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Shaping the Future of Peri-Implant Health: Insights into Bioceramic Implant Materials

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Abstract

Bioceramic implant materials have evolved significantly beyond traditional passive biocompatibility concepts, with contemporary research focusing on bioactive, antimicrobial, and immunomodulatory functionalities to enhance peri-implant tissue stability and long-term clinical success.This review examines recent advances in bioceramic implant technology across five key domains. Additive manufacturing enables patient-specific implant designs with optimized macro- and micro-architectures that enhance bone ingrowth and stress distribution. Surface biofunctionalization strategies, including calcium phosphate coatings, bioactive glass layers, and ion-doped ceramic modifications (strontium, magnesium, zinc), demonstrate enhanced osteogenic potential and accelerated mineralized tissue formation. Antimicrobial approaches targeting biofilm-mediated peri-implantitis include nanostructured ceramic coatings and photocatalytic zirconia surfaces that reduce bacterial adhesion while preserving host cell compatibility. Hybrid implant systems combining metallic cores with ceramic outer layers address mechanical limitations

while maintaining aesthetic and biological advantages. Emerging immunomodulatory surface concepts aim to engineer macrophage polarization toward pro-healing phenotypes, potentially reducing chronic inflammatory reactions associated with peri-implantitis.While preclinical data support the biological promise of these advanced bioceramic systems, long-term randomized clinical trials remain essential to validate their efficacy in reducing peri-implant disease incidence and improving implant survival rates. The integration of digital manufacturing, bioactive surface engineering, and immunomodulation represents a paradigm shift toward biologically optimized, patient-specific implant solutions.

Introduction

Dental implant therapy is widely regarded as a predictable treatment modality for the rehabilitation of edentulism; however, long-term success depends not only on osseointegration but also on the maintenance of peri-implant health. Biological complications, particularly peri-implant mucositis and peri-implantitis, remain prevalent and represent major causes of late implant failure.1,2 Contemporary understanding emphasizes that peri-implant disease is multifactorial, involving host immune response, microbial biofilm accumulation, and implant surface characteristics.3

While titanium implants remain the gold standard because of their mechanical reliability and well-documented clinical performance, concerns related to esthetics, hypersensitivity, and corrosion have stimulated interest in metal-free alternatives.4 Bioceramic materials, especially yttria-stabilized zirconia (Y-TZP), have gained attention due to their favorable biocompatibility, low plaque affinity, and excellent optical properties.5 In addition to bulk material advantages, surface chemistry and topography significantly influence protein adsorption, fibroblast adhesion, and early osteogenic cell activity.6

Recent research has therefore shifted toward optimizing bioceramic implant surfaces through micro- and nano-scale modifications and bioactive coatings aimed at enhancing bone-to-implant contact and promoting stable peri-implant tissue integration.7 From a periodontal perspective, these material innovations are particularly relevant, as improved soft-tissue sealing and reduced bacterial colonization may contribute to long-term peri-

implant stability.8 Consequently, understanding the biological behavior of bioceramic implant materials is critical for shaping future strategies in peri-implant disease prevention and management.

Bioceramic Materials in Dental Implants

Overview

Bioceramic materials are increasingly utilized in implant dentistry because they can be engineered to actively interact with surrounding tissues rather than functioning solely as structural replacements. In implant applications, bioceramics most commonly appear as zirconia-based implants and abutments or as bioactive ceramic coatings such as calcium phosphate or bioactive glass applied to metallic cores. Modern surface science emphasizes biofunctional interfaces capable of influencing early protein adsorption, cellular attachment, inflammatory modulation, and bone apposition. This paradigm shift moves implant design beyond macro-mechanics toward biologically responsive surfaces that directly affect peri-implant tissue behavior.10,12

Zirconia as a Bioceramic Implant Material

Zirconia implants and components, particularly zirconia abutments, have gained popularity due to aesthetic advantages and favorable biologic response. Recent systematic analyses report promising short- to medium-term survival rates and acceptable marginal bone stability with zirconia implants, while acknowledging that long-term data remain more limited compared with titanium systems. Importantly, zirconia’s clinical performance depends significantly on surface characteristics, including micro- and nano-topography and wettability, which influence host tissue response and biofilm formation at the transmucosal interface .9

Calcium Phosphate Bioceramics as Bioactive Coatings

Calcium phosphate coatings represent one of the most studied bioactive ceramic strategies for enhancing osseointegration. These coatings combine the mechanical strength of metallic substrates with the osteoconductive properties of ceramic surfaces. Their composition and crystallinity influence ion release and apatite formation, facilitating

early bone–implant contact

and supporting osteogenic cell activity. Properly engineered calcium phosphate layers have been shown to accelerate bone healing and improve interfacial stability during early integration phases .11

Bioactive Glass and Antibacterial Potential

Bioactive glasses represent another important bioceramic class for implant modification. These materials release therapeutic ions that stimulate apatite formation while potentially exerting antibacterial effects. Recent developments in multi-element–doped porous bioactive glass coatings demonstrate efforts to simultaneously enhance osteointegration and reduce bacterial colonization. Such dual functionality is particularly relevant in the prevention of peri-implantitis, where biofilm control and tissue compatibility are equally critical .13

Soft-Tissue Integration Around Zirconia Abutments

Long-term peri-implant health depends heavily on the integrity of the soft-tissue seal surrounding the implant-abutment complex. Emerging evidence indicates that nano-engineered zirconia surfaces enhance protein adsorption and promote epithelial and fibroblast attachment. Experimental findings demonstrate improved soft-tissue integration and stronger mucosal sealing features compared with non-modified surfaces. These results suggest that surface engineering of zirconia may improve the biological barrier against bacterial ingress and support marginal bone preservation.14

Microbial Ecology and Peri-Implant Health

Material composition influences early microbial colonization and subsequent biofilm maturation. Comparative peri-implantitis models evaluating titanium and zirconia-based materials demonstrate differences in anaerobic enrichment and pathogenic complex development. Some ceramic compositions exhibit reduced dysbiotic shifts under experimental conditions. While translational interpretation requires caution, these findings reinforce the concept that bioceramic surface properties can influence peri-implant microbial ecology and potentially modulate disease susceptibility.15

Osseointegration and Bone-Implant Interface

Biological Basis of Osseointegration

Osseointegration is defined as the formation of a direct structural and functional interface between living bone and the surface of a load-bearing implant, without the interposition of fibrous connective tissue.16 This intimate bone–implant contact is fundamental for achieving primary and secondary stability and is a prerequisite for long-term implant success. At the microscopic level, successful osseointegration is characterized by newly formed mineralized bone in direct apposition 1 to the implant surface. Following implant placement, a cascade of biological events is initiated, beginning with blood clot formation and 10 the adsorption of plasma proteins onto the biomaterial surface. These proteins mediate the recruitment of mesenchymal stem cells and osteoprogenitor cells, which subsequently differentiate into osteoblasts. Osteoblasts synthesize osteoid matrix that progressively undergoes mineralization, leading to the formation of woven bone that is later remodeled into lamellar bone.17 Surface properties—including chemical composition, surface energy, hydrophilicity, and micro-/nanotopography—critically regulate 2 protein adsorption and cellular adhesion. These factors ultimately influence the percentage of bone-to-implant contact (BIC), a

histomorphometric parameter widely used to assess osseointegration.17 Enhanced early osteoblastic attachment and proliferation contribute to improved biomechanical stability during the critical healing period.

Surface Engineering and Bioactivity

Surface engineering strategies have substantially advanced implant integration outcomes. Techniques 7 such as acid etching, sandblasting, plasma spraying, and laser modification increase surface roughness and surface energy, thereby enhancing osteoblastic adhesion and differentiation.18 Clinical and experimental studies have consistently demonstrated that modified implant surfaces achieve significantly higher BIC values compared with machined surfaces, resulting in accelerated secondary stability.18

Bioactive coatings incorporating calcium phosphate, hydroxyapatite, collagen matrices, or

growth factors further stimulate osteogenic signaling pathways at the interface.17 These coatings enhance early mineral deposition and facilitate faster maturation of peri-implant bone. Additionally, nanostructured surfaces that replicate the architecture of the extracellular matrix improve integrin-mediated cell attachment and promote osteogenic gene expression.16 Such biofunctionalization approaches are particularly relevant for bioceramic materials, which inherently exhibit osteoconductive properties and chemical affinity for biological apatite. Nanoscale Interface and Bioceramic Integration

Recent advances in bioceramic implant materials have highlighted the importance of nanoscale interfacial phenomena. [8] Ceria-stabilized tetragonal zirconia polycrystal (Ce-TZP) has demonstrated favorable nanoscale bonding with newly formed hydroxyapatite, facilitating direct mineral attachment without the need for additional surface modification.20 This intrinsic bioactivity supports early interfacial mineralization and enhances mechanical interlocking at the bone-implant junction.

Bioceramic composites and functionally graded materials are increasingly being developed to minimize elastic modulus mismatch between the implant and surrounding bone.16 Reducing this mismatch mitigates stress shielding effects and promotes more physiological load transfer, which is critical for maintaining long-term peri-implant bone stability. Furthermore, osteoimmunological interactions at the interface have gained attention, as the early immune response plays a regulatory role in bone regeneration.21 Modulating macrophage polarization toward a pro-healing phenotype may further optimize osseointegration outcomes in bioceramic systems.

Mechanical Adaptation and Re-Osseointegration

Osseointegration represents a dynamic biological equilibrium between bone formation and resorption rather than a static endpoint. Mechanical loading influences peri-implant bone remodeling through mechanotransduction pathways. Controlled functional loading enhances bone density and maturation, whereas excessive or premature loading may compromise integration.

Experimental evidence indicates that re-osseointegration is possible following mechanical

disruption. In controlled animal models, implants subjected to induced loosening demonstrated renewed bone formation and restoration of stability after appropriate healing periods.19 These findings underscore the regenerative capacity of the bone–implant interface [11] and highlight the importance of optimized loading protocols in clinical implantology.

Peri-Implant Soft Tissue and Microbial Considerations

Soft-tissue considerations

Peri-implant soft tissue forms the first-line seal that separates a highly contaminated oral environment from the osseointegrated portion of the implant. Compared with the periodontal barrier around natural teeth, peri-implant mucosa has structural disadvantages that reduce bonding efficiency at the transmucosal region, making the seal easier to disrupt. Once the seal is compromised, bacteria can penetrate the interface and trigger peri-implant mucositis; without timely management, this may progress to peri-implantitis with marginal bone loss.22

The transmucosal surface is now treated as an “engineered interface,” not an afterthought. Current strategies to strengthen soft-tissue attachment focus on improving surface wettability, creating micro/nano-topographies, altering surface chemistry, and adding bioactive coatings. Importantly, the field is moving toward multifunctional designs—surfaces that simultaneously enhance soft-tissue bonding while adding antibacterial and/or immunomodulatory features to reduce early inflammatory breakdown.22

Zirconia abutments are widely used in esthetic zones, but achieving consistently strong soft-tissue attachment remains a challenge. Evidence synthesized in recent reviews shows that soft-tissue integration around zirconia depends heavily on both micro-design (surface modification methods) and macro-design (abutment/contour factors) that influence epithelial closure and connective tissue behavior. Practical takeaways include matching zirconia surface processing to the intended tissue response and ensuring post-restoration maintenance supports long-term sealing.23

Microbial considerations

Microbial biofilms are central to peri-implant disease biology. Systematic evidence comparing peri-implantitis biofilms with those from healthy implants and periodontitis sites shows that no single organism uniquely defines peri-implantitis across studies; rather, disease reflects complex community shifts. Meta-analytic findings indicate certain species (for example, Aggregatibacter actinomycetemcomitans and Prevotella intermedia) may show higher prevalence in peri-implantitis compared with health, while many taxa are shared across conditions—supporting a dysbiosis-based model rather than a single-pathogen model.24

Sequencing-based systematic reviews further reinforce that peri-implant disease is characterized by dysbiotic communities that vary between individuals and differ in composition and relative abundance compared with periodontal sites. These studies highlight that peri-implantitis can include well-known periodontopathogens but may also show enrichment of organisms less emphasized in classic periodontal patterns, and that diversity/composition shifts are seen when comparing healthy versus diseased peri-implant sites. Clinically, this supports

prevention strategies that focus on disrupting biofilm maturation and maintaining a stable peri-implant ecological balance rather than targeting a narrow microbial list.25

Implant material and surface physicochemistry can shape the peri-implant microbial “signature.” In a controlled preclinical model, microbial communities shifted differently across titanium, zirconia, and ceria-stabilized alumina-reinforced zirconia, suggesting the implant substrate can predispose sites toward or away from dysbiotic evolution under inflammatory challenge. The study also highlights the anaerobic-to-aerobic balance as a potentially useful surrogate marker for monitoring disease trajectory, reinforcing the concept that material choice may influence plaque evolution and peri-implantitis risk at a biological level.26

Peri-Implant Health Outcomes

Clinical assessment of peri-implant health around bioceramic implants, particularly

zirconia-based systems, has increasingly incorporated standardised parameters including [9] bleeding on probing (BOP), probing depth (PD), and radiographic marginal bone loss (MBL). [12] A systematic review and meta-analysis by Roehling and colleagues, which pooled data from six observational cohort studies with a minimum five-year follow-up, estimated mean MBL of 1.1 mm (95% CI: 0.9 to 1.3 mm) and mean PD of 3.0 mm (95% CI: 2.5 to 3.4 mm) around commercially available zirconia implants after five years of loading, findings broadly comparable with titanium benchmarks reported in the parallel literature.27 A separate systematic review restricted to randomised controlled trials and comparing titanium, titanium-zirconium, and zirconia implants reported BOP values of approximately 16.4% for zirconia, overlapping with the 10 to 20% range observed for titanium, and noted that no statistically significant between-group differences in peri-implant mucositis or peri-implantitis incidence were observed across the included studies, although the small number of RCTs limits firm conclusions [28]. Soft tissue outcomes, including mucosal stability and esthetic performance, appear to favour zirconia in the anterior zone, where the tooth-coloured subgingival profile minimises the risk of visible greyish discolouration through thin gingival phenotypes, a clinically relevant consideration that titanium systems do not share .28

The material properties of zirconia are mechanistically relevant to peri-implant tissue behaviour. The lower surface energy and reduced surface roughness of polished zirconia surfaces are associated with diminished bacterial adhesion compared with rougher titanium surfaces in in vitro models, and this has been proposed as a contributing factor to the comparable or slightly lower BOP values observed in some clinical studies .28,29 A network meta-analysis by Pesce and colleagues, which included 18 prospective studies comparing abutment materials, found that zirconia abutments were associated with a statistically significant reduction in MBL of 0.20 mm (95% CI: 0 to 0.40 mm) compared with titanium abutments, alongside numerically lower BOP and PD values, suggesting that the soft tissue integration profile of zirconia at the transmucosal level may confer a measurable biological advantage .28 Wettability and surface chemistry also influence the early soft

tissue attachment response; zirconia surfaces with moderate roughness and appropriate surface energy have been shown to support fibroblast adhesion and connective tissue orientation, though the long-term clinical translation of these in vitro observations into meaningful differences in recession or mucosal thickness has not been consistently demonstrated in controlled trials .29

The available evidence must be interpreted with caution given substantial methodological limitations. Most published studies comparing zirconia 1 and titanium implants are observational in design, often with small sample sizes, heterogeneous surgical and prosthetic protocols, and follow-up periods that rarely exceed five years; the most recent systematic review and meta-analysis of RCTs by Morena and colleagues, which included only six trials and 448 implants, found no statistically significant differences in MBL, BOP, or PD between zirconia and titanium, but noted high heterogeneity across studies and significant variability in implant designs, surface treatments, and outcome definitions.30 This variability in protocols and the absence of standardised outcome reporting make cross-study synthesis unreliable. Furthermore, patient-selection data across included studies are often insufficient to assess how factors such as periodontal history, bone density, and gingival phenotype modify outcomes specifically for bioceramic materials. Longer follow-up data, larger multicentre RCTs, and harmonised outcome reporting frameworks are needed before definitive clinical recommendations regarding the peri-implant health advantages of zirconia over titanium can be made.

Emerging Trends and Future Directions

The evolution of bioceramic implant materials is increasingly driven by advances in biomaterials science, nanotechnology, and digital manufacturing. Contemporary research no longer focuses solely on passive biocompatibility but aims to develop bioactive, antimicrobial, and immunomodulatory implant surfaces capable of enhancing peri-implant tissue stability and long-term success .31

Additive Manufacturing and Personalized Implant Design

Additive manufacturing (3D printing) has enabled the fabrication of customized zirconia

and other ceramic-based implants with controlled macro- and micro-architectures. This technology allows optimization of implant geometry, porosity, and surface texture to enhance stress distribution and bone ingrowth .32 Experimental studies suggest that porous ceramic scaffolds can improve vascularization and early bone formation by mimicking trabecular bone morphology .33 Although still emerging in routine implant dentistry, these strategies represent a promising shift toward patient-specific, biologically optimized implants.

Bioactive Surface Engineering

Surface biofunctionalization is a major area of development in bioceramic implants. Calcium phosphate coatings, bioactive glass layers, and ion-doped ceramic modifications are being investigated to stimulate osteoblast differentiation and accelerate mineralized tissue formation.34 Incorporation of biologically active ions such as strontium, magnesium, and zinc into ceramic matrices has demonstrated enhanced osteogenic potential and improved bone-to-implant contact in preclinical models.35

Such bioactive modifications aim not only to promote osseointegration but also to enhance early peri-implant bone stability, which is critical in reducing susceptibility to inflammatory bone loss.

Antimicrobial and Anti-Biofilm Strategies

Given that peri-implantitis is a biofilm-mediated disease, research increasingly targets antimicrobial implant surfaces. Nanostructured ceramic coatings and photocatalytic zirconia surfaces are being explored to reduce bacterial adhesion while maintaining compatibility with host cells .36 Some experimental surfaces incorporate antimicrobial agents or ions within ceramic layers to inhibit colonization by peri-implant pathogens without impairing osteoblastic activity.37

While in vitro data are promising, long-term randomized clinical trials are still required to determine whether these innovations significantly reduce peri-implant disease incidence.

Hybrid and Composite Implant Systems

To address concerns regarding ceramic brittleness and aging phenomena, hybrid systems

combining metallic cores with ceramic outer layers are under investigation.38 These designs aim to preserve mechanical strength while benefiting from the favorable soft tissue response and aesthetics associated with zirconia-based materials. Ongoing research is evaluating fracture resistance, low-temperature degradation, and long-term clinical stability of such systems.

Immunomodulatory Surface Concepts

A paradigm shift in implant biomaterials involves the development of surfaces capable of modulating the host immune response. Studies exploring macrophage polarization around implant materials suggest that surface chemistry and topography can influence inflammatory pathways.39 Future bioceramic implants may be engineered to promote a pro-healing (M2) macrophage phenotype, thereby enhancing tissue integration and reducing chronic inflammatory reactions associated with peri-implantitis.

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