

Coating techniques for dental implant surfaces

Grazia Marinelli¹
Paola Bassi¹
Laura Ferrante¹
Valeria Colonna¹
Silvia Chieppa¹
Massimo Corsalini¹
Sabina Saccomanno²
Silvia Piccolo³
Mara Fammilume⁵
Ludovica Pergolesi⁵
Robert Marcucci⁵
Marco Farronato^{6,7}
Cinzia Maspero^{6,7}
Fabio Luis Bunemer Guerra⁸
Ana Júlia de Paula Guerra⁸
Andrea Palermo⁴

¹Department of Interdisciplinary Medicine, University of Bari “Aldo Moro”, Bari, Italy

²Department of Life Science, Health and Health Professions, Link University, Italy

³Department of Biomedicine and Prevention, University of Rome “Tor Vergata, Rome, Italy

⁴ Experimental Medicine, University of Salento, Lecce, Italy

⁵D.I.S.C.O., School of Dentistry, Polytechnic University of Marche, Ancona, Italy

⁶Department of Biomedical, Surgical and Dental Sciences, University of Milan, Milan, Italy

⁷ Fondazione IRCCS Ca’ Granda, Ospedale Maggiore Policlinico, Milan, Italy

⁸ São José do Rio Preto, Brazil.

Corresponding Author: Andrea Palermo
e-mail: andrea.palermo@unisalento.it

Abstract

Biocompatible solutions such as endosseous implants enable the restoration of missing teeth. This review explores the key features of various implant surface coatings that promote tissue healing around implants and support long-term clinical success. The analysis is based on recent studies of titanium endosseous implants, which are widely used because of their excellent physical and chemical properties. However, titanium has low bioactivity, which can slow down the process of osseointegration. To enhance cellular interactions and boost biocompatibility, implant surfaces are modified to reduce tissue rejection and encourage biological integration.

This review examines various surface coatings to determine the most effective ones in enhancing osseointegration, epithelial adhesion, and peri-implant health. The properties of implant surfaces are essential for promoting osteoblastic cell adhesion, growth, and distribution, which are critical for maintaining stable anchorage. Additionally, implant surfaces should have antibacterial features to reduce the risk of peri-implant infections, which could adversely affect implant longevity and overall clinical outcomes.

Advancements in surface modification techniques have led to the development of innovative coatings designed to enhance biological interactions and improve



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the long-term performance of dental implants. However, further research is needed to optimize implant materials and surface treatments and reduce clinical failure.

Keywords: bone integration; implant surface; surface modification; dental prosthetic implant; titanium material; surface treatment; peri-implant tissue health; implant anchorage; microbial attachment; crestal bone level.

Introduction

The natural loss of teeth affects individuals physically, functionally, psychologically, and socially (1–12). Implantology has proven to be highly effective among the most reliable and widely adopted surgical techniques (13–16). The primary materials used for dental implants include titanium, zirconium, and polyetheretherketone (PEEK)(17–21) (22–29).

Zirconium implants have excellent aesthetics but a moderate fracture risk (30,31).

Conversely, PEEK implants have shown high failure rates, necessitating further long-term, multicenter studies to validate their reliability(32–35). Titanium remains the gold standard in implantology due to its superior properties, including osseointegration, biocompatibility, mechanical strength, and antibacterial effects(36–42).

Albrektsson introduced the concept of “osseointegration” in 1981 to describe the structural and functional connection between the implant surface and the bone (43–52) (53–57). Several key factors influence proper bone remodeling, including biocompatibility, implant design, surface characteristics, bone quality at the recipient site, surgical technique, and operator expertise (58–62).

There are morphological similarities between the periodontal tissues of natural teeth and those surrounding implants(63–67). However, peri-implant connective tissue has a higher collagen content and fewer fibroblasts than natural periodontal structures(68–71) (72–79). The interaction between the implant’s outermost layer and surrounding biological tissues plays a crucial role in determining the success of osseointegration(80–86).

Biological anchorage between the implant surface and bone tissue is crucial for long-term success, as bone response is closely linked to surface characteristics(87–91). Implant surfaces can be categorized as hydrophilic or hydrophobic(92–95). Compared to hydrophobic surfaces, hydrophilic ones enhance interactions with biological fluids and cells, increasing wettability(96–99). Greater hydrophilicity encourages quick contact with blood clots, speeding up osseointegration(100–103). Some highly hydrophilic surfaces create suction when first contacting blood, improving clot adhesion(104–109). Additionally, rough surfaces improve blood clot retention, supporting fibrin network formation and stabilizing healing (110–115).

During healing, various biological events take place:

- Formation of a fibrin clot that protects the wound, with platelets releasing repair factors.

- Fibrinolysis, leading to clot resorption.
- Osteoclastic activity allows cell migration from the bloodstream.

Implant stability is crucial for successful osseointegration and healing(116–124). Primary stability depends on bone quality, implant design, and surgical technique, while secondary stability arises from bone remodeling and new bone growth around the implant(125–127). Increasingly, research emphasizes the role of surface characteristics in achieving secondary stability (128–131). Initially, bone growth occurs in trabecular bone before extending to cortical bone, with peri-implant bone metabolism peaking within one to four months after surgery (132–134).

Beyond osseointegration, long-term clinical success depends on maintaining a stable bone–implant–soft tissue interface(135–140). Earlier titanium implants had smooth, mechanically polished surfaces, but recent research has shown that roughened surfaces offer greater long-term stability(141–144). Surface treatments aim to increase the bone-implant contact (BIC) percentage, enhance osseointegration, and introduce antibacterial properties to prevent peri-implant illness(145–148). Furthermore, optimized implant surfaces must withstand mechanical stresses such as mastication, ensuring the long-term health of peri-implant tissues(149–151).

This review examines implant surface modifications to identify the most effective structure from a clinical and durability standpoint, aiming to reduce post-surgical complications and patient discomfort(152–155). Given the rapid progress in material science and surface engineering, ongoing research remains crucial for enhancing implant performance and long-term success(156–158).

Materials and Methods

A search was conducted using the following keywords: “Dental implant surface” AND “osseointegration,” analyzing publications in the Scopus, Web of Science, and PubMed databases, limited to articles in English. The review concentrated on studies involving human participants, especially clinical research and case reports.

Titles and abstracts of the retrieved studies were screened, excluding irrelevant articles. Full-text reviews were performed for the remaining studies. Any disagreements between reviewers were resolved through collaborative discussion to reach a consensus. The inclusion criteria were: (1) human in vivo studies; (2) English-language articles; (3) open-access publications; (4) clinical studies; (5) studies examining surface treatments and coatings of titanium dental implants; and (6) in vitro studies providing meaningful insights into implant surface coatings.

Exclusion criteria included: (1) animal studies; (2) publications in languages other than English; (3) non-open-access studies; (4) case reports, review articles, editorials, and book chapters; (5) research focusing on zirconium and PEEK dental implants; and (6) in vitro studies that did not align with the research objective.

Results

The review identified 1262 studies from PubMed, Scopus, and Web of Science databases. After removing 530 duplicate articles, 732 unique papers remained. During initial screening, 442 articles were excluded due to their irrelevance to the research focus. The main reasons for exclusion included: unavailability of the full text (3 articles), animal studies (131 articles), book chapters (1 article), non-clinical and irrelevant in vitro studies (75 articles), reviews and meta-analyses (66 articles), and studies unrelated to the subject matter (166 articles). A further evaluation removed 279 studies because they lacked significant findings, leaving 11 publications that met the eligibility criteria. Among these, 5 were in vitro studies, while the rest focused on clinical applications.

This review underscores the crucial role of implant surface modifications in improving osseointegration and implant stability. Although various surface treatments, including roughening, chemical coatings, and hydrophilization, have shown potential benefits, their long-term clinical effectiveness remains an ongoing area of research. Future developments in implant surface engineering should focus on combining osteoconductive and antimicrobial properties to enhance clinical success further. Considering the complexities of implant biology and patient differences, a multidisciplinary approach that includes materials science, biomedical engineering, and clinical research is essential for optimizing the design of next-generation dental implants.

A literature review emphasizes the increasing focus on implant surface modifications to improve osseointegration and long-term stability. Different implant surfaces have been examined, including hydrophobic and hydrophilic coatings, alkali-treated surfaces, sandblasted finishes, and acid-etched modifications.

Findings indicate that hydrophilic implant surfaces support enhanced interaction with biological fluids, leading to quicker cellular adhesion. However, no clinically meaningful differences were observed between hydrophilic and hydrophobic surfaces regarding peri-implant healing and long-term bone stability.

Additional studies explored the impact of implant topography and chemical modifications on osseointegration quality. Notably, acid etching at 140°C significantly enhanced osteoblast differentiation, improving the implant's osseointegration potential. Similarly, calcium phosphate coatings have demonstrated an ability to improve early bone contact, thereby contributing to greater primary stability.

These findings confirm that modifying implant surfaces is essential for optimizing interactions between the implant and surrounding tissues, improving cellular adhesion, and reducing the risk of clinical failure.

Discussion

Titanium and its alloys have been widely used in dental implantology due to their superior mechanical properties, biocompatibility, corrosion resistance, and high success rates of 95–97% (159–165). A key characteristic of titanium is its ability to form a thin oxide layer (~5 nm thick) upon exposure to air and water,

which enhances its corrosion resistance and promotes its integration with biological tissues (166–168)(169–172). However, despite its advantages, titanium lacks inherent antibacterial properties, making it susceptible to bacterial colonization at the implant collar (173–176). This bacterial adhesion can lead to peri-implant infections, which, if untreated, may compromise implant stability and lead to failure (177–179). Treatment of peri-implantitis often requires antibiotic therapy, raising concerns about antibiotic resistance, financial costs, and patient discomfort (180–182). Therefore, modifications to titanium surfaces are crucial to enhance antibacterial activity and promote early-stage osseointegration, thereby improving long-term implant success (183–186) (Figure 1).

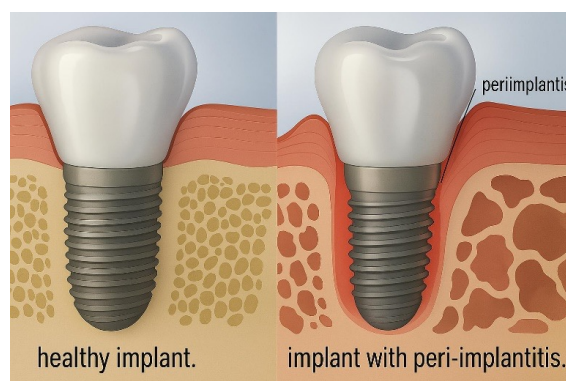


Figure 1. Difference between healthy implants and implants with peri-implantitis

Surface Topography's Effect on Osseointegration

The microstructure and topography of implant surfaces are crucial in interacting with biological tissues (187–194). The stability of an implant depends on both primary and secondary factors (195–197). Primary stability mainly results from mechanical factors, influenced by the macro- and micro-geometry of the implant, as well as surgical placement techniques (198–203). Secondary stability is mainly determined by the surface characteristics of the implant, which affect the biological response of bone cells (204–206). Research has indicated that roughened implant surfaces offer better osseointegration potential than smooth surfaces, as they enhance cellular adhesion, osteoblast proliferation, and matrix mineralization while decreasing osteoclastic activity (207–211).

Hydrophilicity and Wettability of Implant Surfaces

Implant surfaces can be machined, polished, treated, or hybrid (212–214) (215–221). Among these, treated and hybrid surfaces show increased wettability and hydrophilicity compared to smooth, machined, inherently hydrophobic surfaces (222–227). Surface treatments involve adding or removing material at the micro- or nano-scale (228–230) (231–237). Several studies have demonstrated that enhancing the hydrophilicity of an implant surface improves blood

protein adsorption, fibrin network formation, and cellular attachment, all of which help speed up healing and bone integration(238–241). Additionally, implants with hydrophilic surfaces have been linked to a higher success rate in challenging bone conditions, such as those with low bone density or poor regenerative potential(242–245) (Figure 2).

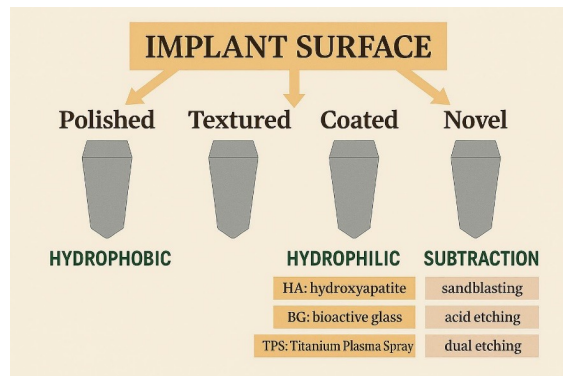


Figure 2. Classification of dental implant surfaces

Effect of Chemical Modifications on Biological Performance

Chemical modifications of implant surfaces aim to enhance their biological properties by altering their surface composition (246–249). One of the most studied modifications involves adding bioactive coatings, such as calcium phosphate, hydroxyapatite, or bioactive glass, to improve bone bonding (250–256). Studies have shown calcium phosphate-coated implants have a higher bone apposition rate than uncoated surfaces (257–261). Similarly, bioactive glass coatings are known to trigger a rapid biological response by promoting the formation of a calcium-phosphate-rich layer on the implant surface (262–264) (265–267). Additionally, chemical treatments such as anodization, acid etching, and alkali treatment have produced nano-structured surfaces with enhanced osteoconductive properties (268–270) (271–275). Applying nanometer-scale modifications increases surface energy and roughness, which boosts cellular attachment and growth (276–281) (Figure 3).

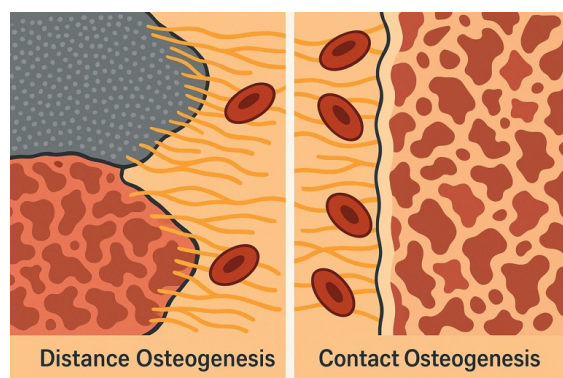


Figure 3. Osteogenesis on implant surface: bone formation and biomaterial integration.

Comparative Analysis of Implant Surface Treatments

The studies included in this review examined various surface treatments and their effects on implant stability and osseointegration (282–287). However, another study showed that alkali-modified surfaces had better initial stability than sandblasted implants, although both types produced similar clinical results after 12 weeks (288–293) (294–299). A further investigation into acid-etched surfaces found that the highest osseointegration potential occurred when titanium surfaces were treated with sulfuric acid at 140°C, indicating an optimal threshold for surface modification (300–306) (307–312). Another comparative study assessed the peri-implant bone response of calcium phosphate-coated versus uncoated SLA (sandblasted, large-grit, acid-etched) implants, and found no significant differences in marginal bone levels after 12 months (313–323). These findings suggest that surface modifications can affect initial implant stability and osseointegration; however, their long-term clinical impact may depend on patient-specific factors and loading conditions (324–328).

Despite the promising results obtained from in vitro and clinical studies, further research is required to optimize implant surface characteristics for improved clinical outcomes (329–338) (339–344). Future investigations should focus on developing multi-functional surfaces that promote osseointegration and possess antimicrobial properties to reduce the risk of peri-implant infections (345–363). Additionally, the long-term stability of surface modifications should be evaluated through extended clinical trials with larger sample sizes (364–372). Researchers should also explore the potential of bioengineered coatings that mimic the natural extracellular matrix to enhance cellular adhesion and tissue integration (373–385). Furthermore, studies investigating patient-related factors, such as systemic health conditions, smoking status, and oral hygiene, are essential for understanding how implant surface modifications interact with host tissues in real-world scenarios (386–422).

Conclusions

This study demonstrated that although all analyzed surfaces facilitated osseointegration and cellular proliferation, those treated with surface irradiation exhibited superior epithelial cell adhesion and increased osteoblastic cell proliferation. However, implant research should not focus solely on enhancing osseointegration to achieve stability. Still, it must also emphasize the crucial role of soft tissues in creating a protective barrier around the implant. This barrier is essential for maintaining peri-implant tissue integrity and ensuring the long-term success of prosthetic rehabilitation.

In implant development, osseointegration must be regarded as an essential element, as it equally contributes to implant stability and the formation of an effective mucosal seal. Investigations into micro- and macro-topographical modifications of implant surfaces should be directed toward designing innovative medical devices that minimize the risk of clinical failure

and enhance overall therapeutic outcomes. The key objectives of surface modifications include improving clinical success in cases of deficient bone quality and quantity, accelerating the osseointegration process to support protocols, stimulating bone regeneration in areas with inadequate alveolar ridge for implant placement, and ensuring a well-sealed mucogingival junction to prevent bacterial penetration.

Ongoing scientific and technological advances continue to foster extensive research within this domain. Nonetheless, incorporating experimental discoveries into clinical applications remains a substantial challenge. Long-term clinical validation is essential to substantiate the efficacy of these innovations in patients, emphasizing the significance of prolonged observational studies before their broad adoption in clinical practice.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest

Abbreviation

Abbreviation	Definition
BIC	Bone implant contact
PEEK	Polyetheretherketone
SLA	Coarse-grain blasting and acid etching

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