REVEIW ARTICLE

Nanotechnology in Endodontics and Prosthodontics: Current Advances and Future Perspectives

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ABSTRACT

Nanotechnology has emerged as a transformative force in modern dentistry, offering unprecedented advancements in both endodontics and prosthodontics through the manipulation of materials at the nanoscale. This review synthesizes current knowledge on nanotechnology applications in these fields, evaluating their impact on treatment outcomes, material performance, and patient care while critically addressing associated challenges and future research directions. In endodontics, nanoparticles have revolutionized root canal therapy by enhancing disinfection efficacy through superior penetration into dentinal tubules, significantly reducing reinfection risks and improving antimicrobial action. Nanomaterial-enhanced sealers and obturating materials exhibit improved mechanical properties, including increased strength, fracture resistance, and adhesion, thereby extending treatment durability. Furthermore, nanotechnology facilitates pulp tissue regeneration via targeted drug delivery systems and scaffolds that support stem cell differentiation and tissue revitalization. In prosthodontics, nanomaterials have dramatically improved the aesthetic and functional quality of dental restorations by closely mimicking the natural optical and structural properties of teeth while enhancing mechanical strength, wear resistance, and longevity. The integration of nanoparticles into prosthodontic materials has also resulted in superior surface hardness, modulus of elasticity, and reduced polymerization shrinkage, alongside antibacterial properties and controlled therapeutic agent delivery that promote oral health and patient comfort. Despite these promising advancements, significant challenges remain, including concerns regarding long-term biocompatibility, cytotoxicity, systemic toxicity, and environmental impact of nanomaterials. The lack of standardized regulatory frameworks and comprehensive clinical safety data further complicates their widespread clinical adoption. Future research must prioritize rigorous preclinical and clinical investigations to establish robust safety profiles, develop application-specific regulatory guidelines, and advance innovative technologies such as smart stimuli-responsive materials, personalized nanotherapies, and nanorobotic interventions. Sustained interdisciplinary collaboration among researchers, clinicians, and regulatory authorities will be essential to fully harness the transformative potential of nanotechnology in dentistry while ensuring patient safety and improved therapeutic outcomes.

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INTRODUCTION

Nanotechnology, defined as the manipulation and engineering of materials at the nanoscale—typically below 100 nanometers has emerged as a transformative force in modern dentistry, fundamentally reshaping the landscape of restorative care, preventive strategies, and diagnostic methodologies [1]. By exploiting the unique physicochemical properties that arise at the nanoscale, nanotechnology has enabled the development of advanced dental materials with superior mechanical strength, antimicrobial efficacy, and biocompatibility [1-3]. The integration of nanomaterials including nanoparticles, nanocomposites, and nanorods into clinical practice has yielded significant improvements in treatment outcomes across multiple dental disciplines, with particularly profound implications for endodontics and prosthodontics.

In endodontics, nanotechnology has revolutionized root canal therapy by addressing critical challenges related to disinfection, material performance, and tissue regeneration. Nanoparticles demonstrate enhanced penetration into dentinal tubules, providing superior antimicrobial action that significantly reduces the risk of reinfection [4, 5]. Furthermore, nanomaterial-enhanced root canal sealers exhibit improved mechanical strength and adhesion, thereby increasing the long-term durability of endodontic treatments [4]. Beyond disinfection and sealing, nanotechnology facilitates targeted drug delivery and supports stem cell differentiation, opening new avenues for pulp tissue regeneration and minimally invasive endodontic therapy [4, 5]. Similarly, in prosthodontics, nanotechnology has dramatically improved the aesthetics, durability, and functional performance of dental prosthetics. Nanomaterials can be engineered to closely mimic the optical and structural properties of natural teeth, resulting in highly lifelike restorations with enhanced strength and wear resistance [6]. Additionally, these materials can be functionalized with antibacterial properties and designed for controlled therapeutic agent delivery, thereby promoting oral health and enhancing patient comfort [6, 7].

Despite these remarkable advancements, the clinical translation of nanotechnology in endodontics and prosthodontics is not without significant challenges. Concerns regarding the long-term biocompatibility, potential cytotoxicity, and environmental impact of nanomaterials remain substantial barriers to widespread adoption [1]. Moreover, the high production costs and evolving regulatory landscape necessitate ongoing interdisciplinary research and collaboration among scientists, clinicians, and regulatory authorities to ensure the safe and effective integration of nanotechnology into routine dental practice [1, 8].

This review aims to provide a comprehensive synthesis of current advancements in nanotechnology applications within endodontics and prosthodontics, highlighting their transformative potential while critically evaluating associated challenges. Specifically, the review will examine the impact of nanotechnology on material properties, treatment precision, and patient outcomes in these fields [1, 8]. Furthermore, it will address key issues related to biocompatibility, safety, and regulatory oversight, offering a balanced perspective on both the opportunities and risks inherent in nanotechnology-driven dental innovations [1]. By elucidating the current state of knowledge and identifying critical gaps for future research, this review seeks to inform clinicians, researchers, and policymakers on the responsible and evidence-based application of nanotechnology in advancing dental care.

FUNDAMENTALS OF NANOTECHNOLOGY IN DENTISTRY

Nanotechnology has significantly impacted the field of dentistry, particularly in endodontics and prosthodontics, by introducing advanced materials and techniques that enhance treatment outcomes. This section will delve into the fundamentals of nanotechnology in dentistry, focusing on the definition and classification of nanomaterials, their physicochemical properties relevant to dental applications, and the mechanisms of their interaction with dental tissues and microbes.

Nanomaterials are defined as materials with at least one structural dimension smaller than 100 nanometers, a scale at which they exhibit unique physicochemical, mechanical, and biological properties that differ substantially from their bulk counterparts. In dentistry, nanomaterials are strategically classified based on their primary functional roles, enabling targeted applications across various clinical domains. Antimicrobial nanoparticles, including silver, zinc oxide, and chitosan nanoparticles, are widely employed for their potent ability to manage biofilm formation and significantly reduce microbial colonization in both restorative and endodontic applications [9]. Therapeutic nanoparticles, such as hydroxyapatite and bioglass nanoparticles, play a critical role in drug delivery systems and regenerative therapies, promoting osseointegration, accelerating tissue healing, and supporting the regeneration of dental hard and soft tissues [10]. Finally, material property-enhancing nanoparticles, such as silica and zirconia, are incorporated into dental composites, ceramics, and polymers to improve mechanical strength, wear resistance, optical aesthetics, and overall material durability, thereby extending the clinical lifespan of dental restorations [9].

The unique physicochemical properties of nanomaterials render them exceptionally well-suited for diverse dental applications, offering functional advantages that are unattainable with conventional materials. The significantly reduced particle size and correspondingly large surface-area-to-volume ratio of nanoparticles enable deep penetration into complex anatomical structures such as dentinal tubules, thereby enhancing antimicrobial efficacy and substantially reducing the risk of bacterial persistence and reinfection in endodontic treatments [11]. Furthermore, nanoparticles exhibit heightened chemical reactivity due to their elevated surface energy, a characteristic that can be strategically exploited to improve the adhesion, mechanical strength, and sealing ability of dental materials, including root canal sealers and prosthodontic restorations [12, 13]. However, the clinical success of nanomaterials is critically dependent on their biocompatibility and long-term safety profile. Ongoing research is therefore focused on optimizing surface modifications and material formulations to minimize cytotoxic effects, prevent adverse tissue reactions, and ensure safe integration into the oral environment, thereby facilitating the sustainable and effective use of nanotechnology in clinical dentistry [10, 14].

Nanomaterials interact with dental tissues and oral microbiota through multiple sophisticated mechanisms, significantly enhancing the therapeutic efficacy of dental treatments. At the antimicrobial level, nanoparticles exert potent bactericidal effects by disrupting microbial cell walls, generating reactive oxygen species, and interfering with biofilm formation and maturation, thereby providing superior disinfection in endodontic procedures compared to conventional antimicrobial agents [13]. Beyond their antimicrobial activity, nanomaterials play a pivotal role in tissue regeneration; nanoscaffolds and nanoparticle-mediated delivery of growth factors facilitate stem cell differentiation and recruitment, promoting pulp tissue regeneration and accelerating the healing of damaged dental structures [11, 13]. Furthermore, nanoparticles enable highly targeted and controlled drug delivery within the oral cavity, ensuring precise therapeutic outcomes with reduced systemic exposure and minimal side effects a feature that is particularly advantageous in managing endodontic infections, inflammation, and postoperative pain [11, 15]. Despite these promising advancements, the clinical translation of nanotechnology in dentistry must be approached with careful consideration of potential challenges and risks. Concerns regarding the long-term biocompatibility, cytotoxicity, and environmental impact of nanomaterials necessitate rigorous preclinical and clinical research, as well as comprehensive regulatory oversight, to ensure their safe and effective integration into routine dental practice. As the field continues to evolve, achieving a balanced approach that maximizes the therapeutic benefits of nanotechnology while mitigating associated risks will be essential for its successful and sustainable application in endodontics and prosthodontics.

NANOTECHNOLOGY IN ENDODONTICS

Nanotechnology has significantly advanced the field of endodontics, offering innovative solutions for root canal disinfection, enhanced irrigation systems, improved obturation materials, regenerative endodontics, and diagnostics. The integration of nanomaterials in these areas has led to improved treatment outcomes, increased antimicrobial efficacy, and potential for tissue regeneration. This overview explores the various applications of nanotechnology in endodontics, highlighting its transformative impact on dental care.

Silver nanoparticles (AgNPs), chitosan, and zinc oxide are commonly used for their antimicrobial properties. AgNPs, in particular, have shown wide-spectrum antimicrobial activity and the ability to penetrate dentinal tubules, enhancing disinfection efficacy compared to conventional methods [16]. Nanocarriers facilitate targeted drug delivery within root canal systems, improving the effectiveness of antimicrobial agents and reducing the risk of reinfection.

Silver nanoparticles have been used as adjuncts to traditional irrigants, demonstrating enhanced antimicrobial activity against resistant pathogens like Enterococcus faecalis [17].

Nanoparticles can modify biofilm matrices, improving the penetration and efficacy of antimicrobial agents in disrupting biofilms [18].

Incorporating nanoparticles into sealers enhances their mechanical properties, antimicrobial action, and sealing ability, leading to more durable endodontic treatments. Nanomaterials improve the biocompatibility of sealers, reducing cytotoxicity and promoting better integration with surrounding tissues.

Nanoscaffolds support pulp tissue regeneration by providing a conducive environment for cell growth and differentiation. Nanotechnology facilitates the delivery of growth factors, enhancing the regenerative potential of endodontic treatments [11].

Nanosensors enable precise detection of infections within the root canal system, improving diagnostic accuracy and treatment planning [19]. Nanoparticle-based contrast agents enhance imaging techniques, allowing for better visualization of dental structures and pathologies [11].

While nanotechnology offers promising advancements in endodontics, challenges such as long-term biocompatibility, potential cytotoxicity, and the need for standardized clinical protocols remain. Ongoing research and interdisciplinary collaboration are essential to address these challenges and fully integrate nanotechnology into clinical practice. Additionally, the potential environmental impact and regulatory considerations of nanomaterials must be carefully evaluated to ensure safe and effective applications in dental care .

NANOTECHNOLOGY IN PROSTHODONTICS

Nanotechnology has significantly impacted prosthodontics, offering advancements in materials and techniques that enhance the functionality, aesthetics, and longevity of dental prosthetics. This field leverages the unique properties of nanomaterials to improve mechanical strength, esthetics, and biological interactions of prosthetic devices. The following sections explore the various applications of nanotechnology in prosthodontics, highlighting its transformative potential. Nanomaterials in Prosthetic Materials Nanocomposites in Crowns, Bridges, and Dentures: Nanocomposites, incorporating materials like silica, zirconia, and nanodiamonds, are used in crowns, bridges, and dentures to enhance mechanical properties such as modulus elasticity and surface hardness. These materials also improve esthetic qualities by mimicking the natural appearance of teeth [6]. Mechanical and Esthetic Enhancements: The integration of nanomaterials reduces polymerization shrinkage and increases filler loading, resulting in prosthetics that are not only stronger but also more visually appealing. This leads to longer-lasting restorations that require fewer replacements [6, 7] Implant Surface Nanomodification Nanostructured Coatings for Osseointegration: Nanoscale modifications on implant surfaces, such as bioactive coatings and anodization, enhance osseointegration by promoting bone healing and stability. These coatings can include hydroxyapatite and growth factors that improve biological performance. Bioactive and Antibacterial Implant Surfaces: Advanced nanostructured surfaces can also provide antibacterial properties, reducing bacterial adhesion and infection risks. This is achieved through the incorporation of antimicrobial agents like silver nanoparticles [1]. Nanotechnology in Impression Materials and CAD/CAM Systems Precision Improvement through Nanofillers: Nanofillers in impression materials enhance the precision of dental impressions, leading to better-fitting prosthetics. This precision is crucial for the success of CAD/CAM systems in creating accurate dental restorations [7]. Digital Workflow Integration: The integration of nanotechnology with digital workflo

ws in CAD/CAM systems streamlines the production of prosthetics, improving efficiency and reducing errors in the manufacturing process [20]. Antimicrobial and Antifouling Prosthetic Surfaces Prevention of Biofilm Formation: Nanotechnology enables the development of prosthetic surfaces that resist biofilm formation, a common cause of prosthetic failure. This is achieved through the use of antimicrobial nanomaterials like silver and zinc oxide [21]. Long-term Clinical Performance: By preventing biofilm formation, these surfaces enhance the long-term clinical performance of prosthetics, reducing the need for frequent replacements and improving patient outcomes. Smart Prosthodontics and Nanotechnology

Stimuli-responsive Materials: Smart materials that respond to environmental stimuli, such as temperature or pH changes, are being developed for use in prosthodontics. These materials can adapt to changes in the oral environment, providing enhanced comfort and functionality. Self-healing and Adaptive Prosthetic Systems: Nanotechnology is paving the way for self-healing prosthetic systems that can repair minor damages autonomously, extending the lifespan of dental restorations and reducing maintenance costs. While nanotechnology offers numerous benefits in prosthodontics, challenges remain, including concerns about biocompatibility, cytotoxicity, and regulatory oversight. The potential for environmental accumulation and systemic toxicity of nanomaterials necessitates careful evaluation and rigorous research to ensure safe clinical applications. Despite these challenges, the future of nanotechnology in prosthodontics is promising, with ongoing research focused on developing smart, personalized therapies and potentially integrating nanorobotics into dental practice [7, 20].

COMPARATIVE INSIGHTS: ENDODONTICS VS. PROSTHODONTICS APPLICATIONS

Nanotechnology has significantly impacted both endodontics and prosthodontics, offering innovative solutions that enhance treatment outcomes. While both fields benefit from the unique properties of nanomaterials, they apply these technologies in distinct ways due to their differing clinical objectives. This section explores the key similarities and differences in the application of nanotechnology in endodontics and prosthodontics, as well as the translational challenges faced by each field.

Nanomaterials have emerged as a transformative component in both endodontics and prosthodontics, significantly enhancing the mechanical, chemical, and biological performance of dental materials. In prosthodontics, the incorporation of nanoparticles improves the strength, durability, and aesthetic properties of restorations, while in endodontics, these materials contribute to superior sealing ability and enhanced antimicrobial performance of root canal sealers [6]. A key shared advantage across both fields is the potent antimicrobial activity of nanoparticles such as silver and zinc oxide, which effectively reduce bacterial colonization and minimize the risk of infection ([6, 7]. Furthermore, nanotechnology has enabled the development of advanced drug delivery systems capable of targeted and controlled release, thereby improving therapeutic outcomes. These systems facilitate localized treatment, such as delivering bioactive agents to inflamed pulp tissue in endodontics or to peri-implant tissues in prosthodontics, enhancing both treatment efficacy and tissue response.

Nanotechnology plays distinct yet complementary roles in endodontics and prosthodontics, reflecting their differing clinical objectives and applications. Endodontics primarily focuses on the diagnosis and treatment of diseases affecting the dental pulp and root canal system, where nanotechnology is leveraged for enhanced disinfection, tissue regeneration, and pain management. In contrast, prosthodontics is concerned with the restoration of dental function and aesthetics, utilizing nanomaterials to fabricate highly durable and lifelike prosthetic restorations [6]. These differences are further reflected in material applications; in endodontics, nanomaterials are commonly incorporated into sealers, intracanal medicaments, and regenerative scaffolds, whereas in prosthodontics, they are widely used in denture bases, crowns, and bridges to improve mechanical strength and aesthetic outcomes [20]. Additionally, nanotechnology has advanced diagnostic capabilities in endodontics through the use of nanoparticle-based contrast agents, enabling precise visualization of complex dental structures, a feature that is comparatively less emphasized in prosthodontic practice[22].

Despite the transformative potential of nanotechnology in both endodontics and prosthodontics, several challenges continue to limit its widespread clinical translation. In endodontics, concerns regarding the long-term biocompatibility and safety of nanomaterials remain prominent, highlighting the need for well-designed clinical trials to validate their efficacy and minimize potential adverse effects. Additionally, the absence of standardized protocols and clear regulatory frameworks further restricts their routine clinical adoption. In contrast, prosthodontics faces challenges primarily related to cost and clinical integration, as the high expense of nanomaterials and the complexity of incorporating them into existing workflows hinder accessibility [6]Moreover, achieving an optimal balance between aesthetic outcomes and functional performance remains an ongoing area of research

[20]. Collectively, these limitations underscore the necessity for continued interdisciplinary collaboration, regulatory advancements, and cost-effective innovations to fully harness the benefits of nanotechnology in modern dental practice.

BIOCOMPATIBILITY, TOXICITY, AND SAFETY CONSIDERATIONS

Nanotechnology has significantly advanced the fields of endodontics and prosthodontics, offering improved materials and techniques. However, the integration of nanotechnology into dental practices necessitates careful consideration of biocompatibility, toxicity, and safety. These considerations are crucial to ensure that the benefits of nanotechnology do not come at the expense of patient health. This section will explore the cytotoxicity and systemic effects, regulatory considerations and standards, and long-term clinical safety of nanotechnology in dentistry.

Nanoparticles incorporated into dental materials, while offering significant functional advantages, may also present potential cytotoxic risks due to their small size and high surface reactivity. These properties can induce oxidative stress, inflammatory responses, and even genotoxic effects in human tissues [23, 24]. Additionally, the route of exposure during dental procedures particularly through inhalation or inadvertent ingestion raises concerns regarding systemic toxicity, with possible adverse effects on vital organs such as the lungs, liver, and kidneys [24]. Commonly used nanoparticles, including silver and zinc oxide, exemplify this dual nature; although they possess strong antimicrobial activity, they may exert cytotoxic effects when applied at higher concentrations. To address these limitations, current research has focused on strategies such as surface functionalization and the application of biomimetic coatings, which aim to enhance biocompatibility and minimize undesirable biological interactions [23]. The regulatory landscape governing the use of nanotechnology in dentistry remains complex and continues to evolve, necessitating strict adherence to established safety standards to ensure both patient protection and environmental safety [25]. Although major regulatory bodies such as the USFDA and the European Medicines Agency (EMA) have developed general frameworks for the evaluation of nanomaterials, these guidelines are not yet sufficiently tailored to address the specific requirements of dental applications. This gap is further compounded by the lack of standardized protocols for the synthesis, characterization, and biological testing of nanoparticles used in dental materials, which challenges consistent regulatory assessment and approval processes [26]. Consequently, sustained interdisciplinary collaboration among researchers, clinicians, and regulatory authorities is critical to establish comprehensive and application-specific safety standards, thereby facilitating the safe and effective clinical translation of nanotechnology in dentistry [23]. Despite the significant advancements offered by nanotechnology in endodontics and prosthodontics, concerns regarding long-term safety remain a critical area of investigation. Current evidence on the chronic effects of nanoparticles is limited, particularly with respect to their potential accumulation in biological tissues, underscoring the need for extensive longitudinal studies. Moreover, well-designed clinical trials are essential to assess the long-term durability and biocompatibility of nanoparticle-enhanced dental materials under functional conditions. The capacity of nanoparticles to interact with biological systems in complex and sometimes unpredictable ways further highlights the importance of continuous monitoring and robust post-market surveillance frameworks [23]. In parallel, future research should prioritize the development of smart, stimuli-responsive nanomaterials capable of adapting to the dynamic oral environment while maintaining optimal safety and therapeutic efficacy. Collectively, addressing these challenges through sustained research, regulatory refinement, and interdisciplinary collaboration is essential to ensure the safe and effective integration of nanotechnology into clinical dental practice.

CURRENT CHALLENGES AND LIMITATIONS

Nanotechnology has significantly advanced the fields of endodontics and prosthodontics, offering innovative solutions for improved dental treatments. However, several challenges and limitations hinder its full integration into clinical practice. These challenges include technical and manufacturing barriers, cost-effectiveness issues, and clinical translation gaps. Addressing these challenges is crucial for the successful adoption of nanotechnology in dental care.

The translation of nanotechnology into routine dental practice is significantly constrained by challenges associated with the production and standardization of nanomaterials. The fabrication of these materials requires sophisticated technologies and precise control over physicochemical properties, making the process technically demanding and resource-intensive. Such complexity can introduce inconsistencies in material quality and performance, ultimately affecting their reliability in clinical applications. Furthermore, scaling up production from laboratory settings to industrial manufacturing remains a major hurdle, as it often necessitates specialized equipment and tightly controlled processes that limit large-scale availability [8, 27]. Compounding these issues is the lack of standardized protocols for the synthesis and characterization of nanomaterials, which complicates quality control measures and regulatory approval pathways, and may lead to variability in clinical outcomes [8, 28].

Economic considerations represent a significant barrier to the widespread adoption of nanotechnology in dentistry. The high production costs associated with advanced fabrication techniques and specialized materials make nanomaterial-based products considerably more expensive than conventional alternatives, limiting their accessibility, particularly in resource-constrained settings. In addition, questions surrounding economic viability persist, as the enhanced performance of nanotechnology-driven treatments must be balanced against their higher costs, requiring clear evidence of long-term cost-effectiveness to support their clinical adoption [20, 28]. Market dynamics further complicate this landscape, as dental practitioners and patients may be hesitant to transition from established, more affordable materials to newer, high-cost nanotechnology-based options, thereby slowing their integration into routine practice.

Despite the considerable promise of nanotechnology in advancing endodontics and prosthodontics, several critical challenges continue to impede its full clinical integration. Foremost among these are concerns related to biocompatibility and safety, as the long-term effects and potential cytotoxicity of nanomaterials remain insufficiently understood, largely due to the lack of comprehensive clinical data [11]. This issue is closely linked to the limited number of well-designed, long-term clinical trials, with much of the existing research still confined to preclinical or early-stage investigations, thereby restricting insight into real-world efficacy and safety [29]. In parallel, regulatory challenges further complicate clinical translation, as the absence of clear, standardized guidelines in many regions creates uncertainty and delays in the approval and adoption of nanotechnology-based dental products. Addressing these interconnected barriers will require coordinated efforts to expand clinical evidence, refine regulatory frameworks, and enhance the safety profile of nanomaterials. Ultimately, sustained interdisciplinary collaboration among researchers, clinicians, and regulatory authorities will be essential to translate the potential of nanotechnology into safe, effective, and widely accessible dental therapies.

FUTURE PERSPECTIVES AND EMERGING TRENDS

The future of nanotechnology in endodontics and prosthodontics is poised for significant advancements, driven by personalized nanodentistry, AI-integrated nanotechnologies, and advanced regenerative approaches. These emerging trends promise to revolutionize dental care by enhancing precision, personalization, and effectiveness of treatments. The integration of these technologies is expected to address current limitations and open new avenues for patient-centered care in dentistry. Below are the detailed future perspectives and emerging trends in this field.

The convergence of nanotechnology and personalized medicine has opened exciting avenues for individualized dental care, with nanodentistry enabling treatments tailored to the unique physiological and pathological characteristics of each patient. One of the most promising developments in this domain is the application of dental nanorobots, which can be programmed to deliver therapeutic agents with unprecedented precision, offering personalized solutions for conditions such as dentin hypersensitivity and caries prevention [20]. Complementing this approach, stimuli-responsive smart materials represent another frontier in personalized nanodentistry; these materials are designed to sense and adapt to dynamic changes in the oral environment such as fluctuations in pH, temperature, or enzymatic activity thereby providing customized therapeutic responses that enhance treatment efficacy [30]. Furthermore, nanotechnology facilitates the fabrication of patient-specific dental materials and prosthetic restorations, which not only improve functional fit and aesthetic integration but also minimize the risk of adverse biological reactions, ultimately advancing the quality and safety of individualized dental care [6].

The integration of artificial intelligence (AI) with nanotechnology represents a transformative paradigm that is poised to significantly enhance both diagnostic and therapeutic capabilities in modern dentistry. AI algorithms can process and interpret complex data generated by nanobiosensors in real-time, enabling rapid and accurate diagnostics that facilitate the early detection of oral diseases and improve clinical decision-making [1]. Beyond diagnostics, AI-driven predictive analytics offer the potential to forecast treatment outcomes and optimize the selection of nanomaterials based on individual patient profiles, thereby ensuring more personalized and effective therapeutic interventions [31]. Furthermore, the development of automated treatment planning systems that seamlessly integrate nanotechnology-based diagnostic data with AI-powered algorithms promises to streamline clinical workflows, reduce human error, and deliver highly customized care tailored to the specific needs of each patient.

Nanotechnology is playing an increasingly pivotal role in advancing regenerative dentistry by significantly enhancing tissue engineering and healing processes. Nanoparticles have demonstrated the capacity to augment the regenerative potential of dental tissues by promoting stem cell differentiation, proliferation, and guided tissue growth, thereby accelerating repair mechanisms. In endodontics, bioactive nanomaterials are being employed to support pulp regeneration and facilitate natural healing, offering promising alternatives to conventional root canal therapy. Additionally, innovations in nanofiber scaffolds provide an optimized microenvironment that mimics the extracellular matrix, enhancing cell attachment, migration, and differentiation, which collectively improve the success rates of regenerative procedures [8]. Despite these promising advancements, several challenges must be addressed to ensure successful clinical translation. Concerns regarding long-term biocompatibility, safety profiles, and the lack of clear regulatory pathways for nanotechnology-based dental products remain substantial obstacles. Furthermore, the high costs associated with the development and integration of these advanced technologies into routine practice may restrict their accessibility and slow widespread adoption. Overcoming these barriers will require sustained interdisciplinary collaboration, rigorous clinical research, ethical oversight, and the establishment of cost-effective production strategies to fully realize the potential of nanotechnology in regenerative and personalized dental care.

CONCLUSION

Nanotechnology has emerged as a transformative force in both endodontics and prosthodontics, offering substantial advancements in dental materials, diagnostic capabilities, and treatment methodologies. In endodontics, the integration of nanoparticles has revolutionized root canal therapy by enhancing disinfection efficacy, mechanical properties, and tissue regeneration potential. The superior penetration of nanoparticles into dentinal tubules enables more effective antimicrobial action, thereby reducing the risk of reinfection, while their incorporation into sealers improves adhesion and durability, contributing to longer-lasting clinical outcomes. Similarly, prosthodontics has benefited from nanomaterial innovations that enhance the aesthetics, strength, and functionality of dental restorations. By closely mimicking the natural appearance of teeth and offering improved wear resistance and antibacterial properties, these materials enhance both patient comfort and oral health. Across both disciplines, nanotechnology has facilitated early disease detection through the development of highly sensitive nanobiosensors and enabled targeted therapeutic interventions with reduced systemic side effects. However, despite these promising developments, significant challenges persist, including concerns regarding long-term biocompatibility, cytotoxicity, environmental accumulation, and the absence of standardized regulatory frameworks.

The clinical implications of nanotechnology are profound. In endodontics, advanced nanoparticle-based sealers and medicaments promise more effective disinfection and enhanced regenerative outcomes, potentially reducing the need for retreatments and improving overall patient prognosis. In prosthodontics, the use of nanomaterials can yield more lifelike and durable restorations, thereby decreasing replacement frequency and associated costs. Yet, the realization of these benefits depends on addressing critical safety and accessibility concerns. Future research must prioritize comprehensive studies on the long-term biocompatibility and potential systemic toxicity of nanomaterials, alongside the establishment of clear, standardized regulatory guidelines to ensure safe clinical translation. Furthermore, the high production costs currently associated with nanotechnology may limit its widespread adoption, particularly in resource-limited settings, underscoring the need for cost-effective manufacturing strategies.

Looking forward, the convergence of nanotechnology with emerging fields such as regenerative medicine, artificial intelligence, and personalized diagnostics holds immense potential to further revolutionize dental care. By fostering interdisciplinary collaboration among researchers, clinicians, and regulatory authorities, and by prioritizing rigorous clinical trials and ethical oversight, the dental community can navigate existing challenges and unlock the full therapeutic promise of nanotechnology. Ultimately, ensuring that these innovations are both safe and accessible will be essential to improving patient outcomes and advancing the standard of care in modern dentistry.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have disclosed any financial or personal relationships that could potentially influence or bias the work presented.

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