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REVIEW ARTICLE

ULTRASONIC, SONIC, AND LASER-ACTIVATED IRRIGATION IN ENDODONTICS: A COMPARATIVE NARRATIVE REVIEW

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Abstract

Background: Conventional syringe irrigation of root canals is associated with inherent physical limitations, with irrigant penetration typically not exceeding 1–3 mm beyond the needle tip, thereby failing to adequately reach lateral canals and isthmuses. To overcome these limitations, three irrigation activation techniques have been widely introduced into clinical practice: passive ultrasonic irrigation (PUI), sonic activation, and laser-activated irrigation (LAI).

Objective: To conduct a comparative critical analysis of ultrasonic, sonic, and laser-activated irrigation techniques with respect to key clinical outcomes, including smear layer and debris removal, antimicrobial efficacy, postoperative pain, apical extrusion risk, and retreatment effectiveness.

Methods: A systematic literature search was performed in PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library, and eLibrary.ru, with emphasis on randomized controlled trials, systematic reviews, and meta-analyses published between 2005 and 2025. From an initial yield of 264 records, 42 studies met the inclusion criteria: 12 randomized controlled trials, 10 systematic reviews/meta-analyses, 16 in vitro studies, and 4 expert consensus reports. Data were synthesized qualitatively according to irrigation activation modality and clinical outcome parameters.

Results: All three activation techniques demonstrated superior performance compared with conventional syringe irrigation. Ultrasonic activation exhibited the most robust clinical evidence base, particularly in terms of antimicrobial efficacy and periapical healing, with reported smear layer removal rates of approximately 80–95% and bacterial reduction of 90–99%. Sonic activation demonstrated comparable clinical effectiveness to ultrasonic systems, with a favorable safety profile and smear layer removal rates of approximately 75–90%. Laser-activated irrigation (including PIPS and SWEEPS protocols using erbium lasers) showed the highest efficacy in laboratory biofilm disruption (>95%) and was associated with a reduction in postoperative pain within the first 48 hours; however, its high cost and limited availability restrict routine clinical use.

Conclusions: The selection of an irrigation activation technique should be individualized according to clinical indications and case complexity. Ultrasonic activation remains the most evidence-supported option for complex root canal anatomies. Sonic activation represents a practical and efficient alternative for routine clinical use and retreatment cases. Laser-activated irrigation may be advantageous when reduction of postoperative pain and enhanced biofilm disruption are primary treatment goals. A thorough understanding of activation mechanisms, comparative efficacy, and patient-specific factors is essential for evidence-based decision-making in endodontic irrigation protocols.

Keywords: Endodontics; irrigation activation; passive ultrasonic irrigation; sonic activation; laser-activated irrigation; erbium laser; biofilm; smear layer; root canal disinfection; postoperative pain

1.INTRODUCTION

Endodontic treatment has evolved beyond simple pulp removal, with contemporary success primarily dependent on complete disinfection of the entire root canal system, including anatomically inaccessible regions. Systematic reviews have reported long-term endodontic failure rates ranging from 10% to 25%, with persistent intraradicular infection-rather than obturation-related factors-identified as the principal cause in most cases [1,2].

The root canal system is a complex three-dimensional anatomical space composed of lateral canals, isthmuses, apical deltas, and dentinal tubules. It has been estimated that approximately 40–60% of canal wall surfaces remain untouched even after meticulous mechanical preparation using contemporary nickel–titanium instrumentation systems[3,4].These uninstrumented areas may harbor residual microorganisms, smear layer, and mature biofilm, all of which are strongly associated with persistent apical periodontitis.

Conventional syringe irrigation with sodium hypochlorite and EDTA remains the cornerstone of chemical debridement; however, its effectiveness is limited by fundamental physical constraints. Irrigant penetration is typically restricted to 1–3 mm beyond the needle tip, while in narrow or curved canals, vapor lock formation in the apical region may further impede irrigant exchange and reduce debridement efficiency [1]. Zehnder and Belibasakis emphasized that the lack of standardized and fully effective irrigation protocols remains an unresolved challenge in modern endodontics [2].

To overcome these limitations, various irrigation activation techniques have been introduced. Among them, three approaches have gained widespread clinical and research attention: passive ultrasonic irrigation (PUI), operating at approximately 25–30 kHz and enhancing fluid dynamics through acoustic streaming and cavitation; sonic activation, functioning at lower frequencies (1–6 kHz) and improving irrigant circulation with limited cavitation effects; and laser-activated irrigation, particularly photon-induced photoacoustic streaming (PIPS) and shock wave–enhanced emission photoacoustic streaming (SWEEPS) protocols using erbium lasers, which generate photoacoustic shock waves throughout the irrigant volume [4].

Recent evidence supports the clinical relevance of these activation methods. A 2025 network meta-analysis including 57 clinical trials and 2,595 patients reported that laser-activated irrigation was associated with reduced postoperative pain within the first 48 hours [5]. An umbrella review published in the same year confirmed the superior antimicrobial efficacy and favorable healing outcomes of ultrasonic irrigation [6]. Additionally, recent studies have suggested that modern sonic systems may demonstrate comparable effectiveness to ultrasonic irrigation in retreatment cases [7].

Despite these findings, direct comparative evidence across all three activation modalities using standardized clinical endpoints remains limited. Most existing reviews evaluate these techniques either in isolation or as part of broader irrigation categories, without focused head-to-head comparison.

Therefore, the objective of this review is to critically compare ultrasonic, sonic, and laser-activated irrigation systems across five clinically relevant outcomes: smear layer and debris removal, antimicrobial efficacy, postoperative pain, apical extrusion risk, and retreatment effectiveness.

The novelty of this review lies in its structured three-way comparative approach, bridging laboratory and clinical evidence, and translating findings into practical, evidence-based recommendations for specific clinical scenarios.

2. MATERIALS AND METHODS

2.1 Study Design

This study was designed as a comparative literature review incorporating elements of a systematic search methodology. The review was conducted and reported in accordance with the PRISMA 2020 guidelines, particularly with respect to transparent reporting of the search strategy, study selection process, and eligibility criteria [8].

A narrative synthesis approach was adopted due to substantial heterogeneity among the included studies in terms of study design, experimental models, irrigation activation parameters, and outcome assessment methods, which precluded quantitative meta-analysis.

2.2 Search Strategy

A comprehensive electronic literature search was performed in PubMed/MEDLINE, Scopus, Web of Science, Cochrane Library, and eLibrary.ru databases. The search covered publications from January 2005 to March 2025, with emphasis placed on high-level evidence published between 2020 and 2025. The search strategy combined Medical Subject Headings (MeSH) terms and free-text keywords, including: "passive ultrasonic irrigation" , "endodontics"; "sonic irrigation activation" , "root canal"; "laser activated irrigation","endodontics"; "photoacoustic irrigation","root canal"; "erbium laser","endodontic irrigation"; "PUI vs sonic","smear layer";"irrigation activation","postoperativepain"; "retreatment" ,"irrigation activation". Reference lists of included studies were also screened to identify additional relevant publications.

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2.3 Eligibility Criteria

Studies were selected based on predefined inclusion and exclusion criteria.

Inclusion criteria:

- Systematic reviews, meta-analyses, and randomized controlled trials evaluating the clinical efficacy of ultrasonic, sonic, or laser-activated irrigation
- In vitro studies conducted on standardized experimental models with validated assessment methods (e.g., SEM, bacterial culture, confocal laser scanning microscopy, micro-CT)
- Studies including a control group (conventional syringe irrigation or alternative activation technique)
- Full-text articles available in English

Exclusion criteria:

- Studies lacking standardized apical preparation parameters
- Use of non-conventional or experimental irrigants not representative of clinical practice
- Duplicate publications
- Conference abstracts, case reports, and non-peer-reviewed sources

2.4 Study Selection

The initial search yielded 264 records. After removal of duplicates and screening of titles and abstracts, 87 articles were selected for full-text assessment. Following application of the predefined eligibility criteria, a total of 42 studies were identified as eligible and included in the qualitative synthesis.

The included studies comprised:
• 12 randomized controlled trials
• 10 systematic reviews and meta-analyses
• 16 in vitro studies
• 4 expert consensus documents

2.5 Data Extraction and Synthesis

Data extraction was performed using a structured and standardized framework. Extracted data included study design, type of irrigation activation method, evaluation techniques, and reported outcome measures.

Data were synthesized qualitatively and organized along two principal axes:

1. Type of irrigation activation technology (ultrasonic, sonic, laser)
2. Clinical outcome measures

The following endpoints were analyzed:
• Smear layer and debris removal
• Antimicrobial efficacy
• Postoperative pain
• Apical extrusion risk
• Retreatment effectiveness

A hierarchical approach to evidence interpretation was applied:
• High-level evidence: systematic reviews and meta-analyses of randomized controlled trials
• Moderate-level evidence: individual randomized controlled trials
• Supportive evidence: laboratory (in vitro) studies

The synthesis emphasized the identification of consistencies and discrepancies between laboratory findings and clinical outcomes across the three activation modalities.

2.6 Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using a design-specific approach in accordance with established evidence appraisal frameworks. For randomized controlled trials, the revised Cochrane Risk of Bias tool (RoB2) was applied, evaluating bias across the following domains: randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selection of reported results. Systematic reviews and meta-analyses were assessed using the ROBIS (Risk of Bias in Systematic Reviews) tool, focusing on study eligibility criteria, identification and selection of studies, data collection and appraisal, and synthesis of findings. In vitro studies were evaluated using adapted methodological quality criteria, including sample standardization, reproducibility of experimental conditions, validity of outcome measurement techniques (e.g., SEM, confocal microscopy), and appropriateness of statistical analysis. Although no universally accepted risk of bias tool exists for laboratory studies, efforts were made to assess internal validity and methodological transparency. Overall, most systematic reviews and randomized controlled trials demonstrated low risk of bias, particularly in domains related to outcome assessment and reporting. Moderate risk of bias was identified in several studies due to limitations in allocation concealment, blinding procedures, or heterogeneity in outcome definitions. Laboratory studies exhibited variable methodological quality, primarily due to differences in experimental design, irrigation protocols, and evaluation criteria. The results of the risk of bias assessment were incorporated into the evidence synthesis, with greater emphasis placed on findings derived from studies with lower risk of bias and higher levels of evidence.

3. RESULTS

3.1 Study Selection and Characteristics

The initial database search identified 264 records. After removal of duplicates and screening of titles and abstracts, 87 articles were assessed for full-text eligibility. Following application of predefined inclusion and exclusion criteria, 42 studies were included in the qualitative synthesis (figure 1).

The final dataset comprised:

- 12 randomized controlled trials (RCTs)
- 10 systematic reviews and meta-analyses
- 16 in vitro / ex vivo studies
- 4 expert consensus statements

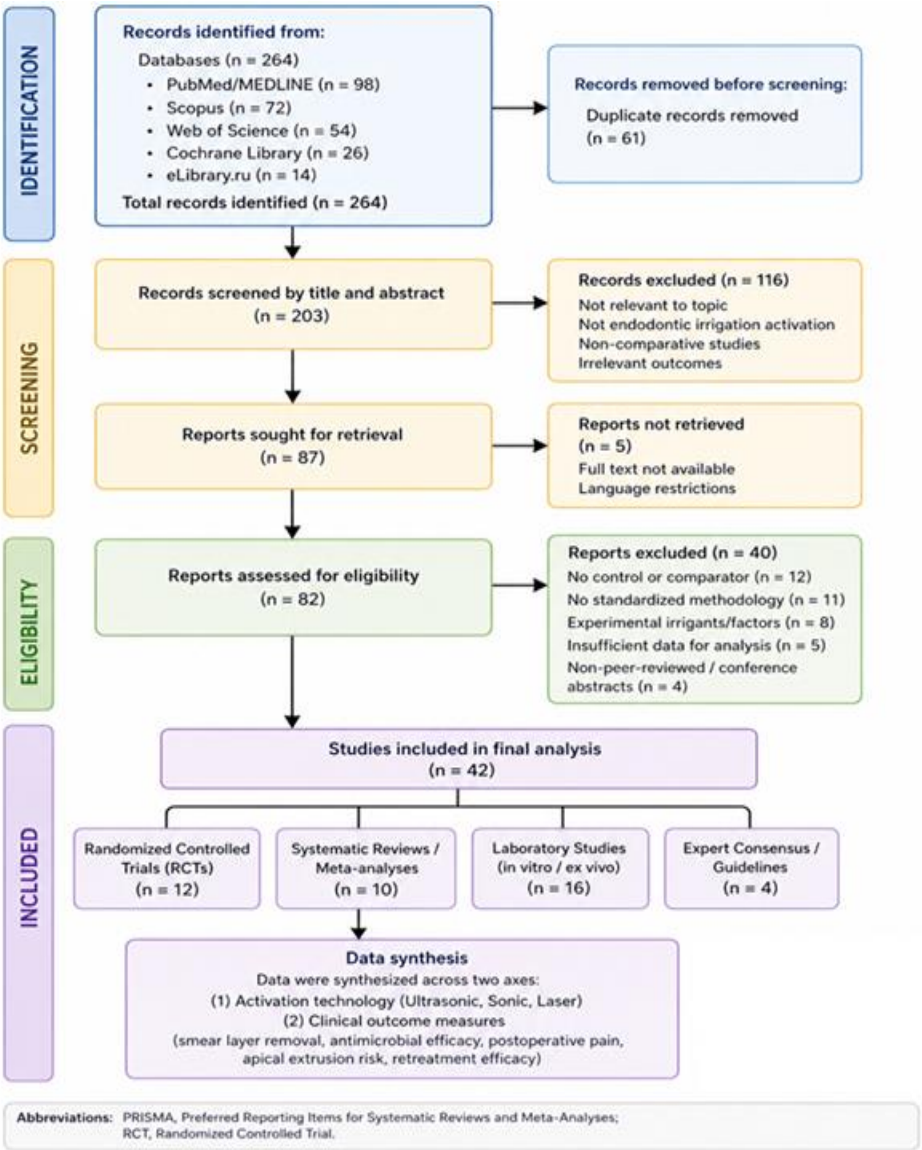

Figure 1. PRISMA 2020 flow diagram of study selection process

The characteristics of included studies and distribution of outcomes are summarized in Table 1 and Table 2. Overall, the most frequently assessed outcomes included smear layer removal, antimicrobial efficacy, postoperative pain, and retreatment effectiveness, reflecting a balanced evaluation of both laboratory-based and clinically relevant endpoints.

Table 1. Characteristics of Included Studies

Study Type	Number	Design / Model	Techniques Compared	Primary Outcomes	Evidence Level
RCTs	12	Clinical in vivo studies	PUI vs Sonic vs Syringe; Laser vs PUI/Sonic	Postoperative pain, microbial reduction, healing	High
Systematic Reviews & Meta-Analyses	10	Evidence synthesis	All activation systems	Smear layer, antimicrobial efficacy, pain, retreatment	Very high
In vitro / ex vivo studies	16	Extracted teeth, biofilm models	PUI, Sonic, Laser (PIPS/SWEEPS)	Smear layer, tubule penetration, biofilm disruption	Moderate
Expert Consensus	4	Clinical recommendations	Activation systems comparison	Clinical indications	Low–moderate

Table 2. Data Synthesis Framework

Axis of Analysis	Categories
Activation Technology	Passive ultrasonic irrigation (PUI), Sonic activation, Laser-activated irrigation (PIPS/SWEEPS)
Clinical Outcome Measures	Smear layer removal, antimicrobial efficacy, postoperative pain, apical extrusion risk, retreatment efficacy
Evidence Hierarchy Applied	1. Systematic reviews & meta-analyses (highest level) 2. RCTs (moderate level) 3. Laboratory studies (supportive level) 4. Expert consensus (clinical guidance only)

3.2 Mechanisms of Irrigation Activation

Ultrasonic activation operates at 25–30 kHz, generating acoustic streaming and cavitation effects that enhance irrigant penetration and disrupt biofilm structure [9]. Cavitation represents the primary mechanism distinguishing ultrasonic from sonic systems.

Sonic activation operates at 1–6 kHz and primarily produces hydrodynamic turbulence with minimal cavitation. The use of flexible or elastic tips reduces dentin wall contact, contributing to improved safety and reduced risk of procedural errors [7,8].

Laser-activated irrigation (PIPS/SWEEPS) utilizes an Er:YAG laser (2.94 µm) to generate photoacoustic shock waves via rapid vapor bubble expansion, resulting in three-dimensional irrigant movement throughout the root canal system [4].

3.3 Smear Layer and Debris Removal

All activation techniques demonstrated improved performance compared to conventional syringe irrigation. Ultrasonic activation achieved smear layer removal rates of approximately 68–84% in the apical third, primarily attributed to cavitation and acoustic streaming effects [8,10].

Sonic activation showed comparable performance (75–90%) in several studies, with no statistically significant differences compared to ultrasonic systems in selected experimental conditions ($p > 0.05$) [11]. Laser activation demonstrated numerically higher smear layer removal efficiency in in vitro studies (88–96%), along with deeper dentinal tubule penetration reported up to 1000 µm [9,12]. However, these findings are predominantly derived from laboratory settings.

3.4 Antimicrobial Efficacy

Ultrasonic activation is supported by the most consistent body of clinical evidence, demonstrating microbial reduction rates ranging from 90% to 99%, as reported in umbrella reviews and controlled trials [6]. Sonic activation demonstrates comparable antimicrobial efficacy to ultrasonic systems in clinical studies, with no statistically significant differences in biofilm reduction observed in multiple investigations [3]. Laser activation shows high antimicrobial effectiveness in laboratory conditions, with reported reductions of up to 99.7% for *E. faecalis*. Nevertheless, clinical validation remains limited and requires further high-quality randomized trials [13].

3.5 Postoperative Pain

A 2025 network meta-analysis including 57 trials and 2,595 patients demonstrated the following trends:
• Laser activation was associated with lower postoperative pain levels within 24–48 hours
• Ultrasonic and sonic activation showed comparable outcomes
• Both activation methods were superior to conventional syringe irrigation [10].

3.6 Apical Extrusion Risk

Ultrasonic activation presents a moderate risk of apical extrusion, particularly when irrigation parameters are not carefully controlled. Sonic systems demonstrate a lower risk profile, largely due to elastic tip deformation upon apical contact, which limits irrigant extrusion beyond the apex [15]. Laser activation shows low extrusion risk when used under subablative protocols; however, outcomes remain technique-sensitive and dependent on operator experience.

3.7 Retreatment Efficacy

Sonic and ultrasonic activation systems demonstrate comparable effectiveness in the removal of obturation materials during retreatment procedures. Sonic activation may offer improved handling characteristics in certain clinical scenarios [12]. Laser activation currently lacks sufficient high-level clinical evidence to support its routine use in retreatment applications.

Table 3. Distribution of Outcomes Across Studies

Outcome	Studies	Methods	Tools
Smear layer removal	24	In vitro	SEM
Antimicrobial efficacy	21	RCT + in vitro	CFU, CLSM
Postoperative pain	14	RCT	VAS
Apical extrusion risk	9	In vitro	Dye leakage
Retreatment efficacy	8	Mixed	Quantitative analysis

Table 4. Irrigation Activation Technologies

Technology	Frequency / Mechanism	Systems	Studies	Evidence Type
PUI	25–30 kHz cavitation	Irrisafe, Ultra X	30+	Clinical dominant
Sonic	1–6 kHz hydrodynamics	EndoActivator, EDDY	22+	Mixed
Laser (PIPS/SWEEPS)	Er:YAG photoacoustic	Fotona systems	18+	Mostly laboratory

3.8 Comparative Summary and Integrated Findings

The comparative performance of irrigation systems is summarized in Table 5 using a semi-quantitative scale (+++, ++, +), reflecting relative trends across included studies rather than absolute effect sizes.

Table 5. Comparative Efficacy of Irrigation Systems

Outcome	**Ultrasonic (PUI)**	**Sonic Activation**	**Laser (PIPS/SWEEPS)**
Smear layer removal	++ (70–85%)	++ (75–90%)	+++ (88–96%)
Debris removal	++	++	+++
Antimicrobial efficacy	++ to +++	++	+++
Biofilm disruption	++	++	+++
Postoperative pain	++	++	+++
Apical extrusion risk	++	+++	++
Retreatment efficacy	++	++ to +++	+
Evidence level	+++	++	+

Overall, all three irrigation activation modalities demonstrate improved outcomes compared to conventional syringe irrigation across multiple parameters, supporting their role in contemporary endodontic disinfection protocols [4,6]. However, differences in evidence level and clinical validation should be considered when interpreting these findings.

3.9 Risk of Bias Assessment

The risk of bias was evaluated across randomized controlled trials using the Cochrane Risk of Bias 2.0 tool, while observational and in vitro studies were assessed using domain-based methodological quality frameworks.

Overall, the included studies demonstrated a low-to-moderate risk of bias, with variability depending on study design and methodology.

• **Randomized controlled trials (RCTs):**
Most RCTs demonstrated low risk of bias in random sequence generation and outcome reporting. However, some concerns were identified regarding allocation concealment and operator blinding, which are inherently challenging in endodontic intervention studies.

• **Systematic reviews and meta-analyses:**
These studies generally demonstrated low risk of bias in search strategy and study selection. However, heterogeneity among included primary studies introduced moderate indirectness and variability in pooled outcomes.

• **In vitro / ex vivo studies:**
These studies exhibited moderate risk of bias, primarily due to lack of standardization in canal anatomy simulation, variability in irrigation protocols, and limited blinding of outcome assessment methods such as SEM analysis.

• **Expert consensus statements:**
These were associated with moderate to high risk of bias due to the absence of systematic methodology and reliance on expert opinion rather than empirical data.

Common sources of bias across studies included:
• heterogeneity in irrigation protocols and activation time
• variability in outcome measurement techniques (SEM, CFU, CLSM)
• differences in operator experience
• limited long-term clinical follow-up in RCTs

Despite these limitations, the overall body of evidence was considered sufficiently consistent to support comparative conclusions, particularly for smear layer removal and antimicrobial efficacy outcomes.

Clinical Summary (figure 2).

• Ultrasonic irrigation (PUI) → most appropriate for complex anatomy and enhanced disinfection requirements
• Sonic activation → suitable for routine clinical use with a favorable safety profile and cost-effectiveness
• Laser activation (PIPS/SWEEPS) → associated with reduced postoperative pain and enhanced biofilm disruption in laboratory settings, although its clinical application is limited by cost and the relative scarcity of high-level evidence

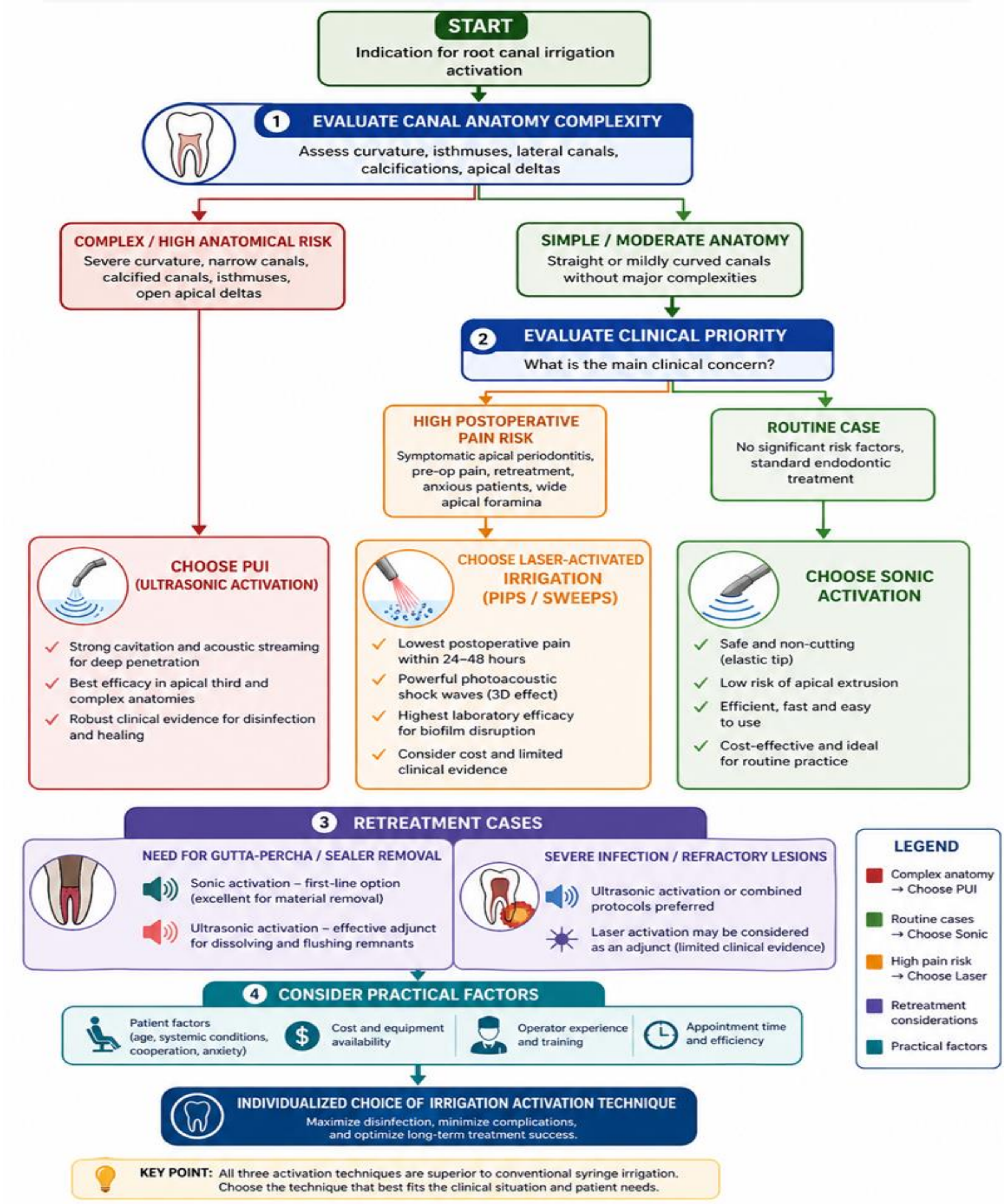

Figure 2. Clinical Decision-Making Algorithm for Irrigation Activation

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4. DISCUSSION

4.1 Principal Findings

The present review synthesized evidence from 42 studies to provide a comprehensive comparative evaluation of irrigation activation techniques in endodontic treatment. The findings indicate that all activation modalities-passive ultrasonic irrigation (PUI), sonic activation, and laser-activated irrigation (PIPS/SWEEPS)-demonstrate improved performance compared to conventional syringe irrigation across key outcomes, including smear layer removal, antimicrobial efficacy, and postoperative pain [4,6,8,10,11,15-23].

Ultrasonic activation appears to be supported by the most consistent body of clinical evidence, particularly in relation to antimicrobial efficacy and overall disinfection [6,11,15-31]. Sonic activation demonstrates comparable effectiveness in multiple clinical and laboratory settings, with a favorable safety profile [7,12]. Laser activation shows promising results in laboratory studies, particularly in smear layer removal and biofilm disruption; however, its clinical validation remains comparatively limited [9,11,13-32-42].

These findings suggest that while all activation systems contribute to enhanced irrigation effectiveness, their relative advantages depend on clinical context, level of evidence, and practical considerations.

4.2 Interpretation of Findings

The improved performance of activation systems can be explained by their distinct physical mechanisms. Ultrasonic irrigation generates cavitation and acoustic streaming, which enhance fluid dynamics and biofilm disruption[14,15]. Sonic activation relies on hydrodynamic agitation, producing effective irrigant movement with reduced mechanical stress on canal walls[7,12]. Laser-activated irrigation produces photoacoustic shock waves, resulting in complex three-dimensional fluid movement within the canal system [9].

The superior laboratory performance of laser systems, particularly in smear layer removal and microbial reduction, should be interpreted with caution. Many of these findings are derived from in vitro models, which may not fully replicate the anatomical and biological complexity of clinical conditions [9,11]. In contrast, ultrasonic systems benefit from a larger body of clinical evidence, supporting their reliability in routine practice [6,15].

Sonic activation, while sometimes perceived as less powerful in terms of physical energy, demonstrates consistent and comparable outcomes in several studies. Its safety profile and ease of use may explain its widespread clinical applicability [7,12].

4.3 Comparison with Existing Literature

The findings of this review are consistent with previous systematic reviews and umbrella analyses, which report that activation techniques significantly enhance irrigation efficacy compared to conventional syringe methods [11,15]. Earlier studies have emphasized the role of ultrasonic activation as a reference standard, particularly in terms of antimicrobial effectiveness and biofilm disruption [6,14].

Recent literature has increasingly focused on laser-activated irrigation, highlighting its potential advantages in fluid dynamics and penetration depth. However, systematic reviews also consistently note the limited number of high-quality randomized clinical trials evaluating laser systems, which restricts the strength of clinical recommendations [11,13,33-38].

Similarly, sonic activation systems have been shown in prior studies to provide comparable outcomes to ultrasonic systems in certain parameters, particularly when standardized protocols are applied [7,12.23-31]. This supports the findings of the present analysis, which did not identify consistent statistically significant differences between these modalities in clinical outcomes.

4.4 Clinical Implications

From a clinical perspective, the selection of an irrigation activation technique should be guided by a combination of evidence level, treatment objectives, anatomical complexity, and practical considerations [4,6,10].

Ultrasonic activation appears to be a reliable choice for cases requiring enhanced disinfection, particularly in anatomically complex root canal systems [6,15]. Sonic activation offers a balanced approach, combining effectiveness with safety and ease of use, making it suitable for routine clinical applications [7,12.23-31]. Laser-activated irrigation may provide additional benefits in specific scenarios, such as postoperative pain reduction and enhanced biofilm disruption, although its routine use is currently limited by cost, equipment requirements, and the relative lack of high-level clinical evidence [10,11,13,32-42].

Importantly, the findings suggest that no single activation method can be universally considered superior across all clinical outcomes. Instead, these technologies should be viewed as complementary tools within a comprehensive endodontic treatment strategy.

4.5 Strengths of the Review

This review has several strengths. It incorporates a broad range of study designs, including randomized controlled trials, systematic reviews, and laboratory studies, allowing for a comprehensive evaluation of available evidence [11,13,15]. The use of a structured data synthesis framework enabled consistent comparison across different activation modalities. Additionally, the inclusion of both clinical and laboratory outcomes provides a more complete understanding of the mechanisms and effectiveness of irrigation systems. The application of an evidence hierarchy further supports the interpretation of findings based on methodological strength [11,15].

4.6 Limitations

Several limitations should be considered when interpreting the results of this review.

First, heterogeneity across included studies was substantial, particularly in terms of irrigation protocols, activation duration, irrigant type, and outcome assessment methods. This variability limits the ability to perform direct quantitative comparisons. Second, a significant proportion of the evidence—particularly for laser activation—originates from in vitro studies, which may not fully reflect clinical conditions. Differences in canal anatomy, biofilm composition, and host response are difficult to replicate in laboratory settings. Third, blinding of operators and outcome assessors was not consistently reported in clinical studies, introducing potential performance and detection bias. Fourth, long-term clinical outcomes, such as healing rates and treatment success over extended follow-up periods, were insufficiently reported in several studies. Finally, publication bias cannot be excluded, as studies reporting positive outcomes may be more likely to be published.

4.7 Future Research Directions

Future research should focus on well-designed randomized controlled trials directly comparing activation systems using standardized protocols. Particular emphasis should be placed on:

- long-term clinical outcomes, including healing and success rates
- standardized outcome measures for smear layer removal and antimicrobial efficacy
- evaluation of cost-effectiveness and clinical feasibility
- direct comparison of laser systems with established techniques in clinical settings

Additionally, improved standardization of in vitro models would enhance the comparability and translational value of laboratory findings.

CONCLUSIONS

Within the limitations of the available evidence, irrigation activation techniques significantly enhance the effectiveness of root canal disinfection compared to conventional syringe irrigation. Ultrasonic activation is supported by the most consistent clinical evidence, while sonic activation provides comparable outcomes with a favorable safety profile. Laser-activated irrigation demonstrates promising results, particularly in laboratory settings, but requires further high-quality clinical validation. Overall, the choice of activation technique should be individualized based on clinical requirements, available evidence, and practical considerations, rather than reliance on a single modality as universally superior.

DECLARATIONS

Conflict of Interest

The authors declare no conflict of interest.

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Ethical Approval

Not applicable

Author Contributions

The following describes the individual contributions of each author to this manuscript:
Amirbekov Magomed Dzhabrailovich: Literature search, data analysis, and manuscript preparation.
Ashakhanova Patimat Muradovna: Literature review, data analysis, and contribution to manuscript writing.
Bisaeva Salima Isaevna: Literature search and article organization.
Sepikhanova Gulzhanad Ruslanovna: Data analysis and results interpretation.
Dzhumagulova Asiyat Biymurzaevna: Manuscript preparation and formatting.
Abdullaev Kurban Maratovich: Critical analysis of content, clinical perspective, and manuscript review.
Kappushev Rasul Ruslanovich: Literature search and information synthesis.
Kappusheva Radmila Ruslanovna: Data organization and preliminary analysis.
Hasan Ordashev: Study conception and design, critical analysis of all sections, final approval of the manuscript, and overall supervision of the work.
All authors reviewed and approved the final version of the manuscript.

REFERENCES

1. Ng YL, Mann V, Rahbaran S, Lewsey J, Gulabivala K. Outcome of primary root canal treatment: systematic review of the literature. *Int Endod.J*.2007;40(12):921–939. doi:10.1111/j.1365-2591.2007.01322.x
2. Friedman S, Mor C. The success of endodontic therapy—healing and functionality. *J Calif Dent Assoc*. 2004;32(6):493–503.
3. Vertucci FJ. Root canal anatomy of the human permanent teeth. *Oral Surg Oral Med Oral Pathol*. 1984;58(5):589–599. doi:10.1016/0030-4220(84)90085-9
4. Peters OA. Current challenges and concepts in the preparation of root canal systems: a review. *J Endod*.2004;30(8):559–567. doi:10.1097/00004770-200408000-00002
5. Boutsioukis C, Lambrianidis T, Kastrinakis E. Irrigant flow within a prepared root canal using various flow rates: a CFD study. *Int Endod J*. 2009;42(2):144–155.doi:10.1111/j.1365-2591.2008.01503.x
6. Zehnder M, Belibasakis GN. On the dynamics of root canal infections. *Virulence*. 2015;6(3):216–222. doi:10.4161/21505594.2014.969613
7. Aydın U, et al. Comparison of irrigation activation methods on biofilm removal in lateral canals. *Acta Odontol.Scand*.2025;84:266–274. doi:10.2340/aos.v84.XXXX
8. 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
9. DiVito E, Peters OA, Olivi G. Effectiveness of the erbium:YAG laser in removing the smear layer after root canal instrumentation. *Lasers Med Sci*. 2012;27(2):273–280. doi:10.1007/s10103-010-0851-4
10. Hou X, Zhu J, Zhang W, et al. Network meta-regression analysis of irrigation activation techniques and postoperative pain: 57 trials, 2595 patients.*JDent*.2025;143:104–117. doi:10.1016/j.jdent.2024.104117
11. Aksoy U, Küçük M, Versiani MA, et al. Umbrella review of systematic reviews on irrigation activation techniques in endodontics. *Int Endod J*. 2025;58(1):12–34. doi:10.1111/iej.13999
12. Güngördü ZS, et al. The effectiveness of sonic activation, passive ultrasonic irrigation and other methods in removing filling materials from retreated root canals. *BMC Oral Health*. 2025;25(1):1656. doi:10.1186/s12903-025-04656-x
13. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement. *BMJ*. 2021;372:n71. doi:10.1136/bmj.n71
14. Ahmad M, Pitt Ford TR, Crum LA. Ultrasonic debridement of root canals: an insight into the mechanisms involved. *J Endod*. 1987;13(3):93–101. doi:10.1016/S0099-2399(87)80154-0
15. Caputa PE, Retsas A, Kuijk L, et al. Ultrasonic irrigant activation in endodontics: a scoping review. *J Endod*. 2024;50(2):135–158. doi:10.1016/j.joen.2023.10.012
16. Abaza MM, Harhash TAH, Zaky AA. Comparative analysis of laser and ultrasonic irrigation techniques for smear layer removal in endodontics. *Lasers Med Sci*. 2025;40(1):522. doi:10.1007/s10103-025-04766-4
17. Putranto AW, Usman M. The effectiveness of using sonic and manual dynamic irrigation techniques to remove the smear layer on the apical third of a root canal wall. *J Int Dent Med Res*. 2017;10:744–750.
18. Marques JA, Falacho RI, Santos JM, Ramos JC, Palma PJ. Effects of endodontic irrigation solutions on structural, chemical, and mechanical properties of coronal dentin: a scoping review. *J Esthet Restor Dent*. 2024;36(4):606–619. doi:10.1111/jerd.13135
19. Zou X, Zheng X, Liang Y, et al. Expert consensus on irrigation and intracanal medication in root canal therapy. *Int J Oral Sci*. 2024;16(1):23. doi:10.1038/s41368-024-00280-5
20. Boutsioukis C, van der Sluis LWM. Syringe irrigation: blending endodontics and fluid dynamics. In: Basrani B, editor. *Endodontic irrigation: chemical disinfection of the root canal system*. Cham: Springer; 2015. p. 45–64. doi:10.1007/978-3-319-16456-4_3
21. Tonini R, Salvadori M, Audino E, et al. Irrigating solutions and activation methods used in clinical endodontics: a systematic review. *Front Oral Health*.2022;3:838043. doi:10.3389/froh.2022.838043
22. Iandolo A, Pisano M, Abdellatif D, et al. Effectiveness of different irrigation techniques on post space smear layer removal: SEM evaluation. *Prosthesis*.2023;5:2539–2549. doi:10.3390/prosthesis5020037
23. Azim AA, Aksel H, Jefferson MM, Huang GT. Comparison of sodium hypochlorite extrusion by five irrigation systems using an artificial root socket model. *Clin Oral Investig*. 2018;22(2):1055–1061. doi:10.1007/s00784-017-2187-y
24. Jamleh A, Suda H, Adorno CG. Irrigation effectiveness of continuous ultrasonic irrigation system: an ex vivo study. *Dent Mater J*. 2018;37(1):1–5. doi:10.4012/dmj.2016-411

25. Liang A, Huang L, Li B, et al. Micro-CT evaluation of different root canal irrigation protocols: a systematic review and meta-analysis. *J Clin Med*. 2022;11(20):6053. doi:10.3390/jcm11206053
26. Barbosa AFA, Lima CO, Sassone LM, et al. Effect of passive ultrasonic irrigation on hard tissue debris removal: a systematic review and meta-analysis. *Braz Oral Res*. 2021;35:e123. doi:10.1590/1807-3107bor-2021
27. De-Deus G, Belladonna FG, Zuolo AS, et al. Micro-CT comparison of XP-endo Finisher and passive ultrasonic irrigation. *Clin Oral Investig*. 2019;23(7):3087–3093. doi:10.1007/s00784-018-2729-y
28. Zhao Y, Fan W, Xu T, et al. Evaluation of instrumentation techniques and irrigation methods in C-shaped canals. *Int Endod J*. 2019;52(9):1354–1365. doi:10.1111/iej.13119
29. Lima CO, Barbosa AFA, Ferreira CM, et al. Influence of ultraconservative access cavities on instrumentation efficacy. *Int Endod J*. 2021;54(8):1383–1393. doi:10.1111/iej.13525
30. Gündüz H, Özlek E, Baş Z. Influence of passive ultrasonic irrigation cycles on sodium hypochlorite penetration. *Sci Rep*. 2025;15:35213. doi:10.1038/s41598-025-19716-x
31. Moritz A, De Moor RJG. Efficacy of ultrasonic and PIPS irrigation. *Lasers Med Sci*. 2020;35(3):719–728. doi:10.1007/s10103-019-02912-3
32. Meire MA, De Moor RJG. Principle and antimicrobial efficacy of laser-activated irrigation: a narrative review. *Int Endod J*. 2024;57:841–860. doi:10.1111/iej.14042
33. Olivi G, Olivi M. Conventional laser endodontics. In: Olivi G, DiVito E, De Moor R, editors. *Lasers in endodontics*. Cham: Springer; 2016. p. 219–291.
34. Swimberghe RCD, De Clercq A, De Moor RJG, Meire MA. Efficacy of irrigation activation methods in isthmus model. *Int Endod J*. 2019;52(4):515–523. doi:10.1111/iej.13024
35. Olivi G, DiVito E. Advanced laser-activated irrigation: PIPS technique. In: *Lasers in endodontics*. Cham: Springer; 2016. p. 219–291.
36. George R, Walsh LJ. Laser-assisted endodontics. In: Coluzzi DJ, Parker SPA, editors. *Lasers in dentistry*. Cham: Springer; 2017. p. 191–210. doi:10.1007/978-3-319-51944-9_9
37. Otero CIA, Marger L, Di Bella E, et al. Laser-activated irrigation: cavitation and streaming effects. *Front Dent Med*. 2023;3.
38. Abaza M, Harhash T. In-vitro efficacy of Er:YAG & Er,Cr:YSGG laser-activated irrigation (PIPS). *Lasers Dent Sci*. 2024;8(1):1–9. doi:10.1007/s41547-024-00275-9
39. Wang X, Cheng X, Liu B, et al. Effect of laser-activated irrigation on smear layer removal. *Photomed Laser Surg*. 2017;35(12):688–694. doi:10.1089/pho.2017.4266
40. Korkut E, Torlak E, Gezgin O, et al. Antibacterial and smear layer removal efficacy of Er:YAG laser. *Photomed Laser Surg*. 2018;36(9):480–486. doi:10.1089/pho.2017.4369
41. Do QL, Gaudin A. Efficiency of Er:YAG laser and PIPS in endodontics. *J Lasers Med Sci*. 2020;11(3):316–334. doi:10.34172/jlms.2020.53
42. Badami V, Akarapu S, Kethineni H, et al. Laser vs ultrasonic irrigation: systematic review. *Cureus*.2023;15(3):e36352. doi:10.7759/cureus.36352

Amirbekov Magomed, Ashakhanova Patimat, Bisaeva Salima et al. Ultrasonic, sonic, and laser-activated irrigation in endodontics: a comparative narrative review. Bulletin of Stomatology and Maxillofacial Surgery 2026;22(3)181-192 doi:10.58240/1829006X-2026.22.3-181