



IMPLANT SURFACES IN ORAL IMPLANTOLOGY: FROM OSSEOINTEGRATION BIOLOGY TO FUTURE DIRECTIONS

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ABSTRACT

Introduction: This review examines the pivotal role of implant surface characteristics in oral implantology, moving beyond basic osseointegration towards actively influencing tissue response. Modern implant success relies on the implant's surface properties, affecting bone integration and the quality of the bone-implant interface. This article provides a comprehensive overview of implant surfaces, analyzing treatments, clinical evidence, biological implications, and future directions. **Materials and Methods:** A literature review was conducted using scientific articles from peer-reviewed sources. Studies addressing implant surface characteristics and their impact on osseointegration were included, and the extracted data was analyzed and synthesized into thematic sections. **Discussion:** The surface of an implant is a biological interface profoundly influencing osseointegration. Key findings include the role of surface roughness in promoting cell adhesion and bone formation, with moderately rough surfaces (Sa values between 1 and 2 μm) being most effective. Chemical surface properties, such as titanium oxides, influence surface energy and wettability, impacting protein adhesion and osteoblastic activity. Surface modifications like alumina blasting and acid etching optimize the titanium-bone interface. Furthermore, soft tissue attachment and transmucosal designs play a crucial role in long-term peri-implant health. The review also addresses advanced strategies such as bioactive surfaces, immediate loading protocols, and considerations for medically compromised patients, as well as digital innovations. **Conclusions:** Implant surfaces are dynamic and strategic in modern implantology. Optimizing surfaces and employing proper clinical management are essential for achieving optimal and lasting aesthetic and functional results.

KEYWORDS: *Implant surface, osseointegration, bioactive surface, surface roughness, peri-implant tissue*

INTRODUCTION

In recent decades, oral implantology has made significant progress, evolving from a pioneering discipline to a highly predictable clinical procedure (1). The success of a dental implant no longer depends solely on its macroscopic design or the material used, but also, and above all, on the implant's surface characteristics (2-4). The interface between the implant and the bone is the focal point of the osseointegration process, a complex biological phenomenon involving the interaction between artificial surfaces and living tissues (5). The surfaces of implants are no longer considered simple passive

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components (6). On the contrary, they actively modulate cellular responses, influencing not only the extent and speed of bone integration, but also the quality of the interface that develops. Their structure, chemical composition, degree of roughness, and surface energy determine how serum proteins are adsorbed, how cells are activated, and how regenerative processes are initiated (7). Scientific literature has clearly demonstrated that intentional surface modifications through mechanical, chemical, or physicochemical treatments can accelerate osteoconduction, increase bone-implant contact (BIC), and improve outcomes even in challenging clinical scenarios such as immediate loading or low-density bone conditions (8,9). These modifications not only facilitate colonization by osteoprogenitor cells but also reduce the risk of early failure, particularly in systemically compromised patients or regenerated sites (10). At the same time, increasing attention has been focused on the transmucosal interface: It is now well-known that the surface of prosthetic abutments and implant collars can significantly influence soft tissue responses. Maintaining peri-implant health depends not only on solid bone anchorage but also on the formation of a stable soft tissue seal capable of protecting the underlying bone from bacterial infiltration and chronic inflammation (11). This article aims to provide a comprehensive and up-to-date overview of the role of implant surfaces in osseointegration, critically analyzing the main available treatments, clinical evidence, biological implications, and future prospects.

MATERIALS AND METHODS

This article is a literature review that aims to provide a comprehensive and up-to-date overview of the role of implant surfaces in osseointegration.

Data Sources

Search for scientific articles published in peer-reviewed journals, specialised textbooks, and online databases (e.g., PubMed, Scopus, Web of Science). *In vitro* studies, *in vivo* studies, systematic reviews, and meta-analyses were considered.

Selection Criteria

The articles were selected based on specific inclusion and exclusion criteria. Inclusion criteria included studies addressing implant surface characteristics (e.g., topography, chemical composition, surface treatments), their influence on osseointegration, soft and hard tissue response, clinical implications, and applied new technologies. Studies that were not relevant to the topic, had inadequate methodology, or insufficient data were excluded.

Data Analysis and Synthesis

The extracted data was critically analysed and synthesised to provide an overview of the topic. The information has been organised into thematic sections to facilitate understanding and discussion of the results. Controversies and areas of uncertainty were highlighted and discussed in light of the available evidence.

DISCUSSION

In modern implantology, the implant surface represents much more than just an area of mechanical contact with the bone: It acts as a true biological interface capable of profoundly influencing the entire process of osseointegration. When an implant is inserted into bone, its surface characteristics determine cellular and molecular responses. The interaction between the implant and the tissue begins with the adsorption of plasma proteins onto the titanium surface, an event that occurs within seconds and shapes everything that follows. The composition, topography, and surface energy determine which proteins bind, in what conformation, and consequently influence the behavior of immune cells, fibroblasts, and, most importantly, osteoblasts. Osseointegration is therefore not a static event, but a dynamic and orchestrated sequence of processes initiated by this first micro-interaction. Pioneering studies by Albrektsson and Brånemark have shown that the stable attachment of bone to the implant surface – what we call osseointegration – is not simply a mechanical result, but is mediated by a specific biological response, favored by certain topographical and chemical characteristics of the surface (1,2). Over the years, research has focused on optimizing this interface, leading to the development of roughened, treated, nanostructured, and even bioactive surfaces. One of the key findings was the role of surface roughness. Moderately rough surfaces, with Sa (Surface Area) values between 1 and 2 μm , have proven to be the most effective in promoting cell adhesion and early bone formation in direct contact with the implant (5). This level of roughness elicits a more favorable cellular response compared to smooth surfaces, which tend to induce distant osteogenesis with longer healing times. Simultaneously, it has been demonstrated that the chemical nature of the surface, particularly its elemental composition and the presence of titanium oxides, influences the surface energy and thus the wettability, a key factor for protein adhesion. Hydrophilic and negatively charged surfaces appear to enhance osteoblastic activity and promote faster mineralization (9). These discoveries have prompted manufacturers to develop sophisticated treatments aimed at

improving the biological properties of implant surfaces. Techniques such as alumina blasting, acid etching, anodic oxidation, and the application of bioactive coatings are now widely used to optimize the titanium-bone interface (6,10). Surfaces treated with aluminium oxide blasting, strong acid etching, or combined techniques such as blasting followed by acid etching (SLA) have demonstrated an increased ability to induce direct bone formation and increase bone-implant contact (BIC) (5,6). These effects also occur in the first few days after implant insertion, positively influencing secondary stability. Furthermore, surfaces with micro- and nanoscale structures have proven particularly effective in influencing osteoblastic behavior, improving cell adhesion, proliferation, and differentiation (12). In these scenarios, surface roughness becomes a strategic factor for the success of the implant.

Chemical and physical characteristics of the implant surface

In addition to morphology, the chemical and physical characteristics of the implant surface play a crucial role in determining the host's biological response. Surface treatments that improve wettability have been shown to significantly improve biological responses both *in vitro* and *in vivo* (13). For example, etching sandblasted surfaces with sulphuric acid and hydrochloric acid produces a multiscale topography that combines micro- and nano-roughness, while simultaneously increasing surface energy. Anodizing not only modifies the topography but also leads to the controlled thickening of the titanium oxide (TiO₂) layer, giving the surface new chemical properties and increased stability. This oxide coating, often enriched with calcium and phosphate, can act as an osteoinductive substrate that stimulates early mineralization (14). The use of bioactive surfaces coated with hydroxyapatite (HA) has also aimed to mimic the composition of natural bone. However, despite their high osteoconductive potential, such surfaces have shown limitations related to poor coating stability and delamination phenomena (15). More recently, the introduction of nanotechnology has enabled the creation of hierarchical surfaces that interact directly with subcellular components, such as integrins and filopodia, thus modulating cell behavior in a targeted manner (16).

Tissue response to the implant surface

The success of a dental implant depends not only on its initial mechanical stability, but, more importantly, on the quality of the biological interaction established between the implant surface and the surrounding tissues. This interaction involves both hard tissues (bone) and soft tissues (mucosa), each of which responds differently depending on the surface characteristics. Osteoprogenitor cells and osteoblasts migrate towards the implant surface in response to mechanical-chemical signals, attach via integrins, and initiate the deposition of the extracellular matrix. This process is strongly influenced by topographies that mimic the native extracellular matrix (12,13). On the contrary, the response of soft tissues is more complex. The formation of a stable epithelial and connective tissue attachment around the implant collar is essential for creating a barrier against bacterial infiltration and ensuring long-term peri-implant health. Animal studies have shown that the morphology of the transmucosal surface influences the height of the junctional epithelium and the arrangement of collagen fibers (17,18). Specifically, surfaces with controlled micro-roughness, micro-channels, or laser-generated patterns (e.g., Laser-Lok®, laser micro-channels) appear to promote parallel or perpendicular alignment of connective tissue fibers relative to the implant axis, partially mimicking the attachment found around natural teeth (19). This translates into greater stability of the mucosal seal and a reduced incidence of mucositis (20) and peri-implantitis over time. However, when peri-implantitis does occur, effective treatment strategies are needed to restore tissue health and prevent further bone loss. Electrolytic cleaning combined with regenerative therapy has shown promise in achieving these goals (21). Additionally, soft tissue management is influenced by the number and timing of stump disconnections and reconnections. The "one pillar, one time" protocol - which involves leaving the pillar in place from the initial placement - has shown positive effects on maintaining biological width and mucosal stability (22).

Connecting and managing the biological seal system

The implant-abutment connection is a critical factor in preserving long-term tissue integrity. It's not simply a mechanical issue – concerning the stability between the implant and the prosthetic component – but also a biological one, as the transmucosal interface acts as the first line of defense against bacterial infiltration. Numerous studies have shown that the connection design directly influences the quality of soft tissue attachment and the prevention of crestal bone resorption (18,22). Flat-top or platform-switching connections have been shown to be more effective in minimizing initial bone loss compared to traditional conical-cylindrical designs, primarily due to their ability to move the implant microgap away from the bone. Additionally, laser-treated surfaces with microstructures, such as circumferential grooves (e.g., Laser-Lok), appear to guide the orientation of collagen fibers, promoting a parallel arrangement that mimics the connective attachment of a natural tooth and improves soft tissue adhesion to the abutment surface (19,22). Recent research has also highlighted how laser-created microtopography can positively influence osteoblast proliferation and bone deposition (23). This results in a more stable mucosal seal and a more effective barrier against microbial invasion.

Prosthetic management also plays a fundamental role: Each disconnection and reconnection of the stump disrupts the seal of the epithelial and connective tissue, increasing the risk of inflammation and bone remodeling (17,24). For this reason, the clinical strategy of "one abutment, once" has become widespread, involving the definitive positioning of the abutment during surgery and maintaining it throughout all prosthetic phases. Geometry has led to the development of convergent or concave collars, which appear to improve soft tissue maturation and aesthetic outcomes, particularly in the anterior region (25).

Advanced Strategies for Implant Surface Optimization

In recent years, scientific interest has increasingly focused on implant surfaces that actively influence cellular and microbial behavior through multifactorial approaches. The goal is no longer just to achieve successful osseointegration, but also to elicit a controlled and lasting tissue response in complex clinical environments. Bioactive surfaces represent an evolution beyond osteoconductive ones: Instead of simply supporting bone growth, they actively stimulate it. Coatings containing calcium phosphate, biofunctional peptides, or growth factors have shown promising results both in vitro and in vivo, although issues regarding the long-term stability of the coating remain (15,26). While traditional surfaces are effective in promoting osseointegration, they often fail to prevent bacterial adhesion, a key factor in the development of mucositis and peri-implantitis. To address this issue, bacteriostatic or bactericidal surfaces have been developed by incorporating silver, zinc, or copper ions, or through laser treatment, nanostructuring, or antibacterial coatings (27). However, the antibacterial effectiveness must be carefully balanced with biocompatibility: Many surfaces that inhibit microbial growth also show cytotoxic effects on human cells. Current research is therefore focused on the development of "smart" surfaces that release antimicrobial agents in a controlled manner or become active only in the presence of bacterial biofilm (28). Finally, multifunctional surfaces, which combine osteoconductive, antibacterial, and immunomodulatory properties, represent the future of implantology. The use of composite biomaterials, engineered microenvironments, and patient-specific genetic customization are among the evolving approaches currently being explored in preclinical and clinical research.

Implant Surfaces and Immediate Loading

The concept of immediate loading represents one of the most advanced and ambitious frontiers in implantology. This protocol offers significant advantages in terms of reducing treatment time and improving the patient experience, but it also requires favorable clinical conditions to ensure long-term success. Therefore, innovative alveolar ridge preservation techniques combined with immediate implant placement can improve outcomes and predictability in these cases. (29) One of the key factors influencing the predictability of immediate loading is the implant surface area. To achieve sufficient short-term secondary stability, it is necessary to promote a rapid biological response and early contact between the implant and the surrounding bone tissue. Moderately rough surfaces have demonstrated greater osteoconductive potential compared to smooth or turned surfaces, contributing to faster bone formation that adheres directly to the implant surface (5,6). An "active" surface accelerates the adsorption of plasma proteins, cell recruitment, and neovascularization, key factors for early integration under functional load. It has also been observed that the surgical protocol, optimization of the implant site, and the adoption of minimally invasive techniques contribute to maintaining high primary stability, an essential prerequisite for initiating early loading (30). These approaches have also proven effective in post-extraction treatments, with or without bone grafting, as demonstrated by Mastrangelo et al. in a multicenter study with a 3-year follow-up, which reported comparable implant survival rates (31). In patients with low bone density, such as the posterior maxilla or systemically compromised individuals, the effectiveness of treated surfaces becomes even more evident. Under such difficult conditions, the surface's ability to stimulate an early osteogenic response can be the determining factor between success and failure (7). Ultimately, the success of immediate loading is closely linked to the quality of the interface established between the implant and the host tissue: An optimized surface, designed to maximize biochemical and cellular interactions during the early stages of healing, is now considered essential for the safe application of early or immediate loading protocols.

Implant surfaces in medically compromised patients

Implant treatment in medically compromised patients or in unfavorable clinical conditions represents a growing challenge in modern dentistry. Conditions such as diabetes, osteoporosis, immunosuppression, smoking, drug-induced osteonecrosis (32), cancer therapies, or bisphosphonate use negatively impact bone healing and increase the risk of early and late implant failure. In scenarios like this, the choice of implant surface becomes even more critical. Studies have shown that moderately rough or bioactive surfaces can partially compensate for the biological limitations of these patients, promoting faster cell colonization and increased extracellular matrix deposition even when regenerative capacity is reduced (6,33). A particularly critical situation concerns regenerated sites or those that have undergone pre-implant

surgery. In these cases, the remaining bone quality and quantity can be compromised, necessitating the use of highly osteoconductive surfaces capable of stimulating new bone formation even under mechanically unfavorable conditions (7). Recent studies have shown promising survival rates for implants placed in regenerated sites using innovative biomaterials (34). In an in vitro study, Gianfreda et al. demonstrated the effectiveness of various decontamination protocols on the surfaces of contaminated implants, highlighting that surface characteristics influence both the response to treatment and the potential for functional osseointegration (35). Finally, in cancer patients undergoing chemotherapy or radiotherapy, the use of biofunctional surfaces and treatments that minimize healing times can improve long-term outcomes. Understanding the molecular state of the disease could contribute to further personalizing the implant approach in the future (36). However, treatment planning in these cases must be multidisciplinary and highly individualized.

Implant Surfaces and Digital Innovation

The advent of digital technology has revolutionized the entire workflow in implantology, including the design and management of implant surfaces (37). Digitalization, from virtual planning to guided surgery (38) and CAD/CAM prosthetics, has made possible a level of precision that was unimaginable just a few years ago. The use of digital facebows is also becoming increasingly widespread, with studies demonstrating their accuracy in vitro (39). Its impact goes beyond technical aspects, influencing biology and the interaction between implants and surrounding tissues. Pre-surgical digital planning, combined with high-resolution three-dimensional imaging and design software, allows for highly precise implant placement, optimizing bone-implant contact in areas of higher bone density. This directly affects initial integration, making the implant surface characteristics even more critical. The adoption of guided surgery and custom implants also minimizes surgical trauma and preserves vascularization at the recipient site. Consequently, the surface quality can express its full osteoconductive potential, especially when combined with immediate loading protocols. Simultaneously, 3D printing and additive manufacturing technologies are opening up new frontiers in the development of customized surfaces, characterized by textures and microtopographies tailored to the recipient site or the patient's clinical condition. Research is currently underway to create customized surfaces with roughness gradients and localized surface functionalization, which could further improve predictability in complex cases. The management of prosthetic restorations has also changed radically. With fully digital workflows, the final abutment can be placed immediately and permanently, reducing disconnections and maintaining the integrity of the biological seal (19,24). Finally, digital technologies are emerging in the surface assessment itself: Digital scanning electron microscopy, 3D profilometry, and automated image analysis now allow for extremely precise and reproducible characterisation of implant surfaces, improving the quality of research and the reliability of clinical data (40).

CONCLUSIONS

In summary, implant surfaces represent a dynamic and strategic element in modern implantology. Several physiological and pathological situations (40,41), such as smoking, osteoporosis, drug-induced osteonecrosis, diabetes, immunosuppression (42,43), cancer therapies (32), or bisphosphonate use negatively impact bone healing (45) and increase the risk of early and late implant failure promoting critical conditions that could be limited using bioactive biomaterials or digital technologies to minimize healing times and improve long-term outcomes (45) as showed in recent studies. The evolution of engineering techniques, from the first targeted approaches to roughness to nanotechnology and bioactive coatings, has profoundly transformed this field. Optimizing wettability, surface energy, and chemical composition, along with the adoption of innovative transmucosal designs such as platform switching and laser-etched microstructures (Laser-Lok), has significantly improved osseointegration and the stability of peri-implant soft tissues. In complex clinical contexts, such as low bone density or medically compromised patients (diabetes, osteoporosis, etc.), high-performance surfaces have been shown to partially compensate for biological limitations, accelerating bone neoformation and improving the predictability of immediate loading. The advent of nanotechnology and its integration with digital workflows herald a future where implant surfaces will be custom-designed to meet individual patient needs, optimizing interaction with surrounding tissues and improving long-term predictability. Future research should focus on developing multifunctional surfaces that combine osteoconductive, antibacterial (with silver, zinc, or copper ions), and immunomodulatory properties, managing the risk of mucositis and peri-implantitis. Furthermore, it is crucial to evaluate the long-term stability of bioactive coatings (calcium phosphate, biofunctional peptides), overcoming the limitations related to delamination. However, it is crucial to emphasize that clinical success does not depend solely on surface characteristics. Proper planning, atraumatic surgery, and adequate prosthetic management remain essential elements. Only through a multidisciplinary approach that integrates the latest technological innovations with a solid biological foundation

and careful clinical management will it be possible to fully harness the potential of implant surfaces to offer patients optimal and long-lasting aesthetic and functional results.

Conflict of interest

The authors declare that they have no conflict of interest.

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