scores among all experimental groups. Because this technique depends on manual movement of a gutta-percha cone rather than mechanically generated energy, it produces comparatively limited hydrodynamic forces within the canal. Dioguardi et al. reported that manual dynamic agitation improves irrigant distribution while preserving dentin integrity.[14] Krongbaramee et al. similarly concluded that manual agitation effectively enhances irrigant action without causing excessive dentinal erosion, supporting the findings of the present investigation.[15]

An important observation in the present study was that dentin erosion was greatest at the 2 mm level from the apical foramen. The confined anatomy of the apical region promotes greater irrigant retention and prolonged contact with dentin, thereby increasing the erosive effect. Wang et al. demonstrated that irrigation protocols involving sodium hypochlorite and EDTA produce greater mineral loss within root dentin, particularly following sequential application.[16] Park et al. further reported that irrigant flow dynamics and apical pressure influence irrigant penetration within the apical third, which may contribute to increased dentinal alteration in this region.[17]

Recent investigations have focused on developing irrigation protocols that achieve effective cleaning while minimizing dentin damage. Mikheikina et al. reported that etidronate-based continuous chelation protocols produced effective smear layer removal with comparatively controlled dentinal erosion.[18] Naladkar et al. also emphasized that recent advances in irrigants and activation systems are directed toward maximizing disinfection while preserving dentin structure.[19] Similarly, Lefevre et al. demonstrated that activation systems influence the chelating action of irrigants and should be selected carefully to balance cleaning efficiency and preservation of dentin integrity.[20]

Although Passive Ultrasonic Irrigation produced the highest dentin erosion in the present study, its superior cleaning ability has been widely recognized. Therefore, the choice of irrigation activation technique should consider both effective canal disinfection and preservation of root dentin. Manual Dynamic Agitation may be preferred in situations where conservation of dentin is a priority, whereas ultrasonic activation may be advantageous when enhanced irrigant penetration and smear layer removal are required. Future studies with larger sample sizes, different irrigant concentrations, and clinical evaluation are recommended to validate these findings and optimize irrigation protocols for routine endodontic practice.

Limitations

The study was conducted in-vitro which may not fully represent the complex biological condition present in the oral cavity. Considering the limited number of samples, the results may have restricted external validity. Only a single irrigation protocol was followed (3% NaOCl and 17% EDTA), whereas variations in concentration, volume, and sequence could influence the extent of dentinal erosion. The assessment of erosion was based on a qualitative scoring system using SEM, which, although widely accepted, may introduce a degree of subjectivity. The study focused exclusively on dentinal erosion but did not focus on parameters such as smear layer removal efficiency, microhardness, fracture resistance, or long-term clinical outcomes.

Conclusion

Within the limits of this study, it can be stated that irrigant activation techniques significantly influence dentinal erosion. Passive ultrasonic irrigation was found to be the most effective in enhancing irrigant action but also resulted in the greatest degree of dentinal erosion, especially in the apical region. The EndoActivator system demonstrated a balanced performance by improving irrigant effectiveness while causing moderate structural changes. Manual dynamic agitation showed the least dentinal erosion as it is comparatively less effective in modifying the canal surface. The results highlight a critical clinical consideration: while advanced activation techniques improve cleaning efficiency, they may also compromise dentin integrity if not used judiciously. Therefore, a careful balance between effective disinfection and preservation of dentinal structure is essential during endodontic treatment.

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Table 1: Descriptive Statistics (Mean ± Standard Deviation)

Group	**2 mm (Mean ± SD)**	**4 mm (Mean ± SD)**	**6 mm (Mean ± SD)**	**8 mm (Mean ± SD)**
Control	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
MDA (Group 1)	1.60 ± 0.51	1.60 ± 0.51	1.40 ± 0.51	1.20 ± 0.42
EndoActivator (Group 2)	2.30 ± 0.48	1.80 ± 0.63	1.80 ± 0.63	1.30 ± 0.48
PUI (Group 3)	2.70 ± 0.48	2.60 ± 0.52	2.40 ± 0.52	2.60 ± 0.52

Table 1 illustrate the mean dentin erosion scores along with standard deviations for all experimental groups at different levels from the apical foramen. The results demonstrate that Passive Ultrasonic Irrigation (PUI) (Group I) consistently exhibited the highest mean erosion scores at all levels, followed by EndoActivator (Group II) and Manual Dynamic Agitation (MDA) (Group III), while the control group showed no erosion.

At the apical level (2 mm), the highest erosion was observed, particularly in the PUI group (2.70 ± 0.48), indicating increased susceptibility of apical dentin to irrigant activation. A gradual variation in erosion values was observed toward the coronal levels. The EndoActivator group (Group II) showed moderate erosion, whereas MDA (Group III) demonstrated comparatively lower erosion across all levels.

Table 2: One-Way ANOVA Comparison Between Groups

Level	F-value	p-value	Significance
2 mm	78.63	<0.001	Highly Significant
4 mm	45.78	<0.001	Highly Significant
6 mm	36.29	<0.001	Highly Significant
8 mm	59.82	<0.001	Highly Significant

Table 2 present the comparison of mean dentin erosion scores among different irrigation techniques using one-way ANOVA at various levels from the apical foramen. The results demonstrate that there was a statistically highly significant difference among the groups at all levels ($p < 0.001$), indicating that the type of irrigation activation technique significantly influences dentin erosion. The table illustrates the variation in F-values across levels, with the highest F-value observed at 2 mm, suggesting maximum intergroup variation in the apical region. A decrease in F-value is noted at 4 mm and 6 mm, followed by a slight increase at 8 mm, indicating variability in the extent of differences along the root canal length.

Table 3: Tukey Post Hoc Test (2 mm)

Comparison	Mean Difference	p-value	Significance
Control vs MDA	0.6	0.0001	Significant
Control vs EndoActivator	1.3	<0.001	Significant
Control vs PUI	1.7	<0.001	Significant
MDA vs EndoActivator	0.7	0.0002	Significant
MDA vs PUI	1.1	<0.001	Significant
EndoActivator vs PUI	0.4	0.055	Not Significant

Table 3 depict the pairwise comparison of mean dentin erosion scores among the different irrigation techniques at the 2 mm level using Tukey's post hoc test. The results show that all experimental groups exhibited significantly higher dentin erosion compared to the control group ($p < 0.05$). Among the experimental groups, passive ultrasonic irrigation (PUI) demonstrated significantly greater erosion compared to manual dynamic agitation (MDA), while EndoActivator also showed significantly higher erosion than MDA. However, no statistically significant difference was observed between EndoActivator and PUI ($p > 0.05$), indicating comparable effects between these two techniques at the apical level.

Table 4: Tukey Post Hoc Test (4 mm)

Comparison	Mean Difference	p-value	Significance
Control vs MDA	0.6	0.0005	Significant
Control vs EndoActivator	0.8	<0.001	Significant
Control vs PUI	1.6	<0.001	Significant
MDA vs EndoActivator	0.2	0.657	Not Significant
MDA vs PUI	1.0	<0.001	Significant

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EndoActivator vs PUI	0.8	0.0001	Significant

Table 4 present the pairwise comparison of mean dentin erosion scores at the 4 mm level using Tukey's post hoc test. The results show that all experimental groups exhibited significantly higher dentin erosion compared to the control group ($p < 0.05$). Among the experimental groups, passive ultrasonic irrigation (PUI) demonstrated significantly greater erosion compared to both manual dynamic agitation (MDA) and EndoActivator. However, no statistically significant difference was observed between MDA and EndoActivator ($p > 0.05$), indicating similar effects between these two techniques at this level.

Table 5: Tukey Post Hoc Test (6 mm)

Comparison	**Mean Difference**	**p-value**	**Significance**
Control vs MDA	0.4	0.031	Significant
Control vs EndoActivator	0.8	<0.001	Significant
Control vs PUI	1.4	<0.001	Significant
MDA vs EndoActivator	0.4	0.108	Not Significant
MDA vs PUI	1.0	<0.001	Significant
EndoActivator vs PUI	0.6	0.005	Significant

Table 5 illustrate the pairwise comparison of mean dentin erosion scores at the 6 mm level using Tukey's post hoc test. The results indicate that all experimental groups showed significantly higher dentin erosion compared to the control group ($p < 0.05$). Passive ultrasonic irrigation (PUI) demonstrated significantly greater erosion compared to both MDA and EndoActivator. However, no statistically significant difference was observed between MDA and EndoActivator ($p > 0.05$), suggesting similar erosive effects between these two techniques at this level.

Table 6: Tukey Post Hoc Test (8 mm)

Comparison	**Mean Difference**	**p-value**	**Significance**
Control vs MDA	0.2	0.354	Not Significant
Control vs EndoActivator	0.3	0.072	Not Significant
Control vs PUI	1.6	<0.001	Significant
MDA vs EndoActivator	0.1	0.905	Not Significant
MDA vs PUI	1.4	<0.001	Significant
EndoActivator vs PUI	1.3	<0.001	Significant

Table 6 present the pairwise comparison of mean dentin erosion scores at the 8 mm level using Tukey's post hoc test. The results show that no statistically significant difference was observed between the control group, MDA, and EndoActivator ($p > 0.05$), indicating similar dentin erosion among these groups at the coronal level. However, passive ultrasonic irrigation (PUI) demonstrated significantly higher dentin erosion compared to all other groups ($p < 0.05$).

Fig 1: Pre-irrigation SEM images were obtained at 2 mm, 4 mm, 6 mm, and 8 mm from the apical foramen at a magnification of ×2500.

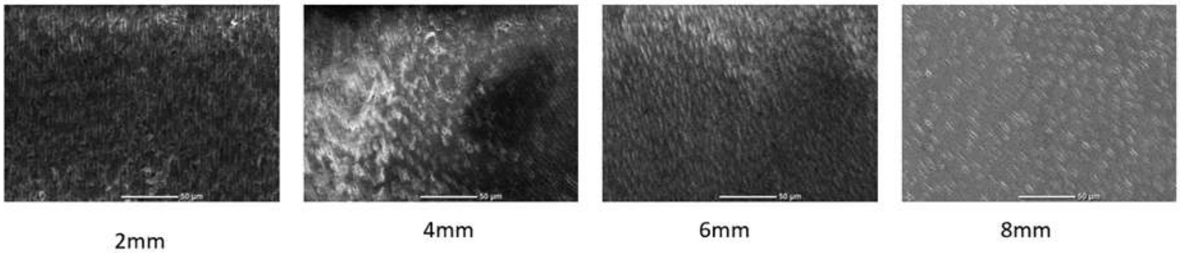

Fig 3: Post-irrigation scanning electron microscope (SEM) images of root canal dentin following sonic activation using EndoActivator, obtained at 2 mm, 4 mm, 6 mm, and 8 mm from the apical foramen at a magnification of ×2500.

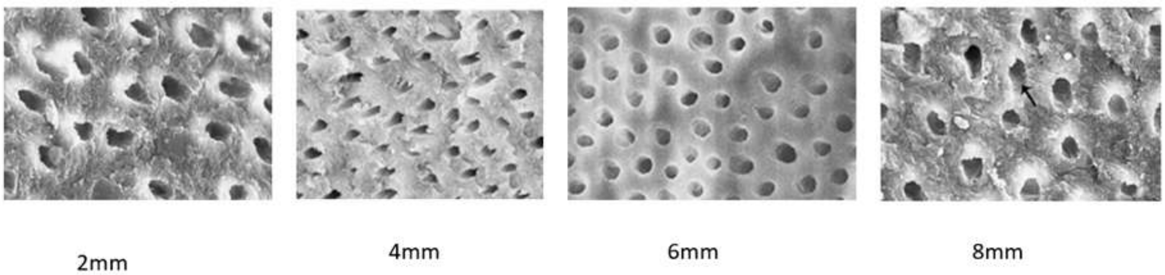

Fig 4: Post-irrigation scanning electron microscope (SEM) images of root canal dentin following manual dynamic agitation, obtained at 2 mm, 4 mm, 6 mm, and 8 mm from the apical foramen at a magnification of ×2500.