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A Review on the Efficacy of Ultrasonic and Laser-Activated Sodium Hypochlorite Irrigation at Different Concentrations in Root Canal Treatment

Wanrong Xie, Meiyi Pan*, Zhen Li, Jinzhi Zhu
Xiangtan Stomatological Hospital, Xiangtan 411100, Hunan, China
**Author to whom correspondence should be addressed.*

Abstract: In root canal treatment, sodium hypochlorite (NaOCl) serves as a core irrigant due to its well-recognized antimicrobial and tissue-dissolving capabilities. However, its clinical efficacy is significantly influenced by concentration, activation techniques, and adjunctive methods. This review systematically examines the differences in therapeutic outcomes among NaOCl concentrations, combined with the mechanisms of passive ultrasonic irrigation (PUI) and laser activation (e.g., Er,Cr:YSGG laser), to explore their synergistic effects. By analyzing relevant literature, this paper discusses how ultrasonic and laser activation enhance NaOCl's antimicrobial efficacy, penetration depth, and impact on dentin. The results indicate that while high-concentration NaOCl (≥ 5%) excels in tissue dissolution, it carries risks of cytotoxicity. In contrast, ultrasonic or laser activation significantly improves the antimicrobial performance and penetration of low-concentration NaOCl (≤ 2.5%), achieving comparable bactericidal effects to higher concentrations. Therefore, selecting appropriate NaOCl concentrations and activation modalities is critical for improving the success rate of root canal therapy. This review further addresses current research limitations and proposes future directions, including standardization of activation protocols, long-term evaluation of biofilm eradication, and clinical translation pathways.

Keywords: Sodium hypochlorite; Ultrasonic activation; Laser activation; Root canal treatment; Antimicrobial efficacy

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1. Introduction

Globally, reports indicate that the prevalence of apical periodontitis increased from 16% to 86% between 2006 and 2017. In China, pulp and periapical diseases are one of the most common oral diseases, with a natural population incidence rate as high as 45%, accounting for about 40% of outpatient cases. These diseases are characterized by severe tooth pain, local swelling, and other symptoms, severely affecting daily life and diet.

Root canal therapy is the primary treatment for pulpitis and periapical diseases. Its success hinges on thorough eradication of intracanal infection, reduction of microbial load, and promotion of periapical healing, all of which depend on three-dimensional cleaning of the root canal system. Due to anatomical complexities such as isthmuses, lateral canals, and canal anastomoses, mechanical instrumentation alone often fails to achieve ideal results, necessitating adjunctive chemical irrigation. NaOCl is widely used for root canal irrigation owing to its potent tissue dissolution and antimicrobial properties. However, its efficacy is influenced by concentration and activation methods, requiring a balance between antimicrobial efficiency, tissue dissolution, dentin structural integrity, and cytotoxicity. In recent years, ultrasonic and laser activation technologies have been introduced to enhance irrigant penetration and antimicrobial performance. This review aims to systematically analyze the mechanisms and clinical evidence supporting the use of different NaOCl concentrations combined with ultrasonic or laser activation, thereby providing a theoretical basis for optimizing root canal irrigation strategies.

2. Concentration-dependent effects of NaOCl: Balancing efficacy and safety

The efficacy of NaOCl in root canal therapy varies with concentration. Low concentrations (e.g., 1%) demonstrate minimal dentin damage [1], whereas high concentrations (e.g., 5.25%) exhibit superior tissue dissolution and antimicrobial activity [2]. Studies suggest that 5.25% NaOCl is considered the "gold standard," with rapid necrotic tissue dissolution validated in multiple *in vitro* studies [3]. Randomized clinical trials indicate that 5% NaOCl achieves a slightly higher root canal healing rate (81.4%) compared to 1% NaOCl (72.1%), though the difference lacks statistical significance [4]. Histological analyses reveal that high-concentration NaOCl completely removes residual pulp tissue from dentinal walls [5]. However, its cytotoxicity remains a concern, potentially leading to postoperative pain and periapical tissue damage.

Notably, clinical outcomes such as postoperative healing rates and pain incidence show no significant differences between 1% and 5% NaOCl [6]. Compared to higher concentrations, 1% NaOCl maintains a favorable balance among antimicrobial capacity, tissue dissolution efficiency, and biocompatibility while minimally affecting dentin compressive strength [7].

2.1. Tissue dissolution capacity

(1) High concentrations (2.5%–5.25%) NaOCl: Effectively remove residual pulp tissue and predentin from canal walls, demonstrating significant organic tissue dissolution. However, prolonged exposure reduces dentin compressive strength (by approximately 20%) and increases cytotoxicity [1].

(2) Low concentrations (0.5%–2.5%) NaOCl: Exhibit weaker dissolution capacity, but when combined with ultrasonic or laser activation, their efficacy approaches that of high concentrations. For example, 1% NaOCl activated by Er,Cr:YSGG laser fully dissolves pulp tissue while causing minimal dentin strength reduction [8].

2.2. Antimicrobial and debris removal efficacy

For loose intracanal debris, NaOCl at any concentration achieves effective irrigation. However, its ability to remove the smear layer from canal walls remains suboptimal. Both 5% and 2.5% NaOCl effectively eliminate intracanal biofilms (e.g., Enterococcus faecalis), whereas syringe irrigation with 0.5% NaOCl alone yields inadequate results [9].

2.3. Impact on dentin integrity

Post-treatment teeth may experience reduced fracture resistance due to structural defects from access preparation and mechanical instrumentation. NaOCl irrigation further influences dentin integrity. Verma *et al.* demonstrated that 1% NaOCl minimally affects dentin compressive strength, while higher concentrations significantly reduce dentin elasticity and flexural strength [3].

2.4. Clinical considerations for concentration selection

Clinical decision-making requires balancing antimicrobial efficiency and safety. For complex anatomies (e.g., isthmuses or resorptive defects), high-concentration NaOCl combined with activation techniques may be preferred. Conversely, low-concentration protocols are safer for high-risk cases (e.g., exposed periapical tissues).

3. Ultrasonic activation (PUI): Mechanisms and evidence-based support

3.1. Hydrodynamic mechanisms of ultrasonic activation

The PUI technology cleverly induces acoustic microstreaming and cavitation effects through non-cutting ultrasonic tips vibrating at frequencies ranging from 25 to 30 kHz. This mechanism significantly enhances the penetration and antibacterial properties of sodium hypochlorite (NaOCl) solutions. Under the action of ultrasonic waves, cavitation occurs within the liquid, forming countless microbubbles. These microbubbles undergo rapid expansion and collapse, which not only amplifies the hydrodynamic effect but also effectively promotes the comprehensive penetration of NaOCl solutions into deeper regions of the root canal.

3.2. Multidimensional evidence of clinical efficacy

Ultrasonic activation technology has demonstrated significant effects in enhancing the antibacterial performance of NaOCl and deepening its penetration depth into dentinal tubules. Specifically, a study by Christo et al. pointed out that even when the NaOCl concentration is only 0.5%, its bacterial elimination effect under ultrasonic activation is comparable to that of 5% NaOCl in a non-activated state [10]. This discovery fully demonstrates the enormous potential of ultrasonic activation technology in compensating for the limitations of low-concentration NaOCl, while also reducing the risk of damage to dentin. However, it is worth noting that although ultrasonic activation technology exhibits excellent effects in most root canal areas, its effectiveness in the apical region still needs further improvement [11]. In addition, research by Faria et al. also confirms that PUI technology can significantly increase the penetration depth of NaOCl into dentinal tubules [12], further reinforcing the clinical value of ultrasonic activation technology in endodontic treatment.

3.3. Optimization of operational parameters

To ensure that the effectiveness of PUI technology is fully utilized, it is necessary to optimize key operational parameters reasonably. Among them, ultrasonic power is typically controlled within the range of 20 to 40%, activation time should be no less than 30 seconds, and irrigation volume is recommended to be maintained at 5 milliliters or more. However, it is worth noting that excessive use of ultrasonic activation technology may lead to the generation of microcracks in dentin [13]. Therefore, in actual operations, medical staff need to carefully adjust each parameter according to the specific situation of the patient and the needs of endodontic treatment to ensure the safety and effectiveness of the treatment.

4. Laser activation (LAI): From cavitation to biofilm eradication

4.1. Mechanisms of laser activation

Laser activation (LAI) utilizes laser energy to induce cavitation in fluids, enhancing NaOCl penetration and antimicrobial activity. When absorbed by water, laser energy generates high-temperature, high-pressure vapor bubbles. The rapid expansion and collapse of these bubbles intensify fluid dynamics, driving NaOCl into deeper canal regions [7].

4.2. Multidimensional evidence of clinical efficacy

Betancourt et al. demonstrated that Er,Cr:YSGG laser activation significantly enhances the antimicrobial efficacy of 0.5% NaOCl, achieving results equivalent to 2.5% NaOCl. Cavitation and acoustic streaming further improve bactericidal effects in apical thirds compared to ultrasonic activation [14].

4.3. Parameter selection and technical challenges

Precise control of laser energy (1–2 W), pulse frequency (10–20 Hz), and fiber tip position (2–3 mm from the apex) is essential. Temperature monitoring indicates that LAI raises intracanal temperatures by 2–5°C, which remains within periodontal tissue tolerance thresholds [15].

5. Synergistic effects of adjunctive techniques: Surfactants and heating

5.1. Controversial role of surfactants

Surfactants (e.g., cetrimonium bromide) reduce NaOCl’s surface tension (from 72 mN/m to 40 mN/m), theoretically improving wettability [16]. However, studies show that adding 0.2% cetrimonium bromide to 2.5% NaOCl does not significantly enhance dentinal tubule penetration. This may stem from surfactant-induced chemical reactions that reduce free chlorine availability [17].

5.2. Innovations in heating techniques

(1) External preheating: Warming NaOCl to 40–60 °C accelerates tissue dissolution but minimally affects periapical temperatures [18].

(2) Intracanal heating: Direct heating of NaOCl via ultrasonic or laser tips to 100 °C significantly improves debris removal [19]. Temperature control is critical to avoid periodontal damage.

6. Synergy between concentration and activation techniques

6.1. 1% NaOCl + LAI

This combination has found a perfect balance between safety and effectiveness. A concentration of 1% NaOCl is relatively low and has little effect on the strength of dentin, resulting in only about a 5% reduction. Despite the low concentration, the combination can still achieve a sterilization rate comparable to high-concentration NaOCl through activation using LAI technology. This means that while maintaining safety, it can also effectively kill harmful bacteria.

6.2. 0.5% NaOCl + LAI

This combination performs well in biofilm removal, with an effect similar to 5.25% NaOCl. Biofilm is a protective film formed by bacteria on the surface of teeth, which is difficult to remove, but this combination can effectively cope with it. However, in order to achieve a clearance effect comparable to 5.25% NaOCl, this combination requires a longer activation time of at least 30 seconds. This requires patience during use and ensuring sufficient flushing time to thoroughly remove biofilms.

7. Clinical recommendations and future directions

7.1. Proposed protocols

Based on current evidence, low-concentration NaOCl (e.g., 0.5%) combined with ultrasonic or laser activation significantly enhances antimicrobial efficacy and penetration while minimizing dentin damage. Thus, clinicians are advised to use low-concentration NaOCl with adjunctive activation.

(1) Complex anatomy: For isthmuses or C-shaped canals, high-concentration NaOCl (≥ 5%) with PUI or LAI is recommended.

(2) High-risk cases: Immature or open-apex teeth should utilize low-concentration NaOCl (1–2.5%) with laser activation.

7.2. Standardization and training

Ultrasonic and laser parameters must be standardized, and clinicians require specialized training to minimize procedural variability.

7.3. Research priorities

(1) Long-term biofilm eradication

In the field of root canal therapy, the removal of biofilms is key to ensuring treatment success and preventing recurrence. However, current research mainly relies on short-term in vitro models to evaluate the clearance effect of biofilms. Although these models can simulate some of the environment inside the root canal, they often cannot fully reflect the growth and changes of biofilms over a long period, as well as the long-term effects of treatment on them. Therefore, to more accurately evaluate the long-term effects of root canal therapy, long-term clinical follow-up studies are needed. This type of research can observe the changes in biofilm after treatment, as well as whether there is a risk of recurrence or persistent infection.

(2) Novel activation technologies

In order to improve the effectiveness of root canal irrigation fluid, researchers are constantly exploring new activation techniques. Among them, the combination of photon-induced photoacoustic flow (PIPS) and nanobubble technology is considered a promising approach. PIPS technology utilizes photon energy to induce molecular vibrations in liquids, thereby generating acoustic microfluidics effects and enhancing the penetration and diffusion capabilities of the rinsing solution. Nano bubble technology enhances the flushing effect of liquids by generating tiny bubbles. Combining these two techniques can further improve the cleaning ability of the flushing solution on the root canal wall, and is expected to achieve better results in areas that are difficult to reach for treatment

(3) Advanced imaging

In order to more accurately evaluate the cleanliness and microstructural changes of root canal therapy, researchers have started using three-dimensional imaging technology. These techniques can provide detailed images of the interior of the root canal, including the morphology of the root canal wall, the distribution of biofilms, and the microstructural changes after treatment. By comparing the images before and after treatment, the effectiveness of the treatment can be intuitively evaluated, and a basis can be provided for subsequent treatment decisions. In addition, 3D imaging technology can also be used to guide the operation during the treatment process, ensuring that the flushing solution can be evenly distributed in the root canal, thereby achieving better treatment effects..

(4) Innovative irrigants

Calcium hypochlorite (CaOCl) and low toxicity sodium hypochlorite derivatives have shown certain potential in clinical applications as novel root canal irrigation solutions. Calcium hypochlorite has strong oxidizing properties and can effectively kill bacteria in root canals and remove biofilms. Low toxicity sodium hypochlorite derivatives, on the other hand, maintain the antibacterial activity of sodium hypochlorite while reducing its irritation to periodontal tissue. To validate the clinical efficacy of these new flushing solutions, rigorous clinical evaluation is required. These assessments can include comparing the effects of different irrigation solutions on root canal cleanliness, irritation to periodontal tissue, and long-term outcomes after treatment. Through comprehensive evaluation, more effective and safer flushing fluid options can be provided for root canal treatment.

8. Conclusion

This study comprehensively reviewed relevant literature and found that in the research on the application of sodium hypochlorite (NaOCl) in endodontic treatment, the efficacy of NaOCl varies with its concentration. Low concentrations cause minimal damage to dentin, while high concentrations exhibit superior tissue dissolution and antimicrobial activity. Although 5.25% NaOCl is regarded as the “gold standard,” 1% NaOCl, when activated by ultrasound or laser, can achieve antibacterial and penetration properties comparable to high concentrations while maintaining good biocompatibility. Ultrasonic and laser activation technologies significantly enhance the penetration and antibacterial performance of NaOCl by inducing acoustic microstreaming and cavitation effects. These technologies not only improve NaOCl’s ability to penetrate deep into the root canal but also enhance its effectiveness in removing biofilms. However, in practical applications, the effectiveness of ultrasonic activation in the apical region still needs improvement, while laser activation requires precise control of laser energy, pulse frequency, and fiber tip position. Additionally, the study explored the impact of surfactants and heating techniques on the efficacy of NaOCl. Surfactants can reduce the surface tension of NaOCl but may also initiate chemical reactions that decrease the availability of free chlorine. Heating techniques can accelerate tissue dissolution, but temperature control is crucial to avoid damage to periodontal tissues. In terms of the synergistic effect of concentration and activation techniques, low-concentration NaOCl combined with laser activation achieves antibacterial effects comparable to high concentrations while maintaining safety. It is noteworthy that although current research has achieved certain academic results, there are still some limitations. For example, evaluations of long-term treatment effectiveness are insufficient, and activation protocols lack standardization, leading to inconsistent research findings. To address these issues, future research should focus on establishing standardized activation protocols and conducting long-term clinical validations to further advance endodontic treatment technologies.

Disclosure statement

The author declares no conflict of interest.

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