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# NANOBOTS IN ROOT CANAL DISINFECTION: CURRENT CONCEPTS, CLINICAL POTENTIAL, AND FUTURE PERSPECTIVES: A NARRATIVE REVIEW

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## ABSTRACT

Effective removal of microorganisms from the intricate root canal system is essential for successful root canal treatment. Nevertheless, traditional chemomechanical preparation frequently fails to fully disinfect hard-to-reach anatomical regions like lateral canals, isthmuses, apical ramifications, and dentinal tubules, leading to persistent infections and treatment failure.[1,2] Recent developments in nanotechnology have brought forth nanobots as a groundbreaking solution to address these challenges. These tiny devices are capable of maneuvering through complex canal structures, accessing dentinal tubules, breaking down microbial biofilms, and precisely administering antimicrobial agents to infected areas.[3,4] In contrast to traditional irrigants that mainly rely on passive diffusion, magnetically driven nanobots can be controlled from outside to obtain precise disinfection while reducing harm to adjacent tissues.[5] Besides mechanically disrupting biofilms, nanobots improve antimicrobial effectiveness through localized drug administration, thus decreasing bacterial survival and the chance of reinfection. Experimental research has shown encouraging outcomes in enhancing root canal cleaning and removing resilient microbes, yet clinical use is still constrained due to concerns regarding biocompatibility, complexity in manufacturing, expenses, regulatory clearance, and long-term safety.[6-8] Continued investigations on biodegradable nanobots, smart navigation technologies, and enhanced magnetic control are anticipated to aid their eventual incorporation into endodontic procedures. This review outlines the existing ideas, mechanisms of action, uses, benefits, drawbacks, and future possibilities of nanobots focused on root canal disinfection.

## INTRODUCTION

Microorganisms within the root canal system are the primary etiological agents of pulpal and periapical diseases. The success of endodontic therapy depends on effective microbial elimination and prevention of reinfection through thorough cleaning, shaping, irrigation, and obturation.[1] However, complete canal disinfection remains difficult because of the complex internal anatomy, including lateral canals, isthmuses, apical ramifications, and dentinal tubules, which are often beyond the reach of conventional instruments and irrigants.[2]

Persistent microorganisms, particularly *Enterococcus faecalis*, exhibit a remarkable ability to survive chemomechanical preparation by forming resistant biofilms and colonizing dentinal tubules, thereby contributing to persistent infections and treatment failure.[1,2] Although commonly used irrigants such as sodium hypochlorite, chlorhexidine, and ethylenediaminetetraacetic acid (EDTA) possess broad antimicrobial activity, their effectiveness is limited by inadequate penetration into biofilms and anatomically complex areas.[3,4]

Recent advances in nanotechnology have led to the development of nanobots as a novel strategy for root canal disinfection. These nanoscale devices can actively navigate the root canal system, disrupt microbial biofilms, and deliver antimicrobial agents directly to infected sites.[5-8] While still under investigation, nanobots show considerable potential to enhance the precision and efficacy of endodontic disinfection, offering a promising adjunct to conventional treatment modalities.[10,11]

**Need for Advanced Root Canal Disinfection**

Complete microbial elimination remains one of the greatest challenges in endodontic therapy despite significant advances in instrumentation and irrigation techniques. The complexity of the root canal system, characterized by lateral canals, isthmuses, apical ramifications, and dentinal tubules, often prevents complete cleaning and creates niches for bacterial persistence.[1,2]

Microorganisms organized within biofilms exhibit greater resistance to antimicrobial agents than their planktonic counterparts. *Enterococcus faecalis*, one of the microorganisms most frequently associated with persistent endodontic infections, can penetrate dentinal tubules, withstand nutrient deprivation, and survive conventional chemomechanical procedures, contributing to post-treatment disease.[1,7]

Chemical irrigants such as sodium hypochlorite, chlorhexidine, and ethylenediaminetetraacetic acid (EDTA) remain indispensable for canal disinfection; however, their effectiveness depends on adequate penetration and contact with infected tissues. Even with activation techniques such as sonic, ultrasonic, laser-assisted, and photoacoustic irrigation, complete disruption of mature biofilms and elimination of microorganisms from inaccessible regions cannot always be achieved.[2,3]

These limitations have encouraged the development of advanced antimicrobial strategies capable of improving root canal disinfection. Nanotechnology has emerged as a promising field, with nanoparticles demonstrating enhanced antimicrobial activity, deeper dentinal tubule penetration, and sustained drug release.[3-5] More recently, nanorobots have been proposed as an innovative approach that combines active navigation with targeted antimicrobial delivery, offering the potential to improve disinfection of anatomically complex root canal systems.[6,7,8,10,11]

**Nanobots: Concept and Mechanism of Action**

Nanobots are nanoscale robotic devices, designed to perform specific biomedical tasks with high precision under external or internal control. They integrate nanotechnology, materials science, and robotics to enable targeted diagnosis and therapy at the cellular or molecular level. In endodontics, nanobots are being investigated as intelligent microdevices capable of navigating the root canal system, detecting microbial infection, and facilitating targeted disinfection.[6,10]

Experimental nanobots are generally composed of biocompatible nanomaterials integrated with magnetic nanoparticles and drug-loaded components. The magnetic core enables controlled movement in response to externally applied magnetic fields, while the surface can be functionalized with antimicrobial agents or bioactive molecules for targeted delivery.[5,8]

The mechanism of action of nanobots involves active navigation**,** biofilm disruption**,** and localized antimicrobial delivery**.** Guided by rotating or alternating magnetic fields, nanobots move through the root canal system and penetrate anatomically inaccessible regions such as dentinal tubules, lateral canals, and isthmuses. Their mechanical motion disrupts the extracellular polymeric matrix of microbial biofilms, exposing embedded bacteria to antimicrobial agents. Simultaneously, nanobots release antimicrobial drugs directly at the site of infection, achieving higher local concentrations while minimizing exposure of surrounding tissues. Certain magnetically actuated nanobots can also generate localized magnetic hyperthermia**,** producing heat that damages bacterial cells and further enhances biofilm eradication.[7,8]

Although still in the experimental stage, nanobots combine precise navigation with targeted antimicrobial action, making them a promising technology for improving root canal disinfection and reducing persistent endodontic infections.[10,11]

**Biofilm Disruption by Nanobots**

Microbial biofilms are the primary cause of persistent root canal infections and represent a major obstacle to successful endodontic treatment. The extracellular polymeric matrix surrounding biofilms protects bacteria from irrigants, intracanal medicaments, and host defense mechanisms, making complete eradication difficult with conventional disinfection methods.[1]

Magnetic hyperthermia is an emerging antimicrobial strategy in which magnetically actuated nanobots generate localized heat when exposed to an alternating magnetic field. This localized thermal effect disrupts the extracellular polymeric matrix of microbial biofilms and damages bacterial cell membranes, thereby enhancing bacterial eradication without causing significant injury to the surrounding dentinal tissues. When combined with targeted antimicrobial drug delivery, magnetic hyperthermia provides a synergistic approach for improving root canal disinfection, particularly against resistant biofilms.[7,8,9] Experimental studies have shown that this combined mechanical and chemical action is more effective against resistant microorganisms than conventional irrigation alone.[7]

Although current evidence is largely limited to laboratory investigations, the ability of nanobots to disrupt mature biofilms and improve antimicrobial penetration highlights their potential as a valuable adjunct to conventional root canal disinfection.[10,11]

**Advantages of Nanobots in Root Canal Disinfection**

Nanobots offer several advantages that may enhance the effectiveness of root canal disinfection. Their ability to navigate complex canal anatomy enables more uniform distribution of antimicrobial agents and improved access to regions that are difficult to reach with conventional techniques.[7,8] In addition, their combined mechanical and antimicrobial action enhances biofilm removal, thereby improving bacterial elimination.[3,7]

Targeted drug delivery minimizes unnecessary exposure of surrounding tissues to antimicrobial agents while maintaining effective local concentrations at the site of infection, potentially reducing the cytotoxic effects associated with conventional irrigants.[3,5] Furthermore, magnetically guided navigation provides controlled movement within the canal system, improving the precision and consistency of disinfection procedures.[8]

Although clinical evidence remains limited, these advantages indicate that nanobots have the potential to improve disinfection efficiency, reduce persistent infection, and enhance the long-term success of endodontic treatment.[10,11]

**Challenges and Limitations**

Despite their potential, the clinical application of nanobots in endodontics remains limited by several scientific and technical challenges. Biocompatibility is a major concern, as nanobots must be non-toxic, biodegradable, and safe for periapical tissues without eliciting adverse biological responses.[5,8]

Precise in vivo navigation and control within the complex root canal system also remain technically challenging. Although magnetic guidance has shown promising results in experimental studies, achieving accurate localization and ensuring complete retrieval or biodegradation of nanobots require further investigation.[7,8]

Additional barriers include high manufacturing costs, the need for specialized equipment, and the absence of standardized clinical protocols. Furthermore, comprehensive preclinical and clinical studies are necessary to establish long-term safety, efficacy, and regulatory approval before routine clinical use.[5,6,11] At present, most evidence is derived from laboratory-based studies, highlighting the need for well-designed animal studies and clinical trials to validate the clinical feasibility of nanobot-assisted root canal disinfection.[7,10]

**Future Perspectives**

Continued advances in nanotechnology and materials science are expected to improve the design, navigation, and safety of nanobots for endodontic applications. Future research should focus on optimizing biocompatibility, controlled drug delivery, and magnetic guidance while establishing standardized clinical protocols. Large-scale preclinical and clinical studies are essential before nanobots can be translated into routine root canal disinfection.[5,7,8,10,11]

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