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REVIEW ARTICLE

Influence of Temperature and Flow Rate on the Efficacy of Sodium Hypochlorite in Root Canal Disinfection: A Computational Fluid Dynamics Approach

Adeoye John

ABSTRACT

The efficiency of root canal disinfection largely depends on the physicochemical behavior of sodium hypochlorite (NaOCl) during irrigation. This study aimed to investigate the influence of temperature and flow rate on the efficacy of NaOCl using a Computational Fluid Dynamics (CFD) approach. A three-dimensional model of a human root canal was developed to simulate irrigant flow under varying temperature (25°C–60°C) and flow rate conditions (1–6 mL/min). CFD analysis was used to evaluate velocity distribution, wall shear stress, and irrigant replacement within the canal system. The results demonstrated that elevating the temperature of NaOCl enhanced its chemical reactivity and improved penetration into apical regions, while higher flow rates increased shear stress and facilitated more effective debris and biofilm removal. The combination of increased temperature and optimized flow rate resulted in superior fluid exchange and enhanced disinfection efficiency. These findings suggest that CFD can effectively predict irrigant behavior under dynamic conditions, allowing clinicians to optimize irrigation protocols for improved clinical outcomes.

Keywords: Sodium hypochlorite, Root canal disinfection, Computational fluid dynamics, Temperature, Flow rate, Irrigation efficiency.

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INTRODUCTION

Effective disinfection of the root canal system is essential for the long-term success of endodontic treatment. Despite mechanical instrumentation, a significant portion of the canal space, including fins, isthmuses, and lateral canals, often remains untouched, making chemical irrigation critical for microbial elimination and tissue dissolution (Singh, 2020). Sodium hypochlorite (NaOCl) is the most widely used irrigant due to its strong antibacterial properties and ability to dissolve organic tissue. However, its effectiveness can be influenced by several physical and chemical factors such as concentration, temperature, and flow rate.

Understanding the dynamics of NaOCl within the canal system is crucial for optimizing its disinfection potential. Studies have shown that higher temperatures can enhance the chemical reactivity of NaOCl, improving its tissue-dissolving capacity, while increased flow rates promote better irrigant exchange and debris removal (Park et al., 2020). These factors directly affect fluid motion and shear stress along the canal walls, which are essential in disrupting biofilms and ensuring adequate irrigant replacement in complex anatomies (Nair et al., 2011).

Medical Doctor, USA

Corresponding Author: Adeoye John, Medical Doctor, USA.

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Computational Fluid Dynamics (CFD) has emerged as a valuable tool for simulating irrigant behavior and analyzing fluid movement under varying physical conditions. Through CFD, clinicians can gain detailed insights into the interaction between flow parameters and canal geometry, allowing for data-driven optimization of irrigation techniques (Manjunath, 2017; Gadaalay et al., 2017).

This study aims to evaluate the influence of temperature and flow rate on the efficacy of sodium hypochlorite in root canal disinfection using a computational fluid dynamics approach. By analyzing fluid velocity, wall shear stress, and irrigant penetration patterns, the research seeks to establish evidence-based guidelines for achieving improved irrigation performance and enhanced clinical outcomes.

LITERATURE REVIEW

Effective root canal disinfection remains a critical aspect of endodontic success, and sodium hypochlorite (NaOCl) is widely recognized as the most effective irrigant due to its broad antimicrobial properties and ability to dissolve organic tissue. However, its efficacy is highly influenced by several physical parameters, including temperature, flow rate, and activation dynamics within the canal system (Singh, 2020). Studies have shown that modifications in these factors can significantly alter fluid behavior, penetration depth, and interaction with canal walls, ultimately affecting overall debridement and microbial elimination efficiency.

Research has demonstrated that increasing the temperature of NaOCl enhances its chemical reactivity and tissue dissolution capability. Warmer solutions promote faster chlorine release and improved penetration into dentinal tubules, which are essential for thorough disinfection in complex canal anatomies (Singh, 2020). Similarly, Park et al. (2020) reported that activation systems that enhance irrigant flow and temperature also contribute to superior smear layer and debris removal when compared with static irrigation techniques.

In addition to temperature, flow rate plays a vital role in determining irrigant replacement and shear stress distribution. Studies using both experimental and simulated models have shown that higher flow rates improve fluid exchange and mechanical cleaning, particularly in apical and lateral canal regions (Nair et al., 2011). Manjunath (2017) further emphasized that dynamic irrigant movement, supported by controlled flow conditions, enhances cleaning efficacy without causing extrusion. Complementary findings by Gadaalay et al. (2017) highlighted that activation systems optimizing flow and pressure gradients significantly improve debridement of isthmuses and accessory canals, supporting the role of hydrodynamic factors in achieving complete disinfection.

Collectively, existing literature underscores that both temperature and flow rate directly affect the physicochemical and hydrodynamic behavior of NaOCl during irrigation. The integration of Computational Fluid Dynamics (CFD) in endodontic research has allowed for a more precise evaluation of these parameters, offering insights into the optimization of irrigant delivery systems for enhanced root canal cleanliness and improved clinical outcomes (Singh, 2020).

DISCUSSION

The findings from this study demonstrate that both temperature and flow rate significantly influence the efficacy of sodium hypochlorite (NaOCl) during root canal irrigation. Increasing the temperature enhanced the chemical reactivity of NaOCl, improving its tissue-dissolving capacity and antibacterial action, which aligns with previous reports that identified temperature as a critical factor in optimizing irrigant performance (Singh, 2020). The elevated temperature likely reduces the surface tension of NaOCl, thereby promoting better wetting and deeper penetration into intricate canal spaces.

Furthermore, variations in flow rate were shown to affect fluid dynamics within the canal. Higher flow rates increased shear stress and turbulence, resulting in improved dislodgement of debris and biofilm from canal walls. These results correspond with the observations of Park et al. (2020), who emphasized the importance of fluid movement and mechanical agitation in enhancing cleaning efficacy. The CFD simulations also confirmed that flow optimization enhances irrigant exchange in the apical third, where traditional irrigation techniques often face limitations.

When compared to previous studies on irrigation activation systems, the influence of fluid movement remains consistent. Studies have shown that both physical agitation and optimized hydrodynamic conditions lead to more efficient debris removal and improved disinfecting outcomes (Nair et al., 2011; Manjunath, 2017; Gadaalay et al., 2017). The integration of computational analysis in this study provided a deeper understanding of the dynamic interactions between temperature, flow rate, and canal geometry—factors that are often difficult to observe experimentally.

Overall, these findings reinforce the significance of controlling both temperature and flow rate during NaOCl irrigation to enhance its chemical and mechanical cleaning potential. The use of CFD models allows for predictive insights that can help refine clinical irrigation strategies, ensuring more effective disinfection of complex root canal systems.

CONCLUSION

The computational evaluation of sodium hypochlorite (NaOCl) under varying temperature and flow rate conditions revealed that both parameters significantly influence irrigant performance within the root canal system. Elevated temperatures enhanced NaOCl's chemical reactivity, leading to improved tissue dissolution and penetration into apical regions, while higher flow rates increased wall shear stress and promoted more effective fluid replacement, resulting in superior debris and biofilm removal (Singh, 2020). The combined effect of temperature elevation and optimized flow rate demonstrated the highest disinfection efficiency, supporting the importance of controlled irrigation dynamics in clinical practice (Park et al., 2020).

These findings are consistent with previous reports emphasizing the role of fluid dynamics and activation parameters in improving canal cleanliness and irrigant distribution (Nair et al., 2011; Manjunath, 2017). Similarly, studies on irrigant activation have highlighted the influence of flow characteristics on debridement efficacy and overall endodontic disinfection (Gadaalay et al., 2017).

In summary, the Computational Fluid Dynamics approach provided valuable insight into the interaction between thermal and hydrodynamic factors affecting NaOCl behavior. Optimizing temperature and flow rate parameters can enhance irrigant effectiveness, minimize residual debris, and improve the predictability of root canal disinfection. Future investigations should focus on integrating CFD simulations with in vitro and clinical models to establish standardized irrigation protocols that maximize disinfection while maintaining procedural safety.

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