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Review article

Unveiling the characteristics and surface modification of titanium, zirconia, and polyetheretherketone dental implants

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Abstract Titanium, zirconia, and polyetheretherketone (PEEK) are among the most extensively studied materials in dental implantology, each offering unique properties that influence their clinical performance. This review systematically compared their physicochemical characteristics and their in vitro and in vivo behaviors. It also evaluated various surface modification techniques designed to enhance osseointegration and antibacterial properties. Titanium, recognized as the gold standard, is renowned for its exceptional mechanical strength and superior osseointegration, although it is associated with a higher risk of peri-implantitis. Zirconia, valued for its excellent aesthetics and compatibility with soft tissues, presents a promising metal-free alternative; however, its brittleness can limit its mechanical reliability. PEEK, a high-performance polymer, offers stress distribution and biocompatibility benefits, but it requires substantial surface modifications to improve its osseointegration capacities. Additionally, this review delved into the prevalence of peri-implantitis, clinical survival rates, and the impact of systemic conditions such as aging, osteoporosis, and diabetes on implant success. The findings underscored the critical importance of material-specific surface treatments and tailored modifications to ensure the long-term success of dental implants.

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Introduction

Dental implants have revolutionized modern dentistry, offering practical and durable solutions for patients with missing teeth. Among the various materials available, titanium, zirconia, and PEEK have emerged as prominent options due to their unique properties and versatility. Titanium is widely recognized as the gold standard in implantology, celebrated for its exceptional mechanical strength, outstanding corrosion resistance, and proven biocompatibility, which ensure its long-term success in clinical applications. Zirconia has gained recognition as a metal-free alternative, prized for its superior aesthetic qualities and excellent tissue compatibility, making it particularly suitable for patients who prioritize natural-looking restorations. PEEK, a high-performance polymer, is emerging as a promising alternative in dental implants. Its remarkable chemical stability, radiolucency, and potential for lightweight, customizable designs set it apart. PEEK provides unique advantages over traditional metallic implants, including reduced stress shielding and improved adaptability to meet patient-specific needs. The selection of these three materials reflects their distinct strengths and ability to address the diverse functional, aesthetic, and clinical demands of dental implantology.

The success of dental implants hinges on several key factors that significantly impact their clinical effectiveness and long-lasting durability.[1] At the forefront is osseointegration, the vital process where the implant securely bonds with the surrounding bone, establishing a solid foundation and withstanding the forces of chewing. Numerous factors play a role in osseointegration, particularly the choice of implant material, which directly influences its biocompatibility. Equally important to implant success are antibacterial properties in safeguarding implant longevity. The oral cavity is populated by diverse bacteria that can settle around implants, forming harmful biofilms and leading to conditions like peri-implantitis.[2] This inflammatory disease of the tissues surrounding the implant is a leading cause of implant failure.[3] To mitigate this risk, implants engineered with antibacterial coatings or surface treatments, such as silver nanoparticles or antimicrobial peptides, are highly effective in preventing bacterial adhesion.

Beyond osseointegration and antibacterial properties, several other factors influence the success of dental implants. Among these factors, the design and material of the implant are paramount, ensuring not only mechanical stability and durability for chewing but also minimizing complications. A skilled surgical technique is indispensable; precise placement with minimal trauma to surrounding tissues can accelerate healing and reduce the likelihood of complications. The quality and quantity of bone at the implant site are equally important; insufficient bone may require preparatory procedures like grafting to ensure adequate support for the implant. Additionally, the patient's overall health, including oral hygiene practices and managing systemic conditions like diabetes, can impact healing and the risk of complications.[4] Finally, follow-up care and maintenance are crucial for the longevity of the implant. Regular check-ups and professional cleaning help monitor the implant's condition and address any issues before they escalate into serious issues.

Among the critical factors in dental implantology, the biofunctional properties of implant materials play a pivotal role in determining success. This study compared the fundamental properties of titanium, zirconia, and PEEK implants, showcasing their unique benefits. Furthermore, it provided an in-depth review of surface treatment strategies that were designed to improve osseointegration and enhance antibacterial properties. This review also emphasized the clinical potential of these three materials and their contribution to advancing the field of dental implantology.

Characteristics of titanium, zirconia, and PEEK

Physiochemical properties

Titanium is the premier choice for long-term implants, renowned for its exceptional strength, durability, corrosion resistance, low density, and remarkable ability to integrate with bone (Table 1). Additionally, with Young's modulus of around 110 GPa, this material provides the necessary rigidity to effectively support dental structures, giving patients confidence in their implants. However, when used alongside other metals, it may cause galvanic reactions that could lead to complications. Aesthetically, titanium is limited by its metallic color, which can be less visually appealing, especially in visible areas. Despite these drawbacks, titanium remains the gold standard for dental implants, thanks to its proven clinical success and high success rates across various dental applications.[5]

Zirconia is a ceramic material gaining popularity in dental implantology, mainly for aesthetic implants. Its tooth-like color and translucency make it an excellent choice for anterior teeth, where appearance is crucial. While zirconia is strong and resistant to breakage, it can become brittle under stress, making it more susceptible to fractures when subjected to high loads. With a density of 6.0 g/cm^3, zirconia ceramic is heavier than titanium. Its Young's modulus is around 210 GPa, significantly higher

Table 1 Physicochemical and mechanical properties of titanium, zirconia, and PEEK.

Property	Titanium	Zirconia	PEEK
Density (g/cm^3)	4.5	6.0	1.3
Weight	Light	Heavier than Ti	Light, much lighter Ti
Aesthetic quality	Low	High	High
Tensile strength (MPa)	965	820	103
Young's modulus (GPa)	110	210	3.5
Flexibility	Rigid, no flexibility	Rigid, brittle	Flexible
Corrosion resistance	Excellent	Excellent	Excellent
Galvanic reactions	Yes	No	No

than titanium's 110 GPa, resulting in greater stiffness. Additionally, zirconia is biocompatible and resistant to dissolution.

PEEK is a high-performance polymer that combines lightweight design with remarkable flexibility, making it an excellent choice for patients with metal allergies or those seeking a metal-free alternative. Its density of just 1.3 g/cm^3 makes PEEK significantly lighter than titanium and zirconia, providing greater comfort and reducing the load on the surrounding bone. PEEK has a much lower Young's modulus (around 3.5 GPa) than titanium and zirconia. Although it possesses moderate strength, its inherent flexibility helps absorb stress, lowering the risk of implant failure, especially in patients with stronger jawbones. It is also biocompatible and highly resistant to degradation, ensuring long-term performance. Additionally, PEEK can be manufactured to closely match the color of teeth, making it an appealing option for patients who prioritize aesthetics.[6] However, PEEK may trigger a more pronounced foreign body response than titanium, as indicated by a higher number of multinucleated giant cells in the soft tissues surrounding the implants.[7] Ultimately, the choice of implant material depends on the distinct physicochemical, mechanical, and biological properties of the three materials, enabling clinicians to tailor the selection to specific clinical applications.

In vitro comparison

The in vitro assessment of implant materials is a crucial initial step before evaluating their in vivo performance.[8,9] Titanium surfaces support greater bacterial adhesion and biofilm accumulation than zirconia, which has been demonstrated to resist biofilm formation more effectively.[10] In contrast, PEEK exhibits variable bacterial colonization depending on the strain and surface properties. Although it initially harbors lower biofilm biomass, certain bacterial species, such as *S. aureus, S. mutans*, and *E. coli*, tend to adhere more readily to PEEK surfaces than to titanium.[11] Regarding in vitro cellular response, titanium substrates generally enhance osteoblast differentiation and result in higher bone morphogenetic protein production compared to PEEK.[12] Fibroblast and keratinocyte activity on zirconia and PEEK is similar, yet titanium consistently supports the highest metabolic activity.[13] The inflammatory response to these materials also varies. Titanium tends to induce higher levels of pro-inflammatory cytokines such as MCP-1, IFN-γ, and TNF-α, whereas zirconia elicits a milder immune response. Nevertheless, zirconia surfaces promote greater neutrophil extracellular trap (NET) release, which may influence immune interactions at the implant surface.[14] In summary, the limited literature indicates that these three implant materials have distinct advantages and limitations under in vitro conditions.

In vivo comparison

Although studying materials in vitro provides valuable insights, examining their behavior in vivo is crucial for understanding clinical outcomes. Titanium, zirconia, and PEEK exhibit distinct biological responses in vivo studies, influencing factors such as soft tissue adaptation, biofilm formation, osseointegration, and immune reactions in different ways. The three materials show similar peri-implant soft tissue responses, with no significant differences in clinical settings, bacterial accumulation, or early inflammation.[15] Pilloni et al. noted that zirconia abutments induced fewer inflammatory cells in the surrounding mucosa than titanium, suggesting a potentially more favorable soft tissue reaction based on human histology.[16] PEEK does not exhibit increased soft tissue inflammation in clinical studies,[15] but it showed heightened immune activation related to bone integration, which may impact long-term stability.[17,18] Wiessner et al. found differences in biofilm accumulation among these materials, with zirconia showing the least microbial adhesion, followed by titanium, while PEEK accumulated the most biofilm.[19] They also reported that this material-dependent biofilm formation was particularly relevant in the posterior regions of the oral cavity, where bacterial accumulation was significantly higher. Additionally, Roehling's study indicated a significantly lower peri-implant bone loss of SLA-treated zirconia implants than SLA-treated titanium implants.[20]

Regarding osseointegration, titanium and zirconia exhibit comparable levels, achieving similar bone-to-implant contact (BIC).[21–23] However, Kohal et al. found that zirconia, with a surface roughness of Ra $= 0.13$ μm, achieved slightly higher BIC than titanium, which had a Ra $= 0.05$ μm, particularly at 14 and 28 days post-implantation.[23] Mechanical testing suggests that titanium exhibits greater removal torque values than zirconia, indicating that titanium provides more substantial secondary stability.[21] However, these different results may arise from variations in surface treatments and the in vivo models used. In contrast, PEEK implants show significantly lower BIC and bone apposition than titanium.[24] PEEK implants often lack proper bone integration, unlike titanium and zirconia, which promote direct bone contact.[18] This is due to an immune-mediated response that leads to soft tissue formation rather than osseointegration. Hassan and Kalluvalappil reported that titanium implants supported a balanced inflammatory and osteogenic response characterized by higher expression of IL-6, TNF-α, and OPG, contributing to effective bone remodeling when compared to PEEK implants.[17] Although zirconia triggers a lower inflammatory response, it still facilitates bone healing.[16] Conversely, PEEK implants exhibit increased immune activation, which negatively impacts osseointegration and favors the formation of adipose tissue over direct bone contact.[18] Additionally, PEEK implants show higher RANKL expression than titanium, suggesting a greater tendency for bone resorption, while titanium demonstrates higher RUNX-2 expression, reflecting its superior osteogenic potential.[17] Table 2 provided a structured overview of the in vivo behavior of titanium, zirconia, and PEEK. It summarized findings related to soft tissue responses, biofilm formation, osseointegration, and immune reactions from various studies, offering insights into how each material performs in biological environments.

Surface modification techniques

The surface properties of materials remarkably affect their interactions with biological tissues, making surface

Table 2 Comparison of in vivo behavior.

Materials	Population	Results	Ref
Abutment: Ti6Al4V, ZrO_2, PEEK	Patients	No significant differences in soft tissue response, bacterial counts, or inflammation. PEEK has slightly higher MMP-8 levels. Bone level changes and peri-implant mucosal health are comparable across all materials.	15
Grade 4 Ti, Ti6Al4V, ZrO_2, PEEK	Patients	COL-I: downregulates in Ti and ZrO_2. MMP-1 and TIMP-1: increases in all groups, but the lowest in Ti. FN, RAC-1, COL-IV, αSMA: downregulates, especially in Ti. CXCL-1 & IL-6: the lowest value in Ti.	16
Ti, ZrO_2, PEEK	Healthy volunteers	Biofilm formation: ZrO_2 < Ti < PEEK ($P < 0.001$). Oral cavity region: higher biofilm accumulation in the posterior than in the anterior area.	19
Implants: Ti, ZrO_2 Closure Caps: Ti, PEEK	Miniature pig	MNGCs: closure caps: PEEK > Ti ($P < 0.05$). Implant types: $P > 0.05$ in MNGC count. Inflammation: no signs of inflammation.	7
Machined Ti neck, ZrO_2 neck	Adult pig	Collagen fiber orientation: mostly parallel or parallel-oblique to the implant surface. Connective tissue adhesion: similar. Surface roughness: higher in Ti than ZrO_2. Plaque formation & esthetics: ZrO_2 has less plaque formation and better esthetics.	25
Ti, PEEK	Rabbit tibia	Allergic response: Ti causes enlarged lymph nodes, whereas PEEK does not. IL-6 and TNF-α: Ti > PEEK. Bone markers: OPG: Ti > PEEK, RANKL and RUNX-2: PEEK > Ti.	17
cp Ti, PEEK	Rabbit tibia	Immune activation: PEEK > Ti. Osseointegration: PEEK failure.	18
Ti, Y-TZP	Rabbit tibia	Removal torque: Ti (15.9 ± 4.18 N·cm) > Y-TZP (11.5 ± 2.92 N·cm) ($P < 0.0001$). BIC: Ti ($35.4 \pm 4.54\%$) ≈ Y-TZP ($34.0 \pm 6.82\%$).	21
Ti, 3D-printed ZrO_2	Rabbit tibia	Surface roughness: ZrO_2 (0.54 μm) > Ti (0.27 μm). BIC: ZrO_2 ≈ Ti.	22
Ti, PEEK	Sprague Dawley rat	BIC and bone apposition: Ti > PEEK ($P < 0.05$). Pullout force: Ti > PEEK ($P < 0.05$). Fixation strength: $P > 0.99$. Ti implant shows slightly better fixation.	24
Ti, ZrO_2	Sprague-Dawley rat	BIC: 14 days: ZrO_2 (30.9%) > Ti (23.2%), 28 days: ZrO_2 (46.6%) > Ti (39.4%). Implant stability: ZrO_2 (9.3 N) > Ti (7.3 N).	23
Ti, PEEK	Labrador dog	Buccal bone crest resorption (IS-C): PEEK (1.0 ± 1.0 mm) > Ti (0.3 ± 0.4 mm) ($P < 0.05$). Soft tissue parameters: $P > 0.05$. Implant integration: both Ti and PEEK implants achieve successful integration.	26

Y-TZP, yttria-stabilized tetragonal zirconia polycrystal; cp Ti, commercially pure titanium; BIC, bone-to-implant contact; IS-C, implant shoulder—crestal bone level; MNGCs, multinucleated giant cells; IL-6, interleukin-6; TNF-α, tumor necrosis factor-alpha; OPG, osteoprotegerin; RANKL, receptor activator of nuclear factor kappa-B ligand; RUNX-2, runt-related transcription factor 2; COL-I/IV, collagen type I/IV; MMP, matrix metalloproteinase; TIMP-1, tissue inhibitor of metalloproteinases-1; FN, fibronectin; RAC-1, Ras-related C3 botulinum toxin substrate 1; αSMA, alpha smooth muscle actin; CXCL-1, C-X-C motif ligand 1.

modifications of dental implant materials essential for improving clinical performance and ensuring long-term success. Various modification techniques have been developed to enhance the osseointegration of titanium, zirconia, and PEEK with surrounding bone and soft tissue to achieve this. Additionally, incorporating antibacterial coatings helps reduce biofilm formation, which lowers the risk of peri-implantitis. Together, these enhancements improve implant stability, minimize complications, and ultimately increase the overall success rate of dental implants.[27]

Sandblasting and acid-etching

The facile SLA (Sandblasted, Large-grit, Acid-etched) method is widely used for modifying the surface of titanium dental implants. Through shot blasting and double acid etching, this SLA method creates a dual roughness, including micro and nano roughness, significantly improving osteoblast-like cell adhesion, proliferation, and differentiation, underscoring the importance of surface roughness in promoting osseointegration.[24,28,29] The rougher SLA surfaces are more osteoconductive than machined surfaces, allowing for faster integration with surrounding bone tissue, which is particularly beneficial under early loading protocols for greater implant stability and longevity.[29] Research conducted by Cho et al. demonstrated that SLA-treated titanium surfaces improve the expression of bone marker genes and alkaline phosphatase activity, which are vital for bone formation.[30] These processes are linked to epigenetic changes, particularly DNA methylation, which influence gene expression related to bone regeneration. Clinical studies have shown that both SLA and SLActive implants achieve high survival and success rates of 95 % and 97 %, respectively, under immediate and early loading protocols.[31] SLActive, a hydrophilic modification of the SLA technique, is specifically designed to improve early osseointegration by enhancing surface wettability. Long-term studies confirm their durability, with a 5-year prospective study showing a cumulative survival rate of 99.1 %[29] and a 10-year retrospective study reporting a survival rate of 98.8 % for SLA implants.[32] Additionally, Salvi et al. indicated that SLA implants can be loaded early without compromising osseointegration while providing primary stability, achieving high success rates for early loading within 2–6 weeks.[33]

Similarly to titanium implants, SLA-treated zirconia implants exhibit osseointegration performance that rivals titanium implants, as evidenced by comparable metrics for BIC and bone volume.[34] It's important to note that titanium surfaces have sharper, more rugged peaks, whereas zirconia surfaces have rounder and shallower granular structures. This difference influences protein adsorption and cellular responses.[35] Unlike titanium and zirconia, PEEK implants do not typically undergo traditional acid-etching treatments due to their polymeric nature. Instead, sandblasting is a common method used to modify the surface of PEEK implants, which increases surface roughness and improves biological performance by enhancing cell attachment, viability, and osteogenic differentiation of stem cells.[36] Sandblasting with Al_2O_3 particles increases the coefficient of friction, which can enhance implant stability; however, it may also lead to increased bacterial adhesion.[37] When combined with chemical modifications, such as phosphorylation, sandblasting can further enhance osseointegration by improving cell responses and BIC.[38] On the other hand, acid etching is another technique used to improve the surface properties of PEEK. For example, Feng et al. pointed out that acid-etched microporous PEEK surfaces with internal cross-linked structures can promote soft tissue integration and help prevent fibrous capsule formation.[39]

Laser treatment

Laser technology has been explored to modify and improve the surface properties of dental implant materials. For titanium implants, lasers such as Nd:YAG, CO_2 and Er,Cr: YSGG have been shown to boost biocompatibility, enhance osseointegration, and increase surface roughness, promoting cellular attachment and proliferation.[40,41] Femtosecond lasers are notable for their ability to create intricate nanostructures on titanium surfaces, which may benefit biomedical applications. Zirconia implants are more challenging to treat with lasers due to their brittleness. Laser-modified zirconia implants exhibit strong osseointegration, with micro-grooved zirconia performing comparably to titanium in animal models.[42] For PEEK implants, CO_2 laser treatments have effectively improved surface roughness and wettability, thereby enhancing biological performance.[43] Interestingly, ultraviolet (UV) laser irradiation has been shown to improve the surface properties of PEEK, promoting better cell adhesion and proliferation.[44] UV laser irradiation involves laser-generated UV light, distinct from non-laser-based UV treatment methods that will be discussed later. Furthermore, combining laser treatment with plasma treatment has enhanced osteoblast adhesion and fostered better osseointegration.[45]

Plasma treatment

Plasma treatment has emerged as a promising method for enhancing the properties of dental implants, boosting their osseointegration, biological activity, and antibacterial performance. In titanium implants, plasma treatments, such as dielectric barrier discharge and argon plasma, improve surface wettability and promote better osteoblast attachment, leading to enhanced bone formation and tissue response.[46,47] Plasma treatment also helps reduce surface contaminants, although its impact on osseointegration can vary based on the specific treatment used.[48] For zirconia implants, plasma treatments—especially nitrogen and carbon plasma modifications—improve cell adhesion, proliferation, and osteogenic differentiation, promoting better osseointegration.[49] Cold atmospheric plasma has been particularly effective in reducing bacterial adhesion and biofilm formation, which helps prevent peri-implant infections.[50] Additionally, plasma treatment increases surface roughness and wettability, improving mechanical stability and biological performance.[51] Regarding PEEK implants, plasma treatment effectively enhances surface properties like hydrophilicity and roughness. Nitrogen plasma treatments boost osteogenic activity, while hydrogen-oxygen plasma treatments enhance bonding strength and overall biocompatibility.[52] Moreover, plasma treatment improves the antibacterial properties of PEEK, making it an excellent choice for dental and orthopedic implants.[53]

UV treatment

UV treatment significantly enhances the surface properties and bioactivity of dental implants. For titanium, UV photofunctionalization removes hydrocarbons, creating super-hydrophilic surfaces that improve osteoblasts' attachment, proliferation, and differentiation.[54] Studies indicate nearly 100 % BIC contact and increased bone integration strength in animal models.[55] Additionally, UV-treated titanium exhibits antimicrobial properties, which help reduce bacterial adhesion and biofilm formation.[56] In the case of zirconia, UV treatment enhances hydrophilicity by decreasing carbon content and increasing oxygen levels, promoting osteoblast attachment and mineralization.[57] Moreover, UV treatment enhances fibroblast attachment, supporting better soft tissue integration.[58] Regarding the surface treatment of PEEK, UV-induced graft polymerization improves its hydrophilicity, wear resistance, and osteoblast differentiation.[59] While titanium and zirconia exhibit the most significant improvements in osseointegration and soft tissue integration, PEEK shows a moderate increase in hydrophilicity, suggesting that further surface modifications may be necessary for optimal clinical performance.[60]

Importance of coatings

In addition to mechanical and energy modalities, coatings on the bioinert surfaces of implants were found to effectively improve their osseointegration, reduce the risk of infection, and enhance corrosion and wear resistance. The surface modification technologies developed for coating materials on titanium, zirconia, and PEEK can specifically target the corresponding challenges, ultimately improving their long-term stability, performance, and clinical success.

Osseoconductive coatings

The surface chemistry of implants can influence the biological response of bone tissues.[61—63] Bioactive hydroxyapatite (HA), a calcium phosphate type, is commonly used for bone repair and regeneration. When bioactive HA ceramics are combined with the excellent mechanical properties of implant substrates, they can create effective osteoconductive implants. HA coatings on titanium implants, for example, mimic the natural mineral structure of bone, which provides an ideal surface for osteoblast adhesion, differentiation, and subsequent bone formation. These biological interactions are crucial for successful clinical outcomes, especially in patients with compromised bone conditions.[64] Various coating methods have been explored to enhance the biological responses of implants. For instance, electrochemical deposition techniques have produced HA coatings with high crystallinity and favorable chemical properties, improving implant integration.[65] Integrating HA with sandblasted and acid-etched zirconia surfaces has been found to promote bone healing, particularly in compromised bone conditions, which can enhance the long-term success of implants.[66] Another innovative approach involves incorporating graphene oxide and chitosan into HA coatings, which has improved bonding strength, cell—material interactions, and overall osseointegration in both in vitro and in vivo models.[67] Studies have indicated that mixed zirconia-calcium phosphate coatings can support osteoblast growth, although a higher HA content may reduce mechanical stability.[68] Fluorinated HA coatings have also been proven to enhance osseointegration significantly compared to uncoated zirconia implants.[69]

When PEEK is used as the substrate, nano-structured HA coatings can improve BIC and promote better osseointegration in animal models.[70] Alternative techniques, such as cold spray deposition, create uniform and well-adhered HA layers that enhance cell viability and calcium deposition.[8] Additionally, when combined with heat treatment, ion beam-assisted deposition has improved implant fixation and increased bone mineral density.[71] More recent advancements, such as laser-driven HA penetration synthesis, have addressed common issues like delamination, leading to a stable, gap-free interface between the bone and implant that enhances long-term integration.[72]

Antibacterial coatings

Preventing peri-implantitis is essential for maintaining the long-term stability of dental implants, as bacterial colonization and biofilm formation are major contributors to implant failure.[73,74] To address this issue, multifunctional coatings have been developed to provide not only antimicrobial properties but also enhance osseointegration, angiogenesis, and anti-inflammatory effects. Silver (Ag) coatings have been widely applied to titanium, zirconia, and PEEK implants among the various antibacterial strategies due to their strong bactericidal effects. Titanium implants with antibacterial coatings incorporate various bioactive materials to enhance antimicrobial and osteogenic performance.[62,63,75—77] ZnO, SiO_2, and Ag_2O-doped HA coatings significantly promoted bone mineralization, osteogenesis, and angiogenesis, while also reducing bacterial growth.[75] A polyhydroxyalkanoate-based coating on Ti implants provided controlled antibiotic release, effectively inhibiting bacterial adhesion while maintaining biocompatibility.[76] Nanostructured CeO_2 coatings also exhibited strong antibacterial properties and anti-inflammatory effects, reducing cytokine expression and oxidative stress.[77]

Similarly, zirconia implant surfaces have been modified with Ag-ion implantation, calcium phosphate coatings, and gallium doping to provide antibacterial properties while preserving biocompatibility. The Ag-doped calcium phosphate coating effectively eliminates *S. aureus* while maintaining osteoblast-like cell compatibility.[78] Yang et al. pointed out that Ag-ion implantation on zirconia abutments demonstrated strong antibacterial efficacy to ensure long-term stability.[79] Zirconia nanotube coatings with antibiotic-loaded poly (lactic-co-glycolic) acid (PLGA) overcoats can provide sustained antibacterial effects while promoting apatite formation.[80]

Regarding PEEK, KR-12 antimicrobial peptides immobilized on PEEK surfaces via polydopamine (PDA) coating have dramatically enhanced bacterial resistance and facilitated superior bone integration.[81] Ag-based coatings on PEEK, such as ionic Ag incorporated into HA-coated PEEK, have shown exceptional efficacy in reducing biofilm formation and infection rates.[82] A Zn—Mg-MOF74 coating combined with dexamethasone has been demonstrated to promote angiogenesis, osteogenesis, and bacteriostasis significantly.[83] This finding underscores a powerful synergistic effect, merging antibacterial properties with regenerative capabilities. Another promising advancement is the development of a nanostructured PEEK surface, which incorporates mechano-bactericidal nanopillars and releases zinc ions.[84] This design effectively reduces bacterial adhesion and expertly modulates immune responses to minimize inflammation.

Clinical considerations in selecting implant coating techniques

Each coating technique has distinct advantages and limitations, guiding clinical decisions according to specific implant materials and patient conditions. Selecting the coating methods should align closely with implant material properties, mechanical requirements, and geometric complexity. For instance, electrochemical deposition produces crystalline, uniform coatings ideally suited for titanium surfaces. In contrast, cold spray coatings provide superior adhesion and uniformity, beneficial for bioinert polymers like PEEK.[8,65] For antimicrobial Ag-containing coatings, careful regulation of Ag ion release is crucial to avoid cytotoxicity and adverse immune responses.[75,79,82] Harnessing the optimal coating technique required a comprehensive integration of clinical indications, the specific characteristics of implant materials, and the patient's unique needs. This holistic approach was crucial for ensuring long-term implant success, minimizing complications, and achieving favorable patient outcomes.

Discussion

Peri-implantitis is a serious pathological condition characterized by inflammation and bone loss around dental implants, primarily driven by the buildup of pathogenic bacteria on the implant surface. If left untreated, peri-implantitis can lead to implant failure,[85] undermining the success of dental restoration efforts. As dental implants gain popularity, it becomes increasingly crucial to understand how different materials influence the onset and severity of peri-implantitis, which is vital for maximizing implant longevity and enhancing patient outcomes. Table 3 summarized the incidence and survival rates of peri-implantitis reported in various studies for titanium, zirconia, and PEEK implants. Among implant materials, a 10-year prospective study reported that 7 % of titanium implants developed peri-implantitis, which is characterized by advanced bone loss and bleeding on probing.[86] Implants showing signs of peri-implantitis often exhibit higher levels of titanium dissolution compared to healthy implants.[87] Furthermore, several factors, including smoking, a history of periodontitis, and systemic conditions like diabetes and obesity, have been identified as significant risk factors for peri-implantitis in patients with titanium implants.[88]

Zirconia implants generally exhibit a lower incidence of peri-implantitis compared to titanium. Karapataki reported no cases of peri-implantitis in zirconia implants over a 5-12-year follow-up period, although some cases of peri-implant mucositis were observed.[89] In contrast, another study documented a 6.7 % incidence of peri-implantitis over five years.[90] While zirconia implants tend to show fewer complications than titanium, peri-implant mucositis—a milder inflammatory condition—is more commonly reported. The rates of mucositis vary, with one study showing a prevalence of 53 %[91] and another reporting 16.7 %.[90] Additionally, there is no significant difference in the development of peri-implant defects between titanium and zirconia implants. Both materials showed significant bone gain, although titanium implants exhibited a higher defect fill. PEEK implants are associated with a low incidence of peri-implantitis, with one study reporting just 1 % of cases.[92] Specifically, it significantly reduces biofilm formation by *S. mutans* and *A. actinomycetemcomitans*.[93] Based on current evidence, PEEK is emerging as a promising alternative to

Table 3 Peri-implantitis incidence and survival rates of titanium, zirconia, and PEEK implants.

Material	Sample size	Follow-up period	Peri-implantitis incidence	Survival rate	Ref
Ti (SLA)	511 implants, 303 patients	10 years	1.8 %	98.8 %	32
Ti (SLA)	374 implants, 177 patients	10 years	7 %	99.7 % (implant) 99.4 % (patient)	86
Ti (TiUnite)	1229 patients from 19 studies	48 months	5.2 %	99.5 % (1 year) 95.14 % (10 years)	94
Ti (TPS)	95 implants, 67 patients	20 years	—	89.5 %	95
ZrO_2 (two-piece)	91 implants, 9 patients	5—12 years	Peri-implantitis: 0 % Peri-implant mucositis: 7.7 %	High survival rates MBL <1.65 mm	89
ZrO_2 (one-piece, two-piece)	29 implants	5 years	Peri-implantitis: 0 % Peri-implant mucositis: 53 %	86 % (implant) 78 % (patient)	91
ZrO_2	30 implants	5 years	Peri-implantitis: 6.7 % Peri-implant mucositis: 16.7 %	93.3 %	90
ZrO_2	161 implants, 71 patients	≥7 years	0 %	77 %	96
PEEK	96 implants, 21 patients	4.5 years	1 %	99 % survival, minimal bone loss	92

SLA, sandblasted, large-grit, acid-etched; TiUnite, titanium oxide anodized surface; TPS, titanium plasma-sprayed; MBL, marginal bone loss.

titanium and zirconia, especially for patients at higher risk of peri-implantitis and those with bruxism.[92]

The long-term survival rates of dental implants play a pivotal role in assessing their reliability and effectiveness. The material properties, the implant design, individual patient conditions, and follow-up duration influence these rates, as outlined in Table 3. A compelling 10-year prospective study has shown an astounding survival rate of 99.7 % at the implant level and 99.4 % at the patient level for SLA titanium implants.[86] In a meta-analysis involving 1229 patients across 19 studies, the survival rate is an impressive 99.5 % survival rate at 1 year and 95.14 % at 10 years for TiUnite-surfaced titanium implants.[94] Notably, one of the most extensive follow-up studies reports a 20-year survival rate of 89.5 % for titanium plasma-sprayed implants.[95] Despite these impressive survival rates, titanium implants have been associated with complications, such as peri-implantitis and patient-related risk factors, which may impact their long-term prognosis.

Regarding zirconia implants, a study following 91 two-piece zirconia implants for 5–12 years reports high survival rates with minimal marginal bone loss ($<$1.65 mm) and no implant loss.[89] Another investigation into one-piece and two-piece zirconia implants over 5 years demonstrates an implant-based survival rate of 86 % and a patient-based survival rate of 78 %.[91] In contrast, a separate study with a 5-year follow-up on 30 zirconia implants shows an outstanding survival rate of 93.3 %.[90] Furthermore, an extensive survey of sandblasted zirconia implants reports a $\geq$7-year survival rate of 77 %.[96] While these findings indicate promising survival rates for zirconia implants, there is a critical need for extended follow-up studies and advancements in implant design to solidify their long-term predictability.

While clinical data on PEEK implants remain limited, early studies suggest they also have high survival rates. One 4.5-year study reports a 99 % survival rate for PEEK implants, with minimal bone loss.[92] Additionally, the survival rate for the PEEK prosthesis is 100 %, demonstrating strong mechanical stability and clinical reliability. Despite these encouraging results, further long-term clinical trials were deemed necessary to necessary to establish the predictability of PEEK implants compared to titanium and zirconia options.

The aging global population, along with systemic conditions such as osteoporosis and diabetes, presents new challenges for dental implantology. Research indicates dental implants have high survival rates in aging populations, with five-year survival rates of 96.1 % among geriatric patients (75 and older)[97] and 92.9 % for those aged 60 and above.[98] A comprehensive 10-year meta-analysis reinforces this confidence, revealing an overall survival rate of 96.4 %.[99] While it is true that the risk of implant failure may be slightly elevated in patients over 65, these statistics strongly argue that age alone should not deter the pursuit of dental implants. Instead of age, it is crucial to consider factors such as periodontal health, systemic conditions, and bone metabolism, all of which may play pivotal roles in the durability and success of implants. Among these systemic conditions, osteoporosis and diabetes were particularly significant, given their strong link to aging and their potential impact on implant outcomes.

Osteoporosis, a systemic condition characterized by decreased bone mineral density and compromised bone strength, was highly prevalent among older adults. Individuals with osteoporosis experience similar implant survival rates as those without, suggesting that the presence of osteoporosis should not deter implant placement.[100] However, the condition can compromise osseointegration due to diminished bone quality and density, potentially resulting in slower integration and impaired bone remodeling,[101] which occur particularly in the posterior maxilla. This may necessitate strategic surgical interventions, such as longer healing periods, utilizing wider-diameter implants, or employing modified implant surfaces.[101]

Recent advancements in implant surface modifications showed promise in enhancing osseointegration and bone regeneration in osteoporotic patients. For example, drug-releasing coatings that incorporate anti-osteoporotic agents may strengthen bone density and implant stability.[102] Additionally, materials containing strontium have shown remarkable therapeutic potential as a non-antibiotic, as they stimulate osteoblast differentiation and inhibit the formation of osteoclasts.[103] Lin et al. demonstrated that strontium-doped titanium surfaces improved osseointegration in osteoporotic animal models.[104] Nevertheless, further large-scale, long-term clinical trials were imperative to thoroughly evaluate these innovative approaches and refine implant protocols for osteoporotic patients.

Diabetes presents significant challenges for the success of dental implants due to its impact on osseointegration, bone metabolism, and peri-implant health. However, well-controlled diabetes does not significantly increase implant failure rates, and diabetic patients can achieve success rates on par with their non-diabetic counterparts.[105] In contrast, poorly controlled diabetes is associated with higher failure rates, particularly during the first year following functional loading, due to delayed healing, microvascular complications, and reduced BIC.[106] To address the challenges faced by diabetic patients, the developed hydrophilic surfaces on titanium-zirconium implants have shown high success rates, regardless of patients' glycemic control levels.[107] These implants help maintain stable peri-implant bone levels and enhance patient-reported outcomes. Equally promising, chemically modified SLA implants have demonstrated comparable stability in poorly controlled diabetic patients, making them a viable option for implant therapy.[108] Also, calcium phytate-modified titanium surfaces have been found to promote bone regeneration and osseointegration in high-glucose environments by reducing oxidative stress and promoting osteogenic differentiation.[109] Carbon nanomaterial-modified biomimetic implants also provide antibacterial and anti-inflammatory properties, benefiting diabetic patients who often experience immune dysregulation.[110] Titanium implants coated with highly crystalline nanostructured HA (nHA) or silicon-substituted nHA (Si-nHA) have been shown to significantly improve osteogenesis, angiogenesis, and osseointegration under diabetic conditions, reinforcing their suitability for implant therapy in diabetic patients.[64] Finally, consistent follow-up care, proper oral hygiene practices, and patient education were vital components in preserving peri-implant health and ensuring long-term stability of implants.

Conclusion

Titanium, zirconia, and PEEK each offer unique advantages and limitations as dental implant materials, which can influence their clinical performance and long-term success. Titanium can be susceptible to peri-implantitis and may release metal ions, which can complicate treatment for patients with metal hypersensitivities. Inherent brittleness and lower fracture resistance of zirconia could limit its durability in the long run. PEEK may need surface modifications to enhance its osseointegration potential. Employing advanced surface modification techniques was vital for enhancing implant performance, such as osseointegration and antibacterial activity. It was also important to recognize that systemic conditions like aging, osteoporosis, and diabetes could significantly impact implant success by influencing bone healing and integration. Therefore, careful material selection and innovative surface treatments were paramount for improving long-term clinical outcomes. The future of dental implantology should lie in developing hybrid materials that leverage the unique properties of titanium, zirconia, and PEEK while addressing their limitations, ensuring improved longevity and functionality.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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