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Review Article

Nanotechnology in dental implantology

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ABSTRACT

Nanotechnology has expanded dental implant surface engineering from conventional macro- and microscale modification to deliberate control of surface characteristics at the nanometre scale. Nanostructured surfaces can modify surface chemistry, energy, roughness, wettability and topography, thereby influencing protein adsorption, cellular adhesion, differentiation and bone formation. Titanium and its alloys remain the principal materials for endosseous dental implants, while nanoscale modification using titanium dioxide nanotubes, hydroxyapatite, calcium phosphate, metallic nanoparticles, bioactive glass, polymers and hybrid coatings has been investigated to improve biological performance. Systematic evidence supports promising preclinical antibacterial effects of TiO_2 nanotubes, but clinical translation remains limited. Studies also emphasize the potential of nano-engineered surfaces to modulate inflammation, osteogenesis, corrosion resistance and localized drug delivery.

Keywords: Nanotechnology, Dental implants, Osseointegration

INTRODUCTION

Osseointegrated dental implants are widely accepted as treatment of choice for missing teeth. In fully edentulous patients implant-supported prostheses are increasingly preferred over traditional complete dentures. Since Per-Ingvar Brånemark introduced the concept of osseointegration, titanium and titanium alloys have remained the principal materials for endosseous dental.[1-5]

Adequate primary stability at implant placement is essential for early clinical success, whereas long-term stability depends on the implant forming a stable Osseointegrated bond with the surrounding bone. The quality of this interface is influenced by implant geometry, loading conditions, surface characteristics and the biological and mechanical properties of the implant material.[6] Osseointegration is a dynamic process involving blood clot formation, protein adsorption, inflammatory cell recruitment, angiogenesis, osteoblast activity and subsequent bone remodelling.[7]

Implant failure may result from inadequate osseointegration, mechanical complications or microbial infection. Peri-implant infection is particularly important because bacterial adhesion and biofilm development can initiate inflammation and progressive supporting bone loss.[8] Biological interactions at the implant-tissue interface occur at the nanoscale. Adsorbed proteins, extracellular matrix components and cellular adhesion structures interact with the implant within nanometre dimensions.[9]

IMPORTANCE OF NANOTECHNOLOGY IN IMPLANTOLOGY

Surface chemistry, composition, energy, roughness, wettability and topography all influence the biological response to an implant. Implant surface architecture can broadly be considered at macro-, micro- and nanoscale levels.

Nanoscale features may influence protein adsorption, cell attachment, cytoskeletal organization, proliferation and osteogenic differentiation.[10]

The initial biological response begins immediately following implant placement. Plasma proteins adsorb to the surface and undergo conformational changes, producing a conditioning layer that influences subsequent platelet, inflammatory and cellular events. Therefore, the biological response to a nanostructured implant is determined not only by the physical nano topography itself but also by the protein layer established on that surface.[11]

Nanoscale modification can increase surface area and alter surface energy and wettability, thereby influencing protein adsorption and cellular attachment. Nanoscale symmetry, disorder and physical cues can also regulate stem-cell behaviour and differentiation.[12] Recent research has further demonstrated that TiO_2 nanotube arrays can influence several stages of osseointegration, from protein adsorption and macrophage responses to angiogenesis and osteogenesis.[13] The contemporary concept has therefore moved beyond simply increasing surface roughness. The objective is to engineer a biologically instructive interface.[14]

MATERIALS USED TO ALTER IMPLANT SURFACE TOPOGRAPHY VIA NANOSCALE MECHANISMS

Metal-based nanostructured implant surfaces

Titanium and alloys

Novel dental implants have been developed incorporating nanostructured titanium which provide increased surface area favourable for protein adsorption and cellular interaction. Titanium dioxide nanotubes (TNTs), produced by anodization are important because their diameter, length and morphology can be controlled. Their tubular architecture can additionally function as a reservoir for antibiotics, ions, proteins or other therapeutic molecules.[6,15]

The biological response to TNTs is influenced by nanotube dimensions. Smaller nanotubes have demonstrated favourable cellular and antibacterial responses in some experimental models, whereas larger nanotubes may provide different osteogenic cues.[15,17]

Such findings emphasize that “nanostructured” should not be considered a single surface category; nanoscale dimensions and surface chemistry must be specified.

Titanium alloys such as Ti-6Al-7Nb have also been investigated because of their strength and corrosion resistance.[18] Contemporary nano-engineering approaches additionally aim to improve the corrosion resistance of titanium and reduce the biological consequences of surface degradation.

A 2025 review highlighted the potential of nanoscale coatings and nanoparticles to simultaneously improve corrosion resistance and the biological performance.[4]

Ceramic-based nanostructured implant surfaces

Ceramic materials, particularly zirconia, have been investigated as alternatives to titanium because of their biocompatibility, favourable mechanical properties and excellent optical characteristics. Zirconia, especially 3Y-TZP, exhibits good cellular compatibility, although low-temperature degradation remains important material limitation.[19,20] Nanostructuring or anodization of zirconia has been explored to improve cellular activity and early osseointegration.[21] However, the clinical evidence supporting zirconia nanostructures remains less extensive than that available for titanium.

Hydroxyapatite (HA) is particularly attractive because of its chemical similarity to the mineral phase of bone. Nanostructured HA can increase surface bioactivity and support early bone formation.[22] β-tricalcium phosphate (β-TCP) is biodegradable and osteoconductive but may undergo relatively rapid resorption.[23] Bioactive glass coatings can stimulate apatite formation and osteogenic responses, although mechanical durability and coating stability remain important considerations.[24]

Polymer-based nanostructured implant surfaces

Polymers such as PEEK, PTFE, PMMA, polyurethane and UHMW-PE have been investigated because of their chemical versatility, adaptability and favourable material characteristics.[25] Polymer nanotopography can be produced using techniques such as electron-beam lithography and polymer demixing. These approaches demonstrate that nanoscale organization can influence fibroblast spreading and proliferation.[26]

Polymeric coatings may also function as carriers for antimicrobial or osteogenic agents. However, their clinical application is affected by coating adhesion, sterilization, degradation, mechanical stability and the ability to retain nanoscale architecture over time.

Hybrid implant surfaces

Hybrid surfaces combine metals, ceramics, polymers and biologically active components to provide multiple functions. Silver-, zinc-, HA/collagen- and other composite coatings have been investigated to provide simultaneous antimicrobial and osteogenic effects.[27]

Silver nanoparticles are particularly attractive because of their broad antimicrobial activity. A 2025 systematic review found promising inhibition of bacterial growth and biofilm formation with AgNP-modified implant surfaces, but the available evidence was predominantly in vitro and raised important questions regarding concentration-dependent cytotoxicity and long-term safety.[28]

The advantages and limitations of nanostructured materials used in dental implant surfaces are given in the Table 1.

Table 1: Nanostructured materials used in dental implant surfaces.

Material/category	Examples	Potential advantages	Major limitations
Metal-based	Titanium, Ti-6Al-7Nb	Strength, corrosion resistance, established clinical use	Surface modification may be required for additional functions
Titanium nanotubes	TiO_2 nanotube arrays	High surface area, cellular interaction, drug-loading potential	Response depends on nanotube dimensions; long-term safety
Ceramic-based	Zirconia, 3Y-TZP	Biocompatibility, strength, esthetics	Low-temperature degradation; limited long-term evidence
Nano-hydroxyapatite	Nano-HA	Osteoconductivity and bone-like chemistry	Coating stability and delamination
β-TCP	β-tricalcium phosphate	Biodegradable and osteoconductive	Relatively rapid resorption
Bioactive glass	Silica-based glass	Apatite formation and osteogenic response	Mechanical/coating durability
Polymer-based	PEEK, PTFE, PMMA, PU	Versatility and potential drug delivery	Sterilization, adhesion and degradation
Hybrid materials	Ag/HA, HA/collagen, Ag- or Zn-containing coatings	Combined antimicrobial and osteogenic functions	Manufacturing complexity and potential cytotoxicity

NANOSCALE TECHNIQUES FOR MODIFYING IMPLANT SURFACE TOPOGRAPHY

The architecture and chemistry of implant surfaces can be modified using physical, chemical and electrochemical methods. The major objectives are to enhance peri-implant osteogenesis, improve corrosion and wear resistance, remove contaminants and introduce antimicrobial or drug-delivery functions.[29]

PHYSICAL METHODS

Plasma spraying

Plasma spraying is an earliest method for depositing calcium phosphate and other coatings on titanium. Precursor materials are projected through a high-temperature plasma jet and deposited onto the implant. It permits relatively rapid coating but may produce variations in thickness, composition, porosity and crystallinity.[20]

Sputtering

Sputtering is a physical vapour deposition technique in which energetic ions eject atoms from a target material to form a thin coating. It allows controlled deposition of adherent bioceramic films and can improve bioactivity and corrosion resistance, although the deposition rate is relatively slow.

Ion implantation

Ion implantation introduces high-energy ions into the superficial region of an implant. It allows modification of surface chemistry while maintaining the bulk properties of the implant and can incorporate biologically relevant ions such as calcium, sodium or fluoride. Surface stresses and ion dose require careful control.

Other methods

Laser treatment can produce controlled micro- and nanoscale structures with high spatial precision. UV photofunctionalization uses the photocatalytic activity of TiO_2 to reduce hydrocarbon contamination, increase surface energy and improve biological activity.

CHEMICAL METHODS

Anodic oxidation or anodization

Anodization is one of the most important methods for producing TiO_2 nanotube arrays. Electrochemical oxidation generates organized nanotubular structures whose diameter and morphology can be controlled by voltage, electrolyte composition, current density and treatment time.[15,30]

Acid treatment

Acid treatment removes surface contaminants and modifies titanium roughness and oxide characteristics. Sulfuric, nitric, hydrochloric and hydrofluoric acids have been used. Treatment parameters influence nanoscale roughness, wettability and surface chemistry.

Alkali treatment

Treatment with sodium or potassium hydroxide followed by heat treatment can generate a nanostructured titanate layer capable of promoting calcium phosphate nucleation and apatite formation. This provides a mechanism for enhancing surface bioactivity.

Sol-gel method

Sol-gel deposition is a versatile wet-chemical technique for producing calcium phosphate, TiO_2, silica and composite coatings. It permits control of coating composition but may be affected by shrinkage, cracking and inadequate adhesion.[31]

Combination of chemical vapour deposition and sol-gel method

Combining deposition techniques can generate multifunctional coatings with improved biological and protective properties. Materials such as diamond-like carbon and niobium oxide have been explored to improve corrosion resistance and surface functionality.

MECHANISTIC INSIGHTS INTO NANOSTRUCTURED IMPLANT SURFACE INTERACTIONS WITH HEMATOPOIETIC CELLS

Biological events begin immediately after implant placement. Blood proteins, platelets, leukocytes and complement components interact with the implant surface. Biocompatibility therefore includes protein adsorption, coagulation, inflammatory responses and subsequent tissue repair.[32]

Nanoscale topography can influence cellular alignment, adhesion, spreading and cytoskeletal organization. These effects may result from altered surface chemistry, interfacial forces, protein conformation and cellular adaptation to nanoscale geometry.[33] TiO_2 nanotube arrays have been reported to influence macrophage behaviour and favour a reparative phenotype, suggesting that nanoscale engineering may regulate the transition from inflammation toward tissue regeneration.[30]

Nanoscale symmetry and disorder can also influence mesenchymal stem-cell differentiation, demonstrating that physical cues at the nanoscale can affect lineage commitment.[34] This suggests that successful implant surfaces may eventually be designed not merely to increase bone-to-implant contact, but to provide appropriate biological signals at successive stages of healing.

FUTURE DIRECTIONS

The future of dental implant nanotechnology is shifting from single-function surface modification toward multifunctional and biologically responsive interfaces. Anodized nano-engineered surfaces capable of delivering growth factors, antibiotics, therapeutic nanoparticles and biopolymers locally. Such localized delivery may be valuable because dental implants must simultaneously achieve osseointegration, soft-tissue integration and resistance to the complex oral microbiome.[35]

Antibacterial property strongly depends on nanopattern morphology and surface chemistry, emphasizing that optimized nanotopography may suppress bacterial survival without compromising cellular attachment.[36]

However, the major challenge is no longer simply producing increasingly complex nanostructures. It is establishing reproducible, stable and clinically meaningful biological effects. Differences in fabrication parameters, nanotube dimensions, coating thickness, bacterial strains, cell models and outcome measures make direct comparison between studies difficult.[1,3,37] Long-term animal studies and well-designed clinical trials are therefore required.

CONCLUSION

Nanotechnology has expanded dental implant surface engineering from conventional roughening toward deliberate control of nanoscale biological interactions. Nanotopography, TiO_2 nanotubes, nanostructured hydroxyapatite, metallic nanoparticles, polymeric coatings and hybrid materials can influence protein adsorption, cellular behaviour, osteogenesis, inflammation and bacterial colonization. Integration of nanotopography with Oste immunomodulation, antimicrobial strategies, soft-tissue integration, controlled drug delivery and additive manufacturing may produce more predictable implant–tissue interfaces. The transition from promising laboratory technology to routine clinical application will require standardized surface characterization, long-term safety assessment and adequately powered clinical trials.

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