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Surface Treatments of Dental Implants - A Review

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Abstract

Dental implant surface modifications have evolved significantly to enhance osseointegration and long-term clinical success. This review provides a comprehensive overview of implant surface treatments, spanning subtractive, additive and advanced nanotechnology-based approaches. Subtractive methods, including grit blasting, acid etching and SLA (sandblasted, large-grit, acid-etched) techniques, enhance surface roughness and bone-to-implant contact (BIC), with SLA considered the clinical gold standard. Additive techniques, such as plasma spraying and bioactive coatings, aim to increase osteoconductivity, though issues like coating stability and delamination remain. Advanced strategies leverage nanotechnology, smart drug-delivery coatings and patient-specific 3D-printed implants to mimic bone extracellular matrix and actively modulate biological responses. These innovations offer potential in preventing peri-implantitis and improving integration, though long-term clinical data are limited. This review underscores the biological basis of surface interactions and highlights future directions in multifunctional, smart and personalized implant technologies.

Keywords: Dental implants, Surface modification, Osseointegration, SLA surface, Additive coatings, Nanotechnology, Antibacterial surfaces, Bone-to-implant contact

Introduction

Dental implantology is one of the most significant advances in restorative dentistry over the past five decades. Since Brånemark's pioneering work, titanium implants have evolved into a predictable treatment option with long-term survival rates exceeding 90–95% at 10–15 years. Compared with conventional prostheses, implants offer superior function, esthetics, alveolar bone preservation and patient quality of life.[1] Implant success is based on osseointegration, defined as a direct structural and functional connection between living bone and the implant surface.[2] As implants lack a periodontal ligament, stability depends on bone-to-implant contact,

making surface modification crucial for enhanced integration, long-term success and prevention of peri-implant complications.

Historical Background of Implant Surfaces

Early titanium implants of the 1960s–1970s had smooth, machined surfaces (Ra <1 µm) with limited bone-to-implant contact and prolonged healing requirements. Subsequent research showed that moderately rough surfaces improved mechanical interlocking and accelerated osseointegration, leading to subtractive techniques such as grit blasting and acid etching and the development of SLA surfaces as the clinical standard. Additive coatings, including plasma-sprayed titanium and hydroxyapatite, and recent nanotechnology-based, antibacterial, and additive manufacturing approaches aim to enhance bioactivity and long-term implant performance.

Biological Basis of Surface Modification

The biological response after implant placement is strongly influenced by surface roughness, chemistry, surface energy and wettability. Immediately, plasma proteins adsorb onto the implant surface, regulating cell adhesion and signalling through their composition and conformation. Roughened surfaces enhance fibrin clot stabilization, promoting early wound healing and cell migration. Moderately rough surfaces (Ra 1–2 µm) favour osteoblast and mesenchymal stem cell adhesion, stimulate osteogenic differentiation, increase alkaline phosphatase activity and upregulate bone-related genes, thereby enhancing osseointegration.[2,5]

Bone-to-Implant Contact (BIC)

Surface modification directly affects the extent of bone contact:

- Machined surfaces: ~15–20% BIC
- Acid-etched surfaces: 40–50% BIC
- SLA surfaces: 60–70% BIC
- Laser-modified and nanostructured surfaces: >75% BIC in animal models.[4,6]

Thus, implant surface modification is not merely a mechanical or cosmetic alteration but a biologically driven strategy essential for predictable osseointegration and long-term implant success.

Classification of Implant Surface Treatments

Implant surface modification techniques can be broadly classified into three categories:

Category	Description	Examples
Subtractive methods	Techniques that remove material from the titanium surface to increase surface roughness and topographical complexity.	Machining, grit blasting, acid etching, dual acid etching, SLA (sandblasting + acid etching), laser modification.[1,12]
Additive methods	Approaches that add coatings or layers onto the implant surface to increase bioactivity.	Titanium plasma spray (TPS), hydroxyapatite coatings, calcium phosphate coatings, biomimetic deposition, drug-eluting coatings.[5]
Advanced and nanotechnology-based methods	Newer strategies aimed at functionalization at the molecular or nanoscale level.	Anodization to create nanotubular TiO_2 surfaces, nanocrystalline coatings, antibacterial nanoparticle incorporation, bioactive molecule immobilization (e.g., BMPs, peptides), smart responsive coatings, patient-specific 3D-printed implants.[4,6,8]

Rationale and Aims of the Review

Although numerous reviews have addressed individual surface modification techniques, there remains a need for a comprehensive synthesis integrating materials science, biology and clinical outcomes. Rapid industry adoption of newer surface technologies has often outpaced the availability of long-term clinical evidence, leaving clinicians uncertain in implant system selection.[1]

This review aims to

1. Provide a detailed overview of subtractive, additive and advanced implant surface treatments.
2. Explain biological mechanisms underlying osseointegration.
3. Evaluate clinical outcomes, survival rates and limitations.
4. Explore future directions in multifunctional and patient-specific implant surfaces.[5]

Subtractive Surface Treatments

Subtractive surface treatments form the foundation of modern implantology. By removing surface material, these methods increase surface area, enhance protein adsorption and improve mechanical interlocking with bone.

Machined (Turned) Surfaces

Machined surfaces were the first implant surfaces used clinically. Produced by lathe machining, these surfaces are relatively smooth (Ra <1 µm) with minimal topographical complexity.

Histological studies demonstrate limited BIC (~15–20%), slower bone apposition and weaker osteoblast adhesion. [6] Clinically, machined implants show acceptable outcomes in dense cortical bone but higher failure rates in trabecular bone, particularly in the posterior maxilla.

Despite these limitations, smooth collars remain useful in modern implant designs to minimize plaque accumulation and maintain peri-implant tissue health.

Grit Blasting (Sandblasting)

Grit blasting involves projection of abrasive particles such as alumina or titanium oxide onto the implant surface, creating irregular macro- and micro-roughness (Ra 1–2 µm). This roughness enhances mechanical interlocking and improves osteoblast adhesion and implant stability. [1] However, concerns regarding residual particle contamination have limited its use as a standalone technique, leading to its combination with acid etching in SLA surfaces.

Acid Etching

Acid etching chemically corrodes the titanium surface using strong acids, creating uniform micropits (0.5–2 µm). Dual acid etching produces submicron features that further enhance biological performance. [5] Acid-etched implants demonstrate improved clot stabilization, faster bone apposition and higher success rates in soft bone compared with machined implants. [1]

SLA (Sandblasted, Large-Grit, Acid-Etched) Surfaces

SLA surfaces combine macroroughness from grit blasting with micropits from acid etching, producing a hierarchical surface topography. These surfaces exhibit BIC values of 60–70%, superior primary stability and predictable early loading protocols. [5,6] SLA remains the most extensively studied and clinically validated implant surface and is considered the current gold standard.

Laser Surface Modification

Laser modification uses high-energy laser beams to create controlled micro- and nano-patterns without physical contact. These surfaces demonstrate high precision, enhanced wettability and reduced contamination risk. Preclinical studies show improved osteoblast response and reduced bacterial adhesion, though long-term clinical data remain limited. [4]

Comparative Evaluation of Subtractive Methods

Technique	Roughness	BIC (%)	Advantages	Limitations
Machined	<1 µm	15–20	Smooth collar	Weak osseointegration
Grit blasted	1–2 µm	30–40	Improved anchorage	Particle contamination
Acid etched	0.5–2 µm	40–50	Faster healing	Residual acid risk
SLA	1.5–2.5 µm	60–70	Gold standard	Cost, complexity
Laser	Variable	>70	Precise, antibacterial	Limited evidence

Additive Surface Treatments

Additive surface treatments differ from subtractive methods by enhancing osseointegration through deposition of bioactive materials onto the implant surface rather than material removal. Their primary objective is to increase the biological activity of titanium by introducing osteoconductive or osteoinductive components. These approaches have evolved from conventional plasma-sprayed coatings to advanced biomimetic and drug-eluting strategies.

Plasma spraying

Plasma spraying was one of the earliest additive techniques, involving the deposition of molten titanium or hydroxyapatite (HA) particles using a high-temperature plasma jet. This process produces a thick (30–50 µm), highly porous coating with increased surface area and roughness. Titanium plasma spray enhances mechanical interlocking, while HA plasma spray promotes direct bone bonding due to its chemical similarity to bone mineral. Although plasma-sprayed surfaces demonstrate rapid early osseointegration and increased bone-to-implant contact, long-term clinical outcomes are inconsistent, with reported risks of coating delamination and inflammatory reactions. Consequently, their use has declined.[4,1]

Hydroxyapatite coatings

Hydroxyapatite coatings are widely studied due to their strong osteoconductivity. HA coatings release calcium and phosphate ions, stimulating osteoblastic activity and accelerating mineralization. Histological studies report high bone-to-implant contact, and early clinical trials showed reduced healing times. However, thick HA coatings may suffer from mechanical instability and dissolution, especially when crystallinity is low. Current research favours thin HA layers applied through sol–gel or biomimetic methods to improve coating stability while retaining bioactivity.[4,5]

Calcium phosphate coatings

Calcium phosphate coatings, including β-tricalcium phosphate and brushite, offer higher solubility than HA and act as temporary scaffolds for bone formation. These coatings support rapid mineralization and are gradually replaced by native bone. While animal studies demonstrate enhanced early bone apposition, limited long-term clinical data and concerns regarding rapid resorption restrict their widespread use.

Biomimetic coatings

Biomimetic coatings aim to replicate the bone extracellular matrix by incorporating collagen, peptides, growth factors, or ECM proteins. These coatings enhance osteoblast adhesion, proliferation and differentiation, providing both osteoconductive and osteoinductive effects. Despite their biological promise, high costs, limited biomolecule stability and regulatory challenges currently restrict clinical application.

Drug-eluting and antibacterial coatings

Drug-eluting and antibacterial coatings address peri-implant infections by combining antimicrobial agents or

anti-inflammatory drugs with osteogenic surfaces. These coatings reduce bacterial adhesion and biofilm formation while maintaining cell viability when drug release is controlled. Although preclinical results are encouraging, clinical evidence remains limited, and issues such as cytotoxicity, manufacturing complexity and regulatory approval continue to pose challenges.

Comparative Evaluation of Additive Methods

Coating Type	Thickness	Bioactivity	Stability	Clinical Use
Plasma-sprayed Ti	30–50 µm	Moderate	Good	Established, less used today
Plasma-sprayed HA	30–50 µm	High	Moderate	Early osseointegration, risk of delamination
Thin HA (sol–gel)	1–10 µm	High	Good	Promising, more stable
CaP coatings	1–10 µm	High	Low–moderate	Experimental
Biomimetic coatings	Variable	Very high	Variable	Experimental, costly
Drug-eluting coatings	Variable	Multifunctional	Variable	Preclinical stage

Advanced and Nanotechnology-Based Approaches

Over the past two decades, dental implantology has shifted from micro-scale surface modification to biologically active nanoscale engineering. While subtractive and additive techniques improved osseointegration over machined surfaces, recognition of bone as a hierarchical nano-to-macro tissue has driven the development of implant surfaces that mimic extracellular matrix cues and actively modulate the peri-implant biological environment using nanotechnology, antibacterial functionalization, smart coatings and additive manufacturing.

Anodization and titanium oxide nanotubes represent a key nanotechnological advancement. Anodization is an electrochemical process that produces an ordered TiO_2 layer with nanopores or nanotubes (20–200 nm in diameter), increasing surface area and wettability. These nanotubes closely resemble collagen fibril dimensions, enhancing osteoblast adhesion and promoting mesenchymal stem cell differentiation toward osteogenic lineages. Additionally, nanotubes selectively adsorb proteins in conformations favourable for cell attachment. A major advantage is their ability to function as drug reservoirs, delivering antibiotics, growth factors or anti-inflammatory agents locally. However, concerns remain regarding mechanical stability and controlled drug release kinetics.[4,8]

Nanostructured surfaces aim to reproduce bone-like topography at the nanoscale using chemical etching, sol–gel techniques, physical deposition or nanoparticle incorporation. Nanocrystalline calcium phosphate coatings, nanopatterned titanium surfaces and polymer-based nanocomposites enhance osteogenic gene expression, mineralized matrix deposition and bone-to-implant contact compared with micro-rough surfaces alone. Certain nanostructures also exhibit intrinsic antibacterial properties, such as nanopillars that disrupt bacterial membranes or metallic nanoparticles providing sustained antimicrobial effects. While clinical evidence is limited, preclinical studies report BIC values exceeding those of conventional SLA surfaces.[4,5]

Antibacterial functionalization targets peri-implantitis by combining osteogenic and antimicrobial properties. Strategies include metallic nanoparticles (silver, zinc, copper), organic coatings such as chitosan and antimicrobial peptides and antifouling hydrophilic polymers that reduce bacterial adhesion. The primary

challenge lies in maintaining cytocompatibility while preventing bacterial resistance.

Smart and responsive surfaces represent the next generation of implant design. These coatings release therapeutic agents in response to local stimuli such as pH changes, enzymes or mechanical loading, enabling on-demand infection control and enhanced bone healing.

3D-printed, patient-specific implants fabricated using additive manufacturing allow customized geometry and controlled porosity that mimics trabecular bone. These implants demonstrate enhanced vascularization, mechanical interlocking and high bone-to-implant contact, although cost, standardization and long-term clinical validation remain limiting factors.[6]

Overall, advanced and nanotechnology-based approaches hold significant promise for creating multifunctional, biologically interactive implant surfaces.

Technique	Key Feature	Biological Benefit	Limitations
Anodization (TiO_2 nanotubes)	Nanotubular structures	Osteoblast adhesion, drug delivery	Release kinetics, stability
Nanostructured coatings	Nanoscale roughness	ECM mimicry, enhanced osteogenesis	Mostly preclinical
Antibacterial coatings	Metallic/organic agents	Prevent peri-implantitis	Cytotoxicity, resistance
Smart surfaces	Responsive release	On-demand drug/growth factor release	Experimental
3D-printed implants	Custom porosity	Patient-specific, vascularization	High cost, limited long-term data

Limitations and Future Perspectives

Despite advancements, peri-implantitis risk, lack of long-term data for advanced coatings, manufacturing variability, patient-related factors and cost remain challenges.

Future implants will integrate multifunctional, smart, nanostructured and patient-specific designs, combining regenerative and antibacterial strategies.

Conclusion

Implant surface technology has evolved from simple machined designs to biologically interactive systems. While SLA surfaces remain the clinical gold standard, emerging nanotechnology and smart coatings promise enhanced integration and reduced complications. Continued interdisciplinary research and long-term clinical validation are essential for future progress.

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