

REVIEW ARTICLE

## Prosthodontics in the Era of Nanomedicine: Advanced Nanotechnology Enhanced Implants and Periodontal Surgery for Functional Oral Reconstruction

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### ABSTRACT

Nanotechnology is revolutionizing prosthodontics by enabling the manipulation of materials at the nanoscale, leading to significant enhancements in the properties of dental materials. This transformation is crucial for improving the performance of implants and periodontal surgeries, ultimately facilitating functional oral reconstruction. This review aims to explore the latest advancements in nanotechnology applications within prosthodontics, focusing on nanomaterials such as nanometals, nanoceramics, and nano resins. It seeks to provide a comprehensive overview of how these innovations can enhance the aesthetic, durability, and functionality of dental restorations. The integration of nanotechnology in prosthodontics not only improves material properties but also paves the way for future research and clinical applications, potentially leading to breakthroughs in oral health management and patient care. While the advancements in nanotechnology present numerous benefits, challenges such as regulatory hurdles and long-term biocompatibility remain critical considerations for its widespread adoption in clinical practice.

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## INTRODUCTION

Nanomedicine, broadly defined as the application of nanoscale science and technology to medical diagnosis, therapy, and prevention, has opened new frontiers in oral health care. By manipulating structures in the range of 1 to 100 nanometers, nanomedicine enables unprecedented control over material properties and biological interactions, allowing more precise, efficient, and targeted interventions than conventional approaches. Within dentistry, this has led to the emergence of nanodentistry, in which nanoparticles, nanostructured surfaces, and nanodevices are used to improve diagnostics, enhance restorative and preventive treatments, and support continuous maintenance of oral health [1].

Against this backdrop, prosthodontics has become a key beneficiary of nanotechnology-driven innovation. As the specialty concerned with restoring and replacing missing or compromised oral structures, prosthodontics increasingly relies on nanomaterials such as nanometals, nanoceramics, and nano-reinforced resins to refine mechanical and esthetic performance of restorations and implants. These materials can improve properties like strength, surface hardness, wear resistance, and polymerization behavior, while also conferring additional functionalities, including antibacterial activity and the capacity for local delivery of therapeutic agents at the prosthesis-tissue interface. In parallel, nano-engineered implant surfaces and regenerative adjuncts are reshaping concepts of osseointegration and peri-implant

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tissue management [2].

The present review is motivated by the need to synthesize and critically appraise these developments and their implications for functional oral reconstruction. Its objectives are to (i) outline the current applications of nanotechnology in prosthodontics, with emphasis on nanotechnology-enhanced dental implants and nanomedicine-assisted periodontal surgery; (ii) analyze the benefits, limitations, and biological and clinical challenges associated with their use; and (iii) highlight emerging directions and research gaps that must be addressed to safely translate these technologies into routine practice. By doing so, the review aims to provide clinicians and researchers with an up-to-date framework for understanding how nanomedicine is transforming prosthodontic practice, while also underscoring the importance of rigorous evaluation of long-term safety, cost-effectiveness, and equitable access [1, 3].

## FUNDAMENTALS OF NANOTECHNOLOGY IN ORAL TISSUES

Nanotechnology has significantly impacted the field of prosthodontics, particularly in enhancing implants and periodontal surgery for functional oral reconstruction. This section of the review paper will delve into the fundamental aspects of nanotechnology in oral tissues, focusing on the nanoscale properties of various oral tissues, the classification and properties of nanomaterials, and the biological interactions of nanoparticles within the oral environment. These insights are crucial for understanding how nanotechnology can be harnessed to improve oral health care.

Enamel is the hardest tissue in the human body, composed primarily of hydroxyapatite crystals organized in a highly ordered structure. At the nanoscale, enamel's dense crystalline structure acts as a barrier to nanoparticle penetration, although its surface can be modified to enhance bonding with nanomaterials. Unlike enamel, dentin contains numerous tubules that allow for the penetration of nanoparticles. This property is exploited in nanotechnology to strengthen dentin and regenerate pulp tissue, offering potential improvements in restorative dentistry [4]. Bone tissue, particularly in the maxillofacial region, benefits from the osteoconductive properties of nanomaterials, which promote bone regeneration and integration with implants. Nanoparticles enhance the mechanical properties and bioactivity

of bone graft materials [5]. Soft tissues in the oral cavity, such as the gingiva, interact with nanoparticles that can aid in wound healing and tissue regeneration. Nanomaterials can also be used to deliver drugs and growth factors to these tissues, enhancing therapeutic outcomes [6].

Nanomaterials applied in dentistry encompass a broad range of systems, including discrete nanoparticles, nanocomposites, nanostructured scaffolds, and, prospectively, nanorobotic platforms, each tailored to distinct clinical purposes in oral health care. Beyond their compositional diversity, their structural attributes particularly particle size, morphology, and surface chemistry play a critical role in governing interactions with oral tissues; for example, the high surface area-to-volume ratio of nanoparticles can markedly enhance bioactivity and promote more intimate integration with dental substrates [5]. These structural features underpin key functional advantages such as intrinsic antimicrobial effects, improved mechanical performance, and the capacity for controlled therapeutic release, which are increasingly exploited to extend the longevity, reliability, and biological performance of dental prostheses and implant systems.

Nanoparticles introduced into the oral cavity are rapidly conditioned by saliva and the resident biofilm, where adsorption of salivary proteins and other biomolecules leads to formation of a protein corona that alters their charge, stability, and biological identity, ultimately modulating bioavailability and interactions with oral tissues [4]. By tailoring nanoscale topography, chemistry, and mechanical properties, many dental nanomaterials are designed to enhance cellular adhesion, proliferation, and differentiation of key cell types such as osteoblasts, fibroblasts, and periodontal ligament cells, thereby supporting tissue regeneration and repair in applications including periodontal therapy and implant integration. At the same time, the growing use of nanoparticles in oral health care raises important safety considerations, as potential cytotoxicity, inflammatory responses, oxidative stress, and the uncertain consequences of long-term or systemic exposure necessitate rigorous preclinical and clinical evaluation [6]. Consequently, while nanotechnology offers significant opportunities to improve the performance of prosthodontic materials and treatments, its successful clinical translation depends on carefully balancing innovation with comprehensive safety assessment,

cost-effectiveness analysis, and strategies to ensure equitable access to nano-enabled dental therapies.

## NANOTECHNOLOGY-ENHANCED DENTAL IMPLANTS

Nanotechnology has significantly advanced the field of dental implants, offering enhanced osseointegration and improved clinical outcomes. This review explores the evolution of dental implants from conventional to nano-engineered surfaces, the techniques used for nanoscale surface modifications, the effects of nanoscale topography on osseointegration, and the biofunctionalization of implants with peptides, growth factors, and bioactive coatings. These advancements promise to revolutionize prosthodontics by improving the integration and functionality of dental implants.

Conventional dental implants historically relied on macro- and micro-scale surface modifications, such as sandblasting and acid etching, to increase roughness and promote mechanical interlocking with the surrounding bone, thereby enhancing early stability and osseointegration [7]. With the advent of nanotechnology, surface design has shifted toward nano-engineered topographies that more closely emulate the hierarchical architecture of natural bone, fostering more favorable biological interactions at the bone implant interface and supporting a more rapid and robust integration process [8]. These nanoscale features significantly enlarge the effective surface area available for cellular attachment, proliferation, and differentiation, which has been associated with accelerated bone formation and improved quality of the bone implant contact compared with conventional micro-roughened surfaces [9, 10].

A wide range of physical and chemical techniques are now used to engineer implant surfaces at the nanoscale, enabling more precise control over their structural and biological behavior. Physical approaches such as plasma spraying, sputtering, and ion implantation can deposit or modify thin layers on the implant surface, while chemical methods including anodization, acid treatments, and sol-gel processes create finely tuned oxide layers and nanostructures with tailored composition and roughness. Among these, anodization is particularly prominent for titanium, as it produces a nanotubular oxide layer that improves corrosion resistance, biocompatibility, and the capacity to support cell attachment and maturation [11, 12]. Collectively, these nanoscale surface modifications

not only optimize mechanical performance but also enhance biological responses by stimulating osteoblastic differentiation, accelerating bone formation at the interface, and thereby contributing to shorter healing periods and more predictable osseointegration [7].

Nanoscale surface topography is a key determinant of dental implant osseointegration, because it governs the initial adsorption of proteins as well as subsequent cell adhesion and lineage-specific differentiation at the implant bone interface [10]. Experimental studies indicate that nano-modified surfaces markedly enhance the attachment and proliferation of osteogenic cells, which translates into faster and more predictable formation of bone around the fixture and thus more robust long-term integration [9, 13]. Among the various nano-architectures investigated, titania nanotubes and related nanostructures have shown particular promise, as they not only stimulate new bone formation but also help reduce the risk of implant failure by improving the quality and stability of the bone implant contact [12].

Biofunctionalization of dental implant surfaces centers on the incorporation of bioactive agents such as peptides, growth factors, and calcium phosphate-based coatings to actively modulate the biological response at the implant-bone interface [9]. These layers can function as local reservoirs for therapeutic biomolecules, gradually releasing them to stimulate bone regeneration, enhance osteoblastic recruitment and activity, and thereby improve the predictability and overall success rate of implant therapy [10, 12]. Evidence indicates that such bioactive coatings not only accelerate early bone formation and strengthen the quality of the bone-implant contact, but also support more stable long-term integration by promoting a more favorable microenvironment for tissue healing and remodeling [14]. At the same time, the translation of nanotechnology-driven and biofunctionalized implant designs into routine clinical practice must be approached critically, as questions remain regarding their long-term performance, potential biological risks, manufacturing complexity, and cost, all of which may limit widespread adoption despite their substantial promise for improving patient outcomes and advancing contemporary prosthodontics.

## SMART AND DRUG-ELUTING NANO-IMPLANT SYSTEMS

The integration of nanotechnology into

prosthodontics has revolutionized the design and functionality of dental implants, particularly through the development of smart and drug-eluting nano implant systems. These systems leverage the unique properties of nanomaterials to enhance osseointegration, deliver therapeutic agents locally, and prevent peri-implant diseases. This section explores the various aspects of these advanced implant systems, focusing on nanoporous and nanotubular designs, local nanocarrier-based delivery, osteoinductive and osteoconductive drug delivery, and their impact on peri-implantitis prevention and early implant stability.

Titanium dioxide nanotubes (TNTs) are commonly generated on titanium implant surfaces by anodization, producing an ordered nanoscale architecture that more closely resembles the hierarchical structure of bone and thereby supports enhanced osseointegration while simultaneously offering a useful platform for localized drug delivery [15, 16]. The introduction of nanoporous and nanotubular surface features improves the quality of the implant tissue interface by facilitating cell attachment, migration, and differentiation, which in turn promotes more reliable integration and may lower the risk of implant failure compared with conventional surfaces [14, 17]. Importantly, these nanotubular designs exhibit good biocompatibility and can be further functionalized with a range of therapeutic agents including growth factors, antimicrobial drugs, and other bioactive molecules allowing controlled local release that enhances both regenerative potential and infection control around dental implants [18].

Nanocarrier-based systems are increasingly being explored in periodontal and peri-implant therapy because they can deliver drugs directly to diseased sites while minimizing systemic exposure. By concentrating antimicrobials and anti-inflammatory agents within periodontal pockets or around implants, these platforms improve local drug bioavailability, reduce required doses, and help limit off-target adverse effects, thereby enhancing overall therapeutic outcomes [19, 20]. In addition, many nanoformulations are engineered as controlled-release systems that sustain therapeutic concentrations over extended periods, which is particularly advantageous for managing peri-implant and periodontal infections where prolonged antimicrobial action is needed to disrupt complex biofilms [21, 22]. Early clinical and preclinical reports, including formulations

incorporating agents such as moxifloxacin, indicate that these targeted, sustained-delivery approaches can more effectively address the microbial and inflammatory burden characteristic of periodontitis, highlighting their potential as adjuncts or alternatives to conventional treatment regimens [22].

Nano-engineered implant systems increasingly combine osteoinductive and osteoconductive strategies to optimize bone-implant integration. Osteoinductive growth factors incorporated into or released from nanostructured implant surfaces can actively stimulate the recruitment, proliferation, and differentiation of progenitor cells toward the osteoblastic lineage, thereby promoting new bone formation and strengthening osseointegration in the critical early healing phase [15, 16]. In parallel, nanotechnology facilitates the design of highly osteoconductive materials and surface architectures that provide a favorable scaffold for bone ingrowth, guiding and supporting tissue deposition along the implant surface, which is essential for long-term mechanical stability [16]. When osteoinductive agents are combined with osteoconductive nano-enabled matrices in integrated delivery or coating systems, a synergistic effect can be achieved, offering a more comprehensive biological environment that both initiates and sustains bone regeneration at the implant site, ultimately improving the quality and reliability of bone implant integration [22].

Nanostructured and smart implant systems offer several important advantages for clinical implant dentistry, particularly in terms of biological stability and long-term success. Their intrinsic antimicrobial properties can limit early bacterial adhesion and biofilm formation on implant surfaces, thereby helping to reduce the incidence of peri-implantitis, one of the principal causes of late implant failure [15, 17]. At the same time, nano-engineered topographies enhance osseointegration and improve the mechanical interlocking between bone and implant, which supports greater early stability, minimizes micromovement under functional loading, and lowers the risk of early failure during the critical healing period [14, 18]. Collectively, these advances translate into more predictable and effective options for oral rehabilitation, expanding the therapeutic possibilities for complex prosthodontic reconstructions [21]. Nevertheless, the clinical implementation of smart and drug-eluting

nano-implant systems must be tempered by a careful appraisal of their limitations, including the need to balance therapeutic efficacy with the risk of cytotoxicity particularly in nanoparticle-decorated designs as well as outstanding questions regarding long-term biocompatibility, regulatory approval, and the practical challenges associated with their widespread adoption in routine dental practice [17].

## NANOMATERIALS IN PROSTHODONTIC COMPONENTS

Nanotechnology is significantly advancing the field of prosthodontics by enhancing the properties and performance of dental materials. This transformation is primarily achieved through the integration of nanomaterials, which offer improved mechanical, optical, and biological characteristics. The following sections explore the specific applications and benefits of nanomaterials in prosthodontic components, focusing on nanocomposite materials, reinforced ceramics, polymers, metal alloys, and their impact on prosthetic outcomes.

Nanocomposites used in prosthodontics are created by dispersing nanoparticles within conventional dental matrices, which leads to notable improvements in key material properties, including higher modulus of elasticity, greater surface hardness, and reduced polymerization shrinkage. By fine-tuning filler size, distribution, and refractive index at the nanoscale, these materials more closely reproduce the translucency, color depth, and light-scattering behavior of natural teeth, resulting in restorations with highly lifelike aesthetics and superior visual integration in the oral environment [2]. In addition to their esthetic advantages, nanocomposites demonstrate enhanced wear resistance and structural stability, contributing to longer service life of prosthetic components, fewer replacements over time, and, consequently, a reduction in long-term treatment burden and overall costs for patients and clinicians [2, 23].

Nanotechnology has facilitated the creation of nano-reinforced ceramics, polymers, and metal alloys that demonstrate markedly improved mechanical strength and wear resistance relative to conventional formulations [24]. Nanoceramics and nanometals are especially valuable in prosthodontics because they combine high biocompatibility with the capacity to endure complex masticatory forces

and abrasive challenges in the oral environment, thereby supporting stable long-term function [24, 25]. By integrating nanoparticles into these material systems, their structural integrity, toughness, and fatigue behavior are enhanced, making them particularly well suited for use in dental implants, frameworks, and other prosthetic components that demand both durability and reliable biological performance [26].

Nanomaterials used in prosthodontics are engineered to deliver both highly refined aesthetics and superior functional performance, addressing key limitations of conventional restorative materials. By manipulating particle size and distribution at the nanoscale, these systems can closely reproduce the translucency, depth of color, and light-scattering behavior of natural teeth, enabling restorations that blend more seamlessly with surrounding dentition and meet increasingly demanding esthetic expectations [2]. At the same time, the incorporation of nanoparticles enhances mechanical strength, fracture resistance, and resistance to surface wear, which supports the long-term durability and functional reliability of crowns, bridges, and other prosthetic components subjected to repetitive occlusal loading [24, 27]. Moreover, the distinctive wear patterns of many nanomaterial formulations help minimize abrasive damage to both the restoration and opposing dentition, preserving surface integrity and occlusal morphology over time and thereby contributing to more stable clinical outcomes [27].

Nanomaterials are increasingly used in prosthodontics to refine both biological and esthetic performance at the prosthesis–tissue interface. By tailoring surface chemistry and topography at the nanoscale, these materials can support more favorable soft-tissue adhesion and sealing around restorations and implant abutments, which may help reduce local inflammation and the risk of soft-tissue complications. In addition, incorporating nanoparticles with intrinsic antimicrobial activity into prosthodontic materials or coatings can contribute to controlling plaque biofilm, lowering the incidence of caries and periodontal infections around prosthetic margins, and improving overall patient comfort [24]. From an esthetic standpoint, nanotechnology enables highly precise control of translucency, chroma, and surface texture, allowing prosthetic components to closely reproduce the appearance and feel of natural teeth and gingival tissues [2]. Nonetheless, despite these advantages,

important challenges remain: the relatively high production costs of some nano-enhanced systems, concerns about potential nanoparticle toxicity, and uncertainties regarding long-term interactions with oral tissues all underscore the need for further experimental and clinical research before these technologies can be implemented widely and safely in routine prosthodontic practice [27].

#### **NANOTECHNOLOGY IN PERIODONTAL SURGERY FOR PROSTHODONTIC PATIENTS**

Nanotechnology has significantly advanced periodontal surgery, particularly for prosthodontic patients, by enhancing tissue regeneration and implant integration. This integration of nanotechnology in periodontics is pivotal for functional oral reconstruction, offering innovative solutions for bone and soft tissue regeneration. The following sections explore the role of periodontal health in oral reconstruction, the use of nano-engineered materials for bone and soft tissue regeneration, and the application of nanotechnology in guided tissue and bone regeneration.

Periodontal health forms the biological foundation for successful prosthodontic treatment, since stable, inflammation-free supporting tissues are essential to provide adequate support, load distribution, and long-term stability for fixed and removable prostheses as well as implants [1]. Healthy periodontal structures help prevent peri-prosthetic and peri-implant infections, preserve alveolar bone and soft-tissue architecture, and thereby maintain both the structural integrity and functional performance of dental restorations over time [1]. Within this context, nanotechnology offers new opportunities to strengthen periodontal health by refining diagnostic sensitivity and therapeutic precision for example, through nano-enabled diagnostics, targeted drug delivery, and regenerative approaches which can improve the management of periodontal diseases and, in turn, facilitate more predictable and durable outcomes in functional oral reconstruction.

Nano-engineered bone grafts and bioceramics, including nanohydroxyapatite and titanium dioxide based systems, are emerging as promising adjuncts for ridge preservation and augmentation because they actively support osteoinduction and biomineralization, thereby creating a more favorable environment for new bone formation [28]. Their nanoscale architecture improves both mechanical performance and biocompatibility,

qualities that are critical for achieving predictable bone regeneration and stable long-term integration of dental implants placed in reconstructed sites [29]. By markedly increasing the available surface area for cell attachment, proliferation, and matrix deposition, these nanomaterials can enhance the quality and rate of bone regeneration compared with conventional grafts, ultimately contributing to more reliable structural support for subsequent prosthetic rehabilitation [30].

Nanofibrous membranes and scaffolds play a central role in guided tissue regeneration (GTR) and guided bone regeneration (GBR) by acting as selective barriers that block rapid epithelial downgrowth while creating a protected space for periodontal ligament and bone cells to repopulate the defect [31]. When nanomaterials are incorporated into these barrier systems, their mechanical strength, bioactivity, and surface characteristics are improved, which in turn supports more stable placement, better tissue integration, and accelerated healing at the regenerative site. Building on these advances, modern 3D printing and bioprinting techniques now allow the fabrication of patient-specific, nanostructured scaffolds whose geometry closely matches complex periodontal defects, optimizing structural adaptation and further enhancing the predictability and quality of regenerative outcomes [32].

Nano-modified biomaterials, including advanced polymer composites and bioactive nanomaterials, are increasingly being applied to soft tissue regeneration because they can closely mimic the architecture and biochemical cues of the natural extracellular matrix, thereby supporting cell adhesion, proliferation, and matrix deposition [29]. By improving the quality and speed of gingival healing and fostering a more stable soft-tissue seal around dental implants, these materials contribute directly to both the aesthetic contour and the functional success of prosthodontic restorations [30]. In parallel, nanotechnology enables the design of localized drug delivery systems that provide controlled release of therapeutic agents such as anti-inflammatory or pro-regenerative molecules at the wound site, further enhancing the soft-tissue healing response and long-term stability [1]. Despite these advantages, important challenges remain, including unresolved questions about the long-term biocompatibility and potential side effects of certain nanomaterials, as well as the

need to refine material compositions and scaffold architectures to optimize clinical performance; addressing these issues through sustained, interdisciplinary research will be essential to fully harness nanotechnology for periodontal and prosthodontic soft-tissue applications.

#### **NANO-BASED ANTIMICROBIAL AND REGENERATIVE ADJUNCTS IN PERIODONTAL THERAPY**

Nanotechnology has emerged as a promising adjunct in periodontal therapy, offering innovative solutions for antimicrobial and regenerative treatments. The application of nanoparticles in periodontal pockets, nano-encapsulated antibiotics, and nano carriers for growth factors are pivotal in enhancing therapeutic outcomes. These advancements are particularly significant in supportive periodontal therapy, especially in prosthodontic cases where maintaining periodontal health is crucial for the success of prosthetic treatments. The following sections delve into the specific roles and implications of these nano-based approaches in periodontal therapy. Nanoparticles such as silver, zinc oxide, and chitosan are increasingly explored as next-generation antimicrobial agents in periodontal and oral applications because they combine broad-spectrum activity with relatively low toxicity compared with some conventional chemotherapeutics [33, 34]. Silver nanoparticles are particularly effective at disrupting bacterial cell membranes and interfering with essential metabolic processes, whereas zinc oxide and chitosan nanoparticles exert antibacterial effects through mechanisms such as membrane damage, generation of reactive oxygen species, and inhibition of biofilm formation, targeting a wide range of oral pathogens [33, 34]. Owing to their small size and high surface reactivity, these nanoparticles can penetrate dense biofilm matrices and deliver antimicrobial activity directly within the biofilm microenvironment, helping to circumvent bacterial resistance mechanisms and enabling more effective and sustained control of infection when incorporated into localized delivery systems for periodontal therapy [18, 35].

Nano-enabled local delivery systems are increasingly being used to place antibiotics and antiseptics directly into periodontal pockets, where they can achieve high local drug concentrations while minimizing systemic exposure and related side effects [36, 37]. By encapsulating active

agents within nanocarriers, such as liposomes or polymeric nanoparticles, these systems provide controlled and sustained release over extended periods, which supports prolonged antimicrobial action and can reduce the frequency of dosing, thereby improving patient compliance [3, 34]. In addition, the nano-encapsulation process helps protect encapsulated drugs from premature degradation in the oral environment, further enhancing their stability and therapeutic efficacy in the management of periodontitis [3, 34].

Nano-enabled regenerative strategies are gaining prominence in periodontal therapy because they can actively deliver biological cues that drive tissue repair rather than merely controlling infection. Nano carriers are used to transport and protect growth factors and other signaling molecules, releasing them in a controlled manner at diseased sites to stimulate regeneration of the periodontal ligament, cementum, and alveolar bone structures that are often severely compromised in advanced periodontitis [1, 38]. Complementing these delivery platforms, nanostructured scaffolds and nanofibrous matrices provide a three-dimensional framework that supports cell adhesion, proliferation, and differentiation, thereby enhancing the formation of new bone and periodontal ligament tissues and significantly boosting the regenerative potential of contemporary periodontal treatment protocols [18, 34].

Maintaining a healthy periodontium is fundamental to the long-term success of prosthodontic rehabilitation, since stable, disease-free supporting tissues are required to provide a reliable foundation for crowns, bridges, and implant-supported prostheses [1, 39]. Nano-based preventive and therapeutic strategies such as targeted antimicrobials, controlled-release drug delivery systems, and regenerative nanomaterials can help halt or slow periodontal disease progression, thereby preserving bone and soft-tissue architecture and improving the prognosis of existing and planned prosthetic work [1, 39]. When incorporated into supportive periodontal therapy, these nano-enabled approaches have the potential to enhance clinical outcomes, shorten treatment times, and increase patient satisfaction, particularly in complex cases where prosthodontic success depends on meticulous control of inflammation and tissue stability [3, 37]. Nonetheless, the clinical translation

of such technologies is not without challenges: concerns about possible toxic accumulation of nanomaterials, discrepancies between encouraging in vitro findings and more variable in vivo responses, and the current paucity of large, long-term clinical trials all highlight the need for cautious implementation and rigorous evaluation [18, 35]. Systematic efforts to address these issues will be crucial for integrating nanotechnology safely and effectively into routine periodontal care and, by extension, for optimizing the quality of life of patients undergoing prosthodontic treatment.

### INTEGRATED NANO-DRIVEN STRATEGIES FOR FUNCTIONAL ORAL RECONSTRUCTION

The integration of nanotechnology in prosthodontics has ushered in a new era of functional oral reconstruction, particularly in complex and full arch reconstructions. This approach leverages advanced materials and digital workflows to enhance treatment outcomes, especially for periodontally compromised patients. The following sections explore the various facets of these integrated strategies, highlighting the role of nanotechnology and digital innovations in modern prosthodontics.

Digital technologies have become central to planning complex prosthodontic and implant cases, particularly in full-arch and multidisciplinary reconstructions. Cone-beam CT, intraoral scanners, and facial scanning systems enable the creation of detailed three-dimensional datasets that can be merged and analyzed in a virtual environment, allowing clinicians to visualize bone anatomy, occlusion, soft-tissue contours, and esthetic parameters with high accuracy before any intervention [40, 41]. When these tools are embedded within a structured, interdisciplinary workflow that brings together prosthodontists, surgeons, orthodontists, and dental technicians, digital planning helps coordinate prosthetic-driven implant positioning, occlusal schemes, and soft-tissue management, thereby reducing biomechanical complications and improving overall predictability [42]. In this integrated setting, digital and analog methods complement each other: virtual planning informs surgical guides and provisional restorations, while clinical feedback is looped back into the digital design process, ultimately streamlining treatment, enhancing efficiency, and elevating the quality and consistency

of full-arch reconstruction outcomes [40, 42].

Nanotechnology has markedly expanded the regenerative armamentarium in periodontics, particularly for patients who present with compromised supporting tissues yet require implant-supported rehabilitation. Nanomaterial-based strategies, including nanoparticle-coated implants and nano-engineered grafts, can actively promote tissue repair by mimicking key aspects of bone formation and remodeling, thereby moving treatment goals from mere repair toward true regenerative excellence. Such coatings improve the quality and speed of osseointegration while simultaneously conferring antimicrobial activity at the implant surface, an important advantage in periodontal patients who are at higher risk for biofilm-mediated complications [14]. By recreating bone-like nanoscale topographies and enhancing cellular adhesion, proliferation, and differentiation, these nano-modified surfaces support more predictable early healing and contribute to superior long-term stability of implants placed in previously diseased sites, ultimately broadening the indications and success rates of implant therapy in the periodontally compromised population [14].

Computer-aided design/computer-aided manufacturing (CAD/CAM) and 3D printing are now integral to contemporary prosthodontics, particularly in full-arch reconstruction, where they streamline both planning and fabrication by enabling the rapid production of highly accurate surgical guides, provisional restorations, and definitive prostheses. These digital technologies reduce chairside time and overall treatment duration, improve fit and precision, and can lower costs by minimizing remakes and procedural inefficiencies [43]. When coupled with fully digital workflows for guided surgery, the virtual plan can be translated directly into the clinical setting, allowing implants to be placed with a high degree of accuracy relative to prosthetically driven positions and anatomical constraints, thereby reducing intraoperative complications and optimizing the biomechanical and esthetic outcomes of the final restoration. The benefits of this approach are further amplified when guided protocols are paired with nano-enhanced implant and restorative materials, which together support precise implant placement, improved osseointegration, and highly predictable functional and esthetic results [41, 44].

The convergence of digital workflows and

nanotechnology in prosthodontics is reshaping both the aesthetic and functional dimensions of oral rehabilitation, with clear benefits for patient satisfaction and quality of life [45]. Digitally driven planning and fabrication enable highly individualized prosthetic designs that account for each patient's anatomical, functional, and esthetic requirements, while nano-enhanced materials contribute superior optical and mechanical properties, resulting in restorations that look more natural and perform more reliably over time [45, 46]. This patient-centric model, supported by precise diagnostics, virtual simulations, and customized prostheses, improves patient-reported outcomes by aligning treatment more closely with expectations and comfort, thereby elevating the overall treatment experience [45, 46]. At the same time, the adoption of these advanced strategies is not without challenges: substantial financial investment, the need for specialized training, and disparities in access can limit widespread implementation, while robust long-term clinical evidence is still emerging to fully validate their safety and effectiveness across diverse clinical scenarios. Even so, the trajectory of current developments suggests that the integration of digital and nanotechnology-based approaches will increasingly enable more predictable, efficient, and patient-friendly prosthodontic care in the coming years [45].

### **SAFETY, REGULATORY, AND ETHICAL CONSIDERATIONS**

The integration of nanotechnology in prosthodontics, particularly in implants and periodontal surgery, presents significant advancements in functional oral reconstruction. However, this progress is accompanied by critical safety, regulatory, and ethical considerations. These considerations encompass the biocompatibility and potential toxicity of nanomaterials, the regulatory frameworks governing dental nanoproducts, the long-term performance and risk assessment of these technologies, and the ethical issues related to their cost-effectiveness and accessibility. Each of these aspects is crucial for ensuring the safe and effective application of nanotechnology in dentistry.

Nanomaterials, by virtue of their nanoscale dimensions and high surface reactivity, can interact with biological systems in ways that differ fundamentally from their bulk counterparts,

raising important questions about potential toxicity and long-term health impacts. Reported concerns include the induction of oxidative stress, inflammation, and organ-specific damage, which underscore the need for systematic biocompatibility evaluation before these materials are widely adopted in clinical prosthodontics and periodontics [47, 48]. Current safety assessment frameworks rely on a combination of *in vitro*, *in vivo*, *ex vivo*, and clinical testing strategies, guided by toxicological benchmarks such as the No Observed Effect Level (NOEL) and the Lowest Observed Adverse Effect Level (LOAEL), to define exposure limits and acceptable risk profiles [47]. Given that nanoparticles can potentially affect multiple organ systems—including lungs, skin, brain, liver, and kidneys through local or systemic routes, robust risk assessment, careful material selection, and the implementation of preventive measures in both manufacturing and clinical use are essential to ensure that the therapeutic benefits of nanotechnology are realized without compromising patient safety [49].

Regulation of dental nanomaterials is evolving to keep pace with their rapid integration into clinical practice, with major agencies such as the U.S. Food and Drug Administration (FDA) and the European Medical Device Regulation (EU MDR) playing central roles in setting safety and performance requirements [47]. These bodies mandate standardized testing protocols and comprehensive preclinical and clinical evaluation to ensure that nanotechnology-enabled devices meet established biocompatibility and risk thresholds before market approval, supported by dedicated nanotechnology programs and guidance documents for medical devices. For multifunctional systems such as magnetic nanoparticles, progression from laboratory research to clinical application depends on navigating regulatory pathways that emphasize detailed characterization, toxicological assessment, and adherence to specific standards for complex, combination-product like devices [50]. Despite these efforts, the lack of harmonized synthesis protocols and nano-specific regulatory frameworks in dentistry continues to impede clinical translation, highlighting the need to update and refine existing medical device regulations to better address issues unique to nanoparticles, including their size-dependent behavior, long-term fate, and potential for off-target effects.

Continuous monitoring of nanomaterials is

essential to assess their long-term performance and potential risks [51]. The dynamic nature of nanotechnology necessitates ongoing research to understand the interactions of nanoparticles within the oral environment. Risk assessments should consider factors such as nanoparticle aggregation and the formation of a biologically active protein corona [52].

Ethical considerations in the use of nanomaterials include ensuring transparent communication and balancing innovation with societal well-being [53]. The high cost of production and potential toxicity of certain nanoparticles raise concerns about their accessibility and cost-effectiveness, necessitating further research to develop economically viable solutions. Addressing these ethical issues is crucial for promoting responsible and equitable integration of nanotechnology in dentistry, ensuring that advancements benefit a broad range of patients [53].

While nanotechnology offers transformative potential in prosthodontics, it is imperative to address these safety, regulatory, and ethical considerations to ensure its responsible application. The ongoing development of standardized frameworks and rigorous testing methods will be essential in overcoming the challenges associated with nanomaterials, ultimately leading to safer and more effective dental treatments.

## FUTURE DIRECTIONS AND RESEARCH GAPS

Emerging nanotechnologies in prosthodontics are poised to revolutionize the field by integrating stimuli-responsive materials, theranostic capabilities, and artificial intelligence (AI) systems. These advancements promise to enhance the functionality, precision, and personalization of dental treatments.

Stimuli-Responsive Materials can change their properties in response to external stimuli such as temperature, pH, or light, offering dynamic solutions for dental applications. For instance, they can be used in smart dental implants that adapt to the oral environment, improving osseointegration and longevity [2]. Theranostic Systems Combining therapeutic and diagnostic functions, theranostic systems in nanomedicine can provide real-time monitoring and treatment of oral diseases. This dual functionality can lead to more effective management of conditions like periodontal disease, where early detection and

targeted therapy are crucial [54]. AI-Integrated Systems can enhance the design and application of nanomaterials by optimizing their properties for specific dental applications. AI-driven tools can improve diagnostic accuracy, treatment planning, and patient outcomes, making prosthodontic procedures more efficient and personalized [55].

Personalized and precision nanomedicine aims to tailor dental treatments to individual patient needs, enhancing the effectiveness and efficiency of prosthodontic care. By analyzing genetic, environmental, and lifestyle factors, personalized nanomedicine can stratify patients into subgroups, allowing for customized treatment plans that address specific needs and conditions. Precision nanomedicine enables the selection of the most appropriate materials and techniques for each patient, improving outcomes and reducing the risk of complications. This approach is particularly beneficial in prosthodontics, where the fit and function of dental prostheses are critical [56]. Nanotechnology can enhance tissue regeneration, offering new possibilities for reconstructive procedures in prosthodontics. Nanomaterials can be engineered to promote cell growth and differentiation, facilitating the repair and regeneration of oral tissues [51].

To fully realize the potential of nanotechnology in prosthodontics, extensive clinical trials and translational research are necessary to address safety, efficacy, and regulatory challenges.

Clinical trials must focus on assessing the long-term safety and biocompatibility of nanomaterials used in dental applications. This includes evaluating potential cytotoxicity and immune responses [56]. Establishing standardized regulatory guidelines is crucial for the widespread adoption of nanotechnology in dentistry. These guidelines should address the unique challenges posed by nanomaterials, such as their scale and novel properties [56]. Research should also prioritize the development of cost-effective nanotechnologies to ensure accessibility and affordability, particularly in resource-limited settings [57].

While the integration of nanotechnology in prosthodontics offers promising advancements, it is essential to consider the broader implications and challenges associated with these technologies. Ethical considerations, such as data privacy and the potential for over-reliance on AI systems, must be addressed to ensure responsible deployment. Additionally, the high initial costs and technical

Table 1. Overview of nanotechnology applications in prosthodontics and periodontal surgery for functional oral reconstruction.

| Section/topic in review                                  | Key nanotechnology concept                                                                              | Main clinical benefits                                                                                                                     | Main limitations/challenges                                                                                   | Example applications                                                                                      |
|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| Fundamentals of nanotechnology in oral tissues [1]       | Nanoscale structure of enamel, dentin, bone; nanoparticle–tissue interactions; protein corona formation | Better understanding of how <b>nanomaterials</b> integrate with oral tissues, supports rational design of implant and restorative surfaces | Potential cytotoxicity, oxidative stress, and inflammatory responses; limited long-term data                  | Surface-modified enamel/dentin bonding, nano-enhanced bone grafts, nano-engineered soft-tissue scaffolds  |
| Nanotechnology-enhanced dental implants                  | Nano-roughened and nanotubular titanium surfaces; physical and chemical nano-surface modifications      | Accelerated osseointegration, improved early stability, higher quality bone–implant contact                                                | Manufacturing complexity, higher cost, uncertain long-term clinical superiority over conventional implants    | Titania nanotube implants, anodized titanium, nano-textured implant collars                               |
| Smart and drug-eluting nano-implant systems              | Titanium dioxide nanotubes, nanoporous coatings, local nanocarrier-based delivery                       | Local, sustained release of antimicrobials and growth factors, better peri-implantitis control, enhanced early bone formation              | Risk of local/systemic toxicity, regulatory barriers, need for precise drug-release control                   | TNT-based antimicrobial implants, growth factor-eluting implant coatings                                  |
| Nanomaterials in prosthodontic components                | Nanocomposites, nano-reinforced ceramics, polymers, and metal alloys                                    | Higher strength and wear resistance, reduced polymerization shrinkage, highly lifelike optical properties                                  | Higher production costs, technical sensitivity, concerns about nanoparticle release and long-term safety      | Esthetic crowns/bridges with nanocomposites, nano-reinforced frameworks, wear-resistant occlusal surfaces |
| Nanotechnology in periodontal surgery                    | Nano-engineered bone grafts, nanofibrous GTR/GBR membranes, nano-modified soft-tissue scaffolds         | Enhanced bone and soft-tissue regeneration, better ridge preservation, improved soft-tissue seal around implants                           | Optimization of scaffold design still needed, long-term biocompatibility not fully established                | Nanohydroxyapatite grafts, nanofibrous GTR membranes, nano-modified gingival scaffolds                    |
| Nano-based antimicrobial and regenerative adjuncts       | Silver, ZnO, chitosan nanoparticles; nano-encapsulated antibiotics; nano-carriers for growth factors    | Strong biofilm penetration, sustained antimicrobial action, promotion of periodontal and bone regeneration                                 | Possible toxic accumulation, gap between in vitro and in vivo results, limited large long-term trials         | Local nanoparticle gels in pockets, nano-antibiotic chips, nano-growth factor delivery systems            |
| Integrated nano-driven strategies with digital workflows | Combination of nanomaterials with CBCT, intraoral scanning, CAD/CAM and 3D printing                     | More predictable full-arch and complex reconstructions, improved fit and esthetics, shorter treatment times                                | High financial and training requirements, unequal access, need for more long-term evidence                    | Guided surgery with nano-enhanced implants, CAD/CAM nano-ceramic full-arch prostheses                     |
| Safety, regulatory, and ethical aspects                  | Biocompatibility testing, NOEL/LOAEL concepts, evolving FDA/EU MDR frameworks, ethical issues           | Structured evaluation of risk, support for safer clinical translation, emphasis on cost-effectiveness and equity                           | Lack of harmonized nano-specific standards, incomplete data on long-term fate of nanoparticles                | Safety protocols for nano-restoratives, regulatory pathways for nano-implants and drug-eluting systems    |
| Future directions and research gaps                      | Stimuli-responsive materials, theranostic systems, AI-guided nanomedicine, personalized nano-therapies  | More personalized, adaptive, and efficient treatments, improved monitoring of disease and response                                         | Need for robust clinical trials, clear regulatory guidance, cost reduction and accessibility in real practice | Smart pH/temperature-responsive coatings, nano-theranostic implants, AI-assisted nano-treatment planning  |

complexity of these technologies may pose barriers to their widespread adoption. Balancing innovation with practical considerations will be key to successfully integrating nanotechnology into prosthodontic practice [55, 56]. The key functional oral reconstruction and nanotechnology applications in prosthodontics and periodontal surgery are summarized in Table 1.

## CONCLUSION

In the era of nanomedicine, prosthodontics is undergoing a significant transformation, with advanced nanotechnology enhancing implants and periodontal surgery for functional oral reconstruction. The integration of nanotechnology

into prosthodontics has led to improvements in material properties, aesthetics, and treatment outcomes, marking a new chapter in dental restoration and rehabilitation. This conclusion synthesizes the key findings from recent research, highlighting the transformative potential of nanotechnology in prosthodontics and its implications for future advancements.

Nanotechnology has enabled the development of nanocomposites that significantly improve the properties of dental materials, such as modulus of elasticity, surface hardness, and polymerization shrinkage. These enhancements contribute to more durable and effective prosthodontic solutions.

The incorporation of nanomaterials into

dental ceramics, resins, and metals has resulted in materials that mimic the natural appearance of teeth with high precision, enhancing the aesthetic outcomes of dental restorations.

Nanotechnology has revolutionized implantology by introducing nanoscale modifications that improve osseointegration and reduce the risk of implant failure. These advancements lead to more reliable and long-lasting dental implants. In periodontal surgery, nanotechnology facilitates regenerative procedures and enhances the effectiveness of non-surgical therapies. The use of nanoparticles in periodontal treatments has shown promising results in improving treatment outcomes and patient comfort.

The future of prosthodontics in the era of nanomedicine holds the promise of further innovations, such as the development of dental nanorobots for precise diagnostics and treatment. These advancements could lead to more personalized and efficient dental care. Despite the potential benefits, challenges remain in the widespread adoption of nanotechnology in prosthodontics, including the need for further research to fully understand the long-term effects and safety of nanomaterials in dental applications.

While the integration of nanotechnology in prosthodontics offers numerous benefits, it is essential to consider the broader implications of these advancements. The rapid development of nanotechnology in dentistry raises questions about the ethical and regulatory aspects of its application, as well as the need for standardized protocols to ensure patient safety and treatment efficacy. As the field continues to evolve, ongoing research and collaboration among dental professionals, researchers, and regulatory bodies will be crucial in addressing these challenges and maximizing the potential of nanotechnology in prosthodontics.

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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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