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EVOLUTION OF DENTAL IMPLANT SURFACE MODIFICATIONS: FROM MACHINED TO BIOACTIVE SURFACES

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ABSTRACT

The long-term success of dental implants is critically dependent on rapid and stable osseointegration. Implant surface characteristics play a decisive role in modulating the biological response at the bone–implant interface. Over the past few decades, substantial advancements have been made in implant surface modification techniques aimed at enhancing bone healing, improving early stability, and reducing the risk of implant failure. This review article discusses the evolution, classification, biological rationale, and clinical relevance of implant surface modifications, with emphasis on contemporary physical, chemical, and biochemical approaches. The current evidence supporting various surface treatments and their clinical implications is also highlighted.

KEYWORDS: Dental implants, surface modification, osseointegration, roughened surfaces, bioactive coatings.

INTRODUCTION

Dental implants have become a predictable and widely accepted treatment modality for the replacement of missing teeth. While implant design and surgical protocols contribute to treatment success, the implant surface has emerged as a key determinant of osseointegration.[1] Early implant systems featured smooth, machined surfaces, which demonstrated acceptable long-term survival but required prolonged healing periods. The quest for faster and more reliable osseointegration led to the development of various surface modification strategies designed to improve bone–implant contact (BIC) and enhance biological integration.

Surface modifications aim to alter the topography, chemistry, surface energy, and wettability of implants, thereby influencing protein adsorption, cell adhesion, proliferation, and differentiation. Understanding these modifications is essential for clinicians to make evidence-based decisions in implant selection, particularly in compromised clinical scenarios such as poor bone quality, immediate loading, and medically compromised patients.

FIG 1.

Biological Basis of Implant Surface Modifications

Osseointegration is a complex biological process involving a cascade of cellular and molecular events at the bone–implant interface. Immediately after implant placement, blood proteins adsorb onto the implant surface, forming a conditioning film that regulates subsequent cell attachment. Surface roughness and chemistry influence osteoblast adhesion, differentiation, and extracellular matrix production.[1]

Microrough surfaces have been shown to enhance osteoblastic activity and increase BIC by providing mechanical interlocking between bone and implant. Nanostructured surfaces further modulate cell behavior by mimicking the natural architecture of bone, promoting early bone formation and improved biomechanical stability.

Classification of Implant Surface Modifications

Implant surface modifications can be broadly classified into physical, chemical, and biochemical methods.

1. Physical Surface Modifications

Physical methods primarily alter surface topography without changing the chemical composition of the implant material.

Machined (Smooth) Surfaces

Machined surfaces are characterized by minimal roughness and were commonly used in early implant designs. Although they demonstrate good long-term survival, they exhibit slower osseointegration and lower BIC compared to roughened surfaces.

Sandblasting

Sandblasting involves the projection of abrasive particles (such as alumina) onto the implant surface to create macroroughness4,. This technique improves initial stability but may leave residual particles if not properly cleaned.

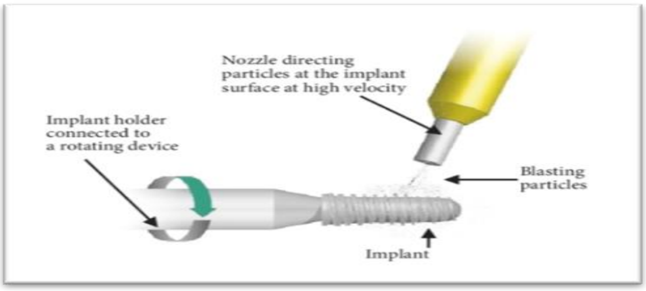

FIG 2

Sandblasted and Acid-Etched (SLA) Surfaces

SLA surfaces combine sandblasting with acid etching to create a micro-rough topography.[2] These surfaces are among the most widely used today due to their proven ability to enhance osseointegration and support early loading protocols.[4,13]

Plasma Spraying

Titanium plasma spraying (TPS) produces a thick, porous coating that increases surface area. However, concerns regarding coating delamination and long-term stability have limited its widespread use.[5]

2. Chemical Surface Modifications

Chemical methods alter surface chemistry and energy, often improving wettability and biological interaction.

Acid Etching

Acid etching alone creates micropits on the implant surface, enhancing osteoblast attachment and BIC.
Strong acids (HCl, H_2SO_4, HNO_3, HF) creates 0.5–2 µm micro-pits, producing uniform roughness, increased surface area, and enhanced osteoblast adhesion.[10]

Dual acid-etching ($HCl + H_2SO_4$ at >100 °C) improves fibrin and osteogenic cell attachment, promoting direct bone formation.[10]

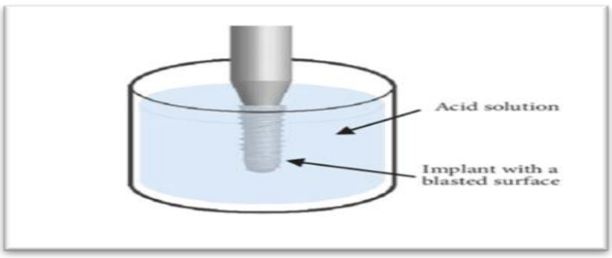

FIG 3

Anodization
Anodized surfaces are produced through electrochemical oxidation, resulting in a porous titanium oxide layer with increased roughness and bioactivity. These surfaces have demonstrated improved bone response and high clinical success rates.[10]

Laser Microtexturing
Uses laser energy to locally melt the implant surface, creating microchannels that promote faster bone healing. The technique allows precise control of wavelength, energy, and pulse duration, producing microstructures with increased hardness and improved corrosion resistance.[3]

Calcium Phosphate and Hydroxyapatite Coatings
Calcium phosphate-based coatings aim to enhance bioactivity by promoting direct chemical bonding with bone. Modern thin coatings have improved adhesion and reduced the risk of delamination seen in earlier plasma-sprayed coatings.[6]

3. Biochemical Surface Modifications
Biochemical approaches incorporate biologically active molecules to directly to influence cellular responses.[13]

Bioactive Molecules and Growth Factors
Surface functionalization with growth factors such as bone morphogenetic proteins (BMPs) and peptides enhances osteogenic differentiation and bone formation.[8]

Antibacterial Surface Modifications
Incorporation of antibacterial agents such as silver ions, zinc, or antimicrobial peptides aims to reduce bacterial colonization and peri-implant infections without compromising biocompatibility.[9]

Nanotechnology and Implant Surfaces
Recent advances in nanotechnology have enabled the creation of nanoscale surface features that closely resemble the natural bone environment. Nanostructured surfaces improve protein adsorption and promote early osteoblast adhesion while potentially reducing bacterial attachment. These surfaces represent a promising direction for future implant designs.[8]

Clinical Implications
The choice of implant surface has significant clinical implications, particularly in challenging situations such as immediate implant placement, poor bone density, and early loading protocols.[12] Roughened and bioactive surfaces generally demonstrate higher survival rates and faster osseointegration compared to smooth surfaces. However, excessively rough surfaces may increase plaque accumulation and the risk of peri-implantitis, emphasizing the need for balanced surface design.[14]

Limitations and Future Directions
- Integration of nanotechnology for smarter, more bioactive surfaces.[16]
- Use of organic/inorganic hybrid coatings for combined benefits.
- Development of drug-delivery implants to reduce infection and speed healing.
- Improved analytical tools (e.g., biomarkers, mass spectrometry) to evaluate success.[15]

Goal: Safer, faster-healing implants with long-term stability, especially for patients with poor bone quality.[17]

DISCUSSION
Implant surface modification has been central to the progress of modern implant dentistry. Earlier implant designs relied mainly on mechanical retention, whereas current approaches focus on modifying surface roughness and chemistry to improve and speed up osseointegration. Classic studies by Albrektsson and Wennerberg showed that moderately rough surfaces provide better bone anchorage6, a finding supported by Buser et al., who reported faster early bone formation and increased bone–implant contact with sandblasted and acid-etched (SLA) implants.[2,4,13]

Micro- and nano-level surface treatments such as sandblasting, acid etching, anodization, and laser texturing increase surface energy and wettability, improving osteoblast attachment and bone healing.[11] Nanostructured surfaces further enhance this response by closely resembling natural bone, leading to better protein adhesion, blood vessel formation, and early bone maturation, which together improve implant stability.[7]

Recent advances in bioactive surface coatings, including growth factors and antimicrobial agents, have shifted implant design toward a more biologically active approach. These surfaces promote bone regeneration while reducing the risk of peri-implant infection, particularly in immediate loading and compromised bone situations.[17]

However, challenges such as coating durability, safety of nanoparticles, and higher costs remain.[10] Future implant surfaces are expected to be multifunctional, combining improved osseointegration, antibacterial protection, and localized drug delivery to achieve long-term clinical success.[8]

CONCLUSION
Implant surface modifications have significantly advanced the field of implant dentistry by improving osseointegration and expanding clinical indications. Contemporary implant surfaces combine optimized topography, chemistry, and bioactivity to achieve predictable outcomes. A thorough understanding of these surface characteristics enables clinicians to select

appropriate implant systems and optimize long-term treatment success.

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