IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

“MINUSCULE YET DYNAMIC” – A MICROROBOTIC VISION IN ENDODONTICS

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Abstract

Robotic technology has revolutionized biomedicine, and microrobots—dynamic systems with controlled locomotion—are emerging as promising tools at the micrometer scale. In endodontics, microrobots aim to minimize procedural errors such as perforations, ledges, and canal transportation by enabling automated probing, access opening, cleaning, shaping, and obturation with enhanced precision and efficiency. Recent advances in small-scale robotics and nanotechnology have led to the development of tetherless microrobots for biofilm disruption and retrieval, utilizing iron oxide nanoparticles with dual magnetic and catalytic functionality. This review highlights their design, mechanisms, applications, advantages, and limitations, while envisioning future developments toward integrated chemical disinfection and tissue regeneration in endodontic therapy.

Introduction

Microrobots, dynamic automated systems with controlled locomotion and functionality, have been increasingly explored for diverse biomedical applications. Unlike traditional robots requiring large motors for function, the controlled actuation and navigation of microrobots are achieved through self-propulsion or external stimuli such as magnetic, ultrasonic, optical, thermal, or electrical actuation (1,2). Among these, magnetically controlled microrobots have shown particularly promising results in targeted drug/gene delivery, minimally invasive surgery, and imaging-guided therapy (1,3). This opens new avenues for endodontics, where precision and minimally invasive approaches are paramount.

Objectives of Microrobot Design

To adapt micro-robotics into clinical dentistry, certain objectives must be clearly defined.

1. **Reduction of manual dependence** – to decrease reliance on the dentist’s hand skills and improve consistency.
2. **Minimization of human error** – to enhance safety, accuracy, and predictability of treatment outcomes.
3. **Precision in diagnosis and therapy** – to achieve highly controlled navigation and targeted endodontic procedures[4].

These objectives serve as the foundation upon which the design specifications are established.

Specifications and Requirements

Building on these objectives, the proposed micro-robotic system must be compact (20 × 20 × 28 mm) yet powerful enough to generate a thrust force of 500 g (4.9 N) for crown and dentin penetration. Furthermore, the device should provide rotational power comparable to conventional endodontic tools while allowing micro-level adjustments in position and angulation. Automated feed rate and travel distance controls ensure accurate canal preparation and termination, while integrated features such as microsensors for probing and apex detection, flexible instruments, and vacuum attachments for debris removal enhance safety and efficiency[5].

Mechanical Design Considerations

To meet these functional requirements, three different design configurations were evaluated. The first concept, a Cartesian-style robot positioned directly above the dental arch, employs threaded rods for X- and Y-axis motion, with vertical Z-axis insertion controlled by a rack-and-pinion system. The second design maintains a Cartesian configuration but relocates actuators away from the immediate field for better accessibility. In contrast, the third design introduces a cylindrical configuration, relying on polar coordinates to guide the end effector with radial arms for precise tool positioning[6]. Each design concept highlights the engineering challenges and possible solutions for creating a clinically viable microrobot.

Movement of Microrobot

Irrespective of the configuration, the microrobot must achieve precise control of motion. Five degrees of freedom are essential: linear motion along the X, Y, and Z axes and angular adjustment around θx and θy. This allows the system to achieve fine tool positioning and accurate entrance angulation within the confined space of the oral cavity. Supported on a saddle-shaped base that rests on reference brackets and the dental arch, the system ensures stability and accuracy during operative procedures^{7} [Figure 1].

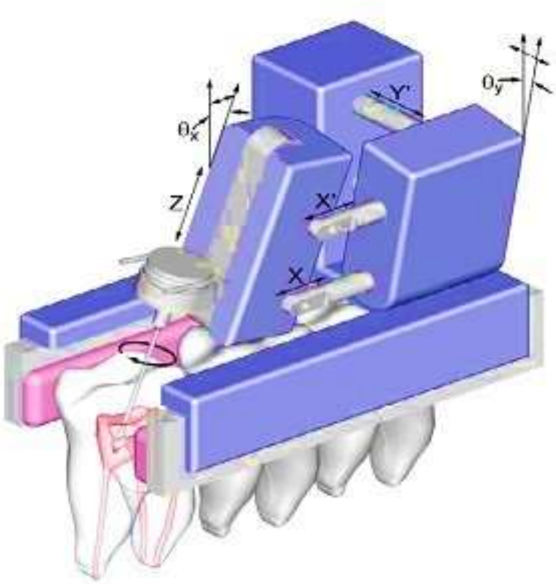

Figure 1: Multifunctional micro-device for automated endodontic therapy

Targeting Endodontic Biofilms

While mechanical precision is vital, the true clinical value of microrobotics lies in its application to endodontic challenges. One of the greatest hurdles in root canal therapy is persistent biofilm infection, which frequently leads to apical periodontitis due to incomplete disinfection of the complex canal system (8-12). Despite advances such as photoacoustic streaming, ultrasonic irrigation, antimicrobial nanoparticles, and photodynamic therapy (13-16), these techniques remain limited in precision and diagnostic capability (17). Here, microrobotics offers a unique breakthrough, combining navigation with biofilm disruption and microbial detection for superior endodontic outcomes.

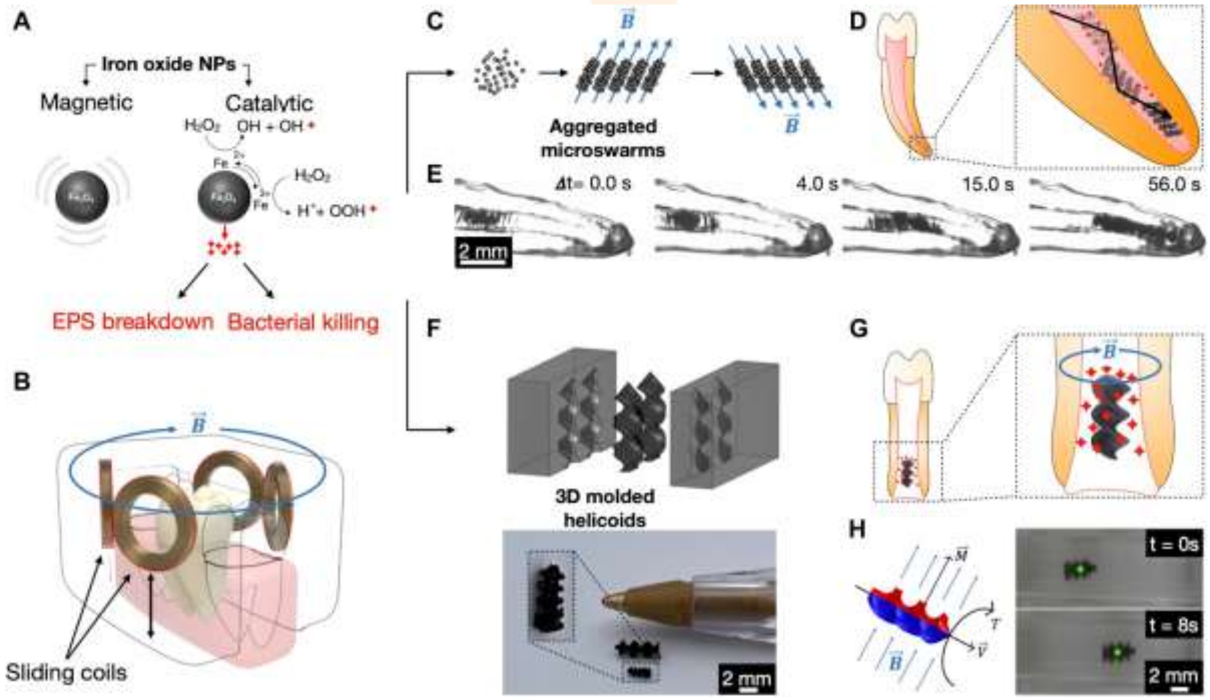

Figure 2 (source): https://pmc.ncbi.nlm.nih.gov/articles/PMC9305841/

Figure 2. Therapeutic and diagnostic microrobotic platforms. (A) Magnetocatalytic nanoparticle (NP) building blocks. (B) Magnetic apparatus for controlled navigation around the alveolar process. (C) Formation of aggregated microswarms under magnetic fields. (D) Aggregated microswarms guided to the apical canal region with simultaneous bioactive release. (E) Direction of microswarms toward the apical region in a root canal replica. (F) Fabrication of NP-embedded 3D helicoids (top) and miniaturized helicoid structures

(bottom). (G) Schematic of 3D helicoids delivering bioactives/drugs to the apical region of an immature root. (H) Left: helicoid motion generated by alignment of magnetic torque (T), dipole moment (M), and magnetic field (B). Right: controlled locomotion of 3D helicoids under applied magnetic torque.

Magnetically Driven Catalytic Antibiofilm Robots

A particularly exciting development is the use of iron oxide nanoparticles (NPs) as building blocks for microrobots capable of disrupting, degrading, and retrieving biofilms within the root canal system. These nanoparticles, with their peroxidase-like catalytic activity, activate H_2O_2 to release reactive species that dismantle biofilms (18,19). Their established biocompatibility and FDA approval further support clinical applicability. When magnetically actuated, either through permanent magnets or electromagnets, these microrobots achieve precise tether-free control, even within confined root canal spaces (20,21). Two platforms have emerged: catalytically active microswarm aggregates for apical biofilm removal and 3D-printed hydrogel-based helicoids embedded with nanoparticles for drug delivery and fluid propulsion.

Aggregated Microswarms

Microswarm assemblies of iron oxide NPs have demonstrated remarkable adaptability to the intricate geometry of root canals (22,23). In experimental models, swarms effectively disrupted mixed-species biofilms, retrieved microbial samples, and achieved significant penetration into apical regions under electromagnetic guidance. The ability of these microswarms to combine mechanical disruption with diagnostic retrieval underlines their potential as next-generation endodontic disinfection tools (24).

3D-Molded Helicoids

In parallel, 3D-molded hydrogel helicoids embedded with iron oxide NPs provide another innovative approach. Their corkscrew-like propulsion under magnetic actuation enables efficient canal navigation, while reactive oxygen species released from the hydrogel matrix enhance biofilm eradication (20). Radiopacity, achieved through bismuth oxide incorporation, allows real-time monitoring with intraoral radiography and CBCT. Furthermore, helicoids can be loaded with antibiotics such as metronidazole and ciprofloxacin for controlled release using oscillating magnetic fields. Collectively, these multifunctional features make helicoids a promising platform for biofilm disruption, targeted drug delivery, and radiographically guided regenerative endodontics (25).

Conclusion

Microrobotics offers a transformative approach to endodontics by enhancing precision, reducing operator dependency, and addressing persistent challenges such as biofilm removal. Magnetically driven catalytic microrobots, microswarms, and hydrogel helicoids demonstrate promising potential for disinfection, drug delivery, and regenerative applications. Although these systems provide automation, their effectiveness still relies on the dentist's supervision, control, and clinical decision-making. While current evidence remains preclinical, continued interdisciplinary research may soon translate these innovations into routine clinical practice.

Future Perspectives

Future work should prioritize further miniaturization, biocompatible materials, and integration with imaging systems for real-time guidance. Development of multifunctional microrobots with antimicrobial, diagnostic, and regenerative capabilities, coupled with AI-driven automation, will be crucial. Importantly, while automation is advancing, maintaining appropriate dentist supervision and control will remain essential to ensure patient safety and clinical accuracy. Ultimately, advancing from laboratory models to clinical trials will determine the true impact of microrobotics in endodontic therapy.

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