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Contemporary irrigant activation techniques in endodontics: A comprehensive review

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Abstract
Effective disinfection of the root canal system remains a critical determinant of endodontic success. Conventional irrigation methods often fall short in eliminating biofilms and debris from complex anatomical structures. This has led to the development and integration of various irrigant activation techniques designed to enhance the mechanical and chemical efficacy of root canal debridement. This article provides a comprehensive overview of both traditional and advanced activation methods, including manual dynamic activation, sonic and ultrasonic irrigation, continuous ultrasonic systems, apical negative pressure irrigation, and advanced technologies such as laser-activated irrigation, photoacoustic streaming, SWEEPS, and the multisonic GentleWave system. Each technique's mechanism of action, clinical protocol, advantages, and limitations are critically discussed. While techniques like Passive Ultrasonic Irrigation and EDDY demonstrate strong performance in smear layer and calcium hydroxide removal, systems like GentleWave and photoacoustic streaming offer promising outcomes in minimally instrumented canals, showing enhanced tissue dissolution and biofilm disruption. Despite technological advancements, no single activation method has proven universally superior across all clinical scenarios. Therefore, selecting an appropriate technique should be based on canal morphology, infection severity, and the desired level of disinfection. Continued research and comparative clinical studies are essential to refine these protocols and optimize patient outcomes. This review emphasizes that combining innovation with sound clinical judgment is key to achieving long-term endodontic success.

Keywords: Irrigant activation, Ultrasonic irrigation, Laser-activated irrigation, Root canal disinfection, GentleWave system, Shock Wave Enhanced Emission Photoacoustic Streaming (SWEEPS)

Introduction
Root canal infections are driven by biofilms. The intricate and diverse root canal system, combined with the multi-species nature of biofilms, makes achieving effective disinfection particularly daunting [1]. The key to successful root canal treatment hinges on precise diagnosis and treatment planning, comprehension of anatomy and morphology, adherence to traditional principles such as meticulous cleaning, disinfection, and obturation, along with proper coronal restoration [2]. Irrigation is regarded as a crucial component of root canal treatment, with its functions and goals varying depending on the type of irrigants used. It reduces friction between the instrument and dentin, improves the cutting efficiency of files, dissolves organic and inorganic materials, and, most importantly, targets root canal biofilms [3].
Achieving substantial bacterial eradication relies on precise mechanical instrumentation, targeted irrigation with antimicrobial solutions, and advanced activated irrigation techniques. Mechanical instrumentation alone does not guarantee complete disinfection. Studies reveal that 35-53% of the root canal walls remain untreated, with biofilm persisting, smear layers forming in inaccessible areas, and non-instrumented surfaces left inadequately disinfected [4].

Irrigation Activation Techniques
Manual Dynamic Activation Technique: Manual Dynamic Irrigation (MDA) is a simple yet cost-effective technique that enhances irrigant delivery and activation within the root canal system.

By utilizing hand files, brushes, or a tapered gutta-percha point, MDA generates turbulence, disrupts gas bubbles, and facilitates the flow of fresh irrigant, improving cleaning in the apical regions. Its effectiveness in biofilm and smear layer removal has been demonstrated, particularly in well-shaped canals with adequate apical taper [5].

The technique employs the in-and-out motion of a gutta-percha cone, creating intracanal pressure changes that promote diffusion through shear stresses. A thin reflux space between the cone and canal walls is critical for allowing irrigant backflow, inducing a robust hydrodynamic effect. Furthermore, MDA ensures the effective mixing of fresh and stagnant irrigant solutions, enhancing cleaning and breaking the vapor lock effect. A significant drawback is apical extrusion. Nevertheless, the risk of apical extrusion can be greatly minimized by agitating the master cone one millimeter short of the working length [6].

Endodontic brushes

The Endobrush is a precision-engineered spiral brush, designed for endodontic use, with durable nylon bristles set in twisted wires and a sleek, ergonomic handle resembling that of a hand file for optimal control and efficiency [7]. NaviTip FX, by Ultradent Products Inc., South Jordan, UT, introduced one of the first commercially available irrigation needles wrapped in a brush-like substance. The NaviTip FX is expertly designed to reach the apex of the canal while simultaneously delivering irrigant and actively scrubbing the canal walls. This dual-action mechanism enhances the mechanical activation, significantly amplifying the chemical efficacy of the irrigants in removing the smear layer and debris. Its performance mirrors the efficiency of a bottle brush, providing a thorough and effective canal cleansing [8, 9].

Ultrasonic Activation

Ultrasonic irrigation is a cutting-edge technique in endodontics that leverages high-frequency sound waves to enhance the efficacy of root canal cleaning and disinfection. Introduced to the field by Richman in 1957, this method has since evolved into a cornerstone of modern endodontic practice [10]. Compared to sonic energy, ultrasonic energy operates at higher frequencies but lower amplitudes. The files are specifically designed to oscillate at ultrasonic frequencies ranging from 25 to 30 kHz [11, 12].

Martin and Cunningham emphasized the effectiveness of ultrasonic instrumentation, crediting its success to the interaction between ultrasonic energy and irrigating solutions, known as the synergistic system [13]. The two primary effects of ultrasound are cavitation and acoustic streaming: Cavitation occurs when ultrasonic energy generates bubbles that expand and collapse violently, creating high temperatures (exceeding 5,000 °C), extreme pressures (over 500 atmospheres), and shockwaves traveling at speeds of over 500 mph. This process effectively cleans canal irregularities, eliminates microorganisms, and excels at reaching difficult or inaccessible surfaces. Acoustic streaming involves fluid currents generated by the shockwaves and the oscillatory motion of the ultrasonic instrument tip, further enhancing the cleaning and disinfecting process. Together, these mechanisms efficiently dissolve and remove contaminants, making ultrasonic instrumentation particularly effective for areas that conventional irrigation cannot adequately reach [14].

- **Passive ultrasonic irrigation (PUI)/ultrasonically activated irrigation (UAI):** In the term Passive Ultrasonic Irrigation (PUI), the "passive" aspect referred to the lack of active or intentional removal of dentin. Although there is no intention to directly contact or modify the root canal walls, the oscillating ultrasonic instrument does make contact with the canal wall during the procedure. As a result, Boutsioukis *et al*. recently proposed the term Ultrasonically Activated Irrigation (UAI) to better describe this interaction [15].

  During ultrasonic activation, a small-diameter ultrasonic tip is positioned within the root canal, approximately 2 mm short of the working length, avoiding contact with the dentinal walls. This free vibration is essential for effectively transmitting energy from the tip to the irrigant. Ultrasonic activation can be achieved using either magnetostrictive or piezoelectric devices [16, 17]. The optimal ultrasonic activation involves one minute per canal, divided into three cycles of 10-20 seconds each, with irrigation renewed after every cycle [18]. However, the effectiveness of Passive Ultrasonic Irrigation (PUI) relies heavily on factors such as the device's power intensity, the availability of free space within the canal, and the absence of any interference at the ultrasonic tip. Additionally, due to the anatomical complexities of the root canal, ultrasonic activation tends to be less effective in the apical region compared to the cervical region. Moreover, file-to-wall contact in the apical third during Passive Ultrasonic Irrigation (PUI) can lead to uncontrolled dentin removal [19-20].

- **Continuous Ultrasonic Irrigation (CUI)**

  To overcome the challenges of extended treatment time, straightening of curved canals, and file breakage, an ultrasonically activated irrigating needle was introduced. This innovation allows for simultaneous activation and replenishment of the irrigant deep within the canals, a technique known as Continuous Ultrasonic Irrigation (CUI). [14] CUI operates by activating an insert directly connected to the ultrasonic unit, enabling continuous delivery of the irrigant while simultaneously activating the insert within the root canal. Studies have shown that CUI generates consistently high fluid velocity and shear stress in the apical 3 mm, significantly enhancing the physical removal of surface-adherent biofilm bacteria [21].

Sonic Activation

Sonic activation systems operate at lower frequencies, typically between 1-10 kHz depending on the specific equipment, and unlike ultrasonic irrigation, they produce lower fluid velocity and shear wall stresses. However, they generate significantly greater amplitude through increased horizontal tip displacement [22, 23]. Modern sonic irrigation devices achieve oscillatory fluid dynamics through the use of various types of activation tips, including metallic files such as Rispisonic and Shapersonic (Micro-Mega, Besançon, Cedex, France); ventilated needle tips like Vibringe (Cavex Holland BV, Haarlem, Netherlands); and disposable polymer tips such as the EndoActivator (Dentsply Sirona, Ballaigues, Switzerland) and EDDY (VDW, Munich, Germany) [22].

EndoActivator

The EndoActivator® is a battery-operated, portable handpiece equipped with a three-speed electric motor designed for the sonic activation of root canal irrigants. It offers selectable speeds of 2,000, 6,000, and 10,000 cpm, allowing clinical flexibility [24, 25]. Although marketed with operating frequencies of 33, 100, and 167 Hz, [26] actual measured vibrational frequencies are slightly higher 160, 175, and 190 Hz, respectively [27]. The device uses flexible, non-cutting polymer tips available in three color-coded sizes size 15/.02, 25/.04, 35/.04 15 [24, 27]. Each tip is 22 mm long and features depth gauge rings at 18, 19, and 20 mm for precise placement [24]. The horizontal agitation of the tip, combined with short vertical strokes, creates a synergistic hydrodynamic effect within the root canal system. This action enhances lateral irrigant penetration, circulation, and flow into anatomically complex and inaccessible areas, thereby improving the overall cleaning efficiency. The EndoActivator® has demonstrated superior performance in promoting irrigant penetration, debris removal, and smear layer disruption compared to static and manual dynamic irrigation [28-30]. A systematic review of *in vitro* studies has demonstrated that the EndoActivator® system shows superior efficacy in removing calcium hydroxide from the middle and coronal thirds of the root canal system, owing to its ability to produce vigorous intracanal fluid agitation and enhance irrigant penetration and distribution [31].

EDDY

EDDY® (VDW GmbH, Munich, Germany) is an airscaler-powered sonic activation system that operates at a frequency of 5,000 to 6,000 Hz. It utilizes flexible polyamide tips (size 20/02), which are softer and more adaptable than traditional stiff metal tips, allowing them to navigate curved canals without compromising root canal anatomy. The high-frequency vibration transmitted by the airscaler induces a three-dimensional oscillating motion in the tip, resulting in cavitation and acoustic streaming. These physical phenomena enhance the cleaning efficacy by facilitating the removal of residual tissue, dentinal debris, and biofilm, while also allowing closer approximation to the apex. Research demonstrates that EDDY performs equal to or better than passive ultrasonic irrigation, combining the effectiveness of ultrasonics with enhanced safety [32, 33]. A 2019 study by Donnermeyer *et al*. concluded that EDDY was significantly more effective than the XP-Endo Finisher and manual irrigation in removing calcium hydroxide from artificial grooves, especially in the apical third of the canal. Though complete removal was not achieved by any method, EDDY and PUI performed equally well and significantly outperformed manual techniques, highlighting EDDY's potential as a safe and effective tool for enhanced irrigant activation and intracanal medicament removal [34].

Self-Adjusting File (SAF)

The Self-Adjusting File (SAF) system offers a minimally invasive 3D cleaning and shaping tailored to the natural morphology of the root canal [35]. Unlike conventional rotary files with solid metal cores, SAF features a hollow, flexible, compressible NiTi lattice design that adapts itself to canal anatomy, especially useful in oval, curved, or C-shaped canals [36]. It allows simultaneous irrigation and mechanical scrubbing, enhancing debridement while preserving dentin integrity. The SAF system includes a specialized RDT handpiece producing 5000 in-and-out vibrations per minute and an irrigation pump (VATEA or EndoStation) that delivers continuous sodium hypochlorite through the file lumen without pressure build-up. This design ensures effective irrigant exchange, even in the apical third, without the risk of extrusion due to low generated pressure (394 Pa compared to 1270 Pa from syringe irrigation) [35]. Micro-CT studies show SAF leaves only 23-25% of canal walls untouched, outperforming rotary files in shaping efficiency [37]. Moreover, it significantly reduces the risk of dentinal microcracks, canal transportation, and post-operative pain [38-40]. SAF also provides superior cleaning of isthmuses and canal fins with minimal packing of debris and offers better obturation outcomes due to cleaner canal surfaces.[41] Clinically, the SAF system achieves enhanced disinfection, especially in oval canals [35].

XP-Endo finisher

The XP-Endo Finisher® (XPEF), introduced by FKG Dentaire SA in 2015, is a unique rotary NiTi instrument designed to enhance root canal disinfection after mechanical preparation. Made from the proprietary MaxWire alloy, it undergoes a phase transformation from a straight shape in the martensitic phase at room temperature to a spoon-shaped configuration in the austenitic phase at body temperature, allowing it to adapt three-dimensionally to canal irregularities. With an ISO tip size of 25 and zero taper, the XPEF is used specifically during final irrigation stages following canal preparation [42]. Studies have shown that its flexible, expanding design enables effective agitation of irrigants and removal of biofilm, debris, smear layer and intracanal medicaments, especially from hard-to-reach areas like narrow apical grooves [43, 44]. While the XP-Endo Finisher has demonstrated good efficacy, systematic reviews conclude that Passive Ultrasonic Irrigation (PUI) often achieves superior performance in overall cleaning efficacy and debris removal [45, 46].

Laser-Activated Irrigation

Laser-Activated Irrigation (LAI) uses the phenomenon of cavitation to enhance the cleaning and disinfection of root canals. When pulsed erbium lasers such as Er: YAG or Er, Cr: YSGG are activated within an irrigant-filled canal, they emit high-energy short-duration pulses that are strongly absorbed by the aqueous medium. This absorption causes rapid superheating and the formation of vapor bubbles, which expand and then collapse violently. The implosion of these bubbles generates powerful shockwaves and intense fluid motion, leading to secondary cavitation events throughout the canal. This dynamic fluid activity, occurring within microseconds, creates a vigorous back and forth movement of the irrigant often referred to as a “breathing mode” which enables effective debris removal and disruption of microbial biofilms even in anatomically complex regions such as isthmuses, fins and lateral canals. Compared to traditional and ultrasonic irrigation methods, LAI produces higher intracanal fluid velocities and achieves efficient cleaning from a distance, reducing the need for direct tip placement into the apical third [47-49].

Antimicrobial photodynamic therapy

Antimicrobial photodynamic therapy (aPDT) is a minimally invasive adjunctive disinfection method that relies on the combined action of three essential components: A photosensitizer (PS), light of an appropriate wavelength, and molecular oxygen [50]. Upon light activation, the photosensitizer transitions from a low-energy ground state to an excited singlet state and then to a longer-lived triplet state. In this state, it can follow two main reaction pathways. In the Type I reaction, the triplet-state photosensitizer interacts with nearby cellular molecules to produce free radicals, which subsequently react with oxygen to Generate Reactive Oxygen Species (ROS) such as superoxide and hydrogen peroxide, damaging microbial cell membranes. In the Type II reaction, which is considered the primary mechanism of microbial cell damage in aPDT, the photosensitizer directly transfers energy to molecular oxygen, producing singlet oxygen a highly reactive form that causes localized oxidative damage to microbial cells. These ROS induce targeted photodamage, leading to microbial cell death [51].

Various light sources are used in antimicrobial photodynamic therapy (aPDT), with the three main types being lasers, LEDs, and halogen lamps. Lasers are commonly used and highly effective in microbial reduction; however, they are costly and may cause tissue damage due to heat generation if not properly controlled. LEDs are more affordable and safer in terms of temperature control but have a limited wavelength range. Halogen lamps offer broad-spectrum light that can be used with various photosensitizers, yet they also pose a risk of heat-induced tissue damage [52]. A key requirement for any light source in aPDT is that its wavelength matches the absorption peak of the photosensitizer, typically within the 630-800 nm range. Commonly used sources include helium-neon lasers (633 nm), argon lasers (488-514 nm), and gallium-aluminum-arsenide diode lasers (630-690, 830, or 906 nm). Diode lasers are especially popular due to their compact size, affordability, and ease of clinical use [53].

aPDT has been shown to significantly reduce microbial load within the root canal system and is effective against both Gram-positive and Gram-negative bacteria, regardless of their growth mode [54]. Its efficacy is influenced by factors such as the type and concentration of the photosensitizer, its application time, the wavelength and power of the light source, and the duration of irradiation. Importantly, it does not adversely affect the structural properties of intraradicular dentin or the bond strength of endodontically treated teeth [55].

Photon-Induced Photoacoustic Streaming (PIPS)

Photon-Induced Photoacoustic Streaming (PIPS) is an innovative laser-activated irrigation technique that enhances root canal disinfection by using a sub-ablative photoacoustic mechanism rather than a photothermal one, minimizing the risk of dentin carbonization and surface damage [56]. The PIPS laser system emits short pulses (around 50 microseconds) at low energy levels (20-50 mJ) and frequencies of 10-15 Hz, generating rapid vaporization of the irrigant and forming vapor bubbles whose expansion and collapse produce intense photoacoustic shockwaves [57]. Unlike conventional laser activated irrigation (LAI), which requires canal enlargement to position the laser tip near the apex, PIPS only needs the laser tip placed in the coronal pulp chamber, enabling minimally invasive treatment. These shockwaves create a three-dimensional irrigant flow, improving debris removal and allowing irrigants to penetrate into otherwise inaccessible areas of the root canal system [58]. A clinical protocol involving cycles of PIPS activation with sodium hypochlorite, water, and EDTA has been shown to be more effective than conventional irrigation and passive ultrasonic irrigation [59]. Studies have demonstrated that PIPS combined with 0.5-6% sodium hypochlorite effectively eliminates resistant bacteria such as *Enterococcus faecalis*, enhances biofilm disruption, and opens dentinal tubules better than traditional irrigation methods, making it a powerful and minimally invasive approach for root canal cleaning [56].

SWEEPS (Shock Wave Enhanced Emission Photoacoustic Streaming)

The SWEEPS (Shock Wave-Enhanced Emission Photoacoustic Streaming) technique is an advanced Er:YAG laser-based irrigation modality developed to enhance the efficacy of root canal disinfection beyond that of traditional single-pulse approaches like PIPS (Photon-Induced Photoacoustic Streaming). Unlike PIPS, which uses a single super-short pulse (50 µs), SWEEPS delivers two ultra-short pulses (25 µs) in rapid succession with an optimized time delay. The first pulse generates a primary vapor bubble, and the second pulse is emitted during its collapse, creating a new bubble that accelerates the implosion of the first. This synchronized bubble interaction produces strong shock waves and high-pressure fluid dynamics, even within narrow and confined root canals.

These shock waves and the resulting turbulent photoacoustic currents create shear stresses and vortical flows that dislodge debris, smear layer, and biofilm from canal walls, including in anatomically complex areas such as isthmuses, lateral canals, loops, and apical ramifications. Secondary cavitation bubbles also form naturally throughout the canal and collapse close to the canal walls, further enhancing cleaning through localized mechanical forces.

Studies have shown that SWEEPS provides superior debris removal compared to PIPS, ultrasonic, and sonic irrigation techniques. It also increases irrigant penetration into dentinal tubules without causing photothermal damage, due to the sub-ablative fluence levels used. Additionally, SWEEPS promotes a laminar "breathing" flow mode that allows irrigants to penetrate more thoroughly. The laser tip is placed in the pulp chamber, allowing effective irrigation without the need for deep intracanal insertion. Overall, SWEEPS has demonstrated improved root canal debridement and disinfection [60-62].

Apical Negative Pressure Irrigation (ANPI)

Apical negative pressure irrigation is a technique that combines the simultaneous use of irrigation and suction, with the suction applied at the apical end of the canal. This approach allows the irrigant to be safely delivered to the full working length without the risk of extrusion beyond the apex. By drawing the solution apically under negative pressure, the technique ensures deeper penetration into complex canal anatomies such as isthmuses, fins, and other irregularities [63]. Apical negative pressure is also effective in eliminating the vapor lock effect, thereby enhancing irrigant flow and improving debridement in the apical portion of the root canal [64].

EndoVac

The EndoVac system (Discus Dental, Culver City, CA) is an advanced apical negative pressure irrigation device designed to safely and effectively deliver irrigants to the working length of the root canal. It consists of a delivery/evacuation tip connected to an irrigant syringe and high-speed suction, along with either a macro- or microcannula attached via a small suction tube. The macrocannula is a plastic tube with an open end (ISO size 55, 02 taper), while the microcannula is made of stainless steel and features 12 offset lateral holes arranged in rows, with a closed tip measuring ISO size 32. When placed in an appropriately enlarged canal (ISO size 35 or more), the system pulls irrigant from the pulp chamber down to the apical third and evacuates it via suction, reducing the risk of irrigant extrusion. Unlike conventional needle irrigation, which must be carefully placed 1-2 mm short of the working length to avoid sodium hypochlorite accidents, the EndoVac allows safe irrigation up to the working length due to its negative pressure mechanism. Studies, including one by

Fukumoto *et al*., have demonstrated significantly lower risks of apical extrusion with EndoVac compared to traditional syringe irrigation, especially when needles are placed close to the apex. This underscores the EndoVac's key advantage safe and effective irrigation at the full working length, with superior apical debridement and reduced risk of complications [65, 66].

Gentlewave irrigation system

The GentleWave® system (GW) is an advanced endodontic irrigation device designed to enhance root canal cleaning and disinfection through a multisonic ultracleaning approach [67] Unlike traditional irrigation methods, GentleWave uses a combination of high-speed fluid dynamics, acoustic energy, and hydrodynamic cavitation to clean the entire root canal system, including anatomical complexities such as isthmuses, lateral canals, and dentinal tubules, without requiring the tip to enter the canal [68]. The system includes a console, a handpiece (positioned 1 mm above the pulp chamber floor), and a waste container. It delivers irrigants at a regulated flow rate of 45 mL/min, striking a metal plate in the handpiece to create a spray, while a 5-point suction system collects excess solution. A degassing step removes dissolved gases to improve cavitation efficiency and eliminate vapor lock. This creates cavitation clouds that implode, producing a wide spectrum of sound waves (Multisonic Ultracleaning) for thorough debridement throughout the canal system. The standard protocol involves irrigation with 3% NaOCl, followed by water, 8% EDTA, and a final rinse with distilled water [67].

The GentleWave system has demonstrated superior outcomes in organic tissue dissolution, outperforming conventional syringe irrigation, passive ultrasonic irrigation, continuous ultrasonic irrigation, and the EndoVac negative pressure system, with a dissolution rate of up to 2.9% per second using 6% NaOCl [69, 70]. It has also shown greater effectiveness in biofilm removal, especially against *E. faecalis*, and deeper NaOCl penetration into dentinal tubules when compared to ultrasonic systems, [71, 72]. It also excels in removing intracanal medications like $Ca(OH)_2$ and hard-tissue debris especially in the apical third [73].

Despite its high performance, the Gentle Wave system's effectiveness in retreatment procedures is comparable to, or slightly inferior to, other irrigation techniques such as passive ultrasonic irrigation (PUI).[74] However, it supports high-quality obscuration in minimally instrumented canals.[75] Clinical studies have reported a 97.3% success rate after 12 months, with no significant difference in postoperative pain compared to conventional methods.

Although the system's cost and need for specific handpieces are considered limitations, Gentle Wave system enables minimally invasive treatment while achieving thorough debridement and disinfection [67].

Conclusion

The success of endodontic treatment relies not only on mechanical instrumentation but also on the effectiveness of irrigation in eliminating microorganisms and debris from the complex root canal system. Advancements in irrigant activation techniques, including sonic and ultrasonic systems, negative pressure irrigation, and laser-based methods, have significantly enhanced the reach, depth, and antimicrobial efficacy of root canal disinfection. Emerging technologies such as the Gentle Wave system and photon-induced photoacoustic streaming (PIPS) offer promising alternatives that can improve treatment outcomes, even in minimally instrumented canals. Although no single technique can be considered universally superior, understanding the advantages and limitations of each method enables clinicians to make informed, case-specific choices. As ongoing research continues to expand the evidence base, the integration of these innovations with sound clinical judgment will remain essential for achieving long-term endodontic success.

Conflict of Interest

Not available

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Not available

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