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Review Article

From surface to success: How implant surfaces shape osseointegration

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ABSTRACT

The field of dental implantology has significantly advanced to address the multifaceted impacts of tooth loss, encompassing physical, functional, emotional, psychological, and social dimensions. Dental implants serve as reliable solutions, ensuring stability, minimal bone loss, and absence of pain or infection. Central to their success is the surface modification of implants, which profoundly influences osseointegration—the process crucial for establishing a functional bond between bone and implant. This review explores various physical modifications of dental implant surfaces, focusing on macro, micro, and nano-level alterations. Macro-level modifications optimize implant geometry and thread design to enhance initial stability and long-term fixation. Micro-level modifications, including grit blasting and acid etching, increase surface roughness to facilitate mechanical interlocking and cell adhesion. Nano-level modifications, such as hydrophilic coatings and bioceramic enhancements, enhance surface energy and promote osteoblastic differentiation, thereby accelerating osseointegration. These surface modifications represent a critical frontier in implant dentistry, promising improved clinical outcomes and patient satisfaction through enhanced integration and reduced healing times.

1. Introduction

The loss of natural teeth not only has significant physical and functional repercussions but also induces profound emotional, psychological, and social impacts on individuals. Implantology emerges as a highly secure and efficacious surgical intervention to address these multifaceted consequences.[1]

Dental implants have a long history, starting in 600 A.D. with the Mayans using shell pieces as teeth. Modern implants began in the 1930s with Vitallium endosteal implants and advanced in the 1940s with spiral stainless-steel designs. A major breakthrough came in 1965 when Dr. Per-Ingvar Brånemark introduced the threaded titanium implant. Since then, implants have improved in shape, size, and surface features to be more successful. Successful implants are stable, cause minimal bone loss, and don't lead to pain or infection.

The surface of dental implants is a critical factor in their success and longevity. Osseointegration, the process where bone cells grow and adhere to the implant, ensures the stability and functionality of the dental implant. The characteristics of the implant surface, its texture, composition, and treatment significantly influence this process. By exploring how these surface properties affect osseointegration, we can enhance implant designs to improve patient outcomes.[2]

Osseointegration is defined as the intimate connection between bone and implant, and the growing emphasis on surface engineering is a noteworthy and intrinsic trend. The bone's response, encompassing rate, quantity, and quality, is intricately linked to the properties of the implant surface. Notably, factors such as composition and charges play a

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crucial role in protein adsorption and cell attachment.[3] Hydrophilic surfaces demonstrate enhanced interactions with biological fluids and cells compared to hydrophobic ones, with hydrophilicity being influenced by the surface's chemical composition.

Different surface textures have varied impacts on osseointegration. Rough surfaces, such as those achieved through sandblasting or acid etching, provide a more extensive area for bone cells to attach, promoting quicker and stronger integration. These textures create microgrooves and ridges that facilitate the initial anchoring of the bone, making the implant more stable from the outset. Conversely, smoother surfaces may not offer the same level of initial stability, potentially leading to longer healing times and less secure implants.[4]

The composition of the implant surface also plays a pivotal role. Materials like titanium and its alloys are commonly used due to their biocompatibility and strength. Advances in surface chemistry, such as incorporating bioactive coatings, can further enhance osseointegration. For instance, adding a layer of hydroxyapatite, a naturally occurring mineral in bone, can improve the implant's ability to bond with the bone, mimicking the natural processes of bone growth and repair.

Research continues to focus on optimizing surface treatments to enhance osseointegration. Techniques such as laser modification and plasma spraying are being investigated for their potential to create ideal surface conditions. These methods aim to produce surfaces that not only promote rapid bone growth but also ensure long-term stability and resistance to complications like peri-implantitis. By unraveling the complexities of how implant surfaces affect osseointegration, we can develop next-generation implants that offer improved performance and reliability for patients.

Differentiating between hydrophilic and hydrophobic implant surfaces is important. Hydrophilic surfaces, unlike hydrophobic ones, encourage interactions with biological fluids and cells, leading to good surface wettability. Interestingly, implant surfaces with the same chemical makeup can show different contact angles for biological fluids based on their surface texture. Rough surfaces, such as those that are sandblasted and etched, are more likely to be wetted compared to smooth surfaces.[1]

2. Osseointegration of Dental Implants

In the historical context, osseointegration of dental implants was initially described as the establishment of a structural and functional connection between newly formed bone and the surface of the implant. This concept was closely associated with the biomechanical idea of secondary stability. The osseointegration process involves a complex sequence of physiological mechanisms similar to those observed in direct fracture healing.[5] The act of drilling an implant cavity mimics a traumatic event to bone tissue, initiating distinct phases of wound healing.

Initially, mechanisms of cellular and plasmatic hemostasis lead to fibrin polymerization and the formation of a blood clot, which serves as a matrix for neoangiogenesis, extracellular matrix deposition, and the infiltration of bone-forming cells. New bone either originates from the borders of the drill hole through distance osteogenesis or is generated by osteogenic cells on the implant surface through contact osteogenesis. In distance osteogenesis, osteoblasts migrate to the surface of the implant cavity, differentiate, and contribute to new bone formation, growing toward the implant in an appositional manner. On the other hand, in contact osteogenesis, osteogenic cells directly migrate onto the implant surface, leading to the generation of de novo bone.[6]

The secondary stability of a dental implant depends significantly on the extent of new bone formation at the bone-to-implant interface. Following Wolff's Law, the subsequent phase involves load-oriented bone remodeling, resulting in the replacement of primary woven bone with realigned lamellar bone. This process aims to optimize the absorption of occlusal load and transmit mechanical stimuli to the adjacent bone. By the end of the remodeling phase, approximately 60–70% of the implant surface becomes covered by bone.[7] This occurrence is termed bone-to-implant contact and serves as a widely used metric in research to assess the degree of osseointegration.

In line with the concept of mechanotransduction, bone remodeling persists throughout an individual's life. Recent research efforts have focused on developing innovative topographies for implant surfaces to enhance osteoblastic migration, adhesion, proliferation, and differentiation.[4]

3. Physical Modifications

Physical modifications of dental implant surfaces are critical for enhancing the integration and performance of implants. These modifications focus on altering the surface topography and texture to improve mechanical interlocking with bone, enhance cell adhesion, and promote osseointegration.[8]

Physical modifications of dental implants can be categorized into three distinct levels: macro, micro, and nano. Each level contributes uniquely to the overall success of osseointegration.

3.1. Macro-level modifications

Macro-level alterations involve changes at a millimeter scale, including the overall geometry of the implant body and the design of its thread patterns. These modifications are crucial for enhancing the primary stability and long-term fixation of the implant within the bone. By optimizing the implant's shape and threads, macro-level modifications ensure better distribution of mechanical loads and minimize micromovements during the initial healing phase.[9]

The design at the macro level includes features such as shape, thread pattern, and surface irregularities. These aspects, collectively known as fixture design, are crucial for determining the implant's surface area, achieving mechanical interlocking with the bone, and ensuring primary stability. Proper implant drilling and the implant's macro geometry are key to successful placement.

The traditional parallel implant design, with a consistent diameter, has been popular for initial stability but is technique-sensitive. In the 1990s, Dr. Jack Hahn introduced tapered implants that mimic the natural tooth root, offering better force distribution and requiring less bone removal, making them ideal for immediate placement and loading.

Thread design on implants is essential for maximizing contact, enhancing stability, and distributing stress. The face angle of threads influences shear force, with lower angles reducing it. Various thread shapes and pitches affect stress transfer and bone contact. Innovations like double and triple thread implants improve insertion and stability by facilitating faster and less traumatic placement.[10]

3.2. Micro-level modifications

Micro-level changes occur at a micrometer scale and are designed to increase the surface area of the implant. This expansion of the surface area is instrumental in improving the formation of the fibrin matrix, which serves as an osteoconductive scaffold.[4] The enhanced surface area supports the adhesion and proliferation of osteogenic cells, facilitating the deposition of new bone matrix around the implant. As a result, micro-level modifications play a vital role in accelerating the early stages of osseointegration.

Machined implant surfaces have long been the standard in implant design, traditionally requiring several months for osseointegration. However, it has been shown that modifying the surface texture can enhance bone-implant contact and biomechanical stability during the initial stages of implantation. As a result, rough surfaces have become dominant in oral implantology, largely supplanting the use of machined surfaces in clinical practice.[11]

The most common types of micro-level modifications for dental implants include grit-blasting, and sandblasting combined with acid etching. These techniques are designed to enhance the surface characteristics of the implants, promoting better osseointegration and stability. Machining involves precise cutting to create a specific surface texture.[12]

3.2.1. Grit blasting

also known as sandblasting, is a widely employed technique to enhance dental implant surfaces by bombarding them with high-velocity abrasive particles such as alumina or titanium oxide. This process creates a roughened texture that significantly increases surface roughness and area, promoting better mechanical interlocking with the bone and facilitating the adhesion, proliferation, and differentiation of osteogenic cells.[13] The enhanced surface topography improves protein adsorption, providing a favourable environment for bone morphogenesis and early-stage bone formation. Consequently, grit-blasted surfaces improve primary stability, accelerate osseointegration, and lead to better long-term clinical outcomes for dental implants.[14]

3.3. Sandblasting and acid-etching

Are complementary surface modification techniques widely utilized in dental implantology to enhance osseointegration. Sandblasting involves propelling abrasive particles like alumina or titanium oxide onto the implant surface at high velocity, creating a macro-roughened texture visible to the naked eye. This process effectively removes contaminants and increases surface area, fostering mechanical interlocking with surrounding bone for improved initial stability and a robust bone-implant interface. On the other hand, acid-etching employs acidic solutions such as hydrochloric or sulfuric acid to modify the titanium oxide layer at a microscopic level, generating a textured surface with pits and irregularities.[15] This micro-roughened surface enhances bioactivity, promoting protein adsorption and facilitating the attachment and proliferation of osteogenic cells crucial for osseointegration. By combining these techniques, dental implants benefit from enhanced macro- and micro-roughness, which synergistically optimize the biological response. This dual approach not only supports immediate stability but also promotes long-term bone integration, ultimately leading to improved clinical outcomes in implant dentistry.[16]

3.4. Nano-level modifications

Nano-level modifications focus on the nanoscale features of the implant surface. These changes aim to enhance surface roughness, wettability, and surface free energy. Improved surface roughness at the nanoscale provides a favorable environment for the initial attachment and growth of cells. Increased wettability promotes better interaction between the implant surface and biological fluids, leading to enhanced protein adsorption and cell adhesion. Additionally, higher surface free energy at the nanoscale supports osteoblastic differentiation, thereby promoting the formation of new bone tissue.

3.4.1. Hydrophilic implants

Regular titanium implants absorb carbonates and hydrocarbons from the air, resulting in low surface energy and hydrophobicity. To counteract this, implants are hydroxylated, rinsed under nitrogen, and stored in isotonic saline until use. Chemical modifications at the nano-scale create a hydrophilic surface with high surface energy, enhancing oxygen absorption and reducing carbon content. For instance, applying a hydroxide ion solution elevates surface energy and hydrophilicity. Implants treated with SLActive® achieve higher hydrophilicity and surface energy, fostering protein affinity, cell attachment, and osteoblast activity, crucial for early osseointegration stages in animal and human studies.[3] Hydrophilic surfaces deter bacterial adhesion by repelling hydrophobic bacteria like P. gingivalis, A. actinomycetemcomitans, and F. nucleatum, potentially improving implant hygiene and long-term efficacy against biofilm formation.

3.4.2. Anodization

Anodization involves creating a thick oxide layer on the implant surface through an electrochemical process. This layer not only improves corrosion resistance but also enhances the surface's bioactivity. Anodized surfaces exhibit increased roughness at the microscopic level, which can improve cell attachment and proliferation.[17]

3.4.3. Hydroxyapatite (HA)

Serves as a source of calcium and phosphate crucial for bone formation, making it ideal for coating titanium implants to enhance their osteoconductive properties. Nano-HA is commonly applied via plasma spraying, where HA particles are heated and deposited onto the implant surface under controlled conditions. Adjusting spray parameters such as gas combination, flow rate, and power influences the physical and chemical characteristics of the HA layer, with an optimal thickness typically ranging from 40 to 50 μm. Clinical studies suggest HA-coated implants promote faster bone integration in challenging bone types like grafted or type IV bone. Additionally, electrochemically deposited fluoridated hydroxyapatite may offer antibacterial benefits against specific pathogens.[4] However, long-term stability and clinical outcomes remain uncertain, as studies show conflicting results regarding osteointegration and microbial contamination between HA-coated and uncoated implants. Concerns also arise regarding HA coating adhesion failures, which may lead to complications like bacterial microleakage and peri-implant tissue issues. Further research is needed to fully assess the efficacy and reliability of HA coatings in dental implantology.[17]

3.4.4. Titanium plasma-spraying

In this technique, titanium powders are fed into a high-temperature plasma torch. The torch heats these titanium particles to extreme temperatures, causing them to melt and fuse onto the implant surface. This results in a titanium plasma-sprayed (TPS) coating with an average roughness of approximately 7 μm. The coating process effectively increases the surface area of the implants, enhancing their osseointegration potential.[3]

3.4.5. Calcium chloride treatment

When titanium undergoes hydrothermal treatment with calcium chloride ($CaCl_2$), the resulting $CaCl_2$-treated titanium (Ca-HT) surface shows improved osseointegration and a better soft tissue seal. This treatment enhances the adsorption of laminin-332 and osteopontin, promoting the adhesion of osteoblasts. Additionally, there is increased attachment of gingival epithelial-like cells and fibroblasts observed on titanium surfaces treated with Ca-HT. Importantly, the Ca-HT treatment does not affect bacterial adhesion, particularly of S. gordonii, suggesting that it enhances cell adhesion without increasing bacterial attachment.[18] It is hypothesized that the presence of calcium on the titanium surface alters the composition of the saliva-acquired pellicle, thereby improving titanium's biocompatibility without promoting bacterial adhesion.

3.4.6. Platelet rich plasma (PRP) and platelet rich fibrin (PRF)

Platelet-rich plasma (PRP) and platelet-rich fibrin (PRF) serve as reservoirs of growth factors that can enhance osteoblast adhesion and improve bone healing. Clinical studies have shown that combining PRP with autogenous bone or organic bone substitutes at the implant site before insertion leads to favorable aesthetic and functional outcomes. In terms of implant surface modification, in vitro research indicates that titanium surfaces treated with PRP or PRF, along with zoledronic acid, exhibit increased filopodia numbers and length in adherent osteoblasts compared to surfaces treated with zoledronic acid alone. This suggests that PRP and PRF may enhance initial bone formation and primary stability of dental implants, especially beneficial in patients undergoing bisphosphonate therapy. However, the comparison between PRP and PRF in stimulating osteogenic cells remains contentious and primarily limited to in vitro studies.[16] Further extensive research is needed to explore the specific growth factors involved, their concentrations, and the actual in vivo effects of PRP and PRF in clinical settings.

3.4.7. Bioactive ceramic coating of dental implant

Among all engineering-based surface modifications for dental and orthopedic implants, coatings enriched with calcium and phosphorus have garnered significant attention. These materials are essential components of natural bone, and their application onto implant surfaces is facilitated by various industrial methods. Most commercially available bio-ceramic coatings, such as Plasma Sprayed Hydroxyapatite (PSHA), are typically 20–50 μm thick. PSHA coatings rely on mechanical interlocking between grit-blasted or etched metal surfaces and the ceramic-like biomaterial to ensure physical integrity during implant placement and function. Studies have shown that PSHA-coated implants exhibit enhanced early bone bonding and bone-to-implant contact. However, they have fallen out of favor in dental practice due to concerns about uniform degradation over extended periods and compromised mechanical properties at the bone-coating interface.[19]

3.4.8. Ion beam assisted deposition (IBAD) of nanothickness bioceramic coatings

To enhance surface osseointegration without the drawbacks of standard Plasma Sprayed Hydroxyapatite (PSHA) coatings as per ASTM F1609-08122, thinner coatings ranging from nanometers to micrometers have been developed for implant surfaces. These thin-film coatings offer controlled composition and thickness, along with improved adhesion to the metallic substrate (40 MPa compared to less than 20 MPa for PSHA-coated implants). Controlled composition and thickness also affect coating dissolution in vivo, potentially enhancing osseointegration early after implantation. However, rapid dissolution of thin films may expose the metallic substrate soon after surgery.[20] Yet, this exposure can lead to close bone contact with the implant substrate at the optical microscopy level post-coating dissolution, which may support favorable conditions for long-term anchorage of the implant device, avoiding complications associated with bone, bioceramic, surface oxides, and metallic substrate interfaces.[20]

4. Conclusion

Dental implantology has evolved significantly, addressing not only the physical and functional repercussions of natural tooth loss but also the profound emotional, psychological, and social impacts on individuals. One of the primary objectives of modifying dental implant surfaces is to reduce the healing period required for osseointegration. This goal is beneficial for both clinicians in implant dentistry and patients alike. As implant macrodesign evolves, surface treatments represent a critical advancement aimed at shortening the time needed for healing before implant restoration. The emerging technology of bioceramic coatings at nanoscale dimensions leverages surface topographies and chemistries to enhance surface osseointegration. This technology is actively being researched both in basic science and clinical settings to determine which properties, whether surface chemistry or subnanometer level texturing, yield the most favorable outcomes. By exploring optimal combinations of implant site preparation, implant materials, and surface modification strategies, there is significant potential to improve implant success rates, particularly in patients with compromised bone quality at implant sites. As this field continues to advance, future studies aim to develop implant surfaces that achieve a balance between rapid and enhanced osseointegration while minimizing biofilm formation, thereby enhancing long-term implant performance.

5. Source of Funding

None.

6. Conflict of Interest

None.

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