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Surface Modifications of Dental Implant - A Review

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Abstract

Dental implants have significantly transformed the landscape of modern dentistry by presenting a dependable solution for the restoration of missing teeth. The efficacy of dental implants is focused upon the achievement of optimal osseointegration, a process in which the implant integrates seamlessly with the surrounding bone tissue. Surface modifications of dental implants play a crucial role in augmenting osseointegration, thereby enhancing long-term implant stability and success rates. This comprehensive literature review endeavors to furnish a detailed information of the various surface modifications employed in dental implants. It will delve into the historical context, classification, as well as macro, micro, and nano surface modifications focussing on elucidating their impact on osseointegration.

Keywords: Dental implants, Osseointegration, surface modification, Macrosurface modification, Micro surface modification, Nano surface modification

Introduction

Modern dentistry relies heavily on dental implants for resilient and long-lasting tooth replacement. However, successful implant procedures hinge on factors like implant material biocompatibility, surface characteristics, condition of implant site and bone quality, surgical technique, healing phase and prosthetic design.1 Surface modifications, particularly roughness and topographical changes, are crucial for enhancing bone integration and mechanical stability.[2] Recent advancements prioritize topographical alterations to foster effective osseointegration, ensuring durability. This review explores techniques to optimize dental implant efficacy and longevity through surface modifications.

History of Surface Modification in Implants:

The historical development of surface modifications for dental implants is depicted in Figure 1.

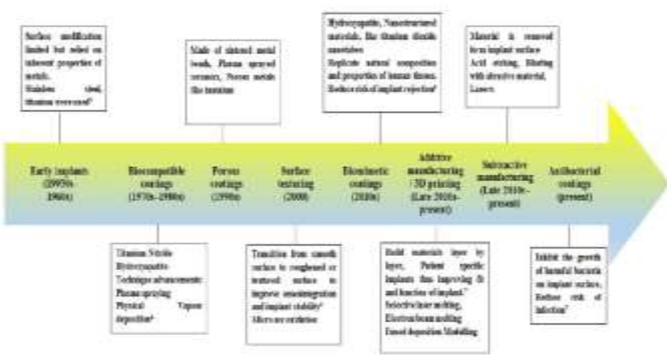

Figure 1: History of surface modifications in implant

Classification of Surface Modifications of Dental Implants

A classification scheme illustrating the various types of surface modifications applied to dental implants is presented in Table 1.

SURFACE TOPOGRAPHY	TEXTURE	IRREGULARITIES	SURFACE TREATMENT	SURFACE MODIFICATION TECHNIQUE	SURFACE ENGINEERING TECHNIQUES
[illegible] et al. 1. Smooth (<0.5 µm) Minimally rough (0.5–1 µm) Intermediately rough (1–2 µm) Rough (2–3 µm) 2. Macro scale Micro scale Nano scale	Concave Convex	Isotropic surface Anisotropic surface	1.Physical (Subtractive) surface treatment: Machined surface Laser etching Abrasive/Sandblasting with grit media Porous tantalum trabecular metal Nanoparticle compaction 2. Chemical (Additive) surface treatment: Acid etching Alkaline treatment Anodization of the surface Fluoride treatment Various treatment Plasma coatings Peroxidation 3.Biological/ Biomimetic surface treatment: Bioactive coatings Attachment of antibiotics Attachment of peptides Attachment of bone remodelling agents Attachment of growth factors 4. Combination of surface treatment: Sandblasting and acid etching Sandblasting, acid etching and chemical modification	1. Based on Mechanical and Chemical process: Additive process: Titanium plasma-sprayed Hydroxyapatite coatings and Calcium phosphate Oxidation Ion deposition Subtractive process: Acid-etching Grit-blasting Mechanical polishing Electropolishing Laser-Microtexturing 2. Based on Biological process: Growth factors Peptides Calcium Phosphate	1. Surface coating techniques: Cladding Chemical vapour deposition Electroplating Sol-gel Hot dipping Plasma and thermal spraying Physical vapour deposition 2. Changing the surface chemistry: Induction hardening Nitriding Friction stir process Carburising 3. Changing the surface metallurgy: Surface hardening Flame hardening Laser hardening Induction hardening Ion implantation Electron beam processing Laser melting Shot peening

Table 1: Classification of surface modifications of dental implants”

Surface Modifications of Dental Implant

Surface roughness significantly impacts implant anchorage in bone tissue. Increased surface roughness enhances the implant's integration with bone tissue via osseointegration, facilitated by a larger developed interfacial area ratio (Sdr). Textured surfaces offer enhanced bone apposition and can direct tissue ingrowth aimed at improving stability by enhancing cellular activity and bone apposition. Surface modifications of dental implants at macro (millimeter to micron scale), micro (1-10 µm), and nano (nano topographies) levels enhance osseointegration and bone formation by promoting initial stability, osteoconduction, osteoinduction, protein adsorption, and osteoblast adhesion, ultimately facilitating bone ingrowth and cell growth onto the implant surface.

Macrosurface Modification

Implant design features are critical for achieving primary stability and ensuring resistance to mechanical loading throughout osseointegration. Key macro design elements include thread shape, amount of force, favorable forces, pitch, helix angle, depth, crestal module, neck configuration, and micro threads. (Figure 2) Thread shapes like Square, Standard V, Buttress, Reverse Buttress, and Spiral shapes optimize stress distribution at the bone-implant interface and enhance surface contact area, supporting Wolff's theory of bone remodeling.[15] Functional occlusal loading induces bone remodeling, with mild loads stimulating bone production, while excessive loads cause microfractures and osteoclastogenesis, increasing implant failure risk.

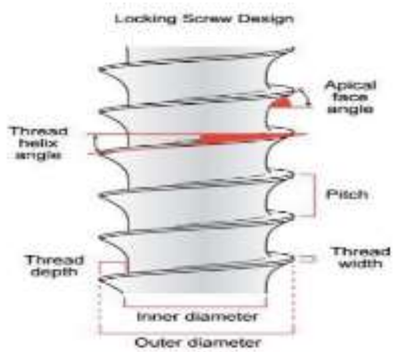

Figure 2: Macro design parts of an implant

Author	Method	Implant design	Bone	Load	Conclusion
Roberts et al[16], 1984	Rabbit femur	V-shaped threads	Cortical and cancellous natural bone	100g horizontal	Lower the pitch, higher the bone to implant contact
Chun et al[17], 2002	FEA	Plateau shape, plateau with small radius of curvature, square, square filled with small radius, triangular,	Jaw bone model	100N axial and 15°	Effective stress decreases with a reduction in screw pitch and an increase in implant length. The plateau shape exhibited the highest effective stress, while the square thread with a small fillet radius showed the lowest stress.
Geng et al[18], 2004	FEA	Stepped screw V thread, thin square thread, thin thread, thick square thread	Two models of cortical and trabecular bone	Oblique and vertical	Effect on stress distribution was observed exclusively in trabecular bone
Steigenga et al[19], 2004	Tibia, rabbits	Square shaped, V thread, Reverse buttress	Cortical and cancellous natural bone	No intentional load	Square thread achieved greater bone to implant contact
Motoyoshi et al[20], 2005	FEA	Ti mini-implants with thread pitches from 0.5-1.5mm	Cortical bone	Traction force of 2N 45° to surface	No difference was found without the abutment, but with the abutment connected, smaller pitch distance led to optimal stress distribution.
Gross KA et al[21],2006	FEA	V-shaped threads with height of 0.2- 0.6mm and thread width of 0.1-0.4mm	Jaw bone models	100N and 50N at axial and 45° angle	45° angle generated more stress than axial load
Abrahamsson and Berglundh[22], 2006	Beagle dogs	Microthreaded or smooth crestal module	Cortical and cancellous natural bone	In occlusion for 10mouths	Microthreaded group had a higher bone-to-implant contact (BIC) in the coronal portion.
Lee et al[23], 2007	17 human patients	With or without microthreaded crestal module	Cortical and cancellous natural bone	Followed for 3 years in occlusion.	Microthreaded group exhibited less marginal bone loss.
Schrotenboer et al[24],2008	FEA	Microthreaded crest module vs. smooth neck	Mandibular premolar region model	100N at 90° vertical and 15° oblique	Microthread implants resulted in higher bone stress.

Table 2: Studies on different implant macro design features

Geng et al.'s study suggests that broader square threads induce lower stress in cancellous bone compared to narrower threads.[18] Tapered implants balance compressive and tensile forces, while V-shaped threads increase shear forces, affecting bone density distribution during dynamic loading.[25] Pitch distance influences insertion speed and stability, with higher thread counts improving stability in compromised bone. Thread helix angle affects insertion success, with single-threaded implants offering the highest stability. Thread depth and width optimize load transfer, particularly in softer bone.[26] Crestal modules manage occlusal forces and aid in bacterial resistance. Rough and smooth neck configurations impact plaque retention and bone loss, with proper placement above the bone crest being essential. Micro threads help preserve marginal bone, though some studies, such as Schrotenboer's, indicate increased bone stress compared to smooth necks.[24]

Microsurface Modification

Microsurface modification techniques enhance osseointegration and implant stability. **Sandblasting** propels small grits like alumina or silica onto a material's surface, creating irregular microtopographies with craters and ridges while inducing a negative surface charge that promotes bone-implant contact. Grit blasting uses ceramic particles, such as titanium oxide and calcium phosphate, to form surface topographies, though residue can interfere with osseointegration. Shot peening introduces compressive stresses via small spherical media, influencing surface roughness. Acid-etched surfaces, created by immersing titanium implants in strong acids, increase micro-roughness and bioadhesion but risk hydrogen embrittlement. The sandblasted and acid-etched (SLA) method combines both treatments, reducing healing times from 12 to 6 weeks and improving bone contact and stability.[27] (Figure 3)

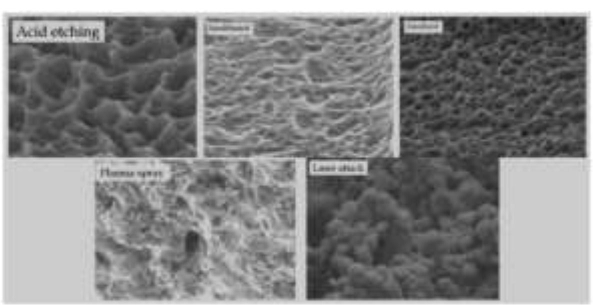

Figure 3: Microsurface modifications and resultant surface topographies

Other Chemical Treatments

Various chemical treatments are used on titanium and titanium alloy surfaces, including solvent cleaning, alkaline etching, passivation, and coating deposition. Solvent cleaning removes contaminants without affecting the implant surface, while alkaline etching with sodium hydroxide creates a sodium titanate gel with a porous, irregular topography. Passivation treatments use nitric acid or heat to uniformly oxidize the surface, enhancing corrosion resistance. Chemical decontamination agents, such as chlorhexidine and citric acid, are also employed during peri-implantitis treatment. Barbour et al.[28] found that chlorhexidine adsorbs rapidly onto titanium oxide, while Alhag et al.2[9] showed that rough surfaces cleaned with citric acid or hydrogen peroxide can reosseointegrate, though chemical treatments may alter surface properties and affect implant performance.

Electrophoresis

Electrophoretic deposition (EPD) coats titanium substrates with uniform, strongly adherent hydroxyapatite (HA) layers. HA particles suspended in solvents are drawn to the cathodic substrate under an electric field. EPD parameters like voltage and HA concentration determine coating morphology. Post-coating sintering at 800°C enhances properties. Coating morphology and bond strength depend on electrochemical deposition parameters, impacting implant applications.

Laser Treatment

Laser treatments offer a precise and contamination-free method for surface modification of titanium implants, enabling the creation of micro- and nano-structured surface roughness. This technique, characterized by short pulses of light focused on one spot, allows for selective surface modification, making it suitable for complex biomedical implants. Laser-treated implants exhibit enhanced osseointegration due to their modified surface characteristics.[30]

Laser peening

A method inducing compressive stress strengthens implants, enhancing fatigue life and improving properties like hardness and corrosion resistance. Laser treatments offer precise control over micro-topography, promoting cell attachment and bone ingrowth directionality. Despite minimal contamination, laser treatment remains promising, surpassing techniques like acid etching and plasma spraying. Overall, laser treatments improve titanium implant biocompatibility and osseointegration, contributing to their long-term clinical success. Gaggl reported high purity surfaces with optimal roughness for osseointegration in laser-treated implants.[30]

Vaccum Treatment

Vacuum treatment, including glow-discharge treatment and ion implantation, offers precise control over processing conditions, particularly cleanliness. Glow-discharge treatment enhances surface energy and wetting characteristics, while ion implantation increases surface hardness and reduces wear debris. Thermal treatment forms crack-free titanium oxide layers, enhancing surface roughness and biocompatibility.

Plasma Spraying

Plasma spraying deposits calcium phosphate (CaP) coatings onto implants, enhancing bioactivity and bone-implant contact. Titanium plasma spray creates rough coatings for osseointegration. TPS implants have high roughness for bone ingrowth but weak bonding may cause instability and ion leakage. (Figure 4)

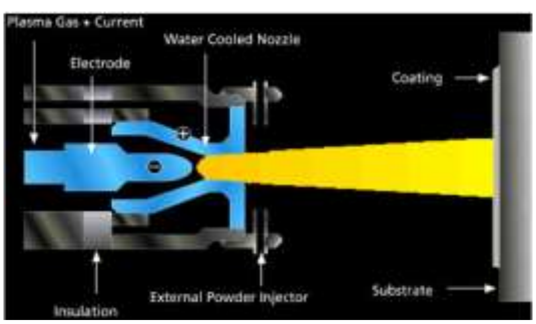

Figure 4: Device used for plasma spraying

Sputter Deposition

Sputter deposition ejects material in a vacuum using high-energy ions. Magnetron sputtering and radio frequency (RF) deposit bioceramic thin films like CaP coatings on titanium implants. RF sputtering offers strong adhesion and control over coating properties, enhancing bone-implant contact. Magnetron sputtering preserves titanium's mechanical properties and maintains bioactivity. However, sputter coating is time-consuming and may produce amorphous coatings with higher Ca/P ratios than synthetic HA. Thickness ranges from 0.5 to 3.0 µm, with variable surface roughness.[31] Sputtered CaP coatings show similar interfacial strength to plasma-sprayed HA coatings, with potential for osseointegration enhancement.

Electrolytic Deposition

Electrolytic deposition is a process that uniformly coats surfaces with hydroxyapatite (HA) while maintaining the original material composition. Modern applications can achieve coatings as thin as 1 µm or even nanometer thickness, such as the Nanotite implant with a 20nm HA layer. Nanoparticles are prepared using calcium nitrate and phosphoric acid with a CaP ratio of 1.67, followed by deposition onto titanium implants through a dip coating technique.

Ultrasonic Spray Pyrolysis

Nanoparticles are produced by aerosolizing precursor solutions like tetra-n-butyl orthotitanate, followed by thermal decomposition and powder collection in a controlled furnace

Figure 5: SEM analysis of titanium dioxide nano powder obtained through ultrasonic spray pyrolysis

Under inert atmosphere. Ultrasonic atomization and precise temperature control yield nanoparticles with specific morphologies and characteristics. (Figure 5)

METHOD	SURFACE ROUGHNESS VALUES
Machined surfaces	5 - 6 µm
Sandblasted surfaces	0.5 - 2 µm
Acid etched surfaces	0.3 - 1 µm
SLA surfaces	1 – 2 µm
Electrochemical treatments	0.3 – 0.9 µm
Vacuum treatments	0.1 – 1 µm
Anodization	Approx. 1.1 µm
Laser roughening	Approx. 2.28 µm
Plasma spraying	5 ± 1 µm

Table 3: Average surface roughness values produced by each surface modification technique

Nanosurface Modification

Blood interaction with implant surfaces during dental implant surgery initiates protein adsorption and thrombus formation, influencing osseointegration. Hydrophilic and rough implant surfaces enhance protein adsorption, promoting cell adhesion through proteins like fibronectin and vitronectin. Platelet-rich plasma supports osseointegration, but excessive concentrations inhibit bone regeneration. Mesenchymal stem cells differentiate into osteoblastic or fibroblastic cells, depending on the microenvironment, with fibrous encapsulation leading to implant failure. Nanoscale surface modifications, such as nanorough titanium, enhance osteoblast adhesion and differentiation.

1. **Organic Nanoscale Self-Assembled Monolayers (SAMs)**

   SAMs involve molecular self-assembly on metal oxides, controlling surface properties like hydrophilicity and influencing fibroblast response and bone formation.

2. **Hydrogels on Titanium Surface**

   Hydrogels, such as polyethylene glycol (PEG), provide biocompatibility and tunable microstructures, which are useful in tissue engineering and guided bone regeneration. (Figure 6)

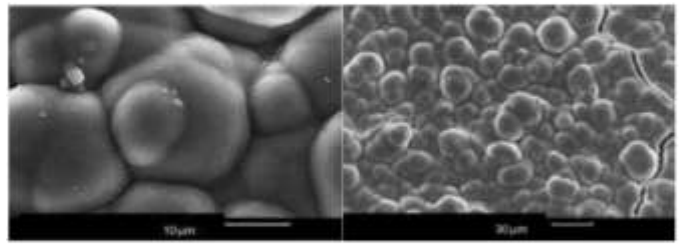

Figure 6: Hydrogels on titanium surface

3. **Titanium Nanotubes**

   Titanium dioxide nanotubes mimic bone microenvironments, promoting osteoblast adhesion and delivering growth factors while preventing bacterial adhesion and biofilm formation. (Figure 7)

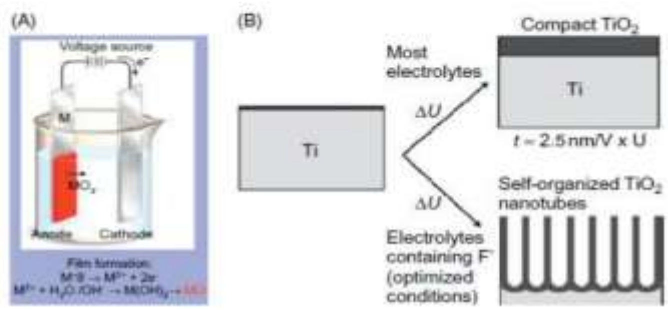

Figure 7: (A) : Anodization results in the oxidation of the metal, creating a solid oxide layer on its surface. (B): The nature of this solid oxide layer—whether it is compact, nanotubular, or nanoporous—depends on the specific conditions, such as the potential, electrolyte, and temperature.

Various bioactive surface coatings have been developed to enhance the performance and integration of dental implants.

Bioactive Surface Coatings

These bioactive surface coatings offer promising strategies to enhance the integration and long-term success of dental implants, although challenges such as coating longevity and thermal compatibility need to be addressed for widespread clinical application.

1. **Bioactive Glass Coatings:**
   Synthetic osteoconductive materials like bioactive glass form strong chemical bonds with bone, promoting osseointegration. Studies have shown greater bone integration and higher removal torque in coated implants compared to uncoated ones.[32]
2. **Hydroxyapatite (HA) Coating:**
   HA, a natural bone component, enhances osseointegration due to its biocompatibility. Plasma spraying and ion beam deposition methods create porous HA coatings that stabilize implants quickly and bond stronger with bone tissue. However, long-term success requires addressing coating resorption and thermal expansion issues.
3. **Calcium-Phosphate Coating:**
   These accelerate bone formation and improve osseointegration, but coating longevity for optimal bone apposition remains debated.
4. **Titanium Nitride (TiN) Coatings:**
   TiN coatings increase corrosion resistance and surface hardness, improving implant durability. Titanium nitride coatings have high surface hardness and mechanical strength, improving the durability of dental implants.
5. **Fluoride Treatment:**
   Fluoride-modified implants enhance osseointegration by promoting osteoblastic differentiation and expression of bone-related genes, leading to improved stability.
6. **Biologially active drugs:**
   Several strategies involving biologically active drugs have been explored to enhance and accelerate osseointegration and reduce the risk of complications associated with dental implant surgery.

a) **Bisphosphonates**

Antiresorptive agents on implant surfaces improve osseointegration, increasing local bone density. Bisphosphonate-loaded implants enhance peri-implant bone density, but challenges remain in grafting and sustaining drug release on titanium surfaces. Optimal drug dosage is crucial as bone density increase is concentration-dependent.[33]

b) **Simvastatin**

A cholesterol-lowering drug, promotes bone formation by inducing BMP-2 expression. It enhances implant integration in animals and accelerates osteogenic differentiation of preosteoblasts in vitro when loaded onto implant surfaces.

c) **Antibiotic Coating**

Antibacterial coatings on implant surfaces have been investigated to prevent surgical site infections. Gentamycin, along with a layer of hydroxyapatite (HA), can be coated onto implant surfaces to act as a local prophylactic agent. Tetracycline-HCl treatment has been effective in decontaminating and detoxifying contaminated implant surfaces, removing the smear layer and endotoxins, inhibiting collagenase activity, and promoting cell proliferation and attachment, as well as blood clot retention on the implant surface during the healing process.[34]

Surface Engineering Techniques

Surface engineering techniques modify the properties of implant surfaces to enhance their performance and biocompatibility. They can be broadly categorized into surface layer addition, surface chemistry modification, surface metallurgy alteration, and organic-inorganic coatings.

Surface Layer Addition Techniques

1. **Cladding:** Bonding two metals together to protect the base metal from the environment and improve surface properties.
2. **Chemical Vapor Deposition:** Exposing the base material to volatile precursors that react and decompose on the surface to produce the desired deposit.[35]
3. **Electroplating:** Using electric current to deposit a uniform, dense, and adherent coating, typically for metals or alloys.
4. **Hot Dipping:** Immersing the base metal into a molten material, such as zinc, to form a metallurgical bond for corrosion protection.

Surface Chemistry Modification Techniques[36]

1. **Induction Hardening:** Using electromagnetic induction to heat the surface of a workpiece and then quenching to increase material hardness.
2. **Nitriding:** Introducing nitrogen into the surface of a metal to harden it, typically used for low-carbon, low-alloy steels.
3. **Carburizing:** Diffusing carbon into the surface of steel to harden it, followed by quenching to lock the carbon into the structure.
4. **Friction Stir Process:** Employing localized plastic deformation using a non-consumable tool to alter the physical and chemical properties of the material.

Surface Metallurgy Alteration Techniques[37]

Surface metallurgy techniques for improving wear and fatigue resistance include:

Surface hardening

Improving wear resistance through the development of a hard martensitic surface, achieved through techniques like laser hardening, induction hardening, flame hardening, electron-beam hardening, and ion implantation.

Flame hardening: Using heat from an oxy-acetylene flame.

Induction hardening: Localized heating using alternating current and a magnetic field.

Laser hardening: Precision heating with a laser beam.

Electron-beam hardening: Rapid surface treatment with high-energy radiation.

Ion implantation: Accelerating ions to induce mechanical and chemical changes.

Laser melting: Melting the surface to refine grain structure and create fine precipitates and depositing one material over another using a laser to improve wear resistance and surface properties.

Organic-Inorganic Coatings on Implant Surfaces[38]

1. **Organic Biomolecule Coatings:** Immobilizing enzymes, proteins, and peptides on implant materials to enhance bone regeneration.
2. **Enzyme Coatings:** Utilizing enzyme-modified surfaces to enhance bone mineralization along the implant surface.
3. **Organic-Inorganic Composite Coatings:** Developing composite coatings that resemble the nano-composite structure of bone tissue, incorporating collagen, CaP minerals, and growth factors to enhance bone growth and fixation.

Gene Coated Implant Surface[39]

Deoxyribonucleic Acid (DNA) Coatings modify implant surfaces with DNA-containing coatings to improve biocompatibility, drug delivery, and bone regeneration through layer-by-layer assembly and electrostatic interactions.

Integrin Coated Implant Surface[40]

Integrin Coatings enhance clinical-grade titanium implants by grafting them with non-fouling polymer coatings functionalized with specific densities of RGD peptide or α5β1-integrin-specific FN fragment FNIII7–10 to improve implant osseointegration.

Conclusion

Successful dental implants relies on osseointegration with surrounding bone, influenced by composition and surface roughness. Rough surfaces enhance anchoring and biomechanical stability, while osteoconductive coatings promote bone healing. Surface modifications at macro, micro, and nano levels aim to maximize bone contact, prevent bacterial colonization, and promote tissue growth. Advances in biomaterials and biomechanics enhances regeneration at molecular level and focuses on stable bone-implant contact and desirable cellular responses.

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