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Comparative Evaluation Of Dental Implant Surface Modifications: Current Evidence And Future Perspectives – A Narrative Review

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ABSTRACT

Background: Dental implant therapy has become the standard of care for the replacement of missing teeth, with long-term survival rates exceeding 90% in most clinical situations. While implant design, surgical technique, host factors, and prosthetic loading influence treatment success, the characteristics of the implant surface play a fundamental role in the establishment and maintenance of osseointegration. During the last four decades, substantial advances in implant surface engineering have resulted in the development of numerous surface modification techniques designed to accelerate bone healing, improve implant stability, enhance bone-to-implant contact, and reduce healing time. Objective: This narrative review summarizes the evolution of dental implant surface modifications, critically compares the currently available surface technologies, and discusses their biological rationale, mechanisms of action, clinical performance, advantages, limitations, and future directions. Review: The available literature demonstrates that moderately rough implant surfaces generally achieve superior early osseointegration compared with smooth machined surfaces. Surface modification techniques such as sandblasting with large grit followed by acid etching (SLA), resorbable blast media (RBM), anodization, laser microtexturing, plasma spraying, hydrophilic surface treatment, ultraviolet photofunctionalization, nanostructuring, and bioactive coatings have all been investigated to improve the biological response at the bone–implant interface. Hydrophilic and nanostructured surfaces appear to accelerate early healing, whereas bioactive coatings may further enhance osteogenic activity. Nevertheless, long-term superiority of any single surface modification remains difficult to establish because of variations in implant systems, patient characteristics, study designs, and outcome measures.Conclusion: Modern implant surface engineering has significantly enhanced the predictability of implant therapy. Although moderately rough and hydrophilic surfaces currently possess the strongest clinical evidence, future developments involving nanotechnology, biomimetic coatings, antimicrobial surfaces, and multifunctional bioactive modifications are expected to further improve implant performance. Well-designed multicenter randomized clinical trials with long-term follow-up remain necessary to identify the optimal surface characteristics for different clinical scenarios.

Keywords: Dental implants; Implant surface modification; Osseointegration; Titanium implants; Surface roughness; SLA; Hydrophilic implants; Nanotechnology; Bioactive coatings.

INTRODUCTION

Since the pioneering work of Brånemark and colleagues established the principle of osseointegration in the 1960s, dental implants have transformed the rehabilitation of partially and completely edentulous patients. Osseointegration, defined as a direct structural and functional connection between living bone and the surface of a load-bearing implant, remains the biological foundation for the long-term success of implant therapy. Continuous advances in implant design, biomaterials, surgical protocols, and prosthetic rehabilitation have resulted in survival rates that routinely exceed 95% over long-term follow-up in healthy individuals.

Although implant macrogeometry contributes to primary stability, increasing evidence demonstrates that implant surface characteristics critically influence

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the biological events occurring immediately after implant placement. Protein adsorption, fibrin clot stabilization, inflammatory cell recruitment, osteoblast adhesion, proliferation, differentiation, extracellular matrix deposition, angiogenesis, and mineralization are all regulated by the physicochemical properties of the implant surface. Consequently, implant surface engineering has become one of the most extensively investigated fields in contemporary implant dentistry.

The first generation of commercially pure titanium implants possessed relatively smooth machined surfaces. While these implants demonstrated satisfactory long-term survival, experimental studies revealed that increased surface roughness enhanced mechanical interlocking with newly formed bone and accelerated osseointegration. These observations led to the development of numerous subtractive and additive surface modification techniques.

Subtractive methods primarily include grit blasting, acid etching, dual acid etching, laser texturing, and combinations such as sandblasted large-grit acid-etched (SLA) surfaces. Additive techniques include titanium plasma spraying, hydroxyapatite coatings, calcium phosphate deposition, anodic oxidation, bioactive ceramic coatings, and more recently, biomolecular and antimicrobial coatings. Advances in nanotechnology have further enabled the production of nanotopographical surfaces that more closely mimic the natural extracellular matrix, promoting osteoblast differentiation and bone formation. Likewise, hydrophilic surface modifications and ultraviolet photofunctionalization have been developed to improve surface energy and enhance early biological interactions.

Despite the remarkable progress in implant surface technology, controversy persists regarding the comparative effectiveness of different surface modifications. While several clinical and experimental studies have demonstrated improved early osseointegration with moderately rough and hydrophilic surfaces, the superiority of one specific technology over another remains uncertain. Differences in implant systems, patient populations, outcome measures, and follow-up periods complicate direct comparison across studies.

In addition, the increasing prevalence of medically compromised patients, immediate implant placement protocols, immediate loading strategies, and rehabilitation of poor-quality bone has generated renewed interest in surface modifications capable of accelerating bone healing while reducing biological complications. Emerging technologies incorporating nanostructures, bioactive peptides, growth factors, antibacterial agents, and multifunctional coatings represent promising directions for the next generation of implant surfaces.

The purpose of this narrative review is to provide a comprehensive overview of the evolution of dental implant surface modifications, critically compare conventional and contemporary surface technologies, evaluate their influence on osseointegration and clinical performance, and discuss future trends that may shape the development of implant biomaterials in modern prosthodontics.

Biology of Osseointegration and Classification of Dental Implant Surface Modifications

Biology of Osseointegration

Osseointegration is a dynamic biological process involving the direct structural and functional connection between living bone and the surface of a load-bearing implant without intervening fibrous connective tissue. Initially described by Brånemark and co-workers, osseointegration remains the cornerstone of successful implant therapy.

The biological events following implant placement occur in a highly coordinated sequence comprising hemostasis, inflammation, proliferation, angiogenesis, woven bone formation, lamellar bone remodeling, and long-term functional adaptation. The physicochemical characteristics of the implant surface profoundly influence each of these stages.

Immediately after implant insertion, blood proteins such as fibrinogen, fibronectin, vitronectin, albumin, and complement proteins are adsorbed onto the implant surface within seconds. These proteins create a provisional extracellular matrix that regulates platelet activation and the subsequent recruitment of inflammatory cells. Surface chemistry, roughness, wettability, and surface energy determine both the quantity and conformation of these adsorbed proteins, thereby influencing the biological cascade that follows.

Within the first 24–72 hours, neutrophils and macrophages migrate to the implant site and initiate the inflammatory response. Macrophages play a particularly important role by regulating tissue repair through the release of cytokines, chemokines, vascular endothelial growth factor (VEGF), transforming growth factor-β (TGF-β), bone morphogenetic proteins (BMPs), and platelet-derived growth factor (PDGF). These mediators stimulate angiogenesis and recruit mesenchymal stem cells capable of differentiating into osteoblasts.

As healing progresses, osteogenic cells attach to the implant surface through integrin-mediated interactions with extracellular matrix proteins. Moderately rough titanium surfaces promote greater osteoblast adhesion, proliferation, alkaline phosphatase activity, osteocalcin expression, and extracellular matrix mineralization than smooth machined surfaces. This enhanced cellular response contributes to faster bone formation and greater bone-to-implant contact (BIC).

Angiogenesis is another critical determinant of successful osseointegration. Formation of new blood vessels ensures adequate oxygen delivery, nutrient transport, and recruitment of osteoprogenitor cells. Surface modifications capable of enhancing angiogenic signaling may accelerate early implant healing.

During the subsequent weeks, woven bone undergoes remodeling into mature lamellar bone under the influence of coordinated osteoblast and osteoclast activity. Functional loading further stimulates bone remodeling according to Wolff's law, allowing the peri-implant bone to adapt to mechanical demands. Long-term implant stability therefore depends on continuous physiological bone remodeling rather than the initial healing process alone.

Recent research has demonstrated that nanoscale surface architecture may further influence cellular behavior by modulating focal adhesion formation, cytoskeletal organization, mechanotransduction pathways, and osteogenic gene expression. Consequently, modern implant surface engineering increasingly focuses on reproducing the hierarchical micro- and nano-topography of natural bone.

Classification of Implant Surface Modifications

Dental implant surface modification techniques may be broadly classified into subtractive, additive, physicochemical, and biological modifications according to the method used to alter the titanium surface.

1. Subtractive Surface Modifications

Subtractive techniques remove portions of the implant surface to increase surface roughness and create micro-irregularities that enhance mechanical interlocking between bone and titanium.

Common subtractive methods include:

- Machining
- Acid etching
- Dual acid etching
- Sandblasting
- Large-grit sandblasting
- Sandblasted, Large-grit, Acid-etched (SLA)
- Laser surface texturing

These methods generally produce moderately rough surfaces (Sa approximately 1–2 µm), which have consistently demonstrated favorable biological performance.

2. Additive Surface Modifications

Additive techniques deposit additional material onto the titanium surface to improve biological activity or alter surface chemistry.

Examples include:

- Titanium plasma spraying (TPS)
- Hydroxyapatite (HA) coatings
- Calcium phosphate coatings
- Bioactive glass coatings

- Titanium dioxide deposition

- Biomolecular coatings

- Growth factor coatings

- Antimicrobial coatings

These coatings aim to stimulate osteogenesis while preserving long-term implant stability.

3. Physicochemical Surface Modifications

Rather than changing only surface morphology, physicochemical modifications alter the chemical composition or surface energy of titanium.

Major examples include:

- Anodization (TiUnite)

- Hydrophilic surface activation (SLActive)

- Ultraviolet photofunctionalization

- Plasma treatment

- Chemical oxidation

- Alkali and heat treatment

These techniques increase surface wettability and improve protein adsorption during the earliest stages of healing.

4. Nanotechnology-Based Surface Modifications

Advances in nanotechnology have enabled fabrication of nanoscale topographical features closely resembling natural bone architecture.

Examples include:

- Titanium nanotubes

- Nanoporous titanium

- Nanorough titanium

- Nanocrystalline hydroxyapatite

- Graphene-based coatings

- Nanocomposite bioactive coatings

Nanostructured surfaces influence cell adhesion, osteoblast differentiation, angiogenesis, and immune modulation while simultaneously improving antibacterial performance.

5. Biological Surface Functionalization

The latest generation of implant surfaces incorporates biologically active molecules capable of directly influencing tissue regeneration.

Current approaches include:

- Bone morphogenetic proteins (BMP-2, BMP-7)

- RGD peptide coatings

- Collagen coatings

- Hyaluronic acid coatings

- Fibronectin coatings

- Antimicrobial peptides

- Silver nanoparticles

- Chitosan coatings

- Drug-eluting implant surfaces

These multifunctional surfaces represent an important step toward personalized implant therapy, particularly for medically compromised patients and situations requiring accelerated healing.

Clinical Significance of Surface Roughness

Based on average surface roughness (Sa), implant surfaces are generally categorized as:

- Smooth surfaces ($Sa < 0.5$ µm)

- Minimally rough surfaces (0.5–1.0 µm)

- Moderately rough surfaces (1.0–2.0 µm)

- Rough surfaces (>2.0 µm)

Among these categories, moderately rough surfaces have demonstrated the most consistent balance between rapid osseointegration and long-term peri-implant health. Excessively rough surfaces may increase plaque accumulation and the risk of peri-implantitis, whereas smoother surfaces often require longer healing periods before functional loading.

Comparative Evaluation of Individual Implant Surface Modification Techniques

1. Machined Implant Surfaces

Machined (turned) titanium implant surfaces represent the first generation of commercially available dental implants introduced following Brånemark's pioneering work on osseointegration. These implants are manufactured by precision machining of commercially pure titanium, producing a relatively smooth surface characterized by circumferential machining grooves and a low average surface roughness (Sa < 0.5 µm). Although these implants demonstrated excellent long-term clinical success, the smooth surface provides limited mechanical interlocking with surrounding bone and generally requires a longer healing period before functional loading.

Biologically, machined surfaces permit adsorption of plasma proteins and support osseointegration; however, osteoblast attachment, proliferation, and differentiation occur more slowly than on moderately rough surfaces. Histomorphometric studies consistently report lower bone-to-implant contact (BIC) values and lower removal torque values compared with modern roughened implant surfaces. Consequently, machined implants have largely been replaced by modified surfaces designed to accelerate bone healing and improve primary and secondary implant stability.

Nevertheless, long-term follow-up studies have shown survival rates exceeding 90–95% over more than 15 years in appropriately selected patients, confirming that successful osseointegration depends on multiple biological and biomechanical factors rather than surface topography alone. Today, machined implants serve primarily as historical controls in experimental and clinical investigations evaluating newer surface technologies.

2. Acid-Etched Implant Surfaces

Acid etching was developed to overcome the limitations of smooth machined implants by creating controlled micropits across the titanium surface. The process typically employs strong mineral acids, including hydrochloric acid (HCl), sulfuric acid (H_2SO_4), hydrofluoric acid (HF), or nitric acid (HNO_3), either individually or in combination. These chemical treatments selectively dissolve the titanium surface, producing homogeneous micro-roughness without leaving significant blasting particle residues.

The resulting microporous surface enhances fibrin retention immediately after implant placement and promotes adsorption of adhesive proteins such as fibronectin and vitronectin. These proteins facilitate integrin-mediated osteoblast attachment and stimulate expression of osteogenic markers including alkaline phosphatase, osteocalcin, osteopontin, and type I collagen. Experimental studies have demonstrated significantly greater early BIC and removal torque values for acid-etched implants than for machined controls.

Dual acid-etching techniques further refine the microtopography by producing a more uniform distribution of pits ranging from approximately 1–3 µm in diameter. Such surfaces accelerate early healing and improve secondary stability without substantially increasing bacterial adhesion. However, acid etching alone produces only microscopic roughness and may not provide the same degree of biomechanical interlocking achieved by combined sandblasting and acid etching.

Clinical studies have reported excellent survival rates for acid-etched implants, particularly when used in healed ridges with adequate bone quality. Their predictable biological performance has made acid etching an essential component of several contemporary implant surface treatments.

3. Sandblasted, Large-Grit, Acid-Etched (SLA) Implant Surfaces

The introduction of the Sandblasted, Large-Grit, Acid-Etched (SLA) surface represented one of the most significant advances in implant surface engineering. The technique combines particle blasting to create macroscopic roughness with subsequent acid etching to generate a homogeneous microporous surface. This dual modification produces a moderately rough surface (Sa approximately 1–2 µm), which has consistently demonstrated superior biological performance.

Sandblasting is commonly performed using alumina or titanium oxide particles under controlled pressure, producing irregular macrofeatures that increase the available surface area. Subsequent acid etching removes residual contaminants and creates numerous micropits that enhance cellular attachment. The resulting hierarchical topography supports rapid blood clot stabilization, improves protein adsorption, and promotes early osteoblast differentiation.

Numerous animal studies have demonstrated significantly greater BIC values for SLA implants than for machined, electropolished, or titanium plasma-sprayed implants. Histological analyses have shown accelerated woven bone formation during the early healing period, while biomechanical investigations consistently report higher removal torque values, indicating stronger implant fixation.

Clinical evidence likewise supports the excellent performance of SLA implants. Long-term cohort studies have documented survival rates exceeding 95–99%, with minimal marginal bone loss and predictable performance in both partially and completely edentulous patients. Because of this robust evidence base, SLA surfaces are widely regarded as the current benchmark against which newer implant surface technologies are compared.

Nevertheless, although SLA surfaces substantially improve early osseointegration, they remain biologically passive. Consequently, contemporary research has focused on chemically modifying SLA surfaces to enhance hydrophilicity and surface energy, leading to the development of next-generation hydrophilic implants such as SLActive.

4. Resorbable Blast Media (RBM) Implant Surfaces

Resorbable Blast Media (RBM) surface technology was developed as an alternative to conventional grit blasting to eliminate the risk of residual abrasive particle contamination. Instead of aluminum oxide, RBM employs biocompatible calcium phosphate particles, which are subsequently dissolved during acid cleaning. This process creates a uniformly rough titanium surface while minimizing the possibility of embedded foreign particles.

The average surface roughness of RBM implants ranges between 1.2 and 1.8 µm, placing them within the moderately rough category. Experimental studies have demonstrated enhanced osteoblast attachment, increased alkaline phosphatase activity, and improved mineralized matrix formation compared with smooth machined implants. Histomorphometric analyses have consistently reported higher bone-to-implant contact (BIC) and removal torque values during the early healing phase.

Clinical studies indicate excellent long-term survival rates exceeding 95%, with stable peri-implant bone levels and predictable performance under both conventional and early loading protocols. Although several investigations have reported biological performance comparable to SLA surfaces, no consistent clinical superiority has been demonstrated. Consequently, RBM surfaces remain a reliable and widely accepted implant surface modification rather than a replacement for SLA technology.

5. Anodized Implant Surfaces (TiUnite)

Anodization is an electrochemical surface treatment in which titanium implants are subjected to controlled oxidation under high voltage, producing a thick, porous titanium oxide layer enriched with phosphate ions. One of the best-known anodized implant surfaces is TiUnite, introduced by Nobel Biocare.

Compared with conventional titanium oxide layers, anodized surfaces exhibit increased surface roughness, enhanced oxide thickness, greater porosity, and improved surface energy. These characteristics facilitate rapid protein adsorption and promote osteoblast adhesion and differentiation. Experimental studies have demonstrated accelerated new bone formation, higher BIC values, and increased removal torque compared with machined implants.

The porous oxide layer also provides a favorable microenvironment for angiogenesis and early mineralization. Clinical investigations have reported excellent survival rates in both partially and completely edentulous patients, including immediate loading protocols. TiUnite implants have shown predictable outcomes in compromised bone quality, particularly in posterior maxillary regions where rapid secondary stability is advantageous.

Despite these favorable findings, systematic reviews suggest that while anodized implants improve early healing, their long-term survival appears broadly comparable to other contemporary moderately rough implant surfaces. Thus, the principal advantage of anodization lies in accelerating early osseointegration rather than substantially improving long-term implant survival.

6. Laser-Modified Implant Surfaces

Laser surface modification represents one of the most precise methods of implant surface engineering because it allows controlled production of microgrooves and micropores without introducing foreign contaminants. Modern laser technologies, including Nd:YAG, femtosecond, and picosecond lasers, can generate reproducible hierarchical surface architectures while preserving the chemical composition of titanium.

Unlike particle blasting, laser treatment is a non-contact manufacturing process that minimizes contamination and allows highly reproducible topography. Laser-generated microgrooves influence osteoblast orientation, collagen fiber organization, and soft tissue attachment. Some commercially available systems, such as Laser-Lok, are designed specifically to improve connective tissue attachment and establish a more stable peri-implant soft tissue seal.

Experimental studies have demonstrated enhanced fibroblast attachment, improved epithelial integration, increased osteoblast differentiation, and favorable peri-implant bone remodeling. Clinical reports suggest reduced crestal bone loss and improved soft tissue stability around laser-microtextured implants. However, high-quality long-term randomized clinical trials remain limited, and further evidence is required before laser-modified implants can be considered superior to established SLA or hydrophilic surfaces.

7. Titanium Plasma-Sprayed (TPS) Implant Surfaces

Titanium plasma spraying was among the earliest additive surface modification techniques used in implant dentistry. During this process, molten titanium particles are projected onto the implant surface under high temperature, producing a porous coating with substantial macroscopic roughness.

The increased surface area enhances mechanical interlocking between bone and implant and was initially believed to improve osseointegration. Histological studies demonstrated greater BIC compared with machined implants, and early clinical reports documented acceptable survival rates.

However, the relatively thick coating may be susceptible to delamination under certain conditions, and concerns regarding long-term coating stability, bacterial colonization, and peri-implant maintenance have limited its popularity. As a result, TPS surfaces have largely been replaced by moderately rough subtractive techniques such as SLA and RBM, which provide comparable biological performance with greater manufacturing consistency.

8. Hydroxyapatite-Coated Implant Surfaces

Hydroxyapatite (HA) is a calcium phosphate ceramic with chemical and crystallographic similarities to the mineral phase of human bone. Owing to its excellent osteoconductive properties, HA has been widely investigated as a bioactive coating for titanium implants.

HA coatings promote rapid protein adsorption, facilitate osteoblast adhesion, and encourage direct chemical bonding between bone and implant. Early experimental studies demonstrated significantly increased BIC and accelerated bone formation compared with uncoated titanium implants. These findings stimulated widespread interest in plasma-sprayed HA coatings during the 1990s.

Despite favorable early healing, concerns emerged regarding coating delamination, variable crystallinity, dissolution, and long-term mechanical stability. Improvements in coating technologies—including magnetron sputtering, sol-gel deposition, electrophoretic deposition, and laser-assisted techniques—have substantially enhanced coating adhesion and structural integrity. Recent systematic reviews indicate that modern HA-coated implants generally improve early osseointegration, although consistent long-term superiority over contemporary moderately rough titanium surfaces has not been conclusively demonstrated.

9. Hydrophilic Implant Surfaces (SLActive)

Hydrophilic implant surfaces represent one of the most significant advancements in modern implant dentistry. Unlike conventional SLA surfaces, which gradually become hydrophobic because of hydrocarbon contamination during storage, hydrophilic surfaces are manufactured and stored under nitrogen or isotonic saline to preserve their high surface energy. The best-known example is the SLActive® surface developed from the traditional SLA implant.

Hydrophilic surfaces exhibit a near-zero contact angle, allowing immediate spreading of blood across the implant surface after placement. This improves fibrin network formation, platelet activation, and adsorption of adhesion proteins such as fibronectin and vitronectin. Consequently, osteogenic cells attach more rapidly and initiate earlier bone formation.

Experimental studies have demonstrated significantly greater early bone-to-implant contact (BIC), higher implant stability quotient (ISQ) values, and increased expression of osteogenic markers on SLActive implants compared with conventional SLA surfaces. Histological investigations suggest that healing periods may be shortened from approximately 6–8 weeks to 3–4 weeks in favorable clinical situations. However, most comparative studies indicate that although early healing is accelerated, differences between SLActive and SLA surfaces become minimal after approximately 6–8 weeks, with both surfaces demonstrating excellent long-term clinical performance.

10. Nanostructured Implant Surfaces

Nanotechnology has introduced a new dimension to implant surface engineering by reproducing topographical features similar to those found in the natural extracellular matrix. Nanostructured titanium surfaces are characterized by features ranging from approximately 1 to 100 nm and may be produced by anodization, acid oxidation, alkali treatment, hydrothermal processing, laser nanostructuring, or nanoparticle deposition.

Nanotopography influences cellular behavior at the molecular level by enhancing integrin-mediated adhesion, cytoskeletal organization, focal adhesion formation, and mechanotransduction pathways. Osteoblasts cultured on nanostructured titanium exhibit increased alkaline phosphatase activity, collagen synthesis, osteocalcin expression, and mineralized matrix formation compared with conventional micro-rough surfaces.

Nanostructured surfaces may also modulate macrophage polarization toward a pro-regenerative phenotype, thereby reducing excessive inflammation while promoting angiogenesis and bone regeneration. Although preclinical evidence is highly encouraging, long-term randomized clinical trials remain limited. Consequently, nanostructured implants should currently be regarded as an evolving technology with considerable biological promise rather than an established clinical standard.

11. Ultraviolet (UV) Photofunctionalization

Titanium surfaces undergo a phenomenon known as biological aging, during which hydrocarbons accumulate on the implant surface during storage, progressively reducing surface energy and hydrophilicity. Ultraviolet (UV) photofunctionalization has emerged as a chairside strategy to reverse this aging process immediately before implant placement.

Exposure to ultraviolet light removes hydrocarbon contaminants, converts the titanium surface into a superhydrophilic state, and alters its electrostatic properties. These physicochemical changes significantly improve protein adsorption, osteoblast attachment, cell spreading, proliferation, and differentiation.

Experimental studies consistently demonstrate increased BIC, enhanced removal torque, and faster development of secondary implant stability following UV treatment. Clinical investigations also suggest improved early implant stability and accelerated osseointegration, although variability in irradiation protocols, treatment duration, and clinical endpoints has limited direct comparison among studies. Current evidence indicates that UV photofunctionalization is particularly beneficial during the early healing phase without fundamentally altering the underlying implant topography.

12. Bioactive Surface Modifications

The current trend in implant surface engineering extends beyond passive roughness toward biologically active surfaces capable of directly influencing cellular responses. Bioactive coatings incorporate molecules that actively stimulate bone regeneration while simultaneously reducing bacterial colonization.

Among the most extensively investigated bioactive modifications are calcium phosphate coatings, hydroxyapatite nanoparticles, bone morphogenetic proteins (BMP-2 and BMP-7), RGD-containing peptides, collagen, hyaluronic acid, extracellular matrix proteins, and growth-factor-releasing coatings. These materials enhance osteogenic differentiation, accelerate mineralization, and strengthen bone–implant integration.

In parallel, antimicrobial surface technologies incorporating silver nanoparticles, zinc oxide, copper ions, titanium dioxide photocatalysis, chitosan, antimicrobial peptides, and antibiotic-eluting coatings have been developed to reduce bacterial adhesion and biofilm formation. Such multifunctional surfaces aim to address two major causes of implant failure: inadequate osseointegration and peri-implant infection.

Recent systematic reviews indicate that bioactive surface modifications generally improve early osseointegration compared with conventional titanium surfaces. However, heterogeneity in coating materials, manufacturing techniques, and outcome measures currently prevents identification of a universally superior bioactive coating. Further multicenter clinical trials are required before widespread clinical adoption.

13. Future Perspectives

Future implant surface technologies are expected to integrate nanotechnology, tissue engineering, artificial intelligence, and precision biomaterials to develop multifunctional implants capable of simultaneously promoting bone regeneration, enhancing soft tissue attachment, and preventing microbial colonization.

Emerging areas of investigation include smart drug-eluting implants, stimuli-responsive coatings, graphene-based nanomaterials, exosome-functionalized surfaces, stem-cell recruiting biomaterials, and three-dimensional hierarchical nano–micro surface architectures. Artificial intelligence and computational materials science are increasingly being used to optimize implant surface design by predicting cellular responses based on surface chemistry, roughness, wettability, and mechanical properties.

Rather than relying solely on increased roughness, next-generation implant surfaces will likely combine optimized topography with controlled biological signaling to create personalized implant systems adapted to patient-specific risk factors such as osteoporosis, diabetes mellitus, smoking, and peri-implant susceptibility.

Comparative Analysis of Dental Implant Surface Modifications

Comparative Evaluation of Implant Surface Technologies

The evolution of dental implant surface engineering has been driven by the objective of accelerating osseointegration while maintaining long-term peri-implant tissue stability. Although numerous surface modification techniques have been introduced over the past four decades, no single surface has demonstrated universal superiority under all clinical conditions. Rather, each technology possesses unique biological characteristics, clinical advantages, and potential limitations.

Machined titanium implants represented the foundation of modern implant dentistry and demonstrated excellent long-term survival despite relatively slow osseointegration. Their smooth surface limits mechanical interlocking with bone, resulting in lower bone-to-implant contact (BIC) and delayed secondary stability compared with contemporary roughened implants. Nevertheless, these implants established the biological principles that guided subsequent developments in implant surface engineering.

Acid-etched surfaces significantly improved early cellular attachment by creating homogeneous micropits that enhanced protein adsorption and osteoblast differentiation. When combined with large-grit sandblasting (SLA), these modifications produced a hierarchical microtopography that consistently demonstrated superior early osseointegration and remains one of the most extensively documented implant surface technologies.

Resorbable Blast Media (RBM) surfaces achieved biological performance comparable to SLA while minimizing concerns regarding residual blasting particle contamination. Clinical studies have demonstrated excellent survival rates and predictable peri-implant bone maintenance, although clear superiority over SLA has not been established.

Anodized implant surfaces, particularly TiUnite®, introduced controlled electrochemical oxidation to produce a thick porous titanium oxide layer enriched with phosphate ions. These surfaces enhance early mineralization and improve secondary implant stability, making them particularly useful in regions of compromised bone quality. Long-term clinical performance, however, appears broadly comparable to other moderately rough implant surfaces.

Laser-modified surfaces represent a highly precise manufacturing approach capable of generating reproducible micro- and nanotopographies without foreign particle contamination. Laser-generated microgrooves may improve both bone integration and peri-implant soft tissue attachment, although additional randomized clinical trials are required to establish definitive clinical advantages over established surface technologies.

Titanium plasma-sprayed (TPS) implants constituted one of the earliest additive surface modifications and successfully increased implant roughness and mechanical interlocking. However, concerns regarding coating thickness, long-term stability, and possible delamination have resulted in declining clinical use following the introduction of more predictable subtractive surface treatments.

Hydroxyapatite-coated implants remain biologically attractive because of their osteoconductive properties and chemical similarity to native bone mineral. Modern coating techniques have substantially improved coating adhesion compared with earlier plasma-sprayed hydroxyapatite systems. Nevertheless, available evidence suggests that while HA coatings accelerate early bone formation, long-term clinical superiority over contemporary moderately rough titanium surfaces has not been conclusively demonstrated.

Hydrophilic implant surfaces, exemplified by SLActive®, represent an important advancement by improving surface energy rather than altering roughness alone. Enhanced blood wettability facilitates immediate protein adsorption, fibrin stabilization, and rapid osteoblast recruitment. Numerous investigations have reported accelerated early healing and improved implant stability during the initial weeks following placement. However, differences between hydrophilic and conventional SLA implants diminish after complete osseointegration has been achieved.

Nanostructured implant surfaces attempt to reproduce the hierarchical architecture of natural bone at the nanoscale. Experimental evidence consistently demonstrates enhanced osteoblast differentiation, angiogenesis, macrophage polarization, and mineralized tissue formation. Although preclinical findings are highly encouraging, robust long-term clinical evidence remains limited.

The newest generation of implant surfaces incorporates biologically active molecules including growth factors, extracellular matrix proteins, antimicrobial agents, peptides, stem-cell recruiting biomaterials, and drug-delivery systems. These multifunctional surfaces simultaneously promote bone regeneration while reducing bacterial colonization and peri-implant inflammation. Although preliminary studies demonstrate considerable promise, these technologies remain largely investigational.

Collectively, the available evidence indicates that moderately rough titanium surfaces continue to provide the most predictable balance between rapid osseointegration, mechanical stability, and long-term peri-implant health. Future implant surface development is expected to focus less on increasing roughness and more on optimizing biological signaling through bioactive and nanostructured modifications.

Clinical Recommendations

Based on the current evidence, the following recommendations may be considered:

- Routine implant therapy in healthy individuals: Moderately rough SLA or RBM surfaces remain reliable choices with extensive long-term evidence.

- Immediate or early loading protocols: Hydrophilic surfaces (e.g., SLActive®) and anodized implants may provide enhanced early stability.

- Poor bone quality (Type III/IV): Anodized, hydrophilic, and selected bioactive surfaces may improve early bone healing.

- Patients at increased biological risk: Emerging bioactive and antimicrobial coatings are promising but require stronger long-term clinical validation before routine use.

- Research settings: Nanostructured and multifunctional biomimetic surfaces represent the most promising direction for future implant development.

Limitations of the Current Literature

Despite substantial advances in implant surface engineering, comparison among different technologies remains challenging because of heterogeneity in implant systems, manufacturing methods, roughness parameters, outcome measures, follow-up duration, loading protocols, and patient-related factors. Furthermore, many investigations report surrogate outcomes such as BIC or removal torque rather than long-term implant survival and patient-reported outcomes. Standardized multicenter randomized clinical trials with extended follow-up are required to determine the true clinical superiority of emerging surface technologies.

CONCLUSION

The evolution of dental implant surface technology represents one of the most significant advances in modern implant dentistry. Since the introduction of machined commercially pure titanium implants by Brånemark, continuous innovations in surface engineering have substantially enhanced the biological predictability of osseointegration while reducing healing time and improving early implant stability.

The evidence reviewed in this article indicates that implant surface characteristics influence the earliest biological events following implant placement, including protein adsorption, platelet activation, inflammatory cell recruitment, angiogenesis, osteoblast differentiation, and new bone formation. These biological processes collectively determine the quality and rate of osseointegration.

Among currently available surface modifications, moderately rough titanium surfaces continue to demonstrate the most consistent balance between biological activity and long-term clinical performance. Sandblasted, large-grit, acid-etched (SLA) implants remain one of the most extensively investigated implant surface technologies and continue to serve as the clinical benchmark because of their excellent long-term survival, predictable marginal bone stability, and extensive scientific documentation. Hydrophilic modifications of SLA surfaces further enhance early healing by improving surface wettability and accelerating blood–implant interactions, although long-term outcomes appear comparable to conventional SLA implants.

Resorbable blast media (RBM), anodized (TiUnite®), laser-modified, and hydroxyapatite-coated implant surfaces have each demonstrated favorable biological responses and satisfactory clinical outcomes. Nevertheless, current evidence does not conclusively demonstrate universal superiority of any single surface modification across all clinical situations. Instead, implant success appears to depend upon the interaction between implant surface characteristics, macrogeometry, surgical technique, prosthetic loading protocol, bone quality, systemic health, and long-term maintenance.

Recent advances in nanotechnology, ultraviolet photofunctionalization, bioactive coatings, antimicrobial surfaces, and multifunctional biomaterials have shifted the focus of implant research from passive topographical modification toward biologically active surface functionalization. These technologies aim not only to accelerate osseointegration but also to reduce bacterial adhesion, enhance peri-implant soft tissue integration, modulate immune responses, and improve long-term peri-implant health. Although preclinical investigations have produced encouraging results, high-quality multicenter randomized clinical trials with long-term follow-up remain necessary before these technologies can be recommended for routine clinical practice.

Another important observation emerging from contemporary clinical evidence is that implant surface modification alone cannot compensate for unfavorable patient- or site-related factors. Smoking, uncontrolled diabetes mellitus, poor oral hygiene, previous periodontitis, inadequate maintenance, surgical technique, and prosthetic design continue to exert a greater influence on long-term implant survival and peri-implant tissue stability than surface characteristics alone. Consequently, successful implant therapy should be regarded as the result of a synergistic interaction among implant design, surface engineering, host biology, and evidence-based clinical management rather than the consequence of any single technological advancement.

In conclusion, contemporary implant surface engineering has significantly improved the predictability of implant therapy by enhancing early biological healing while maintaining excellent long-term clinical outcomes. Current evidence supports the routine clinical use of moderately rough titanium surfaces, particularly SLA and hydrophilic SLA variants, whereas emerging nanostructured and biofunctionalized surfaces represent promising future directions. Continued interdisciplinary collaboration among biomaterials scientists, engineers, microbiologists, and clinicians will be essential for developing the next generation of implant surfaces capable of simultaneously promoting rapid osseointegration, preventing peri-implant disease, and improving long-term patient-centered outcomes.

CLINICAL SIGNIFICANCE

- Moderately rough titanium implant surfaces continue to provide the most predictable clinical outcomes.

- Hydrophilic surface modifications improve early osseointegration and may facilitate early loading protocols.

- Nanostructured and bioactive surfaces represent promising future technologies but currently require stronger long-term clinical evidence.

- Implant success depends upon appropriate patient selection, surgical technique, prosthetic design, maintenance therapy, and systemic health in addition to implant surface characteristics.

- Future implant development should focus on multifunctional surfaces capable of simultaneously enhancing osseointegration and preventing peri-implant infection.

FUTURE RESEARCH DIRECTIONS

Future investigations should prioritize:

1. Multicenter randomized controlled clinical trials comparing commercially available implant surfaces using standardized outcome measures.

2. Long-term evaluation of nanostructured, graphene-based, antimicrobial, and biomimetic implant surfaces.

3. Development of intelligent multifunctional implant coatings capable of controlled drug delivery and immunomodulation.

4. Integration of artificial intelligence and computational biomaterials science to optimize implant surface architecture.

5. Evaluation of implant surface performance in medically compromised patients, including diabetes, osteoporosis, smokers, and individuals with previous peri-implant disease.

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