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Fluid Dynamics Research on Erbium Laser-Assisted Chemical Preparation for Root Canal Therapy: A Review

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Abstract: Microbial infection is a principal etiological factor in pulp and periapical diseases, necessitating effective root canal therapy (RCT) for thorough decontamination of the root canal system. However, conventional mechanical and chemical preparation methods remain inadequate, often leaving significant portions of the canal uncleaned and contributing to persistent infection. The advent of erbium laser-assisted chemical preparation has demonstrated significant potential in enhancing root canal disinfection through advanced fluid dynamics mechanisms, particularly cavitation and photoacoustic streaming. This review explores the fundamental principles governing fluid dynamics in erbium laser-assisted irrigation, with a focus on primary and secondary cavitation effects. The interaction between erbium laser energy and water generates vapor bubbles that induce dynamic fluid movement, enhancing the penetration and distribution of irrigants deep within the root canal system. Key factors influencing fluid dynamics intensity, including laser parameters, working tip design, and water medium confinement, are critically analyzed. Furthermore, recent advancements such as Photon-Initiated Photoacoustic Streaming (PIPS), Photoacoustic Synchronized Transients (PHAST), and Shock Wave Enhanced Emission Photoacoustic Streaming (SWEEPS) are reviewed in the context of their ability to improve fluid motion and irrigation efficacy. While these laser-assisted techniques offer promising improvements over traditional methods, challenges remain in optimizing energy parameters and mitigating the constraints imposed by confined root canal environments. Future research should focus on refining fluid dynamics models and conducting clinical studies to validate the efficacy of these innovations. This review aims to provide a comprehensive overview of current developments in fluid dynamics research related to erbium laser-assisted chemical preparation, offering insights into its potential as an advanced modality for root canal disinfection.

Keywords: Root canal therapy; Laser adjunctive therapy; Erbium Laser; Fluid dynamics; Infection control

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1. Introduction

Microbial infection is one of the primary etiological factors in pulp and periapical diseases. Root canal therapy (RCT) is the preferred treatment modality for pulp and periapical pathologies, with the core objective being the thorough debridement of the infected pulp tissue and contaminants within the root canal system, including residual pulp tissue, biofilms, and microbial toxins [1]. Due to the complex anatomical structure of the root canal system, conventional mechanical preparation alone is insufficient, often leaving approximately 35% to 53% of the canal walls uncleaned [2]. Additionally, mechanical instrumentation can create a smear layer, which hinders the efficacy of disinfection [3]. Regardless of the mechanical preparation system used, significant amounts of dentin tissue along the canal walls are left uncut, with a pronounced limitation of self-limiting cleaning in the apical region [2–6]. Traditionally, chemical preparation has been employed to remove the smear layer and further eliminate infection within the root canal. However, current research indicates that conventional chemical disinfection methods still fall short of completely eradicating the infection. The unique wavelength and tissue interaction properties of the erbium laser (Er:YAG) have demonstrated great potential in root canal cleaning and disinfection. In particular, the application of erbium laser in fluid dynamics, through phenomena such as cavitation and photoacoustic streaming, offers a promising means of enhancing penetration and distribution of irrigants deep within the root canal system. This fluid dynamic enhancement not only improves the flow of irrigants but also significantly boosts the effectiveness of chemical preparation in root canal therapy. This review aims to provide an overview of the advancements in the fluid dynamics of erbium laser-assisted chemical preparation for root canal therapy.

2. Mechanisms of fluid dynamics generation

The fluid dynamics in erbium laser-assisted chemical preparation for root canal therapy are primarily driven by cavitation effects, which involve a series of distinct physical stages.

2.1. Primary cavitation effect

The primary cavitation effect follows the optical physics principles governing the interaction between laser energy and water [7]. The wavelength of the Er:YAG laser allows it to be readily absorbed by hydroxyl (OH^-) groups ($\mu a = 1.247 \times 10^6\ m^{-1}$) [8]. When the erbium laser emits energy, approximately 70% of the pulse energy is absorbed within a thin layer of water molecules ($\leq 1\ \mu m$) surrounding the fiber tip. This rapid energy absorption leads to an instantaneous conversion of optical energy into thermal energy, causing the water to reach its boiling point almost immediately. This results in the formation of vapor bubbles at the tip of the working fiber, initiating the primary cavitation effect [9].

The core principle behind fluid dynamic generation is the difference in compressibility between gases and liquids, meaning that under identical pressure conditions, gas volume changes significantly, whereas liquid volume remains relatively stable. Once a vapor bubble forms, its volume fluctuates in response to internal pressure changes. The surrounding liquid, however, does not exhibit a corresponding volume change but instead undergoes displacement, leading to the first phase of fluid flow.

When the internal pressure of the vapor bubble equilibrates with the surrounding liquid pressure, the bubble enters a collapse phase. During this process, the rapid reduction in vapor bubble pressure causes the surrounding liquid to rush into the previously occupied space. This inward movement of liquid generates a secondary inward flow toward the bubble center. When the inflowing liquid converges, it creates a shock wave, which propagates outward and results in the second phase of fluid flow [10].

2.2. Secondary cavitation effect

Following the initiation of fluid motion by the primary cavitation effect, the generated liquid flow attains a certain velocity and momentum within the pulp chamber and root canal. According to Bernoulli's equation:

$$p + \frac{1}{2}\rho v^2 + \rho gh = C$$

Where, p is the fluid pressure at a given point, v is the velocity, ρ is the fluid density, g is gravitational acceleration, h is the height at that point, and C is a constant.

When the local pressure drops below the static separation pressure of dissolved gases, gas molecules within the liquid are released, forming observable microbubbles. This phenomenon is termed the secondary cavitation effect [11]. Unlike primary cavitation, secondary cavitation bubbles may adhere to the dentinal walls of the pulp chamber or root canal before imploding. This process generates a higher instantaneous shear force on the canal walls, potentially enhancing the decontamination effect. Some researchers hypothesize that the secondary cavitation effect may play an even more critical role in infection removal due to this intensified mechanical impact.

3. Factors influencing fluid field intensity

The intensity of the fluid field during laser-assisted root canal chemical preparation determines the effectiveness of the procedure. Therefore, it is essential to control the factors that influence fluid field intensity. These factors can be summarized into three main aspects:

3.1. Laser parameters

The parameters of pulsed erbium lasers primarily include pulse width, single pulse energy, and frequency. Pulse width determines the peak power and is one of the most crucial factors affecting vapor bubble dynamics. Under constant conditions, a shorter pulse width results in higher peak power, leading to larger vapor bubbles and a stronger induced fluid field. Single pulse energy and frequency jointly determine output power but influence fluid field intensity from different perspectives. Higher single pulse energy generates larger vapor bubbles in free water, increasing fluid movement velocity upon bubble collapse [12]. However, studies have reported that increasing single pulse energy does not enhance fluid field intensity in the root canal system. Frequency does not directly affect vapor bubble formation but can enhance fluid field intensity within a certain range. Research has confirmed that fluid movement velocity in lateral root canals differs significantly between erbium laser pulses at 3 Hz and 4 Hz [13].

3.2. Shape and position of the working tip

During erbium laser-assisted chemical preparation, the shape and position of the working tip play a crucial role in vapor bubble formation and fluid field dynamics[14]. When the pulse width is set between 50–80 μs, a flat-end working tip produces elongated vapor bubbles (channel-like bubbles), whereas a conical working tip (with a taper angle of 34°) forms spherical vapor bubbles [15]. Multiple studies have indicated that conical working tips synchronize the vaporization of surrounding thin-layer water molecules, achieving higher energy conversion efficiency, which allows more optical energy to be converted into kinetic energy under the same parameters [13]. The difference in energy conversion efficiency among different working tips may be due to variations in the thickness of water molecules absorbing the energy. If some laser energy is converted into the internal energy of water molecules without causing vaporization, the efficiency of optical-to-kinetic energy conversion decreases.

When peak power remains constant, the influence of working tip shape on vapor bubble morphology diminishes as pulse width shortens. When the pulse width is set to 1 μs, a flat-end working tip can also generate spherical vapor bubbles, which may be related to the increased concentration of output energy with shorter pulse width [9]. The activation position of the working tip directly affects the constraint imposed by rigid root canal walls on fluid movement. When the working tip is placed within the root canal, the liquid exerts high pressure on the apical region, and fluid exchange in this area is limited, making it less effective for apical cleaning [16]. Placing the laser tip in the apical region can lead to apical extrusion of the irrigant [17, 18]. Consequently, researchers have proposed activating the working tip in the pulp chamber, and further studies have confirmed that pulp chamber activation can also achieve effective cleaning of the apical region.

3.3. Confinement of the water medium

The cavitation effect and fluid field formation in the pulp chamber and root canal system are more complex than in free water. Factors such as the volume of the pulp chamber, the diameter and morphology of the main root canal, and the position of lateral root canals all influence the overall physical process [19]. Initially, researchers aimed to simplify laser-assisted chemical preparation models by selecting free water environments to isolate the effects of laser parameters, protocols, and working tip types on vapor bubbles and fluid motion. However, with further studies, it became evident that the confined space within the pulp chamber and root canal system significantly affects the cavitation effect and fluid field, bringing increased attention to the issue of water medium confinement. Early research primarily focused on differences in bubble formation between free water and confined water environments. In root canal models, lateral expansion of bubbles is restricted by the pulp chamber walls, apical expansion is hindered by liquid resistance, and coronal expansion is obstructed by the optical fiber tip, causing the internal bubble pressure to remain elevated for an extended period [20]. Therefore, under the same energy output conditions, bubbles in confined water environments exhibit slower expansion and collapse rates, longer oscillation cycles, and smaller vapor bubble volumes [21]. In 2011, Matsumoto's experimental results demonstrated that bubble expansion and collapse dynamics in root canals were three times lower than in free water [16], a finding corroborated by Lakuc in 2020 [21]. Subsequent studies compared the effects of different root canal morphologies on vapor bubble formation and fluid movement, revealing that while root canal morphology influences vapor bubble volume, it has minimal impact on bubble oscillation cycles [13]. This may be because changes in pulp chamber and root canal morphology are insufficient to cause a fundamental transformation in water confinement.

4. Practical applications of fluid dynamics

According to research on fluid dynamics, in 2011, DiVito *et al.* improved the working mode of laser-activated irrigation by using ultra-short pulse width erbium lasers to increase peak power. They also adopted a conical working tip to modify vapor bubble morphology and enhance the efficiency of energy conversion between light and heat. Furthermore, they moved the laser activation site from the apical region to the pulp chamber, alleviating some of the water medium confinement effects, and coined this erbium laser-assisted chemical preparation technique as Photon-Initiated Photoacoustic Streaming (PIPS), which they patented in collaboration with Fotona [22]. In 2013, Zhang *et al.* from the University of Hong Kong evaluated PIPS technology and found it to be superior to conventional needle irrigation in cleaning smear layers [23]. In 2019, Korkut *et al.* also confirmed the effectiveness of PIPS in smear layer removal in their study on extracted mandibular molars [24]. Traditional needle irrigation often struggles to clean the apical region, lateral root canals, and isthmus, especially in curved root canals. PIPS technology improves the efficiency of irrigant cleaning and addresses these clinical challenges [25, 26]. Other studies have also applied different erbium laser irrigation techniques, such as the work by Guidotti *et al.* in 2014, who used the Preciso working tip and achieved similar results [27]. This invention marked a significant milestone, and subsequent research showed that PIPS-generated fluid movement velocities were ten times faster than those produced by ultrasonic tips and many times faster than those by conventional needle irrigation [28].

However, the placement of the working tip in the pulp chamber under the PIPS design did not fully eliminate the effects of water medium confinement on vapor bubbles and fluid movement, and its ability to control infection in the apical region was insufficient for clinical needs. To further improve the efficiency of PIPS, Gregorcic *et al.* in 2014 proposed introducing a second pulse of energy at the moment of collapse of the initial vapor bubble formed by the erbium laser pulse. This dual-pulse approach was intended to create a cumulative effect, enhancing the fluid field intensity within the root canal system without significantly altering the vapor bubble volume, thus addressing the problem of inadequate fluid dynamics in confined spaces. Gregorcic's experiments confirmed that, at ultra-low pulse energies (2 mJ), the fluid field enhancement caused by this dual-pulse technique was especially notable, which they termed Photoacoustic Synchronized Transients (PHAST) [9, 29].

In 2018, engineers from Fotona proposed the concept of Shock Wave Enhanced Emission Photoacoustic Streaming (SWEEPS) [30]. The primary goal of SWEEPS was to further improve the restriction of vapor bubbles by the rigid walls of the pulp chamber. The core technology of SWEEPS is a two-pulse erbium laser emission sequence. Current research suggests that the timing of the second pulse should occur before or after the collapse of the vapor bubble formed by the first pulse. Existing studies have confirmed that SWEEPS technology can increase the fluid field intensity within the root canal system. However, there is still debate regarding the mechanism by which the second pulse enhances the fluid field. Three theories have been proposed:

(1) If the second pulse is delivered before the vapor bubble formed by the first pulse has completely collapsed, the second pulse's energy accelerates the collapse speed of the first pulse's vapor bubble, shortening its collapse cycle and intensifying the fluid field formed by the first pulse [10].

(2) If the second pulse is delivered after the first pulse's vapor bubble has collapsed, the fluid dynamics from the first pulse enhance the formation of the second pulse's vapor bubble, increasing its volume and producing a stronger fluid field during its collapse.

(3) The fluid fields generated by the first and second pulses may overlap within the root canal system, independent of the vapor bubble formation process [10].

5. Conclusion

Erbium laser-assisted chemical preparation is a newly emerging laser-based infection control technology developed over the past decade. The laser working tip, placed in the pulp chamber, generates intense cavitation effects, inducing strong agitation of the irrigating fluid. This process effectively cleanses the pulp chamber, root canal walls, and apical regions from infection. Currently, the study of fluid dynamics in erbium laser-assisted chemical preparation remains in its early stages, with numerous physical and engineering challenges yet to be addressed. The development of SWEEPS technology has provided a new perspective for erbium laser applications, and it may represent a promising direction for future research. However, further experimental studies in physics and additional clinical evidence are needed to fully validate its efficacy.

Disclosure statement

The authors declare no conflict of interest.

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