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CURRENT CONCEPTS IN ROOT CANAL IRRIGATION: A NARRATIVE REVIEW OF SODIUM HYPOCHLORITE, EDTA, ULTRASONIC, SONIC, AND NEGATIVE PRESSURE IRRIGATION PROTOCOLS

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ABSTRACT

Successful endodontic treatment depends on effective cleaning and disinfection of the root canal system, as mechanical instrumentation alone cannot adequately eliminate microorganisms, organic tissue remnants, and the smear layer from the complex anatomy of root canals. Irrigation protocols have therefore become an essential component of modern endodontic therapy, combining chemical irrigants with various activation techniques to improve antimicrobial efficacy and debris removal. Sodium hypochlorite (NaOCl) remains the gold standard irrigant because of its unique ability to dissolve organic tissues and eliminate a broad spectrum of microorganisms, while ethylenediaminetetraacetic acid (EDTA) is routinely used to remove the inorganic component of the smear layer and facilitate dentinal tubule penetration. Recent technological developments have introduced irrigation activation systems, including passive ultrasonic irrigation (PUI), sonic activation devices, and apical negative pressure irrigation, which have demonstrated improved irrigant distribution and enhanced cleaning efficiency compared with conventional syringe irrigation.

This narrative review aims to summarize current evidence regarding the effectiveness of contemporary root canal irrigation protocols and to compare their antimicrobial activity, smear layer removal, debris elimination, irrigant penetration, and clinical safety. A comprehensive literature search was performed using major biomedical databases, with emphasis on systematic reviews, meta-analyses, randomized clinical trials, and influential review articles published between 2006 and 2025.

Current evidence indicates that irrigation activation significantly improves canal cleanliness and irrigant penetration compared with conventional needle irrigation. Passive ultrasonic irrigation consistently demonstrates superior performance in smear layer and debris removal, whereas sonic activation offers effective disinfection with greater simplicity and lower equipment requirements. Negative pressure irrigation systems reduce the risk of apical irrigant extrusion while maintaining adequate irrigation of the apical third. Although no single protocol is universally superior in every clinical scenario, combining sodium hypochlorite and EDTA with an appropriate activation technique appears to provide the most predictable clinical outcomes. Future research should focus on protocol standardization and high-quality clinical trials to establish evidence-based recommendations for routine endodontic practice.

KEYWORDS

Endodontics, Root Canal Irrigation, Sodium Hypochlorite, EDTA, Passive Ultrasonic Irrigation, Sonic Activation, Negative Pressure Irrigation

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1. Introduction

Endodontic treatment is primarily aimed at preventing or eliminating apical periodontitis through effective disinfection and sealing of the root canal system. The long-term success of root canal therapy depends on the elimination of microorganisms, infected pulp tissue, and organic and inorganic debris from the complex endodontic space. Despite substantial advances in endodontic instrumentation, complete debridement of the root canal system remains a significant clinical challenge because of the intricate internal anatomy of teeth, including lateral canals, isthmuses, apical deltas, fins, and dentinal tubules, which are frequently inaccessible to mechanical instruments alone [1,8,11].

Microbial biofilms are considered the principal etiological factor responsible for pulpal and periapical diseases. Numerous studies have demonstrated that persistent bacterial infection within untreated anatomical irregularities is one of the leading causes of post-treatment disease and endodontic failure. Consequently, successful endodontic therapy requires not only mechanical shaping of the canal but also efficient chemical irrigation capable of reaching areas beyond the direct action of endodontic instruments [9,11].

Root canal irrigation has evolved from a simple flushing procedure into a fundamental component of contemporary endodontic treatment. Modern irrigation protocols aim to achieve several objectives simultaneously, including dissolution of organic tissue remnants, elimination of planktonic bacteria and biofilms, removal of dentinal debris, dissolution of the smear layer, lubrication of endodontic instruments, and reduction of bacterial recolonization before obturation [1,6,11]. The effectiveness of irrigation depends on multiple factors, including the physicochemical properties of the irrigant, concentration, temperature, volume, duration of application, needle design, and the method used for irrigant activation.

Among currently available irrigants, sodium hypochlorite (NaOCl) remains the gold standard because of its unique ability to dissolve organic tissue while exhibiting broad-spectrum antimicrobial activity against bacteria, fungi, and viruses commonly associated with endodontic infections [11,12]. However, NaOCl alone cannot effectively remove the inorganic component of the smear layer generated during canal instrumentation. Therefore, ethylenediaminetetraacetic acid (EDTA) is routinely used as a chelating agent to dissolve inorganic debris, expose dentinal tubules, and improve penetration of disinfecting solutions into deeper areas of the root canal system [12,15]. The sequential use of NaOCl and EDTA has become the standard irrigation protocol in modern endodontics, although the optimal concentrations, exposure times, and sequence of application remain subjects of ongoing investigation [1,6].

Over the past two decades, significant technological advances have focused on improving irrigant delivery and activation. Conventional syringe irrigation remains the most widely used clinical technique because of its simplicity and low cost; however, it has well-recognized limitations related to restricted irrigant exchange, vapor lock formation, and inadequate penetration into anatomical complexities [6,13]. To overcome these limitations, several activation techniques have been introduced, including passive ultrasonic irrigation (PUI), sonic activation systems such as EndoActivator and EDDY, and apical negative pressure irrigation systems such as EndoVac. These approaches generate hydrodynamic effects that enhance irrigant penetration, biofilm disruption, smear layer removal, and debris elimination, particularly in the apical third of the canal [4,8,9].

Although numerous laboratory investigations, systematic reviews, and clinical studies have evaluated individual irrigation protocols, considerable heterogeneity remains regarding study design, outcome measures, irrigant concentrations, activation times, and methods used to assess cleaning effectiveness. Consequently, there is still no universally accepted irrigation protocol that consistently provides optimal disinfection under all clinical circumstances. Moreover, clinicians must balance antimicrobial efficacy with patient safety, considering potential complications such as sodium hypochlorite extrusion, dentinal erosion, cytotoxicity, and adverse interactions between irrigating solutions [7,12,13].

The growing body of evidence supporting irrigant activation technologies highlights the need for a comprehensive synthesis of current knowledge. Understanding the advantages, limitations, and clinical indications of different irrigation protocols is essential for evidence-based decision-making and for optimizing long-term treatment outcomes.

Therefore, the aim of this narrative review is to critically summarize and compare contemporary root canal irrigation protocols, with particular emphasis on sodium hypochlorite, EDTA, passive ultrasonic irrigation, sonic activation, and apical negative pressure irrigation. The review discusses their mechanisms of action, clinical effectiveness, advantages, limitations, and current evidence supporting their use in modern endodontic practice.

2. Materials and Methods

This study was conducted as a narrative review of the contemporary literature addressing root canal irrigation protocols and their role in modern endodontic therapy. The primary objective was to critically summarize and compare the effectiveness of the most commonly used irrigating solutions and activation techniques, with particular emphasis on sodium hypochlorite (NaOCl), ethylenediaminetetraacetic acid (EDTA), passive ultrasonic irrigation (PUI), sonic activation systems, and apical negative pressure irrigation. The review focused on their mechanisms of action, antimicrobial efficacy, smear layer removal, debris elimination, irrigant penetration, and clinical safety [1,4,6,11].

A comprehensive literature search was performed using the PubMed/MEDLINE, Scopus, and Web of Science electronic databases. Publications published between January 2006 and June 2025 were considered for inclusion, while several landmark studies published before this period were also included because of their fundamental contribution to the development of contemporary irrigation concepts [8,9,11,13].

The search strategy combined Medical Subject Headings (MeSH) and free-text keywords, including *root canal irrigation, endodontic irrigation, sodium hypochlorite, NaOCl, EDTA, passive ultrasonic irrigation, PUI, sonic irrigation, EDDY, EndoActivator, negative pressure irrigation, EndoVac, smear layer removal, biofilm, debris removal, and endodontic disinfection*. Boolean operators ("AND" and "OR") were used to optimize the search and identify studies evaluating different irrigation protocols and activation techniques.

Preference was given to systematic reviews, meta-analyses, randomized controlled trials, prospective clinical studies, and highly cited review articles published in peer-reviewed journals. In vitro investigations were also included when they provided clinically relevant evidence regarding irrigant penetration, antimicrobial activity, smear layer removal, hydrodynamic effects, or debris elimination. Editorials, conference abstracts, case reports, and studies lacking sufficient methodological quality were excluded from the review [2–7].

The selected publications were analyzed qualitatively. Particular attention was paid to five major clinical outcomes: antimicrobial effectiveness, smear layer removal, debris elimination, irrigant penetration into complex root canal anatomy, and the safety of irrigation procedures. In addition, the advantages, limitations, and clinical applicability of individual irrigation protocols were compared to provide an evidence-based overview of current concepts in root canal irrigation [1,2,4,6,8].

Although this article does not represent a formal systematic review or meta-analysis, the literature was selected according to predefined eligibility criteria to ensure that the included studies reflect the highest available level of evidence and the current state of knowledge in contemporary endodontics. The review was designed to provide clinicians with a comprehensive and clinically relevant synthesis of current irrigation strategies while identifying areas requiring further research and standardization [1–4,6].

3. Biological Basis of Root Canal Irrigation

The primary objective of endodontic treatment is the prevention or resolution of apical periodontitis through the effective elimination of microorganisms and their by-products from the root canal system. Although contemporary nickel-titanium instrumentation systems have significantly improved the efficiency of canal shaping, mechanical preparation alone is incapable of completely cleaning the intricate anatomy of root canals. Anatomical complexities such as lateral canals, isthmuses, fins, apical ramifications, and dentinal tubules remain inaccessible to endodontic instruments, allowing microorganisms and organic debris to persist even after meticulous mechanical preparation [1,8,9,11].

Microbial biofilms play a central role in the development and persistence of endodontic infections. Unlike planktonic bacteria, microorganisms organized within biofilms exhibit enhanced resistance to antimicrobial agents and host immune responses due to their extracellular polymeric matrix and complex microbial interactions. Persistent biofilms located in inaccessible areas of the root canal system are considered one of the principal causes of post-treatment apical periodontitis and endodontic treatment failure. Consequently, successful therapy requires effective chemical irrigation capable of disrupting biofilms and delivering antimicrobial agents into areas beyond the reach of endodontic instruments [9,11,12].

Another important challenge encountered during root canal preparation is the formation of the smear layer. This amorphous layer consists of organic tissue remnants, inorganic dentin particles, microorganisms, and their metabolic products generated during mechanical instrumentation. The smear layer covers the canal walls and occludes dentinal tubules, potentially reducing the penetration of irrigants, intracanal medicaments, and root canal

sealers. Although its clinical significance remains debated, most contemporary evidence supports its removal to improve canal disinfection and facilitate more effective sealing of the root canal system [11,12,15].

An ideal root canal irrigant should possess multiple biological and physicochemical properties. These include broad-spectrum antimicrobial activity, the ability to dissolve organic tissue remnants, low toxicity to periapical tissues, adequate lubricating capacity during instrumentation, compatibility with other irrigating solutions, and the capability to penetrate complex anatomical structures without adversely affecting dentin properties. However, no currently available irrigating solution fulfills all of these requirements. As a result, contemporary endodontic therapy relies on the sequential use of complementary irrigants, most commonly sodium hypochlorite and EDTA, together with activation techniques designed to maximize their effectiveness [1,6,11,15].

The effectiveness of irrigation is influenced not only by the chemical properties of the irrigant but also by its hydrodynamic behavior within the root canal system. Conventional positive-pressure syringe irrigation often provides limited irrigant exchange, particularly in the apical third, where the formation of an apical vapor lock may reduce solution penetration. Furthermore, complex canal morphology restricts fluid movement, decreasing the ability of irrigants to reach inaccessible areas containing residual bacteria and debris [6,8,13].

To overcome these limitations, various irrigant activation techniques have been developed to enhance fluid dynamics within the canal system. Passive ultrasonic irrigation generates acoustic streaming and cavitation, improving debris removal and irrigant penetration into irregular anatomical spaces. Sonic activation systems create vigorous fluid movement through high-amplitude oscillation, while apical negative pressure irrigation improves solution exchange in the apical region and minimizes the risk of irrigant extrusion beyond the apical foramen. These technologies have significantly advanced modern endodontic irrigation by increasing cleaning efficiency while maintaining clinical safety [3,4,8,9].

Recent systematic reviews and meta-analyses consistently demonstrate that activation of irrigating solutions results in superior removal of debris and smear layer compared with conventional syringe irrigation alone. Nevertheless, variations in study design, irrigant concentration, activation time, canal anatomy, and evaluation methods have contributed to heterogeneous findings, making it difficult to establish a universally accepted irrigation protocol. Therefore, clinicians should select irrigation strategies based on the available scientific evidence, anatomical complexity, and individual clinical circumstances [2–7].

Understanding the biological principles underlying root canal irrigation is fundamental for optimizing endodontic treatment outcomes. Effective chemomechanical debridement depends on the synergistic interaction between irrigating solutions, activation methods, and proper instrumentation. This integrated approach provides the highest likelihood of reducing the microbial burden, improving canal cleanliness, and promoting long-term periapical healing [1,6,11].

4. Sodium Hypochlorite (NaOCl)

Sodium hypochlorite (NaOCl) is considered the gold standard irrigating solution in contemporary endodontics because of its unique combination of antimicrobial activity and the ability to dissolve organic tissues. Since its introduction into endodontic practice, NaOCl has remained the most extensively investigated and widely used irrigant due to its effectiveness in reducing microbial load and removing necrotic pulp tissue from the root canal system. Unlike other irrigating solutions, sodium hypochlorite is capable of simultaneously disinfecting the canal space and dissolving organic debris, making it indispensable during chemomechanical preparation [1,11,12].

The antimicrobial activity of sodium hypochlorite results primarily from the formation of hypochlorous acid (HOCl), which penetrates bacterial cell walls and oxidizes essential cellular proteins and enzymes. This process disrupts bacterial metabolism, damages nucleic acids, and ultimately leads to irreversible cell death. NaOCl demonstrates broad-spectrum antimicrobial activity against Gram-positive and Gram-negative bacteria, fungi, viruses, and bacterial biofilms commonly associated with endodontic infections. Importantly, it remains effective against *Enterococcus faecalis*, one of the microorganisms most frequently implicated in persistent apical periodontitis and secondary root canal infections [11,12,14].

In addition to its antimicrobial properties, sodium hypochlorite is the only routinely used endodontic irrigant capable of dissolving organic tissue. Through saponification, amino acid neutralization, and chloramination reactions, NaOCl degrades collagen and other organic components of pulp tissue, facilitating the removal of necrotic debris from areas inaccessible to mechanical instrumentation. This tissue-dissolving capability is particularly important in canals with complex anatomy, where residual organic material may serve as a substrate for bacterial recolonization [11,12].

The effectiveness of sodium hypochlorite is influenced by several clinical factors, including concentration, temperature, irrigation volume, contact time, and activation method. Commercially available concentrations generally range from 0.5% to 6%, with higher concentrations demonstrating enhanced antimicrobial activity and faster tissue dissolution. However, increasing concentration is also associated with greater cytotoxicity and a higher risk of tissue damage in the event of accidental extrusion beyond the apical foramen. Consequently, many clinicians prefer using moderate concentrations combined with larger irrigation volumes and activation techniques to maximize efficacy while minimizing complications [1,6,11,14].

Several studies have demonstrated that heating sodium hypochlorite before or during irrigation enhances its tissue-dissolving capacity and antibacterial effectiveness without necessarily increasing its concentration. Similarly, activation techniques such as passive ultrasonic irrigation and sonic activation improve irrigant penetration and fluid dynamics, allowing NaOCl to reach lateral canals, isthmuses, and dentinal tubules more effectively than conventional syringe irrigation alone. These approaches significantly improve debris removal and biofilm disruption while reducing the amount of residual infected tissue within the canal system [3,4,8,9].

Despite its numerous advantages, sodium hypochlorite has important limitations. It does not effectively remove the inorganic component of the smear layer created during mechanical instrumentation, making the use of a chelating agent such as EDTA necessary to achieve complete canal cleanliness. Moreover, direct interaction between NaOCl and certain irrigants, including chlorhexidine, may result in the formation of undesirable precipitates that could compromise treatment outcomes. Appropriate irrigation protocols and adequate intermediate flushing are therefore essential to prevent adverse chemical interactions [11,12,15].

The most serious complication associated with sodium hypochlorite irrigation is accidental extrusion into the periapical tissues, commonly referred to as a sodium hypochlorite accident. Although relatively uncommon, this complication may result in severe pain, swelling, ecchymosis, tissue necrosis, and temporary neurological disturbances. The risk of extrusion can be minimized through careful determination of working length, the use of side-vented irrigation needles, avoidance of excessive irrigation pressure, and the application of negative pressure irrigation systems in anatomically challenging cases [7,13,14].

Current evidence from systematic reviews and meta-analyses consistently supports sodium hypochlorite as the cornerstone of endodontic irrigation. Nevertheless, its clinical performance depends not only on concentration but also on adequate irrigation volume, sufficient contact time, continuous replenishment, and effective activation. Contemporary evidence suggests that optimizing irrigation dynamics may have a greater impact on treatment success than simply increasing NaOCl concentration. Therefore, sodium hypochlorite should be regarded as one component of a comprehensive irrigation protocol rather than a standalone solution [1-4,6,11].

5. Ethylenediaminetetraacetic Acid (EDTA)

Ethylenediaminetetraacetic acid (EDTA) is the most widely used chelating agent in endodontics and represents an essential component of contemporary root canal irrigation protocols. Unlike sodium hypochlorite, which primarily acts on organic tissues, EDTA selectively removes the inorganic component of the smear layer by binding calcium ions within dentin. This decalcification process exposes dentinal tubules, facilitates deeper penetration of irrigating solutions and intracanal medicaments, and improves the adaptation of root canal sealers during obturation [1,11,12,15].

The smear layer is inevitably produced during mechanical instrumentation of the root canal system and consists of both inorganic dentin particles and organic tissue remnants contaminated with microorganisms and bacterial by-products. This layer may obstruct dentinal tubules, limiting the penetration of disinfecting solutions and potentially reducing the effectiveness of canal disinfection. Although the clinical significance of smear layer removal has been debated, the majority of contemporary studies support its elimination to improve canal cleanliness and enhance the quality of root canal obturation [11,12,15].

The chelating action of EDTA occurs through the formation of stable calcium complexes, resulting in superficial demineralization of dentin. A 17% EDTA solution remains the most commonly recommended concentration in clinical practice, with an application time of approximately one minute providing effective smear layer removal while minimizing excessive dentinal erosion. Prolonged exposure to EDTA may lead to excessive demineralization, enlargement of dentinal tubules, weakening of dentin structure, and reduced microhardness, emphasizing the importance of controlled application times during irrigation protocols [11,12,15].

Because EDTA lacks the ability to dissolve organic tissues and exhibits only limited antimicrobial activity, it should not be used as a single irrigating solution. Instead, its greatest clinical benefit is achieved when used sequentially with sodium hypochlorite. In this protocol, NaOCl dissolves organic tissue remnants and exerts antimicrobial effects, whereas EDTA removes the inorganic smear layer, allowing fresh sodium hypochlorite to penetrate deeper into dentinal tubules and previously inaccessible anatomical irregularities. This complementary interaction has become the standard approach in contemporary endodontic irrigation [1,6,11,15].

Nevertheless, the interaction between EDTA and sodium hypochlorite requires careful consideration. EDTA may reduce the concentration of free available chlorine in sodium hypochlorite, thereby decreasing its tissue-dissolving capacity if both solutions are mixed directly. Consequently, current clinical recommendations advocate sequential rather than simultaneous use, with abundant irrigation between solutions to minimize undesirable chemical interactions and preserve the biological effectiveness of each irrigant [12,15].

Recent studies have also investigated the influence of activation techniques on the performance of EDTA. Passive ultrasonic irrigation has been shown to significantly improve the removal of the smear layer, particularly within the apical third and other anatomically complex regions where conventional syringe irrigation demonstrates limited effectiveness. Sonic activation systems have likewise enhanced EDTA penetration into dentinal tubules, although several systematic reviews suggest that passive ultrasonic irrigation generally provides superior cleaning efficiency because of stronger hydrodynamic effects and acoustic streaming [2–4,8,9].

Although EDTA is generally regarded as safe when used according to established clinical protocols, excessive exposure or repeated application may adversely affect dentin integrity. Prolonged chelation has been associated with dentinal erosion, collagen exposure, and decreased fracture resistance, particularly when combined with prolonged sodium hypochlorite irrigation. Therefore, clinicians should balance the benefits of smear layer removal with the preservation of dentin structure by limiting EDTA application time and following evidence-based irrigation protocols [11,12,15].

Current evidence consistently supports the inclusion of EDTA as the final chelating solution during root canal preparation. While EDTA alone cannot provide adequate canal disinfection, its ability to remove the inorganic smear layer substantially enhances the effectiveness of subsequent irrigation and improves the quality of root canal obturation. The combined use of sodium hypochlorite and EDTA therefore remains the most widely accepted irrigation protocol in contemporary endodontic practice and serves as the foundation for additional activation techniques designed to optimize chemomechanical debridement [1,6,11,15].

6. Passive Ultrasonic Irrigation (PUI)

Passive ultrasonic irrigation (PUI) is currently regarded as one of the most effective irrigation activation techniques in modern endodontics. Since its introduction by Weller and colleagues and its subsequent development by van der Sluis et al., PUI has become an integral part of contemporary root canal disinfection protocols because of its ability to significantly enhance irrigant penetration, improve smear layer removal, and facilitate the elimination of debris from anatomically complex areas of the root canal system [3,8,9,13].

Unlike conventional syringe irrigation, PUI utilizes a non-cutting ultrasonically activated tip oscillating at frequencies ranging from approximately 25 to 40 kHz within a previously prepared root canal. The ultrasonic file is positioned passively without contacting the canal walls, allowing the irrigant to circulate freely. This movement generates two important hydrodynamic phenomena—acoustic streaming and, under specific conditions, cavitation—which substantially improve the distribution and effectiveness of irrigating solutions [8,9,13].

Acoustic streaming is considered the primary mechanism responsible for the superior cleaning efficiency of passive ultrasonic irrigation. Rapid oscillation of the ultrasonic tip produces powerful fluid movement within the irrigant, generating shear stresses capable of disrupting microbial biofilms, removing dentinal debris, and transporting fresh irrigant into anatomical regions inaccessible to endodontic instruments. Cavitation, although less consistently demonstrated under clinical conditions, may further contribute to biofilm disruption through the formation and collapse of microscopic vapor bubbles, enhancing the mechanical action of irrigation [8,9,11].

Numerous laboratory investigations have demonstrated that PUI significantly improves the removal of debris and the smear layer compared with conventional needle irrigation. Enhanced irrigant exchange allows sodium hypochlorite and EDTA to penetrate lateral canals, fins, isthmuses, and dentinal tubules more

effectively, increasing both tissue dissolution and antimicrobial activity. This effect is particularly evident in the apical third of the root canal, where conventional irrigation frequently exhibits limited effectiveness because of restricted fluid exchange and vapor lock formation [2–4,8].

Recent systematic reviews and meta-analyses consistently support the superiority of passive ultrasonic irrigation over conventional syringe irrigation. Comparative studies have reported significantly improved smear layer removal, greater reduction of intracanal bacterial load, and more effective elimination of hard tissue debris following ultrasonic activation. Nevertheless, although the majority of in vitro studies strongly favor PUI, clinical studies have shown more variable results because of differences in canal anatomy, irrigation protocols, activation time, and outcome assessment methods [2–4,9].

The effectiveness of PUI depends on several technical factors, including canal preparation size, oscillation amplitude, activation time, irrigant volume, and the position of the ultrasonic tip within the canal. Adequate enlargement of the root canal is necessary to allow unrestricted oscillation of the ultrasonic instrument without contact with dentinal walls. Contact between the vibrating tip and canal walls dampens ultrasonic energy and reduces acoustic streaming, thereby decreasing the effectiveness of irrigation activation. Consequently, clinicians should ensure sufficient canal enlargement before implementing passive ultrasonic irrigation as the final irrigation step [8,9,13].

From a clinical perspective, passive ultrasonic irrigation offers several important advantages. It enhances the effectiveness of existing irrigating solutions without requiring changes in irrigant composition or concentration, making it a relatively simple addition to conventional treatment protocols. Furthermore, ultrasonic activation is compatible with both sodium hypochlorite and EDTA and can be incorporated into final irrigation procedures with minimal additional clinical time. The technique is therefore widely recommended for cases involving complex root canal anatomy, retreatment procedures, and teeth with persistent apical periodontitis [1,6,8,11].

Despite its well-documented benefits, passive ultrasonic irrigation is not without limitations. The effectiveness of ultrasonic activation decreases in severely curved or extremely narrow canals where unrestricted oscillation of the ultrasonic tip cannot be achieved. Furthermore, improper technique or excessive activation within inadequately prepared canals may increase the risk of instrument fracture or unintentional contact with canal walls. In addition, the acquisition of ultrasonic equipment represents an additional financial investment compared with conventional syringe irrigation, although this cost is generally justified by improved cleaning efficiency and enhanced treatment outcomes [8,9,13].

Overall, current evidence identifies passive ultrasonic irrigation as the reference standard for irrigant activation in contemporary endodontics. While no activation technique completely eliminates microorganisms from the highly complex root canal system, PUI consistently demonstrates superior hydrodynamic performance, enhanced irrigant penetration, and improved removal of smear layer and debris compared with conventional irrigation. For these reasons, passive ultrasonic irrigation has become an evidence-based adjunct to chemomechanical preparation and is recommended whenever clinical conditions permit its use [2–4,8,9].

7. Sonic Irrigation

Sonic irrigation has emerged as an effective activation technique designed to enhance the performance of conventional root canal irrigants through improved fluid dynamics and irrigant exchange. Unlike passive ultrasonic irrigation, sonic activation operates at considerably lower frequencies, typically between 1 and 10 kHz, while producing greater oscillation amplitudes. This combination generates vigorous intracanal fluid movement, facilitating irrigant penetration into complex anatomical structures and improving the removal of debris, microorganisms, and remnants of the smear layer [1,3,4,8].

Several sonic activation systems have been introduced into clinical practice, with EndoActivator (Dentsply Sirona) and EDDY (VDW GmbH) being the most widely investigated. The EndoActivator employs flexible polymer tips that oscillate within the prepared canal without cutting dentin, thereby reducing the risk of canal transportation or procedural errors. EDDY utilizes a flexible polyamide tip driven by an air scaler operating at approximately 6,000 Hz, producing high-amplitude three-dimensional movement that enhances irrigant agitation while minimizing direct contact with canal walls [3,4,8].

The principal mechanism of sonic irrigation is based on hydrodynamic agitation rather than direct mechanical contact. Oscillation of the activation tip creates continuous irrigant movement, improving solution replacement throughout the canal and facilitating the disruption of microbial biofilms adhered to canal walls. Enhanced fluid circulation also promotes deeper penetration of sodium hypochlorite and EDTA into dentinal

tubules, lateral canals, and other anatomical irregularities that cannot be adequately reached using conventional syringe irrigation alone [1,3,11].

Numerous laboratory studies have demonstrated that sonic activation significantly improves canal cleanliness compared with conventional positive-pressure irrigation. Systematic reviews have reported superior debris removal, increased irrigant penetration, and improved smear layer elimination following sonic activation. In particular, EDDY has demonstrated promising performance because its flexible tip produces multidirectional movement capable of generating effective hydrodynamic agitation without damaging canal walls. These characteristics make sonic activation an attractive adjunct to conventional irrigation protocols [2–4].

Comparative studies evaluating sonic and ultrasonic activation have produced variable findings. Although passive ultrasonic irrigation generally demonstrates superior smear layer removal and more effective cleaning of the apical third, particularly in narrow or anatomically complex canals, several recent meta-analyses have shown that modern sonic systems—especially EDDY—achieve comparable antimicrobial effectiveness and debris removal under many experimental conditions. The differences between both techniques appear to be smaller than previously reported, suggesting that device design, irrigation protocol, and operator technique may influence treatment outcomes as much as activation frequency itself [2–4,8].

From a clinical perspective, sonic irrigation offers several practical advantages. Flexible polymer activation tips reduce the likelihood of canal transportation and instrument separation while allowing safe activation in curved root canals. Sonic systems are generally easier to operate than ultrasonic devices, require less specialized equipment, and present a shorter learning curve for clinicians. Furthermore, the absence of metallic oscillating tips minimizes the risk of inadvertent dentin removal during irrigation activation [3,4,8].

Nevertheless, sonic activation also has recognized limitations. Lower operating frequencies generate less acoustic energy than ultrasonic systems, which may reduce cleaning efficiency in highly complex anatomical regions or heavily infected canals. In addition, the effectiveness of sonic irrigation depends on adequate canal enlargement, sufficient irrigant volume, and proper activation time. Failure to maintain continuous irrigant replenishment during activation may substantially reduce its antimicrobial effectiveness [3,4,9].

Current evidence supports sonic irrigation as an effective adjunct to chemomechanical preparation, providing clear advantages over conventional syringe irrigation while offering a safe and clinically practical alternative to passive ultrasonic irrigation. Although passive ultrasonic irrigation remains the reference standard for irrigant activation, contemporary sonic systems such as EDDY have demonstrated increasingly comparable clinical performance and represent valuable options in routine endodontic practice, particularly in cases involving curved canals or when ultrasonic equipment is unavailable [2–4,8].

8. Negative Pressure Irrigation

Apical negative pressure irrigation was developed to overcome one of the major limitations of conventional positive-pressure irrigation: inadequate irrigant exchange in the apical third of the root canal and the risk of accidental irrigant extrusion beyond the apical foramen. Unlike syringe irrigation, which delivers the irrigant under positive pressure, negative pressure systems aspirate the solution toward the apex while simultaneously evacuating it through a microcannula. This mechanism allows continuous replenishment of fresh irrigant throughout the canal while substantially reducing the risk of extrusion into the periapical tissues [1,6,7,8].

The most extensively investigated negative pressure irrigation system is EndoVac (Kerr Endodontics), which consists of a master delivery tip, a macrocannula, and a microcannula. During irrigation, sodium hypochlorite or other irrigating solutions are delivered into the pulp chamber and aspirated toward the working length by negative pressure. This continuous circulation promotes effective irrigant replacement, particularly within the apical third, which is often difficult to clean using conventional syringe irrigation because of vapor lock formation and limited fluid exchange [6,7,8].

One of the principal advantages of negative pressure irrigation is its ability to safely deliver irrigating solutions to the full working length. Conventional positive-pressure irrigation frequently fails to exchange irrigant beyond 1–2 mm from the needle tip, whereas EndoVac enables continuous irrigant movement directly to the apical terminus. This feature improves the removal of debris, necrotic tissue, and microorganisms while maintaining a significantly lower risk of irrigant extrusion beyond the apical foramen [6,7,13].

Several experimental studies have demonstrated that negative pressure irrigation provides effective debridement of the apical third and reduces the incidence of vapor lock, a phenomenon in which trapped air

prevents irrigants from reaching the apical portion of the canal. By eliminating this barrier, negative pressure systems enhance sodium hypochlorite penetration and improve overall irrigation efficiency, particularly in narrow or anatomically complex canals [6,7,13].

Clinical investigations comparing EndoVac with conventional syringe irrigation have reported improved apical cleanliness and comparable antimicrobial effectiveness. However, systematic reviews indicate that while negative pressure irrigation offers superior safety and more effective irrigant exchange in the apical region, its overall smear layer removal may be slightly less effective than passive ultrasonic irrigation. Consequently, some authors recommend combining negative pressure delivery with irrigant activation techniques to maximize cleaning efficiency while maintaining procedural safety [2,5,7].

The prevention of sodium hypochlorite accidents represents one of the greatest clinical benefits of negative pressure irrigation. Accidental extrusion of NaOCl beyond the root apex may result in severe pain, swelling, hemorrhage, tissue necrosis, and, in rare cases, permanent nerve injury. Because negative pressure systems aspirate rather than force irrigant toward the apex, they substantially reduce hydrostatic pressure within the canal and minimize the likelihood of extrusion, making them particularly valuable in teeth with wide apical foramina, external root resorption, immature apices, or extensive periapical lesions [7,13,14].

Despite these advantages, negative pressure irrigation also presents certain limitations. The system requires dedicated equipment, additional clinical training, and a more complex irrigation protocol than conventional syringe irrigation. Furthermore, the microcannula may become obstructed by dentinal debris if adequate canal preparation has not been achieved. Economic considerations may also limit its routine use in general dental practice, particularly when compared with simpler activation systems [6,7].

Current evidence supports apical negative pressure irrigation as one of the safest irrigation techniques available in modern endodontics. Although passive ultrasonic irrigation generally demonstrates superior smear layer removal and sonic activation provides effective hydrodynamic agitation, negative pressure irrigation offers unique advantages in terms of apical irrigant delivery and prevention of extrusion-related complications. Therefore, this technique should be considered an important adjunct in cases where patient safety and controlled irrigation are of particular clinical importance [2,5–8].

9. Comparative Analysis of Irrigation Protocols

The success of contemporary endodontic treatment depends not on the use of a single irrigant or activation technique but on the implementation of a comprehensive irrigation protocol that combines chemical and mechanical principles of canal disinfection. Current evidence consistently demonstrates that no individual irrigating solution or activation method fulfills all the biological and clinical requirements necessary for complete root canal debridement. Instead, optimal treatment outcomes are achieved by combining complementary irrigants with appropriate activation techniques tailored to the clinical situation [1,2,6,11].

Sodium hypochlorite remains the foundation of endodontic irrigation because of its unique ability to dissolve organic tissues while simultaneously exhibiting broad-spectrum antimicrobial activity. Nevertheless, its inability to remove the inorganic component of the smear layer represents an important limitation. Conversely, EDTA effectively removes smear layer through calcium chelation but possesses only limited antimicrobial activity and no tissue-dissolving capacity. Consequently, the sequential use of sodium hypochlorite followed by EDTA has become the standard irrigation protocol in modern endodontics, allowing each irrigant to compensate for the limitations of the other [1,11,12,15].

The introduction of irrigant activation techniques has substantially improved the effectiveness of conventional irrigation protocols. Among currently available methods, passive ultrasonic irrigation demonstrates the strongest scientific evidence supporting its clinical effectiveness. Numerous systematic reviews and meta-analyses have reported significantly improved smear layer removal, enhanced irrigant penetration, and more effective elimination of dentinal debris compared with conventional syringe irrigation. Acoustic streaming generated by ultrasonic activation enables irrigants to reach lateral canals, isthmuses, apical ramifications, and dentinal tubules that remain inaccessible during mechanical instrumentation [2–4,8,9].

Sonic activation systems have also demonstrated considerable clinical value and have gained increasing popularity in recent years. Devices such as EDDY and EndoActivator improve irrigant circulation through high-amplitude oscillation, enhancing biofilm disruption and debris removal while reducing the technical complexity associated with ultrasonic activation. Although passive ultrasonic irrigation generally provides superior cleaning of anatomically complex regions, recent comparative studies suggest that modern sonic systems achieve similar antimicrobial effectiveness under many experimental conditions. Therefore, the

differences between ultrasonic and sonic activation appear to be less pronounced than previously believed, particularly when standardized irrigation protocols are followed [2–4,8].

Negative pressure irrigation occupies a unique position among activation techniques because its primary advantage lies in improving procedural safety rather than maximizing hydrodynamic activation. By aspirating irrigating solutions toward the apical region instead of forcing them under positive pressure, systems such as EndoVac substantially reduce the risk of sodium hypochlorite extrusion while maintaining effective irrigant exchange at working length. This feature makes negative pressure irrigation particularly valuable in cases involving immature teeth, open apices, external inflammatory root resorption, or extensive periapical lesions, where accidental irrigant extrusion may result in severe complications [5–8,13].

Despite the growing body of evidence supporting irrigant activation, direct comparison of different techniques remains challenging because of considerable methodological heterogeneity among published studies. Differences in irrigant concentration, canal preparation size, activation time, irrigation volume, tooth anatomy, and outcome assessment methods frequently limit the comparability of available data. Furthermore, most evidence originates from laboratory investigations, whereas high-quality randomized clinical trials directly comparing activation protocols under standardized clinical conditions remain relatively scarce [2–5].

From a practical perspective, clinicians should recognize that irrigation effectiveness depends not only on the choice of irrigating solution but also on the quality of its delivery throughout the root canal system. Increasing evidence indicates that optimizing irrigant dynamics through activation may provide greater clinical benefits than simply increasing irrigant concentration. Consequently, contemporary irrigation protocols should focus on maximizing irrigant replacement, improving penetration into inaccessible anatomical areas, and maintaining continuous chemical activity throughout the procedure [1,3,6,8,11].

Based on the currently available evidence, no universal irrigation protocol can be recommended for every clinical scenario. However, the combination of sodium hypochlorite and EDTA, supplemented with passive ultrasonic or sonic activation whenever possible, appears to provide the most predictable balance between antimicrobial effectiveness, smear layer removal, debris elimination, and procedural safety. Negative pressure irrigation should be considered in situations where minimizing the risk of irrigant extrusion is a clinical priority. Ultimately, the selection of an irrigation protocol should be individualized according to root canal anatomy, pulpal and periapical status, available equipment, and the clinician's experience [1–8,11,15].

10. Clinical Implications and Future Perspectives

The findings of the present review have important implications for everyday endodontic practice. Contemporary evidence clearly demonstrates that successful root canal disinfection depends on the synergistic interaction between mechanical instrumentation, appropriate irrigating solutions, and effective activation techniques. Mechanical preparation alone cannot adequately eliminate microorganisms from the complex root canal system; therefore, irrigation should be regarded as an equally important component of chemomechanical debridement rather than merely an adjunctive procedure [1,6,11].

Current evidence supports sodium hypochlorite as the primary irrigating solution throughout canal preparation because of its unique tissue-dissolving capacity and broad-spectrum antimicrobial activity. However, clinicians should recognize that increasing the concentration of sodium hypochlorite alone does not necessarily improve clinical outcomes. Adequate irrigation volume, continuous replenishment of fresh solution, prolonged contact time, and effective irrigant activation appear to play equally important, if not greater, roles in achieving predictable canal disinfection [1,3,11,14].

Similarly, the routine use of EDTA as a final chelating solution remains an essential component of evidence-based irrigation protocols. Removal of the smear layer enhances the penetration of irrigants and sealers into dentinal tubules, potentially improving the long-term quality of obturation. Nevertheless, prolonged exposure to EDTA should be avoided because excessive demineralization may compromise dentin integrity and reduce fracture resistance. Consequently, clinicians should follow standardized irrigation protocols that balance cleaning efficiency with preservation of tooth structure [11,12,15].

The increasing availability of irrigant activation technologies has significantly changed clinical decision-making in endodontics. Passive ultrasonic irrigation currently demonstrates the strongest scientific support and should be considered whenever equipment and clinical conditions permit. Sonic activation systems provide a practical alternative, particularly in curved canals and general dental practice, whereas negative pressure irrigation offers an additional level of safety in cases associated with an increased risk of irrigant

extrusion. Rather than competing approaches, these techniques should be viewed as complementary tools that may be selected according to anatomical complexity, clinical objectives, and operator experience [2–8].

Despite considerable advances in irrigation technology, several important challenges remain unresolved. Most available evidence originates from laboratory investigations performed under standardized experimental conditions that cannot fully reproduce the biological complexity of clinical endodontic infections. Variability in tooth anatomy, microbial composition, irrigation protocols, and evaluation methods continues to limit direct comparison among studies. Consequently, further well-designed randomized clinical trials using standardized methodologies are necessary to establish evidence-based recommendations regarding irrigant concentration, activation time, and the optimal sequence of irrigation procedures [2–5].

Future developments in root canal irrigation are expected to focus on improving irrigant delivery while minimizing cytotoxicity and preserving dentin structure. Emerging technologies, including laser-assisted irrigation, multisonic activation systems, photoactivated disinfection, nanoparticle-enhanced irrigants, and nanobubble-based irrigation, have shown promising preliminary results in laboratory studies. In addition, advances in biomaterials and computational fluid dynamics may facilitate the development of personalized irrigation protocols adapted to individual root canal anatomy. Although these innovations remain under investigation, they represent promising directions for the next generation of endodontic treatment strategies [1,6,8].

Ultimately, evidence-based clinical decision-making should remain the cornerstone of modern endodontic therapy. Clinicians should integrate the best available scientific evidence with their clinical expertise and the specific anatomical and biological characteristics of each case when selecting irrigation protocols. Continuous advances in irrigation technology are likely to further improve the predictability of root canal treatment, but successful outcomes will continue to depend on the appropriate combination of effective irrigants, activation techniques, and meticulous clinical execution [1–8,11].

11. Conclusions

Effective root canal irrigation remains indispensable for successful endodontic treatment. Contemporary evidence indicates that optimal canal disinfection cannot be achieved by mechanical instrumentation alone but requires a comprehensive irrigation protocol integrating appropriate chemical agents with effective activation techniques. The sequential use of sodium hypochlorite and EDTA continues to represent the foundation of modern irrigation strategies, while activation methods significantly improve irrigant distribution, biofilm disruption, and debris removal.

Among currently available activation techniques, passive ultrasonic irrigation demonstrates the strongest overall evidence supporting enhanced cleaning efficiency. Sonic activation provides a practical and effective alternative, whereas negative pressure irrigation offers unique advantages in reducing the risk of irrigant extrusion in selected clinical situations. Rather than relying on a single irrigant or activation method, clinicians should adopt individualized irrigation protocols based on root canal anatomy, infection severity, and available clinical resources.

Future research should focus on well-designed clinical trials, standardized irrigation protocols, and the development of novel technologies capable of further improving canal disinfection while preserving dentin integrity and ensuring patient safety. Continued advances in irrigation science will contribute to more predictable treatment outcomes and further strengthen evidence-based endodontic practice.

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