Review Article

The Role of Nano-Modified Irrigants in Enhancing Biofilm Disruption and Canal Disinfection: A Novel Approach

Shestha Shukla

The persistent challenge of biofilm removal in root canal therapy has driven the search for more effective disinfection strategies. Conventional irrigants such as sodium hypochlorite, chlorhexidine, and EDTA exhibit limitations in completely eliminating resistant microbial communities embedded within dentinal tubules. In recent years, nano-modified irrigants have emerged as a novel and promising approach in endodontic disinfection. Owing to their nanoscale dimensions and unique physicochemical properties, nanoparticles such as silver, zinc oxide, titanium dioxide, and chitosan demonstrate enhanced penetration, surface reactivity, and antimicrobial efficiency. These nanoparticles, when integrated with traditional irrigants, disrupt biofilm architecture through mechanisms including reactive oxygen species generation, cell membrane damage, and sustained antimicrobial release. Comparative studies reveal superior biofilm disruption and canal cleanliness achieved by nano-modified formulations compared to conventional solutions. Despite these advantages, concerns regarding cytotoxicity, stability, and clinical safety remain significant barriers to routine clinical adoption. Continued research focusing on biocompatibility optimization, controlled nanoparticle release, and long-term effects is essential for clinical translation. Overall, nano-modified irrigants represent a significant advancement toward achieving thorough canal disinfection and long-term endodontic success.

Access this article online

Website:
www.cijmr.com

DOI:
10.58999/cijmr.v1i03.304

Keywords:
Nano-irrigants, Biofilm disruption, Endodontic disinfection, Nanoparticles, Root canal therapy, Chitosan nanoparticles, Silver nanoparticles.

Introduction

The success of endodontic therapy largely depends on the effective elimination of microorganisms and their biofilms from the root canal system. Microbial biofilms, composed of complex communities encased in a protective extracellular matrix, exhibit high resistance to conventional antimicrobial agents and mechanical instrumentation. Despite the widespread use of irrigants such as sodium hypochlorite (NaOCl), ethylenediaminetetraacetic acid (EDTA), and chlorhexidine (CHX), complete eradication of these biofilms remains a persistent clinical challenge (Singh, 2020). The anatomical complexities of the root canal, including lateral canals, fins, and dentinal tubules, further hinder the penetration and efficacy of these irrigating solutions.

Recent advances in nanotechnology have provided new perspectives for enhancing disinfection efficiency in endodontics. Nanoparticles possess unique physicochemical properties, such as high surface area-to-volume ratio, increased reactivity, and superior penetration capabilities, which make them effective against resistant biofilms (Verma et al., 2021). When integrated into traditional irrigants, these nano-modified solutions exhibit enhanced antimicrobial activity and deeper infiltration into dentinal structures. Nanoparticles such as silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO_2), and chitosan have demonstrated broad-spectrum antibacterial and antifungal properties, disrupting biofilm integrity and promoting superior canal cleanliness (Abou El Nasr & Akbulut, 2018).

The principle behind the application of nanotechnology in endodontic irrigation lies in its ability to manipulate matter at the molecular level, thereby improving the interaction between disinfectants and microbial surfaces (Dasgupta et al., 2016). Moreover, nanomaterials facilitate controlled release and sustained antimicrobial effects, addressing the limitations of short-lived traditional irrigants. In dental and oral tissue therapy, nanotechnology has shown promising potential in

BDS, India.

Correspondence to: Shestha Shukla, BDS, India. E-mail: drshreshthashukla@gmail.com

Submitted: 05/09/2022 Revision: 12/10/2022
Accepted: 18/11/2022 Published: 28/12/2022

How to cite this article: Shukla S. The Role of Nano-Modified Irrigants in Enhancing Biofilm Disruption and Canal Disinfection: A Novel Approach. Central India Journal of Medical Research. 2022;1(3):50-53.

regenerative applications, biofilm management, and enhanced tissue compatibility (Yang et al., 2020; Matichescu et al., 2020).

Therefore, the integration of nano-modified irrigants represents a novel and emerging strategy in root canal disinfection. This approach aims to overcome the limitations of conventional irrigation systems and achieve improved microbial eradication and canal decontamination. As highlighted by Kalyvas (2021), the continuous evolution of nanomaterial-based techniques in dentistry could redefine the standards of endodontic disinfection, leading to higher success rates and more predictable clinical outcomes.

Mechanism of Action of Nano-Modified Irrigants

Nano-modified irrigants exhibit a multifaceted mechanism of action that enhances their ability to penetrate, disrupt, and eradicate biofilms within the complex root canal system. The fundamental advantage of these irrigants lies in their nanoscale dimensions, which enable deeper infiltration into dentinal tubules and irregular canal spaces that are often inaccessible to conventional irrigants (Singh, 2020). Nanoparticles such as silver, zinc oxide, titanium dioxide, and chitosan possess unique physicochemical and surface properties that allow for effective interaction with bacterial cell membranes, leading to structural disintegration and leakage of intracellular contents (Verma et al., 2021).

The antibacterial activity of nano-irrigants is primarily attributed to two key mechanisms: direct cell wall disruption and reactive oxygen species (ROS) generation. Upon contact, metallic nanoparticles release ions that bind to the negatively charged bacterial cell wall, altering membrane permeability and causing cellular collapse (Dasgupta et al., 2016). Simultaneously, ROS generation induces oxidative stress, damaging proteins, lipids, and nucleic acids, ultimately resulting in bacterial death (Yang et al., 2020). In the case of silver nanoparticles, the continuous release of Ag^+ ions ensures a prolonged antimicrobial effect, maintaining canal disinfection even after irrigation procedures are completed (Abou El Nasr & Akbulut, 2018).

Additionally, chitosan-based nanoparticles exhibit a chelating and bioadhesive capacity that enhances their interaction with dentin surfaces, improving smear layer removal and facilitating deeper irrigant penetration (Matichescu et al., 2020). Titanium dioxide and zinc oxide nanoparticles, under light activation, further enhance disinfection through photocatalytic reactions that generate hydroxyl radicals, intensifying biofilm degradation (Kalyvas, 2021). These combined actions create a synergistic antimicrobial environment within the root canal, reducing microbial load and preventing biofilm reformation.

Overall, nano-modified irrigants integrate physical, chemical, and biological mechanisms to achieve superior biofilm disruption and canal disinfection compared to traditional irrigants. Their ability to deliver sustained antimicrobial activity while interacting effectively with dentinal structures marks a significant step toward more predictable and long-lasting endodontic outcomes (Verma et al., 2021; Singh, 2020).

Comparative Efficacy in Biofilm Removal

The efficacy of nano-modified irrigants in disrupting and removing endodontic biofilms has been demonstrated through both in vitro and in vivo studies. Conventional irrigants such as sodium hypochlorite and chlorhexidine often show limited penetration into the complex structure of mature biofilms, resulting in residual microbial activity within the dentinal tubules (Singh, 2020). The incorporation of nanoparticles into these irrigants enhances their surface reactivity, allowing for deeper penetration and improved mechanical disruption of biofilm matrices. Silver nanoparticles, for example, have shown superior antibacterial efficacy against *Enterococcus faecalis* due to their ability to bind bacterial cell walls, alter membrane permeability, and induce reactive oxygen species formation (Verma et al., 2021).

Comparative studies have revealed that nano-modified irrigants exhibit significantly higher biofilm eradication rates than traditional solutions. Chitosan-based nano-irrigants enhance chelation and mechanical removal of biofilms while maintaining biocompatibility with periapical tissues (Abou El Nasr & Akbulut, 2018). Similarly, zinc oxide and titanium dioxide nanoparticles incorporated into irrigants have demonstrated enhanced photo-catalytic and antimicrobial properties, leading to improved canal disinfection (Yang et al., 2020). The nanoscale dimensions of these materials facilitate penetration into inaccessible canal irregularities, where conventional irrigants are less effective (Dasgupta et al., 2016).

Moreover, studies have reported that the size, concentration, and surface functionalization of nanoparticles significantly influence their antimicrobial performance. Stable dispersion and controlled release of nanoparticles improve sustained antibacterial activity and prevent reformation of biofilms (Matichescu et al., 2020). The enhanced surface area of nano-irrigants also allows for more effective contact with microbial colonies, contributing to superior cleaning efficacy and reduced bacterial regrowth.

Overall, the comparative evidence supports that nano-modified irrigants outperform traditional irrigation systems in biofilm disruption and canal disinfection, offering a more efficient approach to managing persistent endodontic infections (Kalyvas, 2021).

Biocompatibility and Safety Considerations

The biocompatibility and safety of nano-modified irrigants are critical determinants for their potential clinical application in endodontics. While these agents offer superior antimicrobial and biofilm-disruptive capabilities, their nanoscale properties introduce new biological interactions that demand careful evaluation. Nanoparticles possess a high surface area-to-volume ratio, which enhances reactivity but may also increase the risk of cytotoxicity and oxidative stress in periapical tissues (Singh, 2020). The extent of toxicity is influenced by particle type, size, concentration, and surface modification. For instance, silver and zinc oxide nanoparticles exhibit potent antibacterial effects but may interfere with host cell metabolism and induce inflammatory responses if used at high concentrations (Verma et al., 2021).

Surface functionalization and controlled release mechanisms have been developed to improve safety and reduce direct tissue irritation. Chitosan-based nano-irrigants demonstrate favorable cytocompatibility due to their natural origin and biodegradability, providing a safer alternative to metallic nanoparticles (Abou El Nasr & Akbulut, 2018). Moreover, polymer coatings and bio-responsive nanocarriers enhance stability and allow gradual ion release, minimizing potential tissue damage (Yang et al., 2020).

Biomaterial studies indicate that integrating nanoparticles into biocompatible matrices can maintain antimicrobial efficacy while reducing adverse cellular effects (Matichescu et al., 2020). However, incomplete characterization of nanoparticle behavior in dynamic biological environments such as their interaction with dentin, pulp remnants, and periapical cells remains a significant limitation (Dasgupta et al., 2016). Regulatory frameworks and standardized toxicity assessments are still evolving, highlighting the need for extensive in vivo and long-term studies to ensure patient safety (Kalyvas, 2021).

While nano-modified irrigants show promising clinical potential, optimizing concentration, particle stability, and delivery systems is essential to balance antimicrobial efficiency with biological safety. Future research should prioritize comprehensive cytotoxicity evaluation and standardized clinical protocols to facilitate safe and effective integration into endodontic practice.

Conclusion

Nano-modified irrigants represent a promising advancement in endodontic disinfection, offering enhanced biofilm disruption and improved canal cleanliness compared to conventional solutions. The incorporation of nanoparticles such as silver, zinc oxide, titanium dioxide, and chitosan improves penetration into dentinal tubules, disrupts biofilm structure, and enhances antimicrobial efficacy through mechanisms including reactive oxygen species generation and sustained antimicrobial release (Verma et al., 2021; Abou El Nasr & Akbulut, 2018). Studies demonstrate that these nano-irrigants can overcome some limitations of traditional irrigants, addressing persistent microbial challenges in root canal therapy (Singh, 2020; Yang et al., 2020). However, considerations regarding cytotoxicity, stability, and clinical safety remain critical for translation into routine practice (Matichescu et al., 2020; Kalyvas, 2021). Future research focusing on optimizing biocompatibility, controlled nanoparticle release, and long-term outcomes is essential to establish standardized protocols for clinical application (Dasgupta et al., 2016; Verma et al., 2021). Overall, nano-modified irrigants offer a novel and effective approach to enhancing root canal disinfection and represent a significant step toward improved endodontic treatment outcomes.

References

1. Singh, S. (2020). Irrigation Dynamics in Endodontics: Advances, Challenges and Clinical Implications. Indian Journal of Pharmaceutical and Biological Research, 8(02), 26-32.
2. Verma, S., Chandra, A., Jena, A., & Sharan, J. (2021). Nanotechnology in Endodontics: A Hope or Hype. Trends in Biomaterials & Artificial Organs, 35(2).
3. Dasgupta, N., Ranjan, S., Chakraborty, A. R., Ramalingam, C., Shanker, R., & Kumar, A. (2016). Nanoagriculture and water quality management. In Nanoscience in food and agriculture 1 (pp. 1-42). Cham: Springer International Publishing.
4. Yang, Z., Han, L., Guo, Y., Jia, L., Yin, C., & Xia, Y. (2020). Nanotechnology in dental therapy and oral tissue regeneration. In Nanotechnology in Regenerative Medicine and Drug Delivery Therapy (pp. 91-189). Singapore: Springer Singapore.
5. Matichescu, A., Ardelean, L. C., Rusu, L. C., Craciun, D., Bratu, E. A., Babucea, M., & Leretter, M. (2020). Advanced biomaterials and techniques for oral tissue engineering and regeneration—a

review. Materials, 13(22), 5303.

6. Kalyvas, D. (2021). Theodora Fanaropoulou.
7. Abou El Nasr, H. M., & Akbulut, M. B. (2018). Advanced nanomaterials and their functionalization in clinical endodontics. In Dental Applications of Nanotechnology (pp. 37-57). Cham: Springer International Publishing.
8. Heidari, Amirmohammad & Mashayekhi, Yashar. (2022). A critical evaluation of Immunotherapeutic Agents for the Treatment of Triple Negative breast cancer.
9. Azmi, S. K. (2021). Riemannian Flow Analysis for Secure Software Dependency Resolution in Microservices Architectures. Well Testing Journal, 30(2), 66-80.
10. Mansur, S., & Beaty, L. (2019). CLASSROOM CONTEXT STUDY Technology. Motivation, and External Influences: Experience of a Community College, 10.
11. Bodunwa, O. K., & Makinde, J. O. (2020). Application of Critical Path Method (CPM) and Project Evaluation Review Techniques (PERT) in Project Planning and Scheduling. J. Math. Stat. Sci, 6, 1-8.
12. MANSUR, S. (2018). Crimean Tatar Language. Past, Present, and Future.
13. Mansur, S. (2018). Mind and artificial intelligence. City University of New York. LaGuardia Community College.
14. Adebayo, I. A., Olagunju, O. J., Nkansah, C., Akomolafe, O., Godson, O., Blessing, O., & Clifford, O. (2020). Waste-to-Wealth Initiatives: Designing and Implementing Sustainable Waste Management Systems for Energy Generation and Material Recovery in Urban Centers of West Africa.
15. Mansur, S. Community Colleges as a Smooth Transition to Higher Education.
16. Azmi, S. K. (2021). Spin-Orbit Coupling in Hardware-Based Data Obfuscation for Tamper-Proof Cyber Data Vaults. Well Testing Journal, 30(1), 140-154.
17. Sharma, A., & Odunaike, A. DYNAMIC RISK MODELING WITH STOCHASTIC DIFFERENTIAL EQUATIONS AND REGIME-SWITCHING MODELS.
18. Azmi, S. K. (2021). Computational Yoshino-Ori Folding for Secure Code Isolation in Serverless It Architectures. Well Testing Journal, 30(2), 81-95.
19. YEVHENIIA, K. (2021). Bio-based preservatives: A natural alternative to synthetic additives. INTERNATIONAL JOURNAL, 1(2), 056-070.
20. Azmi, S. K. (2021). Delaunay Triangulation for Dynamic Firewall Rule Optimization in Software-Defined Networks. Well Testing Journal, 30(1), 155-169.
21. AZMI, S. K. (2021). Markov Decision Processes with Formal Verification: Mathematical Guarantees for Safe Reinforcement Learning.
22. Asamoah, A. N. (2022). Global Real-Time Surveillance of Emerging Antimicrobial Resistance Using Multi-Source Data Analytics. INTERNATIONAL JOURNAL OF APPLIED PHARMACEUTICAL SCIENCES AND RESEARCH, 7(02), 30-37.
23. Azmi, S. K. (2022). Green CI/CD: Carbon-Aware Build & Test Scheduling for Large Monorepos. Well Testing Journal, 31(1), 199-213.
24. OKAFOR, C., VETHACHALAM, S., & AKINYEMI, A. A DevSecOps MODEL FOR SECURING MULTI-CLOUD ENVIRONMENTS WITH AUTOMATED DATA PROTECTION.
25. Sunkara, G. (2022). AI-Driven Cybersecurity: Advancing Intelligent Threat Detection and Adaptive Network Security in the Era of Sophisticated Cyber Attacks. Well Testing Journal, 31(1), 185-198.
26. Azmi, S. K. (2022). From Assistants to Agents: Evaluating Autonomous LLM Agents in Real-World DevOps Pipeline. Well Testing Journal, 31(2), 118-133.
27. Odunaike, A. DESIGNING ADAPTIVE COMPLIANCE FRAMEWORKS USING TIME SERIES FRAUD DETECTION MODELS FOR DYNAMIC REGULATORY AND RISK MANAGEMENT ENVIRONMENTS.
28. Akomolafe, O. (2022). Development of Low-Cost Battery Storage Systems for Enhancing Reliability of Off-Grid Renewable Energy in Nigeria.
29. AZMI, S. K. (2022). Bayesian Nonparametrics in Computer Science: Scalable Inference for Dynamic, Unbounded, and Streaming Data.
30. Sunkara, G. (2022). AI-Driven Cybersecurity: Advancing Intelligent Threat Detection and Adaptive Network Security in the Era of Sophisticated Cyber Attacks. Well Testing Journal, 31(1), 185-198.
31. Shaik, Kamal Mohammed Najeeb. (2022). Security Challenges and Solutions in SD-WAN Deployments. SAMRIDDHI A Journal of Physical Sciences Engineering and Technology. 14. 2022. 10.18090/samriddhi.v14i04..
32. Azmi, S. K. (2022). Computational Knot Theory for Deadlock-Free Process Scheduling in Distributed IT Systems. Well Testing Journal, 31(1), 224-239.