

Comparative Analysis of Irrigation Techniques on Root Canal Cleanliness: Evaluating Traditional, Ultrasonic, Laser-Activated, and Mechanically-Assisted Methods for Debris and Smear Layer Removal

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Abstract

Background: Effective root canal cleaning is vital for the success of endodontic therapy. Traditional syringe irrigation often fails to adequately clean complex root canal anatomies, particularly in the apical third, necessitating the development of advanced irrigation techniques. Ultrasonic, laser-activated, and mechanically assisted irrigation systems aim to enhance the removal of debris and smear layers, improving treatment outcomes.

Aim: This study aimed to compare the efficacy of traditional syringe irrigation, ultrasonic irrigation, laser-activated irrigation, and mechanically-assisted irrigation in removing debris and smear layers from root canals.

Methods: Sixty extracted single-rooted teeth were randomly divided into four groups (n=15 per group), each subjected to one of the irrigation techniques. Root canals were prepared using a standardized protocol and evaluated for cleanliness in the coronal, middle, and apical thirds using scanning electron microscopy (SEM). Data were analyzed using one-way ANOVA and Tukey's post hoc tests, with significance set at $p < 0.05$.

Results: Laser-activated irrigation achieved the highest cleaning efficacy, with mean scores of 2.0 ± 0.3 for debris and 2.2 ± 0.3 for smear layers. Mechanically-assisted irrigation also performed well (debris: 2.3 ± 0.4 ; smear layers: 2.5 ± 0.4). Ultrasonic irrigation showed moderate effectiveness, while traditional syringe irrigation was the least effective (debris: 4.1 ± 0.5 ; smear layers: 4.2 ± 0.4). Statistical analysis revealed significant differences among the groups ($p < 0.05$).

Conclusion: Laser-activated irrigation proved to be the most effective technique for root canal cleaning, followed by mechanically-assisted irrigation. Ultrasonic irrigation demonstrated moderate performance, while traditional syringe irrigation showed limited efficacy, particularly in the apical third.

Recommendations: The study highlights the need to incorporate advanced irrigation techniques such as laser-activated and mechanically-assisted systems for better clinical outcomes. Future clinical trials are recommended to validate these findings and assess their long-term impact.

Keywords: Root canal irrigation, Debris removal, Smear layer, Laser-activated irrigation, Scanning electron microscopy (SEM)

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Introduction

Effective cleaning and shaping of the root canal system are essential components of successful endodontic treatment. This process aims to eliminate debris, smear layers, and microbial biofilms from the intricate anatomy of root canals. Traditional syringe irrigation has long been the mainstay for delivering irrigants such as sodium hypochlorite into the canals. However, its effectiveness is limited due to inadequate penetration into complex canal anatomies, particularly in the apical third and lateral canals [1]. This has led to the development and adoption of

advanced irrigation techniques designed to enhance cleaning efficacy.

Ultrasonic irrigation is a significant advancement in endodontic irrigation techniques. It employs high-frequency ultrasonic energy to activate irrigants, creating acoustic streaming and cavitation. This mechanism increases irrigant penetration into lateral canals and dentinal tubules, enhancing debris and smear layer removal. A recent study highlighted that passive ultrasonic irrigation achieves superior canal cleanliness compared to traditional syringe irrigation, especially in the apical third [2].

Laser-activated irrigation (LAI) represents another innovative approach, utilizing laser energy to induce rapid fluid movement and cavitation within the root canal system. This technique improves the delivery and activation of irrigants without direct contact with canal walls, thereby reducing the risk of procedural errors such as canal transportation. A study by DiVito et al. (2020) demonstrated that LAI effectively removed smear layers and biofilms, showing significant improvements over conventional methods [3].

Mechanically-assisted irrigation devices, such as the GentleWave® system, are designed to address the limitations of traditional and ultrasonic methods. These systems employ multisonic energy to create a continuous flow and vortex of irrigants, effectively debriding even the most challenging canal anatomies. Studies have reported that mechanically-assisted irrigation achieves higher levels of cleanliness in lateral canals and isthmuses compared to traditional syringe irrigation [4].

Scanning electron microscopy (SEM) remains a gold standard for evaluating the effectiveness of irrigation techniques. SEM provides detailed imaging of canal walls, allowing quantitative assessment of debris and smear layer removal. Recent advancements in SEM technology have improved the precision of such evaluations, facilitating evidence-based comparisons of irrigation methods [5].

In summary, advanced irrigation techniques such as ultrasonic, laser-activated, and mechanically-assisted systems have demonstrated superior efficacy in enhancing root canal cleanliness. These innovations represent significant progress in endodontic practice, ensuring better treatment outcomes and reducing the risk of post-treatment complications.

Methodology

Study Design: This study is a prospective in vitro experimental study.

Study Setting: The study will be conducted in the Department of Dentistry at Anugrah Narayan Magadh Medical College and Hospital (ANMMCH), Gaya. The duration of the study is three months.

Participants: A total of 60 extracted human teeth will be used as samples in this study. These teeth will be collected from patients undergoing extractions for therapeutic or orthodontic purposes and will be prepared for the study based on standardized protocols.

Inclusion Criteria

- Extracted single-rooted human teeth with straight canals.

- Teeth free of caries, fractures, and external resorption.
- Teeth with no previous endodontic treatment.

Exclusion Criteria

- Multirrooted or severely curved canals.
- Teeth with restorations, cracks, or calcifications.
- Teeth showing evidence of internal resorption.

Bias: To minimize bias, all samples will be randomly assigned to the respective irrigation technique groups using a computer-generated randomization table. A single experienced operator will perform all procedures to ensure standardization and consistency across groups.

Data Collection: SEM will be used to analyze the cleanliness and effectiveness of the irrigation techniques. The samples will be sectioned longitudinally, and debris and smear layer removal will be evaluated at the coronal, middle, and apical thirds of the canals. SEM images will be obtained at a standardized magnification, and the debris and smear layer will be scored using a validated scoring system.

Procedure: The 60 teeth will be randomly divided into four groups of 15 teeth each:

Group A: Traditional syringe irrigation with sodium hypochlorite.

Group B: Ultrasonic irrigation with sodium hypochlorite.

Group C: Laser-activated irrigation.

Group D: Mechanically-assisted irrigation.

Root canals will be prepared using rotary instrumentation under irrigation.

Each group will undergo its respective irrigation protocol.

After irrigation, the teeth will be split longitudinally for SEM evaluation.

SEM images will be analyzed for the presence of debris and smear layers, and the data will be recorded.

Statistical Analysis: Data will be analyzed using SPSS version 23.0. Descriptive statistics will summarize the scores for debris and smear layer removal in each group. Comparisons between groups will be performed using one-way ANOVA, followed by post hoc Tukey's test for pairwise comparisons. A p-value < 0.05 will be considered statistically significant. Results will be presented in tabular and graphical formats.

Ethical Considerations

The study will be conducted following ethical guidelines. Approval will be obtained from the

Institutional Ethics Committee of ANMMCH, Gaya, for the use of extracted teeth. Informed consent will be taken from patients for using extracted teeth in the study.

Results

Participants: A total of 60 extracted teeth were included in the study, divided equally into four

groups of 15 each. Each group underwent its respective irrigation technique, and cleanliness was evaluated using SEM for debris and smear layer removal across coronal, middle, and apical thirds.

Statistical Analysis: One-way ANOVA was used to compare the groups, with Tukey's post hoc tests for pairwise comparisons. Statistical significance was set at $p < 0.05$.

Table 1: Mean Scores for Debris and Smear Layer Removal

Group	Debris Removal (Mean \pm SD)	Smear Layer Removal (Mean \pm SD)	Overall Cleanliness (Mean \pm SD)
Traditional Syringe	4.1 \pm 0.5	4.2 \pm 0.4	4.2 \pm 0.5
Ultrasonic Irrigation	2.8 \pm 0.4	2.9 \pm 0.4	2.9 \pm 0.4
Laser-Activated Irrigation	2.0 \pm 0.3	2.2 \pm 0.3	2.1 \pm 0.3
Mechanically Assisted	2.3 \pm 0.4	2.5 \pm 0.4	2.4 \pm 0.4

Table 2: Region-Wise Mean Scores for Debris Removal

Group	Coronal Third (Mean \pm SD)	Middle Third (Mean \pm SD)	Apical Third (Mean \pm SD)
Traditional Syringe	3.8 \pm 0.5	4.0 \pm 0.6	4.5 \pm 0.5
Ultrasonic Irrigation	2.5 \pm 0.4	2.7 \pm 0.5	3.1 \pm 0.4
Laser-Activated Irrigation	1.7 \pm 0.3	2.0 \pm 0.4	2.5 \pm 0.3
Mechanically-Assisted	2.0 \pm 0.4	2.3 \pm 0.3	2.7 \pm 0.4

Summary of results

Laser-activated irrigation: was significantly more effective due to its ability to thoroughly activate irrigants and reach all regions of the canal, particularly the apical third.

Mechanically-assisted and ultrasonic irrigation: performed similarly, both demonstrating clear advantages over the traditional method.

Traditional syringe irrigation: failed to achieve adequate cleanliness, especially in the apical third, underscoring its limitations.

Discussion

The study evaluated the effectiveness of four different irrigation techniques—traditional syringe irrigation, ultrasonic irrigation, laser-activated irrigation, and mechanically-assisted irrigation—in achieving root canal cleanliness, assessed by debris and smear layer removal across 60 teeth. The results demonstrated significant differences in performance between the groups, with laser-activated irrigation consistently outperforming the other techniques across all parameters.

Laser-Activated Irrigation: was the most effective, achieving the lowest scores for both debris and smear layer removal in all regions of the root canal. This technique demonstrated superior per-

formance, particularly in the apical third, where achieving cleanliness is typically more challenging. The advanced activation mechanism of laser-activated irrigation likely facilitated enhanced

irrigant penetration and agitation, leading to superior debris and smear layer removal.

Mechanically-Assisted Irrigation: ranked second in overall effectiveness, showing consistent performance across coronal, middle, and apical thirds. Its scores for debris and smear layer removal were significantly better than traditional syringe irrigation and slightly less effective than laser-activated irrigation. The mechanical activation provided by this technique likely contributed to improved irrigant distribution and effectiveness.

Ultrasonic Irrigation: provided moderate results, showing clear advantages over traditional syringe irrigation but falling short of the performance of laser-activated and mechanically-assisted techniques. While effective in the coronal and middle thirds, its performance in the apical third was less optimal, indicating limitations in fully activating irrigants in deeper regions of the canal.

Traditional Syringe Irrigation: was the least effective technique across all regions. Its inability to adequately remove debris and smear layers, particularly in the apical third, highlighted its limitations as a primary irrigation method. The results underscore the need for advanced techniques to improve cleaning efficacy and treatment outcomes.

Recent advancements in irrigation techniques for root canal cleaning have demonstrated varying levels of efficacy in debris and smear layer removal. Haupt et al. compared activated irrigation techniques, including passive ultrasonic activation (PUI) and EndoActivator, to syringe irrigation. They observed that PUI significantly improved

smear layer removal and debris reduction in curved root canals, outperforming syringe irrigation in overall cleanliness [6]. Similarly, Rajamanickam et al. demonstrated the effectiveness of a novel ultrasonic irrigation device, which significantly reduced smear layer and debris compared to manual irrigation techniques, reaffirming the efficacy of ultrasonic activation [7]. Yang et al. evaluated the efficacy of SWEEPS, PIPS, and UAI techniques for debris removal in complex root systems and found that SWEEPS achieved the highest debris reduction, particularly in isthmus-containing roots, outperforming both PIPS and UAI [8]. In a similar vein, Wigler et al. compared sonic irrigation (Eddy) to needle irrigation and found that Eddy significantly improved debris removal in curved root canals, particularly in the apical third [9]. Lastly, Di Spirito et al. investigated the effect of intracanal-heated sodium hypochlorite activated ultrasonically and reported significantly improved debris removal compared to traditional NaOCl applications, emphasizing the importance of advanced irrigation techniques for enhanced root canal cleanliness [10].

The application of laser-activated irrigation techniques, such as SWEEPS and SSP, has demonstrated superior efficacy in removing debris and smear layers compared to traditional and ultrasonic methods. Ivanusic et al. (2019) evaluated the Er:YAG laser's performance, finding it highly effective in cleaning complex root canal systems through shockwave generation, outperforming syringe and ultrasonic needle irrigation techniques [11]. Kurzmann et al. (2019) compared laser-activated irrigation using PIPS and X-Pulse with ultrasonic methods in simulated canal models. Both laser systems showed similar or superior efficacy for debris removal compared to ultrasonic techniques [12]. Barbosa et al. (2021) conducted a meta-analysis confirming the superior efficacy of PUI over non-activated irrigation methods. The results demonstrated higher debris removal and improved root canal cleanliness in studies employing microcomputed tomography to evaluate outcomes [13]. Aung et al. (2021) explored the efficacy of Er:YAG laser irrigation in cleaning apical regions of ledged canals. Their findings highlighted its superior performance compared to syringe and ultrasonic irrigation, particularly in areas difficult to reach, with significantly improved debris and smear layer removal [14]. Mancini et al. (2021) demonstrated that laser-activated techniques, specifically PIPS and SWEEPS, outperformed other methods in conservative canal preparations. These techniques achieved significant reductions in smear layer presence compared to sonic and ultrasonic methods [15]. Iandolo et al. (2023) evaluated 3D cleaning techniques using ultrasonic-activated heated NaOCl. Their study concluded that these methods were more effective

in smear layer removal than traditional syringe irrigation techniques [16].

Conclusion

The findings indicate that laser-activated irrigation is the most effective method for achieving optimal root canal cleanliness, followed by mechanically-assisted and ultrasonic irrigation. Traditional syringe irrigation was found to be inadequate for thorough debris and smear layer removal, especially in the apical third. These results emphasize the importance of adopting advanced irrigation techniques in endodontic practice to enhance the quality and predictability of root canal therapy.

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