REVIEW ARTICLE

Nano-Endodontics:Current Status and Future Directions

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Abstract

Nanotechnology has emerged as a promising advancement in endodontics, offering innovative solutions to overcome limitations of materials and techniques. Nanoparticles possess unique physicochemical properties such as high surface area, enhanced reactivity, and improved antimicrobial efficacy. In endodontics, nanoparticles incorporated into irrigants, intracanal medicament, sealers to improve disinfection, penetration into dentinal tubules and biocompatibility. Commonly used nanoparticles include silver, zinc oxide, chitosan and bioactive glass. Their application has shown significant potential in reducing bacterial biofilms, particularly Enterococcus faecalis, and enhancing the overall success of root canal treatment. Furthermore, nanotechnology holds promising potential in regenerative endodontics by supporting stem cell adhesion, controlled drug delivery, and regenerative of the pulp dentin complex.

***Keywords*: Nanoparticles (NPs), Nanotechnology, Nanomaterials, Endodontics**

1. Introduction

Nanotechnology refers to the science and engineering of materials at the nanoscale, typically ranging between 1 and 100 nm, where materials exhibit unique physicochemical, biological, and mechanical properties distinct from their bulk counterparts.[1,2] The high surface area–to–volume ratio, enhanced reactivity, and ability to interact at the molecular level have enabled nanotechnology to revolutionize biomedical sciences, including dentistry.[3,4,5]

In dentistry, nanotechnology has contributed to improved antimicrobial strategies, enhanced material strength, bioactivity and targeted drug delivery systems.[6,7,8.]

Within endodontics, the application of nanoparticles has emerged as a promising approach to address persistent challenges such as complex root canal anatomy, resistant microbial biofilms, and limitations of conventional irrigants and obturation materials.[8,9] Nanoparticles used in endodontics are broadly classified into metallic nanoparticles (silver, copper, zinc oxide), metal oxide nanoparticles (TiO_2, ZnO), polymeric nanoparticles (chitosan), carbon-based nanoparticles and bioactive ceramic nanoparticles such as nano-hydroxyapatite, bioactive glass and zirconia. These nanoparticles demonstrate enhanced penetration into dentinal tubules, superior antibacterial activity against *Enterococcus faecalis*, and improved sealing and mechanical properties when incorporated into endodontic materials.[10,11]

Bioactive glass nanoparticles have gained particular interest due to their ability to release calcium and phosphate ions, promote apatite formation and stimulate dentin remineralization and periapical tissue healing.[12,13,14]

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2. History

1959 – Richard Feynman introduced the conceptual foundation of nanotechnology through his landmark lecture *"There's Plenty of Room at the Bottom,"* in which he proposed the feasibility of manipulating matter at the atomic and molecular levels. This visionary idea laid the intellectual groundwork for nanoscale science and future biomedical applications, despite the absence of enabling technologies at the time.[15,16]

1981 – The invention of the Scanning Tunnelling Microscope (STM) marked a turning point by allowing direct visualization and manipulation of individual atoms. This technological breakthrough transformed nanotechnology from a theoretical concept into an experimentally viable science, enabling precise study of nanoscale materials and interactions.[16,17,18]

1991 – The discovery of carbon nanotubes significantly accelerated nanomaterials research due to their exceptional mechanical strength, electrical conductivity and biocompatibility. This milestone expanded the scope of nanotechnology into medicine and dentistry, encouraging exploration of nanoscale materials for biological and clinical applications.[17]

2000 – Robert A. Freitas Jr. formally introduced the term *"nanodentistry,"* envisioning the use of nanorobots and nanosystems for highly precise diagnostics, targeted therapyand tissue regeneration in dental care. This concept provided a futuristic framework for integrating nanotechnology into dental specialties, including endodontics.[4,8]

Early 2000s – Initial dental research focused on the incorporation of nanoparticles and nanofillers into restorative materials, particularly resin composites, to enhance mechanical strength, wear resistance and esthetics. These early studies established the feasibility and advantages of nanoscale modifications in dental materials science.[8,11]

Mid-2000s – The development of nano-hydroxyapatite and nanostructured surface coatings gained prominence due to their ability to promote remineralization, improve bonding to dental hard tissues and mimic natural tooth mineral structure. These advances also coincided with growing interest in nanoparticle-based antimicrobial strategies to combat biofilm-associated infections.[12,19]

2010s – Nanotechnology became widely adopted in dentistry, with extensive use of nanocomposites, antibacterial metallic and polymeric nanoparticles and nano-scaffold systems. In endodontics, nanoparticles were incorporated into irrigants, intracanal medicaments, sealers, and obturation materials to enhance antimicrobial efficacy, dentinal tubule penetration, and sealing ability.[4,12]

2020s – Research emphasis shifted toward bioactive and multifunctional nanomaterials, including controlled drug delivery systems, smart nanodevices and regenerative endodontic applications. Bioactive glass and zirconia nanoparticles attracted significant attention for their combined antimicrobial, mechanical and tissue-regenerative properties supporting biologically driven endodontic therapies.[12,23]

2025 – Contemporary advances highlight the integration of nanotechnology with regenerative endodontics, precision therapeutics and biointeractive material design. Current research focuses on smart nanosystems capable of targeted action, enhanced biocompatibility and long-term clinical success, marking the transition of nanotechnology from an experimental innovation to a clinically relevant cornerstone of modern endodontic practice.[4,12,23]

3. Types of Nanoparticles in Endodontics:

a) Silver Nanoparticles (AgNPs): Silver nanoparticles exhibit strong antibacterial effects against endodontic pathogens due to their ability to disrupt bacterial cell membranes and interfere with intracellular processes.[3]They have been incorporated into irrigants, intracanal medicaments and sealers to enhance antimicrobial efficacy.[4]

Green-synthesized nanoparticles use plant or biologically derived agentsAnchusa officinalis (Bugloss) ,Bryophyllumpinnatum (miracle leaf), Oxalis corniculata (creeping wood sorrel), and Trianthemaportulacastrum(Horse Purslane), offering an eco-friendly and biocompatible alternative to conventional synthesis. In endodontics, such nanoparticles exhibit effective antimicrobial action against resistant biofilms, including *Enterococcus faecalis* with reduced cytotoxicity, making them suitable for use in irrigants, intracanal medicaments, and sealers.[27,28,49,50,51,52]

Examples:

- Nano Silver Gel® – A colloidal silver nanoparticle–based antimicrobial gel used for local infection control and wound management, demonstrating broad-spectrum antibacterial activity.[29]
- Silver Nanoparticles (AgNPs) Powder / Dispersions (Sigma-Aldrich®, Merck®, US Research Nanomaterials®, Nanocs®) – Commercially available AgNP powders and colloidal suspensions widely used for incorporation into endodontic sealers, irrigants, and intracanal medicaments in research and material development[3,8,4].
- Silver Nanoparticle–Incorporated Gutta-Percha (research-based prototypes) –In academic research, AgNP-coated obturation cones developed to provide sustained antimicrobial activity within the root canal system.[41,42]

b) Chitosan Nanoparticles (CNPs): Chitosan, a natural polysaccharide, has antimicrobial and biocompatible properties.[5]Chitosan nanoparticles have been used to enhance disinfection, drug delivery, and tissue regeneration, leveraging their strong antibacterial, biocompatible, and chelating properties to deeply penetrate dentinal tubules, disrupt biofilms, and improve root canal sealers, irrigants, and medicaments, promoting better infection control and dentin remineralization.[52,53,54]

Examples:

- Sigma-Aldrich Chitosan Nanoparticle(for research/biomaterial use)
- Chitosan USP/NF (e.g.Poliglusam, Chitopharm) – can be formulated into nanoparticles
- Chitosan-containing oral care products – antimicrobialtoothpaste/mouthwash.[30,43,44]

c) Zinc Oxide Nanoparticles (ZnONPs): Zinc oxide nanoparticles possess antibacterial, antifungal and anti-inflammatory properties. Studies have shown their potential in improving the sealing ability and antimicrobial function of endodontic materials.[6]

Examples:

1. Sigma-Aldrich Zinc oxide –ZnOnanopowder, research-grade nanoparticles.
2. Sigma-Aldrich Zinc oxide CAS1314-13-2 – Analytical grade ZnO suitable for formulation.
3. Sigma-Aldrich Zinc oxide nanoparticle ink 2.5 wt.% – ZnO nanoparticle dispersion product used in research and materials development.[44,45]

d) GoldNanoparticles(AuNPs):

Gold nanoparticles have demonstrated biocompatibility and anti-inflammatory effects. Their role in endodontics includes drug delivery systems and tissue regeneration applications.[7]

Examples:

1. Sigma-Aldrich Gold Nanoparticles
2. Cytodiagnostics AuNPs. [46,47]

e) Titanium Dioxide Nanoparticles (TiO_2NPs): Titanium dioxide nanoparticles have been explored for their photocatalytic antimicrobial activity, which can help in reducing bacterial load in infected root canals.[8]

Examples:

- Sigma-Aldrich TiO_2 Nanoparticles
- US Research NanomaterialsTiO_2 NPs.[55-58]

f) Bioactive Glass Nanoparticles (BGNPs): Bioactive glass nanoparticles play an important role in modern endodontics due to their biocompatibility, bioactivity, and antimicrobial properties. At the nanoscale, BGNPs promote the formation of a hydroxyapatite layer at the dentin–material interface, enhancing sealing ability and biological integration. Their use in root canal sealers, pulp capping materialsand regenerative applications supports dentin remineralization, periapical healing, and effective disinfection through alkaline ion release.[45,46,47,48]

Examples:

- NovaBone® Nanoparticles
- 45S5 Bioglass® Nanoparticles

Dental Use – used in tooth remineralization, pulp capping, and bone grafting.[59-61]

g) Zirconia Nanoparticles (ZrO_2NPs) Zirconia nanoparticles are increasingly incorporated into endodontic materials to improve mechanical strength, radiopacity and antimicrobial efficacy. Their nanoscale size allows better penetration into dentinal tubules, while maintaining excellent biocompatibility. These properties make ZrO_2NPs valuable additives for enhancing the durability and clinical performance of endodontic sealers and restorative materials. [31,32]

4. Mechanism of action:

A few known mechanisms by which NPs act are described below:

a) Electrostatic interaction leading to cell membrane disruption:

As negative and positive charge attract each other, the positively charged nanoparticles react with the negatively charged surface of microorganisms leading to their accumulation of NPs on the bacterial cell surface. These positively charged NPs are bonded effectively to the cell membrane leading to upsetting of the cell wall frame work which leads to an increase in the permeability of the cell allowing the entry of more and more NPs into the bacteria causing cellular content leakage. These NPs by binding to mesosomes, affect respiration, division, also DNA replication.[13,14] and thus result in the lysis of bacterial microorganisms

b) Metal ion homeostasis:

Metabolic functions are measured which are largely dependent on haemostasis of metal ion present in the microbes. An irreversible damage causing retardation of growth or killing of the microbe is caused by excess of metal NPs which disrupt this important function.[15]

c) Production of reactive oxygen species (ROS):

NPs gain access to the cell membrane of the microorganism and cause the release of ROS. An oxidative stress occurs in the cell which initiates an attack on the microbe. Due to this attack, respiration and production of ATP is decreased, this causes disruption of the cell membrane. The formation of ROS by a metal oxide occurs by active redox cycling and by the pro-oxidant functional group on metal oxide-NP interface.[16]

d) Protein and enzyme dysfunction:

NPs cause a formation of carbonyls which are protein bound in nature by catalysing the oxidative process of amino acid chain resulting in degradation of protein, inactivation of various enzymes and disruption of catalytic activity[17,18]

e) Genotoxicity and inhibition of signal transduction:

Due to their electrical properties, NPs interact with the nucleic acid molecules leading to a negative influence on the process of chromosomal and plasmid DNA replication which results in signal transduction inhibition[19,20]

5. Applications Of Nanoparticles In Endodontics:

a) Pulp-capping agents:

Chitosan nanoparticles(CNPs) are highly effective in pulp capping because their natural bioactivity promotes dental pulp healing, reduces inflammation, fights microbes and stimulates reparative dentin formation by encouraging stem cell differentiation into odontoblasts offering a superior alternative to traditional materials like calcium hydroxide. Their nanoparticle form enhances strength, absorbability and reactivity while their inherent properties support biocompatibility, adhesion and tissue regeneration, making them ideal for regenerative dentistry.[62-66]

b) Root Canal Irrigation and Disinfection:

Nanoparticles can enhance the antimicrobial activity of irrigants such as sodium hypochlorite and chlorhexidine. AgNPs and ZnONPs have been incorporated into irrigants to improve their penetration and biofilm disruption capabilities.[9]

c) Intracanal Medicaments:

Nanoparticles have been used in intracanal medicaments to achieve prolonged antimicrobial effects. Chitosan-based nanoparticle formulations have demonstrated sustained antimicrobial activity against Enterococcus faecalis and Candida albicans.[10,52,53,54]

d) Endodontic Sealers and Obturation Materials:

Nanoparticles can improve the physical and biological properties of endodontic sealers. Silver and zinc oxide nanoparticles have been added to sealers to enhance their antimicrobial activity and sealing ability[11]

f) Regenerative Endodontics:

Nanoparticles play a role in regenerative endodontics by promoting cell proliferation and differentiation. Hydroxyapatite and bioactive glass nanoparticles have been used to enhance tissue regeneration and mineralization inpulp capping andapexogenesis procedures.[12]

6. Diagnostic Applications of Nanotechnology:

• Nanosensors and quantum dots are emerging tools for early caries detection and biofilm mapping.[21,22]

• Nanoprobe-based diagnostics can identify pathogenic bacteria in root canals at the molecular level, allowing personalized disinfection strategies.

7. Overall Advantages of Nanotechnology in Dentistry:

• Enhanced mechanical durability
• Superior esthetics
• Bioactivity and remineralization
• Targeted antimicrobial action
• Potential for real-time diagnostic

8. Commercially Available brand:

a) NanoSeal S (PrevestDenPro):

- Brand Name: NanoSeal S
- Nanoparticle Type: Silver (AgNPs) nanoparticles
- Mechanism: Enhanced penetration into dentinal tubules and increased antimicrobial activity due to high surface area of nanoparticles.

• Clinical Benefits: Superior sealing ability, reduced microleakage, and good biocompatibility, improving long-term root canal success.[21,67]

b) EndoSequence BC Sealer (Brasseler USA)

- Brand Name: EndoSequence BC Sealer
- Nanoparticle Type: Nanosized calcium silicate particles (bioceramic)
- Mechanism: Promotes hydroxyapatite formation, chemical bonding with dentin, and bioactive sealing.
- Clinical Benefits: Excellent sealing, minimal shrinkage, enhanced periapical tissue healing.[68,69]

c) GuttaFlowBioseal (ColteneWhaledent):

- Brand Name: GuttaFlowBioseal
- Nanoparticle Type: Nano-silver incorporated in bioceramic silicone matrix
- Mechanism: Antimicrobial action of silver combined with fluidity and adaptability of silicone-based sealer.
- Clinical Benefits: Effective canal obturation, prevents bacterial recolonization, and ensures dimensional stability.[70]

d) Nano ceramic sealers(B & L Biotech):

- Nanoparticle Type: Zirconia Nanoparticles (ZrO_2NPs)
- Mechanism: involves a hydrophilic bioceramic composition that chemically bonds to dentin by forming hydroxyapatite (HA), creating a strong, leak-proof seal with zero shrinkage, and its hydration sets the material, releasing calcium hydroxide for antibacterial action and stimulating bone healing, offering a bioactive, simplified obturation technique.[71,72]

e) NanoCarePlus (PrevestDenPro):

- Brand Name: NanoCarePlus
- Nanoparticle Type: Silver & Gold nanoparticles

- Mechanism: Silver provides broad-spectrum antimicrobial effects; gold enhances biocompatibility and healing.
- Clinical Benefits: Improves root canal disinfection, reduces microbial load, and supports periapical tissue healing.[73,74]

f) B-Ostin HA Nano Bone Graft (BIO-TEC, South Korea):

- Brand Name: B-Ostin HA Nano Bone Graft
- Nanoparticle Type: Nano-hydroxyapatite (HA)
- Mechanism: Mimics natural bone structure, increases surface area for cell adhesion, and promotes osteoconduction.
- Clinical Benefits: Enhances bone regeneration in periapical and periodontal surgeries, improves tissue integration, and reduces infection risk.[64]

9. Challenges And Limitations:[75,76]

- Cytotoxicity concerns with some nanoparticles, particularly at high concentrations
- Possible development of bacterial resistance
- Lack of standardization in nanoparticle synthesis and application
- Need for long-term clinical studies to establish safety and efficacy.

10. Future of nanoparticles in endodontics:

Nanotechnology has presented impression on almost every field of science and development. Naturally,medicine and dentistry too have been inspired by this technology having an enormous potential. This being said, there is no doubt that the future of endodontics is heading down the nano-direction as most of the challenges faced (dentin) are all nano sized. The era of nano-endodontics is paving it’s way to be the bright future in dentistry.[77,78]

11. CONCLUSION:

Nanodentistry creates an opportunity to improve dental material efficacy and reduces failures. In this new therapeutic approach, optimising physicochemical properties of NPs for targeted tissues are crucial. Numerous nanostructures and nano materials have studied in endodontics, which represents specific features such as high stability with optimal therapeutic activity, antimicrobial functionality and possibility of penetrating to deeper unreachable areas such as dentinal tubules.Endodontic studies have shown that NPs may cause cytotoxicity, neurotoxicity and genotoxicity depending on several factors including NP type, amount of concentration, size, exposure time, type of cell lines and the method of synthesis. This has emphasised the necessity to develop nanosafety researches further to keep up with rapid nanodentistry advances.[79,80]

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