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Redefining Implant Surfaces for Enhanced Osseointegration –A Review

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ABSTRACT: Dental implant success depends on effective osseointegration, which is strongly influenced by implant surface properties. Implant surface technology has evolved from smooth machined surfaces to micro- and nano-structured designs that enhance bone integration and reduce healing time. This review outlines the biological basis of osseointegration and major surface modification strategies used in implant dentistry, including physical, chemical, and biological modifications. Recent advances such as nanotechnology, bioactive coatings, and antimicrobial surfaces are also discussed. These modifications improve osteoconductivity, reduce bacterial colonization, and promote long-term implant stability

KEYWORDS: Dental implants, Osseointegration, Implant surface modification, Nanostructured surfaces, Bioactive coatings, Titanium implants.

I. INTRODUCTION

This narrative review was developed to summarize established and emerging implant surface modification strategies, with emphasis on their effects on surface topography, wettability, chemistry, cellular responses, osseointegration, bacterial adhesion, and peri-implant tissue health. Foundational literature was considered alongside recent reviews and experimental/clinical studies addressing contemporary surface technologies. Particular attention was given to nanostructured, bioactive, antibacterial, , immunomodulatory, and multifunctional surfaces.Dental implants have become one of the most reliable and commonly used treatmentoptions in modern dentistry. A key factor responsible for the long-term successof implant therapy is osseointegration, which was first described by Branemarket al. (1969) as a direct structural and functional connection between living bone and the surface of a load-bearing implant.this concept significantly transformed the field of implant dentistry(1). Successful osseointegration is influenced by several factors such as bone quality, implant material, surgical technique, and the surface characteristics of the implant. Among these factors, implant surface characteristics play a major role in influencing biological responses and ultimately affect the clinical success of the implant.

Implant surfaces have evolved from machined smooth designs to micro-roughened and nanostructured topographies to improve early bone contact. Roughened surfaces have demonstrated higher success rates, particularly in areas of poor bone density, due to improved mechanical interlocking and enhanced cellular activity.

Surface modifications also influence protein adsorption, cell adhesion, and osteoblast differentiation during the early stages of healing. However, increased surface roughness may also create favorable conditions for bacterial adhesion and biofilm formation(2). Therefore, modernimplant surface modifications aim to enhance osteoconductivity, reduce microbial colonization, and improve long-term implant stability and clinical success.

Historical Evolution of Implant Surface Technology

A major advancement occurred in the 1950s when Swedish orthopedic surgeon Per-Ingvar Brånemark accidentally observed that titanium had the ability to bond directly with bone during experiments conducted on rabbits. His commercially pure titanium screw-type implant showed the first consistently reliable clinical outcomes(3). Subsequently, surface treatments such as sandblasting, acid-etching, plasma spraying, and anodization were introduced to increase surface roughness and surface energy, thereby enhancing osseointegration.

Later, during the 1990s, the introduction of micro-roughened implant surfaces such as SLA (Sand-blasted, Large-grit, Acid-etched) and anodized implants demonstrated better bone-to-implant contact and faster healing compared to earlier implant surfaces(4).More recently,

advancements in nanotechnology and biological coatings have led to the development of biofunctional implant surfaces that better mimic the natural bone microenvironment.

Biological Mechanisms of Osseointegration

Osseointegration is the process by which the bone firmly attaches to the surface of the implant, providing stability and support. Following implant placement, bleeding at the surgical site leads to fibrin clot formation, while platelets release growth factors that attract immune cells and mesenchymal stem cells (MSCs). During healing, macrophages and neutrophils remove debris and support angiogenesis, whereas MSCs differentiate into osteoblasts responsible for bone matrix deposition. Bone formation occurs via two pathways—Bone formation around dental implants occurs through two mechanisms: contact osteogenesis, which takes place directly on the implant surface, and distance osteogenesis, which originates from the surrounding bone(5).The immature woven bone is later remodeled into organized lamellar bone, providing long-term mechanical stability in accordance with Wolff's Law(6). Key cellular components involved in this process include osteoblasts, osteoclasts, MSCs, and macrophages, which collectively regulate bone formation, remodeling, and healing(7).

Surface Topography and Wettability

Surface topography plays an important role in mechanical anchorage and cellular response during osseointegration. It is classified into macro (>100 µm), micro (1–100 µm), and nano (<1 µm) levels. Macro features influence implant geometry and stress distribution, while micro-roughness produced by sandblasting or acid-etching enhances bone-to-implant contact and osteoblast attachment. Nano-topography, created by techniques such as anodization and laser modification, influences protein adsorption, cell signaling, and osteogenic differentiation.

In implant surface modifications, surface wettability describes the functional capacity of the implant surface to attract and interact with biological fluids, and it is commonly evaluated by measuring the contact angle. Hydrophilic surfaces improve protein adsorption and cell spreading, thereby accelerating osseointegration. Techniques such as UV photofunctionalization increase surface hydrophilicity and enhance early bone healing.Surface topography and wettability are closely related factors that significantly influence implant bioactivity and clinical performance.(8)

Classification of Implant Surface Modifications

Surface modification methods can be broadly divided into three categories: physical, chemical, and biological.

1.**Physical modifications**: These involve mechanical and topographical changes, such as machining, grit blasting, and laser ablation. They enhance surface area and provide micro-retentive features for bone interlocking.

2.**Chemical modifications:**Techniques like acid-etching, anodization, fluoride treatment, and plasma oxidation alter surface chemistry to improve wettability and bioactivity.

3. **Biological modifications:**These include coating surfaces with bioactive molecules like bone morphogenetic proteins (BMPs), peptides, or calcium phosphate to mimic bone matrix.

1.Physical modifications

Machining

Machined implant surfaces appear smooth macroscopically but contain microscopic grooves and ridges produced during manufacturing. These surface irregularities support osteogenic cell attachment and bone matrix deposition.

Grit-Blasting

Grit-blasting roughens the implant surface by projecting titanium dioxide particles at high velocity. Compared with machined implants, grit-blasted surfaces demonstrate improved osseointegration and higher survival rates, particularly in low-density bone(9).

Sandblasting and Acid-Etching

Sandblasted-acid etched (SLA) implant surfaces are produced by sandblasting the surface with large grit particles (250–500 µm) and subsequently etching the surface with an acid (HNO_3/HF) to create micro-irregularities. This increases surface area, improves bioadhesion, and enhances bone-to-implant contact.

Nano-Level Modifications

Nano-level modifications involve altering the implant surface using materials ranging in size from 1 to 100 nm. These nanoscale surface modifications are designed to enhance biological interactions at the bone–implant interface. Common nano-level modifications include laser ablation and nanocomposite coatings, enhance protein adsorption, osteoblast adhesion, and osseointegration while reducing bacterial adhesion.

Laser Ablation

Laser ablation is a nano-level surface modification technique in which nanoscale

channels are created around the implant collar region. Compared to machined surface implants, laser-ablated implants have demonstrated higher bone-to-implant contact and greater torque removal values, indicating improved implant stability. Furthermore, unlike the usual parallel orientation of connective tissue fibres around implant surfaces, fibres surrounding laser-ablated surfaces tend to orient perpendicular to the implant surface. These nanoscale channels are believed to act as a biological seal by enhancing connective tissue and bone attachment while preventing epithelial downgrowth(5).

Nanocomposite

Additionally, dental implants have been coated with nanocomposite materials to modify their mechanical characteristics to more closely resemble natural bone. Nanocomposite coatings incorporating materials such as titanium dioxide, silver, hydroxyapatite, and carbon nanotubes improve biocompatibility and osseointegration. Silver nanoparticles additionally provide antibacterial activity against staphylococcus aureus, assisting in preventing peri-implantitis.

2. Chemical Modifications

By increasing surface hydrophilicity and bioactivity, chemical alterations are carried out to enhance osseointegration and decrease the formation of biofilms.

Hydrophilic Implants

Conventional titanium implants tend to become hydrophobic due to the adsorption of hydrocarbons from the environment. Chemical treatments such as hydroxylation and saline storage increase surface energy and hydrophilicity, thereby improving protein adsorption and cellular attachment(10).

Discrete Crystalline Deposition

Discrete crystalline deposition (DCD) is a sol-gel technique in which calcium phosphate nanoparticles are deposited on double acid-etched titanium surfaces. These coatings enhance osteoconduction and improve bone-to-implant contact by modifying surface nanotopography.

Anodic Oxidation/Anodization

The technique of anodic oxidation produces a thicker coating of TiO2 by electrochemically altering the titanium implant surface. Additionally, the thicker TiO2 layer caused by anodic oxidation has a variety of porosities that promote osteoblast adhesion and gingival fibroblast deposition, adhesion, and proliferation. The altered surface is osteoconductive as a result. Anodised implants had a 100% survival rate with no indication of infection or pathologic process, while converted titanium plants had a 96.4% survival rate, according to a clinical study.

Fluoride Treatment

Fluoride modification promotes osteoblast proliferation, differentiation, and bone mineralization, thereby enhancing bone formation around implants. Low concentrations of fluoride are sufficient to improve bone binding without causing cytotoxic effects.

Hydroxyapatite (HA)

One of the most commonly used methods for achieving this surface modification is plasma spraying, where a plasma flame containing hydroxyapatite (HA) particles is heated to nearly 15,000 K and sprayed onto the titanium implant surface. Electrochemical deposition of fluoridated hydroxyapatite has also been reported to exhibit antibacterial activity, particularly against Staphylococcus aureus and Porphyromonas gingivalis.(11). However, Albertini et al., in a clinical study, reported complications related to poor adhesion of the HA coating and peri-implant tissue problems associated with these implants.

UV Treatment/Photofunctionalization

By changing the hydrophilicity of titanium surfaces and promoting protein adsorption, osteoblast adhesion, and early osseointegration, UV treatment (also known as photofunctionalization) increases the osteoconductivity of the titanium implant surface(12). Del Curto et al. demonstrated that titanium treated with anodised heat and then exposed to UV radiation showed a decrease in S. mutans, S. salivarius, and S. sanguis adhesion while increasing cellular metabolic activity, including bone cell proliferation and differentiation.

Titanium plasma-spraying

This method includes providing titanium powders into a high-temperature plasma torch. These titanium particles melt and merge onto the implant surface as a result of the torch's intense heating. As an outcome, a titanium plasma-sprayed (TPS) coating with an average roughness of around 7μm is produced. By efficiently increasing the implant's surface area, the coating procedure improves their potential for osseointegration.

Bioactive ceramic coating of dental implant

Modifications of dental implants. The majority of bio-ceramic coatings that are sold commercially, including Plasma Sprayed Hydroxyapatite (PSHA), are usually between 20 and 50 µm thick. To maintain stability and physical integrity during implant insertion and functional loading, plasma-sprayed hydroxyapatite (PSHA) coatings depend on mechanical interlocking between the ceramic-like biomaterial and the grit-blasted or etched titanium surface. Studies have shown that PSHA-coated implants demonstrate enhanced bone-to-implant contact and improved early bone bonding(13).

Ion beam assisted deposition (IBAD)

IBAD produces thin bioactive coatings with improved adhesion and controlled thickness, enhancing early osseointegration while reducing complications associated with thicker coatings.However, the metallic substrate may become visible shortly after surgery due to the quick disintegration of thin layers. However, after the coating dissolves, this exposure may result in close bone contact with the implant substrate at the optical microscopy level, which may promote favourable conditions for the implant device's long-term anchorage and prevent issues with bone, bioceramic, surface oxides, and metallic substrate interfaces.

Calcium chloride treatment

The surface of titanium treated with CaCl2 (Ca-HT) exhibits superior soft tissue sealing and osseointegration. This therapy increases osteopontin and laminin-332 adsorption, which encourages osteoblast adhesion. Furthermore, fibroblasts and gingival epithelial-like cells have been found to adhere more readily to titanium surfaces. Crucially, the Ca-HT treatment had no effect on bacterial adherence, especially S. gordonii, indicating that it improves cell adhesion without raising bacterial attachment(14).

Atmospheric Pressure Plasma Processing

Without changing the surface topography of titanium, atmospheric pressure plasma processing enhances surface hydrophilicity and encourages cell attachment. Similarly, applying non-thermal atmospheric pressure plasma jet (NTAPPJ) to titanium surfaces increases osteogenic activity, improves osseointegration, and decreases bacterial adhesion and biofilm formation, especially against Gram-negative bacteria, which may be more susceptible to oxidation from NTAPPJ(15).

Plasma Oxidation

Plasma oxidation enhances the wettability and hydrophilicity of titanium implant surfaces. Plasma-oxidized SLA surfaces have demonstrated improved bone-to-implant contact and higher removal torque values, indicating enhanced osseointegration(16).However, further in vivo studies are required to establish its long-term clinical applicability.

3. Biological Modifications

Platelet Rich Plasma (PRP) and Platelet Rich Fibrin (PRF)

PRP and PRF are rich in growth factors that enhance osteoblast adhesion and bone healing. Surface treatment with PRP or PRF has shown improved osteoblast activity and may enhance early bone apposition and primary implant stability, particularly in patients receiving bisphosphonate therapy.(17)

Extracellular Matrix (ECM)

Collagen, chondroitin sulphate, vitronectin, and fibronectin are among the extracellular matrix (ECM) substances secreted by fibroblasts during osseointegration that direct osteoprogenitor cells to the functional surface. Therefore, incorporating extracellular matrix (ECM) components onto the implant surface can enhance cell–ECM interactions, which in turn activate various signalling pathways that promote bone healing and osseointegration. When compared to uncoated surfaces, ECM-coated implants have shown improved bone growth and maturation.

Peptides

Arginylglycylaspartic Acid (RGD)

RGD peptides promote osteogenic cell adhesion and migration through integrin-mediated interactions. Improved bone-to-implant interface and peri-implant bone regeneration have been demonstrated with RGD-coated implants.

P15 Peptide

P15 is a synthetic peptide that mimics the cell-binding domain of collagen and enhances osteoblast attachment, spreading, and differentiation(18).Fusion of P15 with antimicrobial peptides has also demonstrated biofilm inhibitory effects.

Sclerostin-Antibody

Sclerostin-neutralizing antibodies promote osteoblast differentiation and bone regeneration by modulating the Wnt/β-catenin pathway.

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Experimental studies suggest improved osseointegration, particularly under osteoporotic conditions.

Growth Factors

Bone Morphogenic Proteins (BMPs)

BMPs, especially BMP-2, BMP-4, and BMP-7, stimulate bone regeneration and enhance bone-to-implant contact when coated on implant surfaces.

Platelet-Derived Growth Factor (PDGF)

PDGF promotes collagen synthesis, bone matrix deposition, and soft tissue healing. PDGF-coated
implants have shown enhanced osseointegration in experimental models (19).

Fibroblast Growth Factor (FGF)

FGF-2 stimulates osteoblast proliferation and differentiation. FGF-coated titanium implants have demonstrated improved cellular activity and enhanced osseointegration in vivo.

Drugs

Statins

Statins such as simvastatin may enhance osseointegration by stimulating BMP and VEGF expression, thereby promoting bone formation and bone-to-implant contact. Simvastatin-coated titanium surfaces have shown increased osteogenic activity in vitro(20).

Bisphosphonates

Bisphosphonate-coated implants have demonstrated improved bone-to-implant contact, removal torque, and new bone formation(21).However, some studies suggest these coatings may increase bacterial adhesion and biofilm formation(22).

Antimicrobials

Antimicrobial implant surfaces are designed either to release antimicrobial agents (Type I) or to possess permanently bonded antibacterial coatings (Type II). These surfaces reduce bacterial adhesion and biofilm formation, helping to prevent peri-implant infections.

Recent Advances and Novel Surface Technologies

Advances in nanotechnology and biomimetic engineering have led to next-generation implant surfaces with enhanced osteoconductive and antimicrobial properties. Nanostructured titanium, laser-textured surfaces, hydroxyapatite, calcium phosphate, magnesium-based coatings, graphene, and titanium dioxide nanotubes have shown improved osseointegration and reduced bacterial adhesion. Emerging multifunctional coatings integrating antibacterial agents and growth factors aim to simultaneously promote bone regeneration and prevent peri-implant infections. Femtosecond laser micromachining enables the fabrication of precisely controlled microgrooves and anisotropic surface patterns, providing directional cues for cellular alignment and potentially promoting oriented or perpendicular connective-tissue fibre attachment. Laser-induced periodic surface structures (LIPSS) offer another emerging approach for generating controlled micro/nanotopographies that can modulate cellular behaviour, wettability and implant–tissue interactions. These advanced laser-based technologies represent promising strategies for developing biomimetic implant surfaces, although their clinical applicability requires further validation through long-term in vivo and clinical studies.

Clinical Implications of Surface Modifications

Surface modifications improve primary stability, accelerate healing, and enhance implant survival, particularly in low-density bone. Hydrophilic and moderately rough surfaces demonstrate superior osseointegration and support early loading protocols. However, excessively rough implant surfaces may promote bacterial accumulation and increase the risk of peri-implantitis. Studies have shown that moderately rough surfaces (Sa = 1–2 μm) offer an ideal balance between enhanced osseointegration and maintenance of peri-implant tissue health.

II. DISCUSSION

The evidence suggests that surface modifications significantly enhance the cellular response and mechanical stability of dental implants. Comparative studies indicate that nanostructured and hydrophilic surfaces outperform traditional machined or micro-roughened designs in early bone healing. However, inconsistencies in study designs, animal models, and measurement parameters complicate direct comparisons. Future studies must focus on long-term human trials and the synergistic effect of combined surface features. Furthermore, immunomodulatory and smart surfaces capable of releasing antimicrobial or osteogenic agents on demand are promising directions.

III. FUTURE PERSPECTIVES

The future of implant surface engineering lies in multifunctional and personalized designs. Advanced 3D printing and nanofabrication allow for tailored topographies and porosities. Smart coatings capable of controlled drug release, coupled with AI-assisted surface optimization, may revolutionize implantology. Epigenetic surface modulation and integration of bioactive nanomaterials will enable faster, infection-resistant osseointegration even in compromised bone conditions.

IV. CONCLUSION

Implant surface modification has evolved into an interdisciplinary field combining materials science, nanotechnology, and biology. From machined surfaces to bioactive and nanostructured coatings, these innovations have profoundly improved osseointegration and clinical outcomes. The integration of multifunctional, antibacterial, and osteoinductive surfaces represents the future of predictable and durable implant therapy.

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