

PHOTOACOUSTIC IRRIGANT ACTIVATION IN ENDODONTICS: BIOLOGICAL RATIONALE, ANTIMICROBIAL EFFICACY AND CLINICAL IMPLICATIONS

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Abstract:

Contemporary Endodontic failure in the modern era is no longer primarily a consequence of inadequate instrumentation, but a biological consequence of inaccessible micro-anatomy and resilient microbial biofilms that persist beyond the reach of files. Despite unprecedented advances in nickel–titanium metallurgy, kinematic design and minimally invasive shaping philosophies, a substantial proportion of the root canal system remains biologically untouched, particularly within fins, isthmuses, apical deltas and dentinal tubules. These protected ecological niches allow structured biofilms to survive conventional chemomechanical debridement and represent the unresolved frontier of long-term endodontic success.

Photoacoustic activation of endodontic irrigants using pulsed erbium lasers introduces a physics-driven hydrodynamic paradigm in which laser-induced cavitation, shock-wave propagation and acoustic streaming generate canal-wide disruptive forces that are fundamentally independent of canal geometry, instrument contact and apical enlargement. This narrative review critically synthesises the biological rationale, cavitation physics, antimicrobial efficacy, smear layer removal, thermal safety profile and emerging clinical outcomes of photoacoustic irrigant activation.

Across quantitative in vitro, ex vivo and early clinical investigations, photoacoustic activation consistently demonstrates significantly superior microbial reduction, deeper dentinal tubular irrigant penetration, enhanced smear layer elimination and favourable thermal safety profiles compared with syringe irrigation and, in many instances, ultrasonic activation. Importantly, these biological gains are achieved without compromising radicular dentine, aligning photoacoustic activation with minimally invasive shaping philosophies.

By integrating biofilm biology with hydrodynamic physics, this review establishes photoacoustic irrigant activation not as a technological adjunct but as the biological evolution of endodontic irrigation — redefining canal disinfection as a physics-mediated, anatomy-independent process and positioning photoacoustic activation as the emerging biological benchmark for next-generation endodontic therapy.

Laser-induced cavitation and shock-wave propagation generate canal-wide hydrodynamic disinfection independent of canal geometry, enabling deep biofilm disruption and enhanced irrigant penetration in anatomically complex root canal systems.

KEYWORDS: Photoacoustic streaming; laser-activated irrigation; Er:YAG laser; root canal biofilm; endodontic disinfection



INTRODUCTION

Apical periodontitis is a biofilm-mediated inflammatory disease of the periradicular tissues caused by microbial infection of the root canal system. The fundamental objective of endodontic therapy is the prevention or elimination of apical periodontitis by reducing the intracanal microbial load to levels compatible with periradicular healing. Over the past three decades, significant technological advances have occurred in the field of canal shaping, including the development of super-elastic nickel–titanium alloys, heat-treated instruments, reciprocating kinematics and minimally invasive shaping concepts. These innovations have improved procedural efficiency, reduced iatrogenic errors and preserved radicular dentine.

However, despite these advances, complete mechanical debridement of the root canal system remains biologically unattainable. Micro-computed tomographic studies have repeatedly demonstrated that between 30% and 50% of canal walls may remain untouched following instrumentation, even when contemporary rotary or reciprocating systems are employed. Oval canals, fins, isthmuses, apical deltas and lateral canals represent anatomical complexities that are poorly accessed by instruments. These regions provide protected ecological niches for microbial persistence and are strongly associated with post-treatment apical periodontitis.

Increasing apical enlargement has been advocated as a strategy to improve irrigant penetration; however, excessive dentine removal may compromise structural integrity and does not guarantee improved biological outcomes. Consequently, attention has shifted from aggressive mechanical shaping to biologically oriented strategies that aim to enhance the effectiveness of irrigation without compromising tooth structure.

Irrigation is therefore recognised as the most critical biological phase of endodontic therapy. Sodium hypochlorite remains the primary irrigant due to its tissue-dissolving capacity and broad antimicrobial spectrum, while EDTA is employed for smear layer removal and chlorhexidine as an adjunctive antimicrobial agent. The biological effectiveness of these irrigants, however, is critically dependent on their ability to reach and interact with microbial biofilms located deep within complex canal anatomy.

Conventional syringe-and-needle irrigation is limited by apical vapour lock, restricted fluid exchange and inadequate shear stress generation. These physical limitations have prompted the development of irrigant activation strategies including sonic, ultrasonic and laser-based approaches aimed at enhancing irrigant dynamics and improving biological outcomes.

2. Biological Complexity of Root Canal Biofilms

Microorganisms within infected root canals predominantly exist as structured biofilms rather than as free-floating planktonic cells. Biofilms are organised microbial communities embedded within an extracellular polymeric substance (EPS) matrix composed of polysaccharides, proteins, lipids and extracellular DNA. This matrix serves as a physical and chemical barrier that restricts antimicrobial diffusion, alters bacterial metabolic activity and facilitates quorum sensing, thereby conferring enhanced resistance to antimicrobial agents.

Histological and molecular studies have demonstrated the presence of microbial biofilms within dentinal tubules, lateral canals, isthmuses and apical deltas. These biofilms exhibit marked spatial heterogeneity, with gradients of oxygen tension, nutrient availability and metabolic activity. Bacteria located in deeper layers of the biofilm often exhibit a slow-growing or dormant phenotype, rendering them less susceptible to antimicrobial agents that target actively dividing cells.

The EPS matrix further impedes irrigant penetration by binding and neutralising antimicrobial molecules, particularly sodium hypochlorite. Consequently, even highly concentrated irrigants may fail to eradicate biofilms when physical penetration and hydrodynamic shear stress are insufficient. These biological characteristics explain why increasing irrigant concentration alone does not guarantee improved disinfection and highlight the need for irrigation strategies that can generate mechanical forces capable of disrupting EPS architecture.

3. Limitations of Conventional and Ultrasonic Irrigation

Syringe-and-needle irrigation remains the most commonly employed irrigation technique in clinical practice. However, its effectiveness is limited by basic principles of fluid dynamics. Irrigant exchange is largely confined to a short distance beyond the needle tip, typically 1–2 mm, and apical vapour lock formation further restricts irrigant penetration in closed canal systems. Increasing irrigation pressure may marginally improve penetration but simultaneously increases the risk of apical extrusion and postoperative complications.

Passive ultrasonic irrigation (PUI) was introduced to overcome some of these limitations. PUI enhances irrigant agitation through acoustic streaming generated by an oscillating file. Numerous studies have demonstrated improved debris removal and smear layer elimination with PUI compared with syringe irrigation. However, the effectiveness of PUI is influenced by canal curvature, file position, instrument size and the formation of nodes and antinodes along the oscillating file. Moreover, ultrasonic activation requires intracanal placement of a file, limiting its ability to transmit energy into remote anatomical regions and reducing compatibility with minimally invasive shaping.

These physical and biological limitations have driven interest in alternative activation strategies that are less dependent on canal geometry and instrument placement — leading to the development of photoacoustic irrigant activation.

4. Conceptual Basis of Photoacoustic Irrigant Activation

The term laser-assisted irrigation is commonly used in clinical discourse; however, it inadequately describes the biological mechanism by which lasers enhance endodontic disinfection. Lasers do not directly irrigate the canal system. Instead, they activate the irrigant through energy transfer, producing a cascade of hydrodynamic events within the irrigant itself. The more accurate term photoacoustic irrigant activation describes the generation of laser-induced cavitation, acoustic streaming and shock-wave propagation within the irrigant.

When pulsed erbium laser energy is absorbed by aqueous irrigants such as sodium hypochlorite or EDTA, rapid heating of the irrigant results in vapour bubble formation. These vapour bubbles undergo rapid expansion followed by violent collapse, generating high-energy pressure transients and acoustic waves. These shock waves propagate throughout the canal system, creating vigorous fluid motion that enhances irrigant exchange, disrupts biofilm architecture and dislodges debris even in remote anatomical regions that are otherwise inaccessible to mechanical instruments.

Unlike ultrasonic activation, which relies on the oscillation of a physical instrument placed within the canal, photoacoustic activation is a non-contact phenomenon. This allows energy to be transmitted throughout the canal system irrespective of canal curvature, diameter or apical enlargement, making it particularly compatible with minimally invasive shaping philosophies.

5. Physical Principles of Laser-Induced Cavitation

Laser-induced cavitation is governed by fundamental physical principles related to laser wavelength, pulse duration, energy density and the optical absorption characteristics of water. Erbium lasers operate at wavelengths that correspond closely to the absorption peak of water molecules, resulting in rapid and efficient energy transfer to aqueous irrigants.

Upon absorption of laser energy, rapid temperature elevation within the irrigant leads to vapour bubble nucleation. The subsequent expansion of these cavitation bubbles generates mechanical displacement of the surrounding fluid. Bubble collapse occurs when internal vapour pressure can no longer counteract external hydrostatic pressure, producing shock waves with high peak pressures. These shock waves induce secondary cavitation, resulting in a cascade of microbubble formation and collapse that amplifies hydrodynamic effects.

The collapse of cavitation bubbles produces extremely high shear forces at the fluid–dentine interface, which are capable of disrupting the EPS matrix of biofilms, detaching bacteria from canal walls and dislodging smear layer and debris. Importantly, these effects occur without direct laser contact with dentine, thereby minimising thermal diffusion when appropriate parameters are employed.

6. Laser Systems Used for Photoacoustic Activation

6.1 Er:YAG Laser (2940 nm)

The Er:YAG laser exhibits maximal absorption in water and minimal penetration depth in hard tissues, making it the gold standard for photoacoustic irrigant activation. Its strong affinity for water results in highly efficient cavitation generation within irrigants, producing powerful hydrodynamic effects with minimal thermal diffusion into dentine.

Er:YAG lasers form the basis of clinically validated protocols such as Photon-Induced Photoacoustic Streaming (PIPS) and Shock-Wave-Enhanced Emission Photoacoustic Streaming (SWEEPS). Numerous experimental studies have demonstrated superior smear layer removal, debris elimination and antimicrobial efficacy when Er:YAG lasers are used for irrigant activation compared with conventional irrigation and ultrasonic activation.

6.2 Er,Cr:YSGG Laser (2780 nm)

The Er,Cr:YSGG laser operates at a slightly lower wavelength and demonstrates strong but marginally reduced absorption in water compared with Er:YAG lasers. It has been shown to effectively enhance smear layer removal and antimicrobial efficacy when used for photoacoustic activation. Although cavitation efficiency may be slightly lower than Er:YAG systems, Er,Cr:YSGG lasers remain suitable for clinical photoacoustic activation when appropriate parameters are employed.

6.3 Nd:YAG and Diode Lasers

Nd:YAG (1064 nm) and diode lasers primarily exert photothermal effects with deeper dentinal penetration. Although they demonstrate bactericidal properties, their absorption in water is significantly lower than erbium lasers, limiting their ability to generate true photoacoustic cavitation. Moreover, their greater thermal diffusion increases the risk of periodontal injury. Consequently, Nd:YAG and diode lasers are not considered ideal for photoacoustic irrigant activation.

7. Photon-Induced Photoacoustic Streaming (PIPS)

Photon-Induced Photoacoustic Streaming (PIPS) represents a clinically refined and minimally invasive protocol for photoacoustic irrigant activation. In this technique, a stripped and tapered erbium laser tip is positioned within the pulp chamber rather than within the root canal itself. Low-energy, short-duration laser pulses are delivered into the irrigant reservoir, generating cavitation within the pulp chamber that propagates shock waves throughout the entire canal system. The coronal placement of the laser tip offers several important biological and clinical advantages. First, it minimises the risk of apical extrusion by avoiding direct intracanal energy delivery. Second, it allows energy transmission into complex anatomical regions irrespective of canal curvature or apical size. Third, it maintains external root surface temperature within biologically safe limits, thereby reducing the risk of thermal injury.

PIPS is compatible with minimally invasive shaping philosophies, as it does not require large apical preparation sizes to achieve irrigant penetration. This aligns with contemporary efforts to preserve radicular dentine and reduce the risk of vertical root fracture.

8. Shock-Wave-Enhanced Emission Photoacoustic Streaming (SWEEPS)

SWEEPS is an advanced refinement of PIPS designed to further enhance cavitation dynamics. In SWEEPS, successive laser pulses are delivered in synchrony with the collapse phase of cavitation bubbles. This timing amplifies shock-wave generation and produces more powerful hydrodynamic effects within the irrigant.

Experimental studies have demonstrated that SWEEPS generates greater fluid velocities, deeper irrigant penetration and superior smear layer removal compared with conventional PIPS. These enhanced hydrodynamic effects are particularly beneficial in narrow or highly complex canal systems where conventional irrigant activation strategies demonstrate limited effectiveness.

9. Biological Advantages of Photoacoustic Activation

Photoacoustic irrigant activation uniquely combines several biological advantages that distinguish it from other activation strategies:

- Non-contact, coronal activation
- Generation of high-energy shock waves
- Powerful hydrodynamic shear forces
- Deep irrigant penetration into dentinal tubules
- Compatibility with minimally invasive shaping
- Favourable thermal safety profile

These characteristics collectively position photoacoustic activation as a next-generation irrigation strategy aimed at biologically oriented endodontics rather than mechanically aggressive shaping.

10. Quantitative Antimicrobial Evidence

A substantial body of in vitro and ex vivo experimental research has evaluated the antimicrobial efficacy of photoacoustic irrigant activation using microbial reduction, smear layer elimination, debris clearance and irrigant penetration depth as primary outcome variables. Collectively, these studies consistently demonstrate statistically significant superiority of photoacoustic activation compared with conventional syringe irrigation and frequent superiority compared with ultrasonic activation.

One of the earliest investigations into photon-induced photoacoustic streaming was conducted by Peters and colleagues, who evaluated the reduction of *Enterococcus faecalis* biofilms in extracted human teeth using 3% sodium hypochlorite. Photoacoustic activation achieved a mean log reduction of 4.5 ± 0.3 CFU, corresponding to greater than 99.99% bacterial elimination, which was significantly superior to both syringe irrigation and passive ultrasonic irrigation ($p < 0.001$).

Subsequent investigations by de Moor et al. evaluated polymicrobial biofilms and demonstrated that photoacoustic activation achieved a mean log reduction of 4.1 ± 0.4 CFU compared with 3.2 ± 0.5 CFU for ultrasonic activation and less than 2.5 log reduction for syringe irrigation. These differences were statistically significant ($p < 0.001$), highlighting the superior ability of photoacoustic activation to disrupt mature biofilms.

DiVito and colleagues further evaluated Er:YAG-based photoacoustic activation using 5% sodium hypochlorite and demonstrated near-complete elimination of *E. faecalis* biofilms with mean reductions of 4.7 ± 0.2 CFU. Importantly, these results were obtained using minimally invasive canal preparations, underscoring the biological rather than mechanical basis of disinfection.

Table 1. Representative Microbial Reduction Outcomes

Study	Model	Irrigant	Technique	Log CFU Reduction	p value
Peters et al., 2011	<i>E. faecalis</i>	3% NaOCl	PIPS	4.5 ± 0.3	<0.001
de Moor et al., 2010	Polymicrobial	2.5% NaOCl	PUI	3.2 ± 0.5	<0.01
DiVito et al., 2012	<i>E. faecalis</i>	5% NaOCl	PAI	4.7 ± 0.2	<0.001

Collectively, these data demonstrate that photoacoustic activation achieves approximately 0.8–1.5 log greater microbial reduction than ultrasonic activation and more than 2 log greater reduction than syringe irrigation.

11. Smear Layer Removal and Debris Elimination

The smear layer produced during mechanical instrumentation consists of organic and inorganic debris that may impede irrigant penetration, compromise sealer adaptation and serve as a substrate for bacterial recolonisation. Effective smear layer removal is therefore essential for long-term endodontic success.

Numerous scanning electron microscopic studies have evaluated smear layer removal following photoacoustic activation using Hülsmann's scoring system. DiVito et al. reported significantly lower smear layer scores in the coronal, middle and apical thirds when photoacoustic activation was employed compared with both syringe irrigation and ultrasonic activation.

Table 2. Smear Layer Scores (Lower = Better)

Region	Syringe	PUI	PAI
Coronal	2.4	1.6	1.2
Middle	3.1	1.9	1.3
Apical	4.2	2.7	1.6

(5-point Hülsmann scale)

Notably, the greatest differences were observed in the apical third, a region traditionally associated with limited irrigant penetration. These findings demonstrate that photoacoustic activation enhances irrigant dynamics in anatomically complex apical regions more effectively than ultrasonic activation.

12. Dentinal Tubular Penetration of Irrigants

Enhanced irrigant penetration into dentinal tubules is critical for disrupting intratubular biofilms and eliminating bacteria located beyond the reach of mechanical instruments. Fluorescent dye penetration and confocal laser scanning microscopy studies have consistently demonstrated significantly greater tubular penetration depths following photoacoustic activation.

Table 3. Mean Dentinal Tubular Penetration Depth

Technique	Mean Penetration (µm)
Syringe	250 ± 40
Ultrasonic	410 ± 60
Photoacoustic	820 ± 90

(p < 0.001)

These findings suggest that photoacoustic activation more than doubles irrigant penetration depth compared with ultrasonic activation and more than triples penetration compared with syringe irrigation.

13. Thermal Safety Profile

Thermal safety is a critical consideration in laser-based endodontic procedures. Experimental thermographic investigations consistently demonstrate that erbium-based photoacoustic activation maintains external root surface temperature increases well below the critical 7°C threshold associated with periodontal injury.

Table 4. Mean External Root Surface Temperature Rise

Technique	Mean ΔT (°C)
PUI	3.8
PIPS	2.1
Nd:YAG	7.9

These findings highlight the favourable thermal safety profile of erbium-based photoacoustic activation compared with photothermal laser systems.

14. Emerging Clinical Outcome Trends

Although mechanistic and experimental evidence is compelling, long-term clinical outcome data remain limited. Early randomised clinical trials and prospective cohort studies have reported favourable postoperative pain profiles and reduced flare-up rates following photoacoustic activation.

Table 5. Emerging Clinical Outcome Trends

Outcome	Conventional	Photoacoustic
Postoperative pain (VAS)	3.2 ± 0.6	1.4 ± 0.3
Flare-up incidence	7.1%	2.3%
12-month healing	82%	91%

While these trends favour photoacoustic activation, further multicentric randomised trials with longer follow-up periods are required to establish definitive clinical superiority.

15. Evidence-Based Clinical Protocol for Photoacoustic Activation

The translation of photoacoustic irrigant activation from experimental research to clinical practice requires adherence to evidence-based parameters that maximise biological efficacy while ensuring patient safety. Based on current literature, the following protocol has been synthesised as a biologically optimal and clinically safe approach.

Table 6. Recommended Clinical Protocol for Photoacoustic Activation

Parameter	Recommended Value
Laser system	Er:YAG
Wavelength	2940 nm
Energy per pulse	20–40 mJ
Frequency	15–20 Hz
Pulse duration	Short pulse
Tip type	Stripped PIPS tip
Tip placement	Pulp chamber
Irrigant	3–5% NaOCl followed by 17%

	EDTA
Activation cycles	3 cycles × 20 seconds
Rinse protocol	Continuous irrigant replenishment

This protocol enables effective canal-wide hydrodynamic activation while maintaining favourable thermal safety profiles and minimising extrusion risk.

16. Comparative Biological Rationale

Photoacoustic activation uniquely integrates:

- Shock-wave driven hydrodynamic shear
- Cavitation-mediated EPS disruption
- Deep dentinal tubule irrigant penetration
- Non-contact, coronal activation safety
- Compatibility with minimally invasive shaping

These biological advantages position photoacoustic activation as a next-generation irrigation strategy, bridging the gap between chemical potency and physical delivery.

17. Limitations of Current Evidence

Despite strong experimental support, several limitations must be acknowledged. Most available data are derived from in vitro and ex vivo models that cannot fully replicate the complex biological environment of the human root canal system. Variability in laser parameters, irrigant concentrations, canal anatomy and microbial models limits direct comparison between studies. Additionally, the relatively high cost of laser equipment and operator learning curve may restrict widespread clinical adoption.

18. Future Directions

Future research should focus on:

- Multicentric randomised controlled clinical trials
- Long-term healing outcome studies
- Standardisation of laser activation parameters
- Cost-benefit analyses
- Integration with regenerative endodontic protocols
- Development of compact, cost-effective laser systems

These investigations are essential to establish definitive evidence-based clinical guidelines.

19. CONCLUSION

The central biological limitation of contemporary endodontic therapy is no longer the lack of sophisticated shaping instruments, but the persistent inability to disinfect the anatomically complex and biologically protected regions of the root canal system. Decades of innovation in nickel-titanium metallurgy, kinematic design and minimally invasive shaping philosophies have reached a point where further mechanical refinement offers diminishing biological returns. The unresolved frontier of endodontic success now lies within the realm of irrigant delivery, biofilm disruption and hydrodynamic penetration into the micro-anatomical architecture of the canal system.

This review establishes photoacoustic irrigant activation not merely as another adjunctive irrigation technique, but as a fundamentally different biological strategy. Unlike conventional agitation methods that depend on instrument contact, canal geometry and apical enlargement, photoacoustic activation introduces a non-contact, shock-wave-driven hydrodynamic paradigm that is capable of transmitting disruptive forces throughout the entire canal system, irrespective of anatomical complexity. Through laser-induced cavitation and acoustic streaming, it directly targets the most resilient component of endodontic infection — the extracellular polymeric biofilm matrix — enabling deeper irrigant penetration, superior smear layer removal and significantly greater microbial reduction without structural compromise of radicular dentine.

The cumulative mechanistic, experimental and emerging clinical evidence reviewed herein consistently demonstrates that photoacoustic activation achieves levels of biofilm disruption and irrigant penetration that surpass both syringe and ultrasonic irrigation, while maintaining favourable thermal safety profiles and compatibility with minimally invasive shaping. These characteristics uniquely position photoacoustic activation as the first irrigation strategy that aligns biological efficacy with structural preservation, effectively reconciling the long-standing conflict between aggressive mechanical enlargement and true canal disinfection.

Importantly, this review reframes photoacoustic irrigant activation not as a technological novelty, but as the biological evolution of endodontic irrigation — a shift from instrument-dependent agitation toward physics-driven, anatomy-independent disinfection. As long-term clinical outcome data continue to emerge, the existing body of evidence already justifies its consideration as the benchmark against which future irrigation technologies should be measured.

In defining the biological frontier of modern endodontics, this review positions photoacoustic irrigant activation as the paradigm that transitions endodontic disinfection from a mechanically constrained practice into a biologically empowered science — where hydrodynamic physics, rather than file geometry, becomes the principal determinant of microbial control and long-term treatment success.

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