Endodontic Irrigation: From Current Concepts to Future Innovations

Introduction

Successful endodontic therapy depends on effective elimination of microorganisms, organic tissue remnants, and smear layer from the root canal system. However, the intricate anatomy of root canals,including fins, isthmuses, lateral canals, and apical deltas, limits the effectiveness of mechanical instrumentation alone. Consequently, chemical irrigation plays a critical role in achieving adequate disinfection and enhancing long-term treatment outcomes.[1]

Sodium hypochlorite (NaOCl) remains the primary irrigant in contemporary endodontics because of its broad-spectrum antimicrobial activity and unique ability to dissolve organic tissue. Nevertheless, its cytotoxicity, unpleasant characteristics, and inability to remove the inorganic component of the smear layer highlight the need for adjunctive solutions.[2] Chelating agents such as ethylenediaminetetraacetic acid (EDTA) are therefore used to remove the inorganic smear layer, while chlorhexidine (CHX) contributes substantivity and additional antimicrobial coverage.[3] Despite these combined protocols, persistent intraradicular infections, particularly those involving Enterococcus faecalis biofilms, continue to challenge predictable disinfection.[4]

In response to these limitations, contemporary research has focused on enhancing irrigant delivery and antimicrobial efficacy. Activation systems such as passive ultrasonic irrigation, laser-activated irrigation, and apical negative pressure have demonstrated improved irrigant penetration, smear layer removal, and short-term reduction in postoperative pain compared with conventional syringe irrigation.[5,6] At the same time, novel irrigant formulations—including nanoparticle-based systems, herbal extracts, electrochemically activated solutions, and multifunctional “all-in-one” irrigantshave emerged with the goal of improving biofilm disruption while minimizing cytotoxicity.[7,8]

Recent umbrella reviews and systematic analyses emphasize that although activated irrigation and advanced formulations improve short-term antimicrobial and cleaning outcomes, evidence regarding superior long-term periapical healing remains inconclusive.[9] Additionally, the shift toward minimally invasive endodontics has introduced new challenges, as conservative canal preparations may restrict irrigant exchange and fluid dynamics.[10] These evolving clinical paradigms necessitate irrigation strategies that combine chemical potency, biological safety, and effective hydrodynamic activation.

Therefore, modern endodontic irrigation is transitioning from conventional mono-solution protocols toward integrated, technology-driven approaches designed to maximize disinfection while preserving tooth structure. This review aims to examine current concepts in endodontic irrigation and explore recent innovations shaping the future of root canal disinfection.

Keywords

Endodontic irrigation, Root canal disinfection, smear layer removal, Biofilm disruption, Sodium hypochlorite (NaOCl), Ethylenediaminetetraacetic acid (EDTA), Chlorhexidine (CHX), Irrigation activation, Passive ultrasonic irrigation (PUI), Normal saline, Multisonic ultracleaning (GentleWave), Laser-activated irrigation

Conventional Irrigants: Mechanisms and Limitations

Sodium Hypochlorite (NaOCl)

Sodium hypochlorite (NaOCl) continues to be extensively used as an endodontic irrigant due to its broad antimicrobial efficacy and its distinctive ability to dissolve organic and necrotic tissues within an intracanal environment throughout the root canal system.[2] Its antimicrobial action is primarily driven by an oxidative chain of reactions that disrupt microbial biofilms.[11] Despite a substantial reduction in microbial load through the combination of instrumentation and irrigation, complete eradication of bacteria and canal disinfection are not reliably achieved and residual bacteria at obturation may compromise treatment success.[2]

The bacterial elimination capacity, proteolytic activity and biological toxicity of NaOCl are influenced by several clinical variables including concentration, contact time, volume and temperature. Lowering the concentration limits cytotoxic effects but leads to a decline in antimicrobial efficacy and organic tissue dissolution. Prolonged exposure is especially essential in necrotic canals to maximizeantimicrobial efficacy, while higher volume promotes bacterial elimination by facilitating intracanal flushing. Thermal activation of NaOCl enhances its tissue-dissolving efficacy, as solutions heated to approximately 45℃demonstrated effects comparable to 5.25% NaOCl at room temperature, with reduced systemic toxicity.[15]

Although NaOCl offers several clinical benefits, its ineffectiveness against inorganic components of the smear layer means it cannot achieve complete smear layer elimination when used alone.[11] Furthermore, accidental apical extrusion throughapical foramen can lead to significant risk of cytotoxic reactions associated with intense pain, hemorrhage, swelling, ecchymosis, tissue damage and possible neurosensory complications.[13] NaOCl presents with several limitations includingundesirabletaste and odor, corrosive properties, compromising dentin biomechanical integrity and impaired dental pulp stem cell viability at high concentrations.[12,14] As a result, implementation of carefully regulated irrigation protocols that include activation techniques or final EDTA rinse is widely recommended to maximize antimicrobial effectiveness while minimizing adverse effects.[2]

Normal Saline

Normal saline is commonly utilized in endodontic practice due to its excellent biocompatibility with periapical tissues. However, saline-assisted mechanical instrumentation alone does not provide adequate elimination of pulp tissue, dentinal debris and microbial biofilms from the canal system. Saline primarily provides mechanical debridement and lubrication but lacks inherent chemical disinfecting properties, therefore is not suitable as a primary irrigant. The commonly used 0.9% w/v solution is used in conjunction with chemically active irrigants.[15]

Saline serves as an intermediate or terminal rinse following elimination of irrigants residual after canal preparation and minimizing the risk of harmful irrigant interactions.[15] Although saline lacks intrinsic bactericidal properties, saline has been shown to result in significant reduction in microbial counts when it is used as control irrigant, highlighting the importance of mechanical preparation and hydrodynamic flushing in the reduction of bacterial counts. Saline effectiveness is enhanced by passive ultrasonic activation resulting in improved removal of planktonic microorganisms compared with conventional syringe irrigation. Because of its excellent biocompatibility, saline is commonly used as a final rinse in endodontic procedures to promote dental pulp stem cell adhesion and regeneration after stronger chemical irrigants.[15]

Chlorhexidine (CHX)

Chlorhexidine gluconate (CHX) is frequently employed in endodontic practice due to its extensive antimicrobial spectrum against Gram-positive and Gram-negative bacteria. In root canal treatment, it is generally applied at a 2% concentration and demonstrates bactericidal effects at higher concentrations and bacteriostatic effects at lower concentrations. One of the key advantages of CHX is its substantivity attributed to strong affinity for dentin and enabling extended antimicrobial release, with 2% CHX demonstrating prolonged effectiveness lasting several weeks.[15]

CHX is incapable of dissolving organic tissue or adequately disrupting mature biofilms, which restricts its capacity in accomplishing total canal debridement when used independently. The antimicrobial properties are further reduced in the presence of organic matter and its ability to penetrate into well-established biofilms remains limited. The sequential application of CHX with NaOCl or EDTA leads to precipitate formation which can obstruct dentinal tubules causing tooth discoloration and compromise apical sealing.[17] Despite its established biocompatibility, inadvertent extrusion into periapical tissues can induce inflammatory reactions and has been associated with alteration in tooth color, oral tissue pigmentation, gingival epithelial desquamation and unpleasant metallic taste.[15] Strategies including heating CHX or addition of surfactants can improve antimicrobial activity and dentinal diffusion, however, the clinical safety of these methods is not yet well-established.[17] Consequently, CHX is more appropriately used as a supplementary or final irrigant instead of primary irrigating solution.

Chelating Agent (EDTA)

Successful root canal disinfection requires elimination of both the organic and inorganic components of the smear layer, given that no single irrigant can effectively target both components simultaneously. Since NaOCl is limited to dissolving organic matter, the use of chelating agents like ethylenediaminetetraacetic acid (EDTA) is necessary to achieve comprehensive smear layer elimination. The application of chelating agents was first introduced by Nygaard-Østby in 1957, originally suggesting a 15% EDTA solution, whereas modern clinical practice protocols predominantly utilize a neutralized 17% EDTA formulation.[15]

EDTA eliminates the smear layer by binding to calcium ions in dentin to form soluble calcium complexes, with demineralization stopping once the chelating capacity is exhausted. Studies indicate that final irrigation with 17% EDTA for 1-3 minutes effectively removes the smear layer, while ultrasonic activation particularly in the apical third of the canal system, significantly improves its action.[15] Beyond smear layer elimination, EDTA promotes the release of growth factors from the dentin matrix and attenuates NaOCl cytotoxic effects, making it particularly relevant in regenerative endodontics.[11] EDTA demonstrates limited antimicrobial properties, and excessive contact can lead to dentinal erosion and reduction in microhardness, potentially weakening tooth structure.[12]

Limitations of Conventional Irrigation Delivery

Conventional syringe-and-needle-based irrigation provides limited irrigant penetration into the apical third region, accessory canals and complex canal anatomy, often resulting in inadequate debridement and microbial control. Passive syringe irrigation results in low flow velocities and low shear stress, which diminishes debris clearance and biofilm disruption along canal walls.[16] Computer-based fluid flow analyses reveal the presence of stagnation zones and uneven irrigant distribution, particularly in apical areas, which reduce effective irrigant exchange and antimicrobial activity.[5]

A key limitation of conventional irrigation is the apical vapor lock phenomenon, in which trapped air obstructs the delivery of fresh irrigant from reaching the length and compromises antimicrobial action in the apical third region.[16] Additionally, syringe irrigation offers insufficient irrigation renewal, leading to rapid depletion of chemically active components and reduced antibacterial efficacy over time.[5] [Figure 1].

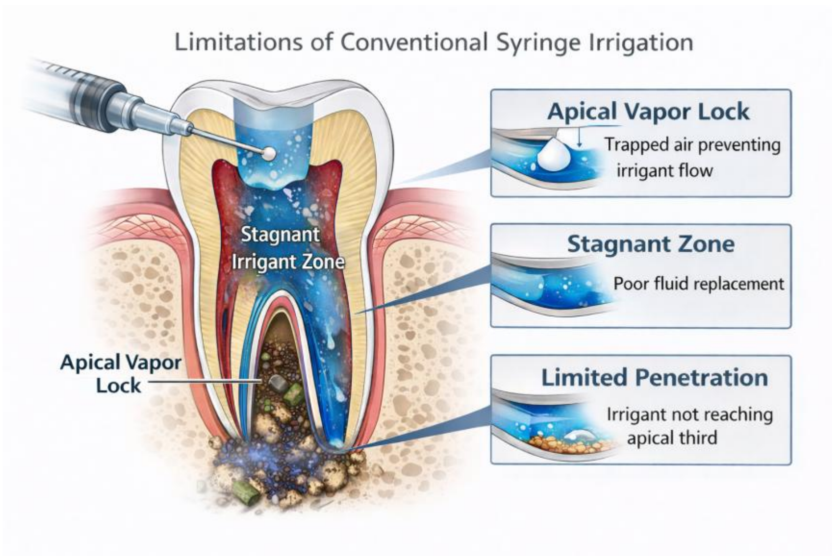

Figure 1. Limitations of Conventional Syringe Irrigation

From a procedural standpoint, the performance of syringe-based irrigation is influenced by certain factors such as needle gauge, irrigant volume, delivery frequency, temperature, canal diameter and dimensions, and irrigant age; however, conventional techniques cannot simultaneously optimize all variables. Although smaller-diameter needles may enhance penetration depth, they commonly create a stagnant zone near the apex, limiting effective irrigant exchange.[15]

Conventional irrigation methods present a risk of apical extrusion, especially under excessive pressure or in presence of compromised apical anatomy, potentially resulting in periapical tissue damage. Overall, these shortcomings indicate that syringe irrigation alone is insufficient for predictable canal disinfection results, thereby indicating the need for adjunctive activation techniques or advanced delivery systems.[16]

Advanced Endodontic Irrigants

Nanoparticles:

Endodontic infections are polymicrobial in nature, with Enterococcus faecalis being the most prevalent Gram-positive facultative anaerobe in persistent intraradicular infections. Its elimination is challenging due to the complex root canal anatomy that limits mechanical instrumentation, as well as its ability to penetrate dentinal tubules and form biofilms. Regular root canal disinfectants don’t kill all bacteria effectively, especially tough ones hiding in biofilms. Here is where nanoparticles emerged as alternatives.[4]
The complex anatomy of the root canal system makes effective cleaning and shaping difficult, allowing bacteria to persist despite the use of various irrigants and intracanal medicaments. Increasing microbial resistance to conventional agents has led to the introduction of antibacterial nanoparticles in endodontics.

In endodontics, nanoparticles have been explored for multiple applications, including biofilm elimination, dentin hypersensitivity management, tissue regeneration, reinforcement of the compromised dentinal matrix, and incorporation into irrigants, intracanal medicaments, sealers, and restorative materials to enhance antimicrobial efficacy.[18]

Pulpal and periradicular diseases are primarily caused by polymicrobial endodontic infections that develop as biofilms within the root canal system. These biofilms consist of bacterial cells embedded in an extracellular polymeric matrix that provides mechanical stability, nutrient support, and increased resistance to conventional irrigants and medicaments. Altered bacterial growth patterns and gene expression within the biofilm further enhance microbial virulence and antimicrobial resistance. Owing to these challenges, nanoparticles have recently gained attention as promising antimicrobial agents due to their enhanced antibiofilm properties.[18]

Nano versus bulk materials:

Unlike bulk materials, nanoparticles not only damage bacterial cell walls but also interfere with essential bacterial enzymes involved in DNA replication and RNA synthesis, ultimately leading to bacterial death.[18]

Antibacterial mechanisms of nanoparticles:

Nanoparticles exert antibacterial effects through multiple mechanisms. First, they bind to bacterial cell membranes via electrostatic interactions, disrupting membrane integrity, polarity, and essential functions such as respiration, nutrient transport, and energy production, leading to cell death. Second, nanoparticles generate reactive oxygen species (ROS), which damage proteins and DNA and impair bacterial survival. Additionally, metal-based nanoparticles disrupt metal ion homeostasis and metabolic functions, causing irreversible cellular damage.

Nanoparticles also induce protein and enzyme dysfunction by oxidizing amino acid side chains, resulting in loss of catalytic activity. Furthermore, their interaction with cellular biopolymers interferes with DNA replication and signal transduction, ultimately inhibiting bacterial growth or causing cell death.

Chitosan nanoparticles have demonstrated significant antibiofilm activity against Enterococcus faecalis, particularly when combined with zinc oxide, in a time- and concentration-dependent manner. Their ability to penetrate dentinal tubules makes them suitable for disinfecting complex root canal systems. Unlike conventional antimicrobials, chitosan nanoparticles are not affected by bacterial efflux pump mechanisms and retain efficacy in the presence of dentin and dentin matrix. Studies have also shown enhanced antimicrobial effects when chitosan nanoparticles are combined with chlorhexidine, supporting their potential use as an endodontic irrigant or irrigant adjunct.[18]

Poly (lactic-co-glycolic acid) nanoparticles loaded with methylene blue enhance light-activated antimicrobial therapy, significantly reducing bacterial counts in infected root canals, indicating their potential as an adjunct to conventional endodontic irrigation.[18]

Silver nanoparticles (Ag Np) and zinc oxide nanoparticles (ZnO Np) have shown strong ability to kill bacteria (antimicrobial effect) and break down bacterial communities stuck together in layers (antibiofilm effect). When silver nanoparticles were added to dental materials or used inside root canals: They improved disinfection during root canal treatment, they could be used either as an intracanal dressing (left inside the canal between visits) or as an irrigant (liquid used to flush the canal). Zinc oxide nanoparticles were found to prevent Enterococcus faecalis (a bacteria commonly responsible for failed root canals) from sticking to the dentin walls and breaking apart and destroying existing biofilms formed by this bacteria.[4]

Metal nanoparticles such as silver (Ag-NPs) and zinc oxide (ZnO-NPs) have shown significant antibiofilm activity against Enterococcus faecalis in root canals, highlighting their potential as adjunctive endodontic irrigants.[4] Ag-NPs disrupt bacterial cell membranes, interfere with DNA and protein function, and increase cell permeability, while ZnO-NPs exert bactericidal effects through high pH, cell wall disruption, cytoplasmic leakage, and zinc ion–mediated metabolic interference[18]. Both nanoparticles reduce bacterial counts comparably to conventional irrigants, particularly when combined with passive ultrasonic activation. Although highly effective against planktonic bacteria and partially against biofilms, neither achieves complete eradication, and clinical use is limited by concerns such as dentin discoloration, cytotoxicity, and the need for further in vivo validation.[18] Magnesium oxide (MgO) and magnesium–halogen nanoparticles exhibit strong antibacterial activity against endodontic pathogens, including E. faecalis, S. aureus, and Candida albicans. These nanoparticles disrupt bacterial membrane potential, induce DNA binding and lipid peroxidation, and generate reactive superoxide anions, leading to cell death. When incorporated into irrigant solutions, MgO nanoparticles enhance the antibacterial efficacy of conventional irrigants such as sodium hypochlorite and chlorhexidine, supporting their potential use as adjunctive endodontic irrigants.[18]

Studies by Bukhari et al. demonstrated that iron oxide nanoparticles (IO-NPs) combined with hydrogen peroxide (H_2O_2) provide superior disinfection of dentinal tubules compared to conventional irrigants. Microbial infection of dentinal tubules is a primary cause of apical periodontitis and endodontic treatment failure. Conventional irrigants like NaOCl and CHX mainly disinfect superficial dentin, leaving many bacteria viable in tubules. Iron oxide nanoparticles (IO-NPs) combined with H_2O_2 show superior antimicrobial activity against E. faecalis, especially in middle and outer dentin zones. This works via pH-dependent nanocatalysis, where IO-NPs activate H_2O_2 to generate free radicals that rapidly kill bacteria while remaining safe at physiological pH. Other nanoparticles, such as silver and chitosan, also show antimicrobial effects but require prolonged contact, limiting their use as irrigants.[19]

Effect of Nanoparticles on Fracture Resistance:

Studies have shown that roots irrigated with nanoparticles—silver (SNPs), titanium (TNPs), and zinc oxide (ZNPs)—exhibit higher fracture resistance (FR) compared to those treated with saline, chlorhexidine (CHX), or sodium hypochlorite (NaOCl). While NaOCl effectively dissolves biofilms, it cannot remove the smear layer, may be inactivated by organic matter, and weakens dentin by degrading its organic matrix, reducing FR, microhardness, and elasticity. CHX preserves dentin strength, maintains resin-sealer bonding, forms less smear layer, and helps prevent microleakage. Metal nanoparticles have gained attention for their antibacterial properties and potential use as root canal irrigants. Their small size allows deeper penetration into biofilms and complex canal anatomy, overcoming limitations of conventional irrigants. SNPs provide sustained broad-spectrum antibacterial activity via silver ion release, ZNPs retain activity against E. faecalis even after aging and inhibit MMPs, and TNPs generate free radicals to prevent bacterial adhesion. Pre-treatment with EDTA removed the smear layer, improving nanoparticle penetration and sealer bonding. Enhanced FR observed with nanoparticles may also be due to their high surface area, energy, and improved contact with dentin and collagen, though this requires further study. Their nanoscale size allows deeper penetration into dentinal tubules (~1 µm), potentially providing sustained antibacterial effects and inhibiting bacterial adherence. However, limitations such as prior EDTA use, testing only one sealer, and lack of long-term antibacterial and systemic assessments exist, and further research is needed to evaluate nanoparticles' effects on dentin wettability, sealer bonding, and root integrity.[20]

Herbal Irrigants:

Herbal products show considerable potential in endodontics due to their antimicrobial efficacy, biocompatibility, low cost, ease of use, and minimal risk of microbial resistance. They may serve as effective alternatives to conventional irrigants and medicaments, helping overcome limitations such as cytotoxicity and limited penetration into dentinal tubules. Although in vitro findings are promising, comprehensive preclinical and clinical studies are required to confirm their safety, biocompatibility, and clinical effectiveness. Herbal agents are generally safe when used correctly; however, improper use may lead to adverse effects. Therefore, further evidence-based research is essential before their routine clinical application in endodontic practice.[21]

Successful endodontic therapy relies on effective access preparation, biomechanical cleaning, disinfection, and three-dimensional obturation of the root canal system. Due to the complex canal anatomy, persistent biofilms often remain, making chemical irrigants essential alongside mechanical instrumentation for removal of necrotic tissue, biofilm, and smear layer. An ideal irrigant should be antimicrobial, capable of dissolving organic tissue and smear layer, biocompatible, non-toxic, non-irritating to periapical tissues, and should not compromise sealer adhesion. Sodium hypochlorite is widely used because of its strong antimicrobial and tissue-dissolving properties, but its drawbacks include toxicity, allergic potential, unpleasant taste, risk of extrusion injuries, and inability to remove the smear layer. Other conventional irrigants such as chlorhexidine, EDTA, and citric acid also have limitations, including tooth discoloration and reduced dentin microhardness. Owing to these disadvantages, there has been a growing interest—particularly in India's traditional medicinal systems—in herbal endodontic irrigants. Phytochemical agents offer advantages such as high antimicrobial efficacy, anti-inflammatory, antioxidant and antiseptic properties, biocompatibility, cost-effectiveness, easy availability, minimal tooth staining, lower toxicity, and reduced microbial resistance, especially against Enterococcus faecalis, making them promising alternatives to synthetic irrigants.[22]

Herbal root canal irrigants have been studied for their functional properties and can be classified based on their actions. Many herbal extracts, such as neem, Triphala, garlic, green tea, tulsi, miswak, and turmeric, have demonstrated significant antimicrobial activity against common endodontic pathogens. A subset of these agents also exhibits chelating ability, allowing effective removal of the smear layer, while some possess both antimicrobial and chelating properties. Additionally, a few herbal extracts, including garlic and Sapindus mukorossi, have shown the capacity to dissolve pulp tissue. These findings highlight the multifaceted potential of herbal irrigants as safe, biocompatible, and cost-effective alternatives or adjuncts to conventional endodontic solutions.[22]

Primary endodontic infections are mainly caused by obligate anaerobic bacteria, which can persist in complex areas of the root canal, making complete eradication difficult. Effective disinfection requires mechanical preparation combined with chemical irrigation, influenced by factors such as microbiota, access cavity design, canal preparation, irrigant type, volume, contact time, and needle design. Sodium hypochlorite (NaOCl) is the primary irrigant for its antibacterial and tissue-dissolving properties, though high concentrations can weaken dentin, while EDTA is used for chelation. Herbal irrigants are being explored as alternatives, but standardized protocols for contact time, concentration, and volume are lacking. Needle design and flow rate are also critical for effective disinfection.[7]

This systematic review assessed studies comparing NaOCl with herbal agents for antimicrobial efficacy. Herbal agents investigated included triphala, green tea polyphenols, Morinda citrifolia, neem, oregano extract, carvacrol, tulsi, cinnamon, Syzygium aromaticum, and Zataria multiflora. Among these, triphala was most effective, followed by green tea, while Morinda citrifolia was least effective. Results for neem and oregano were inconsistent. Due to heterogeneity in study design, concentration, and type of irrigant, no single herbal agent can be recommended as an alternative to NaOCl. Overall, most herbal agents showed inferior antimicrobial activity compared to NaOCl, with only oregano and Zataria multiflora showing comparable efficacy.[7]

Future studies should standardize concentration, volume, contact time, and assess fresh versus stored extracts, potential precipitate formation, and discoloration. While herbal agents are promising adjuncts, they cannot currently replace NaOCl for effective root canal disinfection.[7]

Alternative Irrigants:

Ozone as irrigant

Ozone, particularly in its aqueous form, has been investigated for root canal disinfection due to its strong antimicrobial properties. Studies show that ozonated water can significantly reduce bacterial load, including E. faecalis and C. albicans, though its efficacy is generally slightly lower than sodium hypochlorite (NaOCl). In some lab studies, higher ozone concentrations, longer application times, or using it with ultrasonic activation or other irrigants (NaOCl or chlorhexidine) achieved comparable results, but these cases were exceptions. Ultrasonic activation improves ozone's effectiveness, with manual irrigation showing lower microbial reduction. Aqueous ozone is less cytotoxic than NaOCl or gaseous ozone and is biologically safe, with additional benefits such as tissue oxygenation and immune modulation that may aid healing. It works by oxidizing bacterial membranes and intracellular components, increasing permeability and causing cell lysis. While effective, its antimicrobial efficacy is generally slightly lower than sodium hypochlorite, and activation (e.g., ultrasonic) improves results. Most evidence is in vitro, with no standardized clinical protocols, so ozone cannot yet fully replace traditional irrigants but may serve as a safe adjunct[23] and less cytotoxic.[24]

Photodynamic therapy (PDT)

Photodynamic therapy (PDT) is an adjunct to conventional endodontic treatment that enhances bacterial elimination. It involves applying non-toxic photosensitizers, such as methylene blue, which are activated by specific wavelengths of light in the presence of oxygen. This activation produces toxic oxygen species, including singlet oxygen and free radicals, which primarily target microbial cell walls and membranes, and can also damage DNA. Phenothiazine-derived photosensitizers are commonly used in endodontic PDT studies.

Conventional irrigation with a syringe often fails to clean the apical and complex areas of the canal, so agitated irrigation methods like passive ultrasonic irrigation (PUI) and the XP Endo Finisher have been developed to enhance disinfectant penetration and remove debris. The XP Endo Finisher is a flexible, non-tapered file that adapts to the root canal's shape, cleaning irregular areas effectively. This study is the first to investigate the combined use of PDT, PUI, and XP Endo for root canal disinfection.
Photodynamic therapy (PDT) alone is insufficient to eliminate E. faecalis in root canals, but when combined with irrigation solutions like NaOCl, it significantly improves bacterial reduction. The XP Endo Finisher with PDT showed the highest effectiveness (~98–99%). Ultrasonic activation also enhanced results. While promising as an adjunct, PDT cannot replace conventional irrigation, and further in vivo studies are needed to confirm its efficacy across different canal anatomies.[25]

MTAD (Mixture of Tetracycline, Acid, and Detergent)

Biopure mixture of tetracycline acid and detergent (MTAD) (Tulsa, Dentsply) contains 3% doxycycline (tetracycline isomer) 150 mg/5 ml, 4.25% citric acid, 0.5% polysorbate 80 (surfactant). The main goal of endodontics is thorough root canal disinfection, but bacteria like Enterococcus faecalis often persist due to virulence and biofilm formation. Standard irrigants (NaOCl, CHX, EDTA, IKI) are effective, with 5.25% NaOCl plus 17% EDTA as the gold standard, though this can weaken dentin. MTAD is used as a final rinse but shows no clear advantage over NaOCl/EDTA. Surfactants like cetrimide (CTR) and SDS enhance antimicrobial activity by reducing surface tension and disrupting bacterial membranes. This study found that combining CHX with CTR or SDS improved E. faecalis eradication compared to CHX alone, offering effective disinfection while potentially lowering the need for higher, more toxic irrigant concentrations. Further studies on biofilms, cytotoxicity, and tooth models are needed.[26]

QMix:

QMix is commonly presented as an advanced final irrigant that combines smear-layer removal and antimicrobial activity in one solution. Its formulation is described in the literature as including EDTA (for chelation/smear-layer removal), antimicrobial components with chlorhexidine-like behavior, and a surfactant to reduce surface tension and improve wetting and penetration into dentinal tubules. This positions QMix primarily for use in the final irrigation phase, when the aim is to optimize dentin surface cleanliness and reduce residual microbes prior to obturation.[28]
A clinically important aspect highlighted in the open-access evidence is endotoxin reduction. In infected canal models, QMix has been shown to reduce lipopolysaccharide (LPS) levels, which matters because endotoxin is implicated in periapical inflammatory responses. This adds a rationale for QMix use beyond simple "bacterial count reduction," supporting its role in improving the chemical environment of the canal system near the end of treatment.[29]

At the same time, QMix should be placed correctly in the sequence because it is not a substitute for NaOCl's tissue dissolution. The evidence base treats QMix as a finishing irrigant: it is used after NaOCl has performed the heavy lifting in organic tissue dissolution and bulk antimicrobial action, and then QMix helps address smear layer/inorganic aspects and residual disinfection goals to support improved conditions for obturation.[28,32]

Calcium hydroxide pastes / solutions:

Calcium hydroxide is primarily used as an intracanal medicament because its high pH supports antimicrobial activity and can neutralize bacterial by-products during inter-appointment dressing. Clinically, it is usually placed as a paste, and its effectiveness as a medicament is well accepted; however, the persistent issue is not whether it works as a medicament but how reliably it can be removed before obturation, especially from the apical third and anatomical irregularities.[30,32]

Experimental evidence demonstrates that conventional syringe irrigation alone often leaves calcium hydroxide remnants, particularly in complex anatomy and challenging canal shapes. This is clinically important because residual $Ca(OH)_2$ can interfere with sealer penetration/adaptation and may compromise the quality of obturation. Therefore, removal is treated as a critical step—not optional cleanup—before sealing the canal system.[30]

Evidence supports a “chemistry + activation” approach: using chelators such as EDTA and applying activation techniques (e.g., ultrasonic/sonic agitation) improves calcium hydroxide removal compared with non-activated syringe irrigation, although complete removal is still difficult to achieve consistently. The realistic clinical conclusion is that protocols should be designed to maximize removal in hard-to-clean regions, using activation as standard practice when calcium hydroxide medicament has been used.[30]

Photo-activated irrigants (photoactivated disinfection / antimicrobial photodynamic therapy):

Photoactivated disinfection (PAD), also termed antimicrobial photodynamic therapy (aPDT), is based on a triad: a photosensitizer, light at a matching wavelength, and oxygen. Light activation triggers energy transfer processes that generate reactive oxygen species (ROS), particularly singlet oxygen and free radicals, which exert antimicrobial effects through oxidative damage to cell membranes, proteins, and nucleic acids. In endodontics, methylene blue and toluidine blue O are among the most frequently described photosensitizers, and activation is commonly achieved using diode lasers or LEDs, with clinical relevance tied to the ability to reach bacteria in dentinal tubules and complex anatomical areas that conventional approaches may not completely disinfect.[27,31]

Evidence synthesis in the PAD literature consistently positions this method as adjunctive: it can add microbial reduction after conventional chemo-mechanical preparation, but it does not replace sodium hypochlorite because it lacks organic tissue dissolution and cannot reliably replicate NaOCl’s combined tissue-dissolving and broad antimicrobial role. Reviews describing modern canal disinfection emphasize PAD’s usefulness in reducing residual microbial burden (often studied with E. faecalis) while also stressing that PAD’s effect depends heavily on successful delivery of all three components—photosensitizer distribution, appropriate light delivery, and oxygen availability.[27,32]

Technique factors strongly influence results. Parameters such as photosensitizer concentration, contact time, canal cleanliness (smear layer and debris can impede penetration), irradiation time, wavelength, and the practicality of delivering light into the full canal space all shape efficacy. Because ROS effects occur locally, limitations in penetration and activation can lead to inconsistent outcomes, which is why PAD is commonly recommended as a final supplementary disinfection step once shaping/cleaning has already reduced debris and improved access to the canal system.[27,31]

Reactive solutions (oxidation-based irrigants):

Reactive irrigant solutions aim to disinfect using oxidative chemistry that damages microbial structures and genetic material. This broad category includes approaches such as ozonated water, electrochemically activated (ECA) solutions (electrolyzed saline), and other oxidizing mixtures that rely on reactive oxygen/chlorine species for antimicrobial effect. The rationale for investigating these agents is typically framed around improved biocompatibility compared with stronger sodium hypochlorite concentrations, while maintaining meaningful antimicrobial action as part of irrigation regimens and/or activation protocols.[1,32]

Across endodontic irrigation reviews, a consistent limitation is that oxidative solutions often show more variable performance in the real canal environment, especially when organic load is present. Organic debris, dentin remnants, and biofilm architecture can reduce antimicrobial impact, and many reactive solutions do not provide meaningful organic tissue dissolution—an important clinical differentiator because removal of necrotic tissue and organic debris is central to debridement. As a result, reactive solutions are generally not framed as drop-in replacements for NaOCl but rather as adjuncts or alternatives in selected contexts.[1]

From a practical “evidence-safe” standpoint, the literature supports using reactive solutions with realistic expectations: they can contribute antimicrobial action, and activation methods can enhance performance, but NaOCl remains the most consistently effective irrigant when both antimicrobial action and tissue dissolution are needed. Therefore, reactive solutions are best positioned as adjunctive disinfectants, alternative options when NaOCl use is limited, or components within broader activation-supported irrigation strategies rather than the core irrigant for routine chemo-mechanical preparation.[1]

Electrolyzed water / super-oxidized water in endodontics:

Electrolyzed water, often referred to as electrochemically activated (ECA) water or super-oxidized water, is produced by the electrolysis of a dilute saline solution, resulting in solutions rich in reactive chlorine and oxygen species, most notably hypochlorous acid. These reactive species exert antimicrobial effects by causing oxidative damage to bacterial cell membranes, enzymes, and nucleic acids. In endodontics, electrolyzed and super-oxidized water have been investigated as irrigant solutions due to their antimicrobial properties combined with comparatively favorable biocompatibility profiles. The primary rationale for their use is to achieve microbial reduction with lower cytotoxicity than higher concentrations of sodium hypochlorite.[1,33]

Experimental studies and reviews demonstrate that electrolyzed and super-oxidized water exhibit antimicrobial activity against common endodontic pathogens, including Enterococcus faecalis. However, their antimicrobial efficacy is highly dependent on factors such as solution concentration, exposure time, and the presence of organic matter. When organic debris, dentin remnants, or mature biofilms are present, the antimicrobial effectiveness of these solutions is significantly reduced. This limitation is particularly relevant in infected root canal systems, where organic load is almost always present during treatment. As a result, their performance is generally less predictable than sodium hypochlorite under clinically realistic conditions[1,33].

Another important limitation of electrolyzed and super-oxidized water is their minimal organic tissue-dissolving capacity. Unlike sodium hypochlorite, these solutions do not effectively dissolve necrotic pulp tissue or organic debris, which is a critical requirement for thorough canal debridement. Consequently, while electrolyzed and super-oxidized water may contribute to microbial reduction, they cannot fulfill the dual role of disinfection and tissue dissolution that defines sodium hypochlorite as the primary irrigant in endodontics. Current evidence therefore supports their use mainly as adjunctive irrigants or as alternative solutions in selected clinical situations where sodium hypochlorite use is contraindicated or must be limited.[1]

Irrigation Activation Systems

A) PASSIVE ULTRASONIC IRRIGATION (PUI)

Definition and Mechanism

Passive ultrasonic irrigation can be performed with a small file or smooth wire (size 10-20) oscillating freely in the root canal to induce powerful acoustic microstreaming.[34] PUI functions without simultaneous instrumentation, and ultrasonic irrigation has proved to be more powerful than sonic activation in eliminating debris.[35]

Clinical Protocol (2025 ESE Guidelines)

The European Society of Endodontology 2025 S3 guidelines place PUI at the heart of the irrigation protocol, with ultrasonic activation of warmed sodium hypochlorite, a final chelation step with EDTA, and a neutralizing rinse.[36]Randomized controlled trials report greater than 99% bacterial reduction, markedly better smear-layer removal, and a significant drop in postoperative pain compared with conventional syringe irrigation.[36]

Clinical Efficacy

- **Bacterial Reduction**: Two 2024 studies showed significantly better smear layer removal in the apical third, and a 2023 randomized trial found a 38% drop in moderate post-operative pain.[36]
- **Cost-Effectiveness**: A dedicated ultrasonic unit and tips pay for themselves in fewer than 40 cases if retreatments fall from 8% to 2%.[36]
- **Cleaning Efficacy**: Compared with traditional syringe irrigation, PUI removes more organic tissue, planktonic bacteria and dentine debris from the root canal.[34]

Technical Considerations

The taper and diameter of the root canal were found to be important parameters in determining the efficacies of dentine debris removal, and irrigation with sodium hypochlorite is more effective than with water.[37] However, in severely curved canals, the ultrasonic activation tip's performance may be compromised since contact of the tip with the curved canal wall is inevitable, with high risk of straightening or otherwise damaging the original canal curvature.[38]

B) LASER-ACTIVATED IRRIGATION (LAI)

Photon-Induced Photoacoustic Streaming (PIPS)

Technology and Mechanism: PIPS is not a thermal event but rather sub ablative, creating turbulent photoacoustic agitation of irrigants that move fluids three dimensionally throughout the root canal system even to the apical terminus, using extremely low energy (20 mJs or less) below the threshold of ablation for dentin.[39]

The laser-activated irrigation technique is based on the creation of cavitation phenomena and acoustic streaming in intracanal fluids related to the photomechanical effects of lasers at low settings, with Er:YAG laser used with sub-ablative energy and ultra-short pulses (50 µs) leading to intracanal cavitation and shockwaves.[40]

Clinical Advantages:

- Investigations from a histological study found half of the samples treated with the PIPS irrigation protocol to be rendered completely free from infection, with the group having a 99.5% median reduction in bacterial count.[41]
- Irrigation using PIPS increased the canal volume and eliminated debris from the canal system 2.6 times greater than standard needle irrigation.[42]
- PIPS creates improved cleaning and debridement of organic and inorganic tissue left by instrumentation, with the tip activated in the access cavity outside the root canal system.[39]

SWEEPS (Shock Wave-Enhanced Emission Photoacoustic Streaming): SWEEPS is based on the emission of a couple of consecutive laser pulses, with the second subsequent laser pulse shooting into the liquid at an optimal delay time from the first pulse when the initial bubble is in the final phase of its collapse, producing acceleration of laser-induced bubbles' collapse and leading to shock wave emission even in narrow root canals

SWEEPS and EDDY exhibited superior bacterial killing efficacy within dentinal tubules, with SWEEPS, PIPS, and EDDY achieving the highest biofilm removal rates of 99.56%, 99.46%, and 99.46% respectively in main canal spaces.[36]

Postoperative Pain Reduction

Diode LAI demonstrated superior efficacy to needle irrigation in reducing pain 6-48 hours post-treatment, though the impact of PIPS was unclear with no difference observed between PIPS and needle irrigation, while PIPS mitigated post-endodontic pain better than manual dynamic activation, sonic and ultrasonic activation.[43]

Comparative Studies

Er:YAG LAI and PIPS outperformed other methods in 33 of 59 articles reviewed, though there was great variety in study designs including bacterial incubation time, laser parameters, irrigation protocols, and irrigating solution used.[40]

Safety Considerations

Diode laser and PIPS caused less bacterial extrusion compared to passive ultrasonic irrigation.[41]

C) NEGATIVE PRESSURE AND MULTISONIC SYSTEMS

1. APICAL NEGATIVE PRESSURE IRRIGATION (EndoVac System)

Mechanism of Action: EndoVac uses suction to pull irrigant down the root canal and then up and away into the high-vacuum suction unit, eliminating the need for applying positive pressure, with no risk of pushing sodium hypochlorite beyond the apical foramen.[38]

System Components: The EndoVac system is composed of three basic components: Master Delivery Tip (MDT) that delivers irrigant to the pulp chamber and evacuates it concomitantly; a Macrocannula made of flexible polypropylene with an open end of 0.55 mm diameter used to suction irrigants to the middle segment; and a Microcannula with closed end and external diameter of 0.32 mm with 12 microholes (0.1 mm diameter each) that can be used in canals enlarged to size 35 or larger and should be taken to working length.

2. MULTISONIC ULTRACLEANING SYSTEM (GentleWave)

Technology Overview: The GentleWave Procedure utilizes Multisonic Ultracleaning technology, which enables procedure fluids to reach through the entire root canal system; unlike ultrasonic wavelength technology which uses a single wavelength, this system generates multiple acoustic frequencies simultaneously.[44]

The interplay of Multisonic energy, vortical fluid dynamics, and chemistry of the treatment fluid result in enhanced dissolution and removal of organic matter including pulp tissue and biofilm from the root canal system.[45]

Clinical Performance:

- **Tissue Dissolution**: Tissue dissolution efficacy of the GentleWave System was compared with different conventional and contemporary endodontic systems at different temperatures and concentrations of NaOCl.[45]
- **Biofilm Removal**: The residual biofilm removal effect of GentleWave is superior to passive ultrasonic activation in the isthmus and apical region, which is known to have complex root canal anatomy.[54]
- **Minimal Instrumentation**: Because the GentleWave System has the ability to clean in such a comprehensive way, less traditional instrumentation is required, creating potential to dramatically reduce procedure time and remove less structural dentin, helping preserve structural integrity of the tooth.[46]

Comparative Efficacy: Previous in vitro and in vivo studies evaluated the ability of different instrumentation techniques and irrigation protocols to eliminate lipopolysaccharides, and given their limited effectiveness, supplemental treatments with passive ultrasonic irrigation and photodynamic therapy have been investigated.[47]

Er:YAG and Er,Cr:YSGG lasers were highly promising with results close to multisonic ultracleaning, and needle irrigation and passive ultrasonic activation may not be able to provide competent debridement in treating necrotic oval root canals.[48]

Comparative Summary:

Advantages by System:

PUI:

- Widely adopted and evidence-based
- Cost-effective
- Significant bacterial reduction (>99%)
- Better smear layer removal
- Reduced postoperative pain

LAI (PIPS/SWEEPS):

- Highest bacterial reduction (99.5% median)
- Superior tissue dissolution
- 2.6× better debris removal vs conventional
- Minimal instrumentation required
- Lowest postoperative pain
- No thermal damage to dentin

Negative Pressure (EndoVac):

- Maximum safety (no apical extrusion)
- Effective apical irrigation

- Overcomes vapor lock
- Comparable antimicrobial efficacy to conventional

Multisonic (GentleWave):

- Superior biofilm removal in complex anatomy
- Minimal instrumentation
- Preserves tooth structure
- Single-visit treatment
- Comprehensive cleaning of isthmuses and lateral canals

Limitations:

PUI: Technique-sensitive, risk of canal damage in curved canals, instrument contact issues

LAI: High equipment cost, limited in vivo studies, technique variability in literature

Negative Pressure: Requires canal enlargement to size 35+, equipment cost

Multisonic: Highest equipment cost, limited long-term clinical data

Clinical Outcomes of activated irrigation systems

Activated irrigation systems have been introduced to enhance the clinical effectiveness of root canal disinfection by improving irrigant penetration, hydrodynamic activity, and debris disruption.[5,6] Clinical investigations evaluating these systems have focused on both patient-centered outcomes, such as post-operative pain, and treatment-related outcomes including canal cleanliness, antibacterial efficacy, irrigant delivery to working length, and periapical healing.[6]

Across multiple clinical studies, activated irrigation has demonstrated a consistent short-term advantage over conventional needle-syringe irrigation in reducing post-operative pain, particularly within the first 24–48 hours following treatment.[6] A range of activation techniques—including ultrasonic, sonic, apical negative pressure, and mechanically assisted systems—were associated with lower pain scores and reduced analgesic intake compared with conventional irrigation.[6] This benefit is likely related to enhanced debris removal and reduced apical extrusion achieved through controlled hydrodynamic activation, especially in systems operating under negative pressure.[6] However, differences in pain outcomes were not sustained beyond the early post-operative period, indicating that the analgesic benefit of irrigant activation is predominantly short-lived.[6]

With respect to debridement efficacy and canal cleanliness, activated irrigation systems generally outperformed conventional irrigation methods.[6] Histological and microscopic analyses consistently demonstrated improved removal of dentinal debris and smear layer, particularly in anatomically complex regions such as the apical third and canal isthmuses.[6] Ultrasonic activation was frequently associated with superior canal and isthmus cleanliness, while apical negative pressure systems showed enhanced apical debris removal with a reduced risk of irrigant extrusion.[6] These findings support the role of hydrodynamic forces, acoustic streaming, and mechanical agitation in disrupting debris and biofilm adherent to canal walls beyond the capabilities of needle irrigation alone.[6]

Evidence regarding antibacterial efficacy remains variable. Several randomized clinical trials reported greater reductions in cultivable bacterial counts with activated irrigation—particularly passive ultrasonic activation—when compared with conventional needle irrigation.[5] Mechanical activation using systems such as XP-endo finisher also demonstrated improved bacterial reduction relative to needle irrigation and some other agitation devices.[5] However, other studies reported no statistically significant difference between activated and conventional irrigation techniques.[6] In some instances, activated irrigation was associated with increased detectable bacterial counts immediately after activation, a finding attributed to the mechanical disruption of biofilms and smear layers that may transiently increase recoverable microorganisms without necessarily compromising overall disinfection.[6]

The effectiveness of activated irrigation systems in delivering irrigants to the working length has been evaluated in a limited number of clinical studies.[6] Available evidence suggests that both passive ultrasonic irrigation and apical negative pressure systems achieve improved irrigant penetration to working length compared with conventional needle irrigation.[6] Nonetheless, differences between activation techniques were not always statistically significant, and the scarcity of clinical data limits definitive conclusions regarding comparative efficacy.[6]

Long-term clinical outcomes, particularly periapical healing assessed radiographically, have not shown a significant difference between activated and conventional irrigation methods.[6] Studies using periapical radiographs and cone-beam computed tomography reported comparable rates of lesion reduction and resolution irrespective of irrigation technique.[6] Variables such as pre-operative lesion size and master apical file size appeared to exert a greater influence on healing outcomes than the method of irrigant activation.[6] These findings suggest that while activated irrigation improves short-term procedural and symptomatic parameters, its impact on long-term periapical healing remains limited.[6]

Overall, current clinical evidence indicates that activated irrigation systems provide measurable benefits in short-term outcomes, including reduced post-operative pain, improved canal cleanliness, enhanced debridement, and, in some cases, greater bacterial reduction compared with conventional irrigation.[6] However, heterogeneity in study design, activation protocols, irrigant formulations, and outcome assessment methods limits direct comparison across studies. Further well-designed randomized clinical trials with standardized methodologies and long-term follow-up are required to clarify the role of activated irrigation systems in improving sustained endodontic treatment outcomes.[5,6]

Future Innovations and Research Directions

Traditional irrigants such as sodium hypochlorite remain cornerstones; however, their limitations, including cytotoxicity and corrosive nature have driven research toward multifunctional irrigants with broad antimicrobial efficacy, tissue-dissolving capacity, biofilm disruption, smear layer removal and improved biocompatibility. Advancements in irrigant formulations are expected to simplify treatment protocols, while improving antimicrobial properties. Whereas traditional techniques require multi-step application of sodium hypochlorite and chelating agents, multifunctional irrigants aim to integrate desirable properties of conventional irrigants into a single formulation. In a comparative study evaluating such solutions mainly Triton and Endojuice, Triton demonstrated better tissue dissolution, closely matching the performance of sodium hypochlorite. Endojuice excelled in smear layer removal and exhibited significantly lower cytotoxicity and genotoxicity than Triton, however, it requires prior sodium hypochlorite application for optimal smear layer dissolution and biofilm removal.[8]

The long-term success of a tooth following root canal treatment is strongly influenced by the remaining tooth structure. Minimally invasive endodontics is guided by this principle, focusing on preserving as much healthy tissue as possible. It prioritizes preservation of peri-cervical dentin and structural integrity, and presents a distinct challenge for irrigation protocols to accomplish deeper disinfection within more conservative canal preparations. The shift towards minimally invasive endodontics creates a unique challenge for irrigation efficacy as conservative canal preparations may constrain the volume and flow of irrigants.[10]

Recent research highlights the significant potential of non-thermal plasma (NTP) for endodontic irrigation, particularly through underwater discharge plasma, which operates by creating plasma directly in a liquid medium.[51] The antimicrobial action of underwater discharge plasma (UDP) is primarily mediated by reactive oxygen and nitrogen species, leading to cell membrane disruption, protein denaturation and biofilm degradation.[6] Cold plasma technologies, which enable microbial inactivation, biostimulation and surface modulation are transforming the medical field[51]. Nevertheless, their clinical superiority and safety in endodontics remain to be validated through further research.[51]

Artificial intelligence has brought significant advancements across multiple sectors and in the field of dentistry, particularly endodontics, AI contributes to improved diagnostic accuracy and enhanced clinical outcomes. The integration of artificial intelligence with irrigation systems will depend on interdisciplinary collaboration and well-designed studies.[49]

Current research primarily relies on culture-based methods that fail to detect many endodontic microbes, necessitating more advanced diagnostics for accurate antimicrobial testing.[1] Despite in vitro studies, there is a persistent lack of high quality clinical studies to ensure long term efficacy and widespread clinical adoption of new formulations as in vitro studies are limited in their ability to replicate the clinical conditions.[52] Future research must prioritize establishing the safety and biocompatibility of irrigants.[8] Large, multicenter randomized clinical trials are necessary to compare irrigants, evaluate irrigation protocols and measure long term outcomes across diverse patient populations.[50]

Conclusion

Endodontic irrigation remains the cornerstone of successful root canal therapy, compensating for the anatomical and biological limitations of mechanical instrumentation. Conventional irrigants such as sodium hypochlorite, chlorhexidine, and EDTA continue to form the backbone of chemo-mechanical preparation due to their well-established antimicrobial and chelating properties. However, none of these agents independently fulfills all the criteria of an ideal irrigant, particularly with respect to simultaneous tissue dissolution, smear layer removal, biofilm disruption, and optimal biocompatibility.[9]

Emerging irrigant technologies, including nanoparticles, herbal formulations, ozone, photodynamic therapy, QMix, and electrochemically activated solutions—represent promising attempts to address the shortcomings of traditional protocols. Nanoparticle-based systems demonstrate enhanced antibiofilm activity and deeper dentinal penetration, although concerns regarding cytotoxicity, discoloration, and limited long-term clinical validation persist.[4,19] Herbal irrigants offer attractive biocompatibility profiles and reduced toxicity but currently lack sufficient standardized clinical evidence to replace sodium hypochlorite.[7] Similarly, ozone, reactive solutions, and photoactivated disinfection have shown encouraging antimicrobial effects but remain adjunctive rather than primary disinfection strategies.[23,27]

Activation systems have significantly improved the effectiveness of irrigation by enhancing irrigant penetration and hydrodynamic disruption. Passive ultrasonic irrigation, laser-activated irrigation (PIPS and SWEEPS), apical negative pressure systems, and multisonic ultracleaning technologies consistently demonstrate superior debris removal and improved smear layer elimination compared to conventional syringe irrigation.[50,53] Short-term clinical benefits, particularly in reducing postoperative pain and enhancing canal cleanliness, are well documented. However, current evidence suggests that these activation systems do not consistently translate into superior long-term periapical healing outcomes.[6]

Future innovations are shifting toward multifunctional irrigants capable of integrating antimicrobial, chelating, and tissue-dissolving properties within a single formulation.[8] Advances in minimally invasive endodontics further necessitate highly efficient irrigation systems capable of achieving deep disinfection within conservative canal preparations.[10] Novel technologies such as non-thermal plasma, artificial intelligence-guided irrigation protocols, and bioengineered antimicrobial systems represent the next frontier in endodontic disinfection.[49,51] Nevertheless, the transition from promising in vitro findings to routine clinical adoption requires robust, multicenter randomized controlled trials with standardized methodologies and long-term follow-up[9,52]

In summary, while sodium hypochlorite remains the gold standard irrigant, the future of endodontic irrigation lies in synergistic integration, combining advanced chemical formulations with sophisticated activation technologies to achieve safer, deeper, and more predictable canal disinfection. Continued interdisciplinary research will be essential to translate emerging innovations into clinically reliable, biologically sound protocols that enhance long-term treatment success.

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