Nanoparticles in Endodontics: Bridging Science and Clinical Application

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INTRODUCTION

Persistent endodontic infections remain difficult to eliminate due to the resistance of some pathogens, especially *Enterococcus faecalis*, the organization of bacteria in biofilms, and the difficulty in successfully disinfecting the most remote areas of the root canal anatomy **(1, 2)**. Traditional irrigants and intracanal drugs are ineffective against some bacterial strains, have limited penetration, and provide only short-term activity **(2, 3)**. **Nanoparticles (NPs)** offer **enhanced antimicrobial performance**, **deeper diffusion**, and **controlled drug release**, making them a **promising strategy to overcome these limitations and improve root canal disinfection (3, 4, 5)**. This work focuses on the most relevant nanoparticles currently explored in endodontics, including silver, chitosan, silica-based, selenium, herbal-derived, lipid-based and calcium hydroxide nanoparticles **(1–6)**.

TABLE 1. TYPES OF NANOPARTICLES AND THEIR MAIN CHARACTERISTICS

Nanoparticle Type	Composition / Structure	Primary Advantages	Limitations
Silver NPs (AgNPs)	Metallic Ag; core-shell structures	Strong broad-spectrum antimicrobial effect; Reactive Oxygen Species generation; Membrane disruption	Potential genotoxicity; Stability issues; Dose-dependent cytotoxicity
Chitosan NPs (CS-NPs)	Cationic biopolymer	Biocompatible; Chelation effects; Tubule penetration; Biofilm disruption	Limited long-term stability; Formulation variability
Silica NPs	Porous silica (often loaded with Ag or Chloroexidine (CHX))	High loading capacity; Controlled drug release	Possible aggregation; Requires surface modification
Selenium NPs (SeNPs)	Elemental selenium	Potent antibiofilm effect; Synergistic with Photodynamic Therapy	Narrow therapeutic window
Herbal / Propolis NPs	Plant-derived compounds encapsulated in polymers	Biocompatible; Antioxidant	Lower standardization; Variability in active compounds
Lipid NPs (e.g., CHX-loaded)	Solid lipid or nanostructured carriers	Sustained release; Compatibility with sealers	Complex synthesis; Stability concerns
Calcium hydroxide NPs	Nanoscale $Ca(OH)_2$	Improved penetration; Greater alkalinity; Enhanced antimicrobial action	Short-term activity; Solubility issues
Polymeric NPs (e.g., PLGA, PCL, PLA)	Biodegradable aliphatic polyesters	Controlled drug release; tunable degradation; High biocompatibility	More complex synthesis; Dependent on solvent removal; Cost

TABLE 2. MECHANISMS OF ACTION OF NANOPARTICLES AGAINST ENDODONTIC PATHOGENS

Mechanism	Description	Types of Nanoparitcles Involved
Membrane disruption	Increased permeability, rupture, cytoplasmic leakage	**AgNPs, CHX-loaded NPs, SeNPs**
Generation of reactive oxygen species (ROS)	Oxidative damage to proteins, lipids, DNA	**AgNPs, SeNPs**
Inhibition of DNA replication	Interaction with phosphorus/sulfur groups in DNA	**AgNPs, SeNPs**
Protein synthesis inhibition	Ribosomal denaturation and protein expression arrest	**AgNPs**
Chelation and biofilm matrix destabilization	Interaction with Ca^{2+} and biofilm components	**Chitosan NPs**
Enhanced drug delivery	Controlled release into tubules, prolonged antimicrobial effect	**Silica NPs, lipid NPs, polymeric NPs**
Synergy with Photodynamic therapy or irrigants	Increased ROS or enhanced cell death	**SeNPs, herbal NPs**

TABLE 3. TRANSLATING NANOPARTICLES INTO CLINICAL ENDODONTICS

Advantages	Challenges
Superior antimicrobial and antibiofilm efficacy	Potential cytotoxicity/genotoxicity (e.g., AgNPs)
Enhanced penetration into complex anatomy	Regulatory barriers and classification
Controlled and sustained drug release	Variability in synthesis protocols
Compatibility with sealers and hydrogels	Long-term biosafety not fully established
Potential integration into regenerative therapies	Cost and scalability

TABLE 4. APPLICATIONS OF NANOPARTICLES IN ENDODONTICS

Application	Nanoparticles Used	Outcomes
Irrigation solutions	AgNPs, CHX-NPs, Herbal NPs	Increased disinfection, reduced biofilm
Intracanal drugs	$Ca(OH)_2$-NPs, Chitosan NPs	Improved tubule penetration and sustained effect
Sealers	AgNPs, CHX-loaded Lipid NPs	Enhanced antimicrobial properties without compromising flow
Regenerative endodontics	Chitosan NPs, Bioactive sílica NPs	Growth factor release, dentin conditioning
Photodynamic therapy	SeNPs	Increased ROS and biofilm eradication

CONCLUSIONS

Nanoparticles consistently demonstrate **strong antimicrobial and antibiofilm effects** against *E. faecalis*, *S. mutans* and mixed-species biofilms, with several systems, such as silver, selenium, chitosan, propolis and lipid-based nanoparticles, showing significant Colony-Forming Units reduction and enhanced biofilm disruption. These materials also **improve dentinal tubule penetration** and **exhibit synergistic benefits when combined with irrigants or photoactivated therapies**. Overall, nanoparticle-based platforms offer superior disinfection potential compared with conventional agents, positioning **nanotechnology as a promising pathway toward more predictable and biologically oriented endodontic treatments.**

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