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TAILORING POROSITY, STRENGTH, AND BIOACTIVITY IN TITANIUM-BASED DENTAL IMPLANTS

Dental Science

Rajashree Ganguly*	Professor and Head, Department of Periodontics & Implantology, Kusum Devi Sunderlal Dugar Jain Dental College & Hospital, Kolkata, West Bengal, India *Corresponding Author
Madhumita Majumdar	Professor and Head, Department Of Oral and Dental Sciences, JIS University, Kolkata, India
Tamal K. Pal	Emeritus Professor and Director(Research), JIS University, Kolkata, India
Santanu Dhara	Professor, Biomaterials and Tissue Engineering Group, School of Medical Science and Technology, IIT Kharagpur, West Bengal, India

ABSTRACT

Titanium and its alloys are the ideal material for dental implants, being superior in mechanical properties, corrosion resistance and biocompatibility. Nonetheless, solid titanium implants present some limitations such as the high stiffness that contributes to stress shielding, poor osseointegration, limited blood vessel formation and possible biologic incompatibility. This has led to the design of porous titanium implants that are more like the mechanical and biological properties of bone. Through controlled porosity, these implants decrease the elastic modulus difference between the implant and host bone to promote load transfer and reduce bone resorption. The porosity interconnects encouraging more profound ingrowth of bone tissue, vascularization, and providing better long-term stability. Moreover, coating the surface of porous implants with bioactive materials enhance the cell adhesion, proliferation, and prevention of infection such as peri-implantitis. The advent of 3D printing has now made customised pore architecture a reality, with patient-specific implants tailored to achieve the ideal balance between mechanical strength and biological integration. In spite of these interesting advances, a trade-off between mechanical resistance and porosity has to be achieved, as well as durable bioactive coatings covers and production costs must be handled. In this review, the importance of porosity as it pertains to the mechanical properties, bio-activity and resistance to infection that dictate enhanced dental implant performance is described and future work directions for next generation dental implants with tailored functionality for improved clinical success in dental rehabilitation is provided.

KEYWORDS

Dental Implant, Titanium Implant, Porous Titanium, Bioactive Material, Osseointegration

1. INTRODUCTION

Titanium and its alloys are considered to be the 'gold standard' with regard to dental implant materials, due to their adequate mechanical properties, corrosion resistance, and high biocompatibility. Dental implants fabricated from solid titanium have good long-term clinical success, especially those made of commercially pure titanium (CpTi) and Ti–6Al–4V and can reach up to 98% of survival rates with long follow-up period (Jorge et al., 2013). Nevertheless--even though widely accepted--solid implants made of titanium have some inherent disadvantages that have initiated research on improved materials and designs.

One of the problems of solid titanium implants is their stiffness, causing stress shielding and bone resorption. The elastic modulus of bulk titanium is much higher than that of human bone, which leads to mechanical mismatch and long-term stability and integration problems. Secondly, despite the fact that titanium is overall looked upon as biocompatible, the question emerging around the release of titanium ions, allergies and the lack of aesthetic since the material is metallic in color have increased the need for new materials developments (Aissi et al., 2025; Nasution & Hermawan, 2016).

Porous titanium implant has been developed and become one of the most promising breakthroughs in the field of dental implantology to overcome these drawbacks. Through a controlled titanium pore structure, these implants provide a nearer approximation of the architecture and properties of natural bone. Porous titanium implants can be softer to allow more uni form stress distribution and reduce bone resorption. The interconnected porosity not only promotes osseointegration through allowing in growth of bone tissue but also induces vascularization, which is necessary for implant survival in long term (Martinez-Marquez et al., 2020).

Furthermore, bioactive coatings and surface treatments can be applied on the surface of the porous titanium implants. The combined topographical roughness and chemical modification has been demonstrated to affect cell attachment, proliferation, and differentiation to a greater extent than uncoated or simply roughened surfaces. These improvements result in both rapid healing and added implant stability, particularly in patients with poor bone density.(G. Yang et al., 2023).

The development of porous over solid titanium dental implants and design rationale are herein reviewed in this study. It explores porosity's effect on osseointegration, mechanical stability, vascularization, and infection management, and is informed by contemporary clinical and preclinical findings. The review also discusses a number of problems associated with the porous implant production, such as mechanical imperfection, poor coating response and high production costs. The future direction for the field is also discussed, such as patient-specific implant fabrication by means of advanced additive manufacturing as well as smart bioresponsive surfaces for improved functionality. (Pałka & Pokrowiecki, 2018; Shayganpour et al., 2015).

In this review, based on the current research and clinical application of porous titanium implants, an account of the rational design of porosity, mechanical strength, and bioactivity, customization of titanium implants will be given. The discussion will be aimed at how porous implants can address the deficiencies of traditional solid titanium dental implants, and enhance patient satisfaction in dental rehabilitation.

2. Present Titanium-Based Dental Implants and Their Limitations

Currently, titanium (Ti) and its alloys are the most commonly used materials in dental implants, due to their high biocompatibility and excellent mechanical properties. In the past twenty years, Ti-based dental implants have achieved great success, with a total success rate of 98.8%, fracture rate of 0.08%, and failure rate of 1.2% in a follow-up of 250-359 dental implants from 473 clinics with an average observation time of 4.5 years (Shin et al., 2014). Commercially pure titanium (CpTi) and Ti–6Al–4V are the most widely used and studied dental implant materials. They provide sufficient strength, corrosion resistance, stability in physiological environments, and a relatively mild tissue reaction, which promote favorable quality bone-implant contact and osseointegration.(Shah et al., 2016; Silva et al., 2022).

Although there are significant advantages to using Ti and its alloys as dental implants, they still have several drawbacks. The drawbacks of Ti-based dental implants can be divided into aesthetic issues, biological problems, and progress in bioengineering events. Currently, in the area of aesthetic improvement, efforts are being made to provide better replacement materials for Ti–6Al–4V and CpTi dental implants that will be whitened at a reasonable cost. Substituting Ti with other metals such as zirconium or using ceramic materials has been proposed to achieve a more aesthetic outcome since these materials are naturally white and more resemble natural teeth compared to dark Ti. However, there is currently no concrete evidence confirming that joining the titanium gray infiltrates on the fixture surface convert thin tissue into thick tissue and continues to be a plausible treatment plan(Aissi et al., 2025; Luczak et al., 2025; Nasution & Hermawan, 2016).

In the area of biological concerns, Ti is no longer considered an entirely bioinert material, as several studies have observed symptoms of metal allergies in patients receiving Ti dental implants and reports of high concentrations of Ti alloying elements, including Al, V, and Fe, in the vicinity of the oral implants, urine, serum, and local lymph nodes. These elements are potentially harmful to the human body. However, the clinical relevance of the above findings remains to be studied, as several studies have previously confirmed the good biocompatibility and reliability of Ti-based dental implants for long-term usage in the oral environment. Several studies involving low-frequency mechanical stimulation using a frequency of 0.5 Hz and a strain of 1000 με showed significant adverse effects on the survival of Ti implants by shortening the contact and bridging duration of osseointegration. These phenomena, together with the aesthetic concern, have prompted some dental patients who are psychologically fearful of dark Ti to request metal-free dental implants (Comino-Garayoa et al., 2020; Kim et al., 2019).

Figure 1: Limitation of Solid Titanium Based Dental Implants

3. Porous Titanium Implants

Ti and Ti alloys are preferred in many clinical implants for their favorable stiffness-to-weight ratios and corrosion resistance, making them ideal for dental implants. To reduce the rigidity of Ti implants, several treatments have been developed. For example, one of the presently most popular and effective strategy is to add porosity to Ti alloy implants that simulates the natural bone environment. In such modifications, pore size is crucial; pores that are too large (>800 μm) can jeopardize stability during implantation. Additionally, surface coating by polymeric oligomers can produce nanosphere coatings, enhancing surface area. Low-temperature calcination effectively bonds drugs to porous Ti. A dual porosity coating allows for a drug reservoir in larger pores, while smaller pores assist protein absorption for sustained release. Coated Ti implants can deliver drugs for up to 72 days, facilitating protein release. Additionally, studies proved that a porous Ti scaffold promotes osteogenic activity by aiding mouse MC3T3-E1 cell migration in a 3D context.(Luan et al., 2019; Zhang et al., 2020) Regularly spaced pores in a Ti alloy minimize rigidity and stress shielding, improving osteogenic activity. The mechanical properties of scaffold materials are critical; PEGDA networks with CaCO3 microspheres yield porous hydrogels with bone-like strength. An ideal scaffold pairs a dense core with a porous shell for optimal performance. Porous Ti implants demonstrate excellent biocompatibility and bioactivity, bolstered by surface oxidation and growth factor-enhanced adhesion (Tsai et al., 2019; F. Yang et al., 2017).

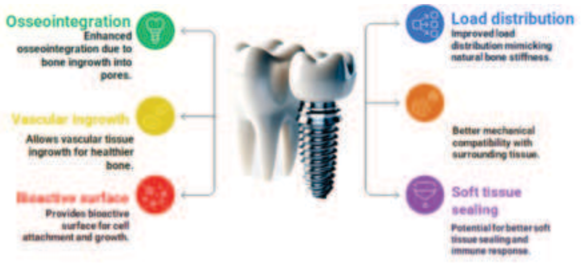

Figure 2: Advantages of Porous Titanium Implants

3.1. Need for Porous Implants

Titanium and titanium alloys are the most commonly applied materials for dental implants, crowns or bridges, and fixed partial dentures. A recent focus within biomaterials in research, and clinical applications is on porous implants. Porous Ti and Ti alloy bio-metamaterials allow for unique encouraging patients with bone maladies: the long-term implant failure is a major clinic problem, causing from insufficient osseointegration, insufficient mechanical properties mismatch to host bone, bacterial contamination and consequent biofilm formation, and fibrous tissue formation on implant surface. Addressing these issues, porous bioactive Ti-based biomaterials have several benefits compared with conventional solid materials, improved bone healing. As bone-like chemical composition, porous implant structures have higher biocompatibility and bioactivity. With porous Ti and Ti alloy bio-metamaterials, osseointegration is also improved, and superior results have been accomplished in relation to mechanical properties (Seesala et al., 2024; Wally et al., 2015).

3.2. Types of Porous Titanium Implants

Pore size regulation of porous titanium dental implants and the resulting biological and mechanical properties are of prime importance. Although solid implants themselves can have good mechanical properties, they often do not integrate well with bone. In contrast to this crosslinking, the addition of microporosity (pore sizes of 0.1–10 μm) is thought to improve protein adsorption and early healing via increased cellular attachment, while restricting penetration further into the tissue. Macroporous implants with pores > 100 μm provide better osseointegration since they support a good bone cell ingrowth and vascularization, ensuring a better bone to implant interface, which is highly relevant for load bearing applications. Hierarchically porous implants, which contain both micro- and macroporosity, are an advanced concept which can accommodate early biological signaling and long-term mechanical protection. Furthermore, nanoparticles with pores smaller than 100 nm for surface coating enlarge wettability and bioactivity of surface, thereby promoting initial cellular responses and likely antibacterial properties. Advances in additive manufacturing facilitate control over the architecture of pores and permit fabrication of implants adapted to patient-specific anatomy and function. By designing and controlling pore-size, implant designers can optimize the correlation between mechanical strength and biological integration, to allow better implant healing, decrease of implant failure, and better clinical results for dental applications. Table 1 summarizes the implants with different pores sizes and its influence on their application and functionality.(Mendonça et al., 2008; Taniguchi et al., 2016)

Table 1: Types of Implants Based on Types of Porosity

Implant Type	Material/System	Porosity Type	Pore Size Range (μm)	Porosity (%)	Features/Applications	References
Microporous Implants	Titanium, Hydroxyapatite	Micropores (<10 μm)	0.1–10	Low (5–15%)	Improved protein adsorption; limited cell infiltration	(Karageorgiou & Kaplan, 2005; LeGeros, 2008)
Macroporous Implants	Titanium, Bioceramic (CaP, TCP)	Macropores (>100 μm)	100–1000	30–70%	Promotes vascularization and bone ingrowth	(Bansiddhi et al., 2008; Taniguchi et al., 2016)

Hierarchical Porous Implants	Bioactive glass, Calcium phosphates	Micro + Macro porosity	Micro: 1–10 Macro: 100–500	40–85%	Combines early protein attachment with deep cell and vascular invasion	(Bose et al., 2013; Wang et al., 2016)
Nanoporous Coated Implants	Laser-treated Titanium, Nanohydroxyapatite	Nanopores (<100 nm)	0.01–0.1	Very low (<5%)	Enhances surface reactivity, cell adhesion, antibacterial properties	(Mendonça et al., 2008; Nandhini et al., 2021)
3D Printed Scaffolds with Controlled Porosity	Bioceramic (Fluoroapatite, β-TCP), Titanium alloys	Precisely controlled porosity	100–800	40–90%	Customized mechanical and biological performance; used in critical defect repair	(Gómez-Cerezo et al., 2021; Murr et al., 2012)
Multiphase Bioceramic Systems	Magnesioapatite, Fluoroapatite composites	Interconnected micro/macro	100–1000	50–85%	Gradient porosity and composition for controlled degradation and bioactivity	(Bohner, 2010; Dorozhkin, 2011)
Dendritic Bioceramic Scaffolds	Calcium phosphate, Bio-glass	Biomimetic hierarchical	Micro: <10; Macro: 200–500	45–75%	Popcorn-like or dendritic architectures for enhanced osteoconduction and bioactivity	(Kokubo & Takadama, 2006; Valletregi, 2004)

3.3. Properties Based on Pore Size
The features of bulk titanium specimens with macropores (multiple sizes) were compared with those produced by 3D printing techniques. It is established that the type II/IV macropores of teeth bone and dental implants are best suited to titanium specimens of multiple sizes. It is recommended to fabricate the implants with multiple macropores via 3D printing given the freedom of designing complex internal structures. The predicted models were verified by inspecting porous specimens' porosity and surface area. The creep response of a porous structure is affected by pore size ratio. The proposed multi-pore titanium structure with the maximum size ratio of 3.8% displays better damping capacity and lower creep strain (F. Yang et al., 2017)

3.3.1. Mechanical Properties
Ideally, the effective pore size (meaning the diameter of a sphere that can pass through the pore) for bone tissue engineering is between 60 and 400 μm, whereas for pure Ti the Ultimate Tensile Strength (UTS) and yield strength are 120 MPa and 100 MPa, respectively. (Abbasi et al., 2020; Mour et al., 2010; Wu et al., 2017) Permeability and load-bearing stability are indirectly proportional. It is well-established that osteoporosis results in the microstructural deterioration of bone, with struts connecting pores fatigue and failing over time. Thus, larger macropore sizes should be incorporated into the design of dental implants. Porous structures that can be placed and press-fitted without mechanical fixation are also more favorable in terms of safety and efficacy. However, surface area available for cell growth, mechanical integrity, and bone integration are also critical. Skeletal bones offer great variability in macro- and microstructural designs with tilt angles with the presence of porosity in the micrometer and nanometer ranges playing multiple roles in its functions. Due to these complexities, it is difficult to manufacture stochastic structures and to tailor the pore size and shape.(Buccino et al., 2024) For HA coating, the flexural strength, which is the most critical property for HA coatings, should be greater than 30 MPa which is the tensile strength of the bone tissue, or significant cracks will occur on the coatings, leading to implant loosening. Bioactive HA coating should be formed quickly after implantation, while the excessive formed HA may lead to the fractures of the coating.(Converse et al., 2007; Miri et al., 2024)

3.3.2 Chemical Properties
Surface roughness and mechanical locking between the implant surface and surrounding bone tissue is an important feature of osseointegration, together with the bioactivity of implants (Deng et al., 2014). To coalesce usefully porous titanium and hydroxyapatite (HA)-coated titanium implants, it is required to improve the bonding strength by optimizing surface morphology or enhancing the coating quality. Consequently, the introduction of alkali and heat treatment offers a simple and effective approach to obtain porous titanium implants with considerable compressive elastic modulus, enhanced fatigue strength, and improved bioactivity. Superficial characteristics including pore size, shape, porosity, and structure are not the only properties affecting osseointegration. The biochemistry of the implants plays an important role as well. The bioactivity is highly correlated with the biochemistry of the implant manufacturing and surface chemistry. The chemistry of the implant dictates how it can interact with bodily tissue and facilitate a biological reaction at the surface to form a direct bond with living bone. Generally, surface coating materials can be classified into several groups based on the mechanism of bioactivity. Of those, bioactive glasses and certain glasses-ceramics can enhance mineralization when immersed in Simulated Body Fluid (SBF), leading to the formation of a bone-like apatite layer on the surface. (Ylänen et al., 2000).

Currently, different surface modifications including the sol-gel method, plasma spraying, bioactive glass coating, and electrophoretic deposition have been used to fabricate bioactive coatings. Among those methods, hydrothermal chemical reaction is widely used to synthesize hydroxyapatite (HA) coatings and heat treatment can significantly improve their adhesion strength to substrates. (Drevet et al., 2024; Garrido et al., 2022; Owens et al., 2016).

3.3.3 Bioactivity
An advanced implant biomaterial with high clinical relevance warrants similarity with the structure of natural bone. Therefore, introducing the fabrication flexibility, maximizing the strength of the bioactive scaffold through innovative design strategies are both interesting and challenging (Yang et al., 2023). 3D-printed continuous porous titanium scaffolds with unique enclosure structures are reported, which can better imitate the natural bone architecture. It was also demonstrated that the mechanical, biological and in vivo bone regeneration properties of the scaffolds can be tailored by adjusting the geometric parameters of the porous titanium scaffolds design. Because of the high elastic modulus of titanium, the locally lowered stress of the implants and enhanced bone–titanium integration after bone augmentation are of great importance for persistent retention of those titanium implants. (Doi et al., 2020).

To further enhance the bioactivity of titanium alloy (Ti6Al4V), anodic oxidation of the porous titanium alloy was investigated for the first time and right after 3D printing. After anodizing, TiO_2 nanolayers were evenly coated on the porous titanium surface, and the loading rate and hydrophilicity of the porous sample were significantly improved. Both osteoblast proliferation and adhesion assays proved that the anodic oxidation of porous titanium alloys is advantageous for cell proliferation due to the porous structure, hydrophilicity, and bioactivity of the TiO_2 surface. Bone ingrowth was observed in the inside parts of the porous titanium scaffolds, which were successfully connected to the surrounding bone.(De Sousa et al., 2024).

4. Enhanced Bioactivity in Porous Implant
The complex interactions between the implant and its biological environment require an assessment of the bioactivity from different points of view. Such assessment must take into consideration osseointegration, its vascularization, and incorporation into the host bone and the control of infection especially biofilm formation (Steffanie Rappe et al., 2022).

4.1 Osseointegration
Osseointegration is referred to direct anchoring of an implant into the bone tissue, and therefore, it requires a new woven bone formation from the surrounding host bone tissue. This new bone formation occurs from microscopic sites of contact, and it evolves spatially and temporally into a mature lamellar bone-implant interface, which is mechanically effective both in load transfer and in the prevention of micromotions.

Clinical and preclinical research has shown that pure porous titanium dental implants promote superior osseointegration when compared to solid implants by facilitating the actual ingrowth of bone — osseoincorporation — opposed to the bone just growing on the surface. A groundbreaking histomorphometric study in rabbit tibiae showed that porous surfaces with pore sizes in the optimal range of 100-400μm achieved significantly greater bone neoformation and mechanical interlocking at the bone-implant interface than the rough-surfaced implants, even though both of them established mature trabecular bone. This, more intensive ingrowth of bone into interconnected pores enlarges contact area and improves mechanical stability.(Brentel et al., 2006).

Another animal study on dogs demonstrated significantly higher bone-implant contact (BIC) and more new bone formation within the porous scaffold of implants with open, trabecular like porosity (up to 70-80%) as early as 4 weeks after implantation in a pilot study. These interconnecting pores served as highways for nutrient delivery, vascular ingrowth and osteoblast-like activity, and established biological fixation that exceeded solid titanium implants when measured by early stability and bone-ingrowth.(Hong et al., 2020).

A systematic preclinical review has established that porous-surfaced implants (like the Trabecular Metal® system) show significantly greater bone formation in the peri-implant bone and BIC% than solid-surfaced implants, although the heterogeneity of individual studies does not allow to perform a quantitative synthesis.

Porous titanium theoretically reduces stress shielding by matching elastic modulus to that of bone, promoting a greater rate of diffusion of nutrients and oxygen and a three-dimensional bone ingrowth, leading to better and more durable osseointegration. This is evidence in favor for the clinical benefit of porous over solid titanium implants. (Ahmed et al., 2021; Seesala et al., 2024).

4.2 Vascularization

The vascularization of the newly formed and already present bone is key to ensure the transport of nutrients, growth factors, and oxygen as well as the removal of debris and metabolic wastes. A successful implant design must ensure the concurrent enhancement of osseointegration and maturation of the bone-implant interface, as well as its vascularization. To this end, survival of the plate-shaped samples was ensured while harvesting the specimen formats to be used, i.e., cylindrical without vascularization and cylindrical with vascularization.

Porous titanium implants dramatically improve vascularity of the implants compared to the solid counterparts, which is essential for another osseointegration and long-term stability of the implants. The interconnected porous structure provides pathways that enable rapid infiltration of blood vessels to carry oxygen and nutrients required for bone formation and remodeling. Pore sizes from 100 to 400 μm in clinical and preclinical studies have been found to be particularly useful in directing angiogenesis-new blood vessel growth representative of osteogenesis (bone generation) within and around the implant.(Dabrowski et al., 2010; Yoo, 2013).

Solid implants on the other hand, are mainly dependent on superficial bone contact and have no potential to penetrate deep into vasculature, with biological integration only being possible at the peripheral boundary of the solid implant. It is reported that Titanium implants containing less than 0.5% of open porosity presented markedly increased vascular extinction, and lower bone regeneration compared with those with open porosity higher than 0.5%. (Pałka & Pokrowiecki, 2018).

Likewise, Taniguchi et al. (2016) concluded that the amount of vascularization and, therefore, bone in-growth was directly influenced by the degree of porosity and the interconnection of pores of the Ti porous implants the same as in the rabbit model- by means of using porous titanium implants manufactured out of the EBM technology.(Taniguchi et al., 2016).

The increased vascularity with porous implants not only promotes a faster healing process, but also minimizes the potential for implant resorption by allowing for a more stable and biologically incorporated environment. This vasculature supply is critical to supply bone remodeling and mechanical support over time.

4.3 Infection Control

While the biocompatibility and mechanical properties of dental implants are essential for their survival, the control of biofilm formation is also extremely important to avoid peri-implant infections. The development of biofilms around the implant surface following the initiation of osseointegration is a fast process, requiring only a few hours. Biofilm formation around dental implants may cause inflammation, infection, and ultimately, loss of the bone-implant integration; therefore, biofilm control is essential for the optimal performance of any biomaterial, including dental implants. Immediate loading protocols require competitive mechanical properties and the rapid enhancement of osseointegration to perform in a satisfactory manner.

Porous implants afford a significant reduction in bacterial adhesion and biofilm formation, relative to solid implants, mainly because of their tailored surface properties and functionality. In vitro studies with porous titanium surface modified in pore topology, surface roughness and hydrophilicity have shown a decrease of >80-95% in bacterial attachment compared to conventional plasma-sprayed porous titanium and a stimulation of osteogenic and endothelial cells proliferation. (Gasik et al., 2012).

For example, surfaces with a pore size of about 100-200μm, show an optimal pore size distribution thus maximizing control while inhibiting colonization by both MRSA and Pseudomonas aeruginosa which two pathogen related to clinical peri-implantitic infections. (Beltrán et al., 2019) Porous coatings of about 50% porosity with pores up to 50μm have also been demonstrated to have a nearly five fold decrease in colonization by S. aureus compared to solid titanium surfaces. (Braem et al., 2014).

In addition to its passive architectural advantages, porous titanium can be loaded with antimicrobial agents. It has been shown that impregnation of porous structures with silver nanoparticles allows for prolonged antimicrobial release, providing more effective long-term antimicrobial activity than for same-coated solid implants, because of increased antimicrobial retention, and a more controlled release behaviour. These approaches involve synergistically providing a mechanical barrier against infection and actively functioning as antimicrobials.(Guo et al., 2021).

Collectively, permeable titanium implants induce prevention of infection from (1) unfavorable microenvironments of biofilm formation by customized porosity and surface energy, (2) reductions in microbial adhesion via optimized roughness and hydrophilicity, and (3) continuous local delivery of antimicrobial substances. These changes serve to prevent peri-implant infections and promote long-lasting implant anchorage.

5. Challenges and Future Directions

Nevertheless, the porous titanium implants based on techniques such as powder metallurgy currently available in the market despite of its higher costs, and difficulty in reusing the waste materials. Moreover, they are normally uniformly porous with low filament connectivity, which is crucial for tissue ingrowth. (Lascano et al., 2019) Moreover, a partially porous structure is preferred for long-term mechanical stability, as too large or deep pores will greatly diminish the mechanical properties and also increase the risk of implant fracture, which has been a serious engineering challenge. To address these issues, the pursuit of novel bi-rooted titanium-based dental implants with tailored porosity, strength, and bioactivity is proposed to enhance tissue healing and osseointegration (Seesala et al., 2024; Yuan et al., 2019).

A proper application of coatings can give an implant bioactivity and elasticity, unless the thickness is high, and improve wear behaviour and corrosion resistance of the implant. Off-the-shelf coatings can be applied as well, but on its own they don't achieve highly active scaffolds. The combination of topographical roughness and coating has been found to achieve better cell attachment and proliferation compared to rough coatings or coatings. The fact that Ti surfaces can be improved chemically and mechanically indicates that it can also be improved structurally, increasing its qualified applications. The porous Ti scaffolds are reported with good mechanical properties and design aimed at mimicking the structure of bone only (Comín et al., 2017; Martinez-Marquez et al., 2020). However, the appropriate coating material and techniques poses some challenges.

The rigidity of porous bone replacement materials is essential for guiding the body's repair response. On the other hand, inaccurate shaping can hinder new bone formation and load-bearing capacity. Stable load transfer pathways are crucial to avoid fatigue cracking; otherwise, the repair response may falter, rendering the construct unsuitable. Cracks typically emerge at high bending moment spots where support is lacking. Challenges arise from securely knitting ceramic spheres to minimize movement. Coatings and sanding efforts have been made, but size variations lead to incomplete densification from plastic movement at high temperatures. Sterilization and bioactivity treatments are also problematic (Huang et al., 2021). Maximum sintering and treatment temperatures are critical since high heat can cause excessive densification and lower bioactivity. Methods promoting small crystals and residual porosity at 600 °C can drastically alter apatite properties beyond 800 °C (Oliveira et al., 2021). Effective strategies are needed to limit temperatures in porous bone replacements. Bioactivity and osseointegration involve creating a hydrated layer on silicon surfaces, mimicking bone activity to aid in osteogenic precursor and calcium salt migration (Martinez-Marquez et al., 2020).

Spreading the innovations and improving coatings methods of traditional implants can lead to better results in revisions and treatment of complex cases. All the findings bode well for the future application of those porous implants both in vivo with the biocompatibility and osseointegration studies, and ex vivo.

6. CONCLUSION

Titanium and titanium-based alloys have been the materials of selection for dental implants because of their excellent mechanical properties, non-corrodibility, and biocompatibility. Solid titanium implants, however, have drawbacks such as stress shielding, low osseointegration, being aesthetically unacceptable and prone to bacterial colonisation. These deficiencies have spurred the creation of porous titanium dental implants, which demonstrate an exciting evolution in implant technology.

One solution to address some of these limitations were porous-smooth titanium implants, which more appropriately resemble in structure and mechanical behavior natural bone. Controlled porosity lowers the difference in rigidity between implant and bone, leading to a better load distribution and reducing stress shielding. The interconnected porous structure not only improves osseointegration with deeper bone infiltration but also favors vascularization which is very important for the long-term success of an implant. Additionally, the implant supported bioactive coatings and surface treatments can also increase cell adhesion, proliferation and antibacterial abilities.

In spite of these encouraging features there remain challenges. Such aspects consist the optimization of pore size and architecture for the tradeoff between mechanical strength and biological integration, the establishment of dependable and enduring bioactive coatings, and the economic viability of large scale manufacturing by sophisticated methods like additive manufacturing. These challenges should be considered when future research and development is made, to guarantee the clinical safety as well as long term performance and cost effectiveness.

It is anticipated that the future of dental implantology is the development of new biomaterials, appropriate engineering of implant structures, and biologically active surface modification. Supply decisions will influence the productive capability of one's Porous titanium implants, osseointegration, vascularization and infection control capabilities, and provide the possibility to increase patient outcomes for the dental restoration.

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