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Review Article

Titanium Implant Corrosion and Peri-Implant Disease: Current Concepts and Future Directions

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ABSTRACT

The titanium implants have been widely accepted as an ideal material for orthopaedic and dental surgery, due to good biocompatibility, strength and osseointegration. However, the commercially used titanium implants are not without complications; corrosion has been a big concern. As described, corrosion of titanium implants is rare. Still, it can result in the release of titanium ions and particles that activate inflammatory pathways related to the development of peri-implant diseases (e.g., peri-implantitis). These factors may cause tissue necrosis, bone resorption, and ultimately, implant failure. Recent works have increasingly reported corrosion as one of the major factors in the progression of peri-implantitis connected with bacterial infection and lack of oral cleanliness, which lead to implant failure. Corrosion product may trigger the activation of the immune system, like macrophage activation and production of pro-inflammatory cytokines. In this review article, the literature regarding corrosion of titanium implants and their relationship with peri-implant diseases in the light of changing approaches to avoid such hazards is evaluated. Surface treatments, the use of modern titanium alloys, bioactive coatings and customised implant solutions are considered, in order to improve the corrosion resistance and prolong the lifetime of titanium implants. The most important research will be to combine these advances, eventually leading to enhanced patient success and less implant failure from problems related to corrosion.

Keywords: Biocompatibility, Corrosion, Implant Failure, Peri-implantitis, Titanium Alloys

BACKGROUND:

TDA implants are now a mainstay of modern orthopaedic and oral-maxillofacial surgical practice, used throughout the world due to their excellent biocompatibility, strength and durability [1]. Most commonly, these devices are metallic implants composed of pure titanium or a titanium alloy, which can bond with bone in the human body to form what is called osseointegration and have become a popular material for implants, including prosthetic devices and dental jaw implants, as well as joint replacements [2]. Although titanium implants have been widely used and proven clinically successful, concerns about their long-term performance, mainly corrosion behaviour and its potential implications in peri-implant diseases, have recently emerged [3].

While rare under typical circumstances, corrosion of titanium implants can result in certain environments and conditions, such as exposure to aggressive biofluids, mechanical strain or damage to the implant surface [4]. The main issues are that corrosion may cause to release of metallic ions or particle debris, which can generate biological reactions resulting in local tissue inflammation, infection, and finally peri-implant disease. These are, for instance, peri-implantitis in dental implants and periprosthetic infections in orthopaedic endoprostheses (devices) and cause a considerable amount of clinical problems which may result in implant/therapy failure [5].

Peri-implant disease is an inflammatory process affecting the soft and hard tissue surrounding an implant, which in its most severe form (peri-implantitis) also includes co-existing bone loss [6]. Although peri-implant disease has been traditionally linked to a lack of oral hygiene and bacterial colonisation, evidence is growing that corrosion products of titanium-based implants can exacerbate or even play a role in initiating the inflammatory responses inherent to this pathology. Knowledge about such mechanisms and their surgical relevance in influencing the foreign body reaction to implants is pivotal when trying to minimise implant failure rates and improve patient care [7].

Other than corrosion, the biocompatibility of titanium implants also depends on factors such as the implant design, surface modifications or mechanical conditions in which the work implant operates [8]. In this context, research has also been conducted aiming at making the surface of titanium implant more optimal, such as using porous coated biomaterials to coat the implants or developing new types of titanium alloys that is more resistant to corrosion but have improved osseointegration. These advancements are intended to minimise the possibility of corrosion-related issues and enhance implant stability and lifespan [9].

Furthermore, attention should be given more to the exploration of the mechanisms involved in the interactions between the implantation metals and their surrounding tissue, which including other researches focusing on foreign body reactions like corrosion products and immune response [10]. This may in turn facilitate the emergence of more advanced materials and implant designs with reduced potential for corrosion and peri-implant diseases. In addition, personal medicine treatments, including the patient's health status, location of implant and material, could serve as an important strategy to minimise complications related to implants [11].

This review discusses current knowledge on the corrosion of titanium implants, their linkage to peri-implantitis, and emerging ways to control such risk. This article intends to demonstrate in both dental and orthopaedic environments the importance of material science, patient factors, and clinical management for ultimate long-term success with titanium implants by presenting new developments and future directions.

REVIEW:

Corrosion of Titanium Implants: Mechanisms and Impact

Titanium has good resistance to corrosion and other chemical attacks, by virtue of a stable oxide (TiO_2) film on its surface. However, the protective oxide layer may be degraded upon exposure to acidic pH or high mechanical forces, resulting in local corrosion [12]. During the corrosion of these components, titanium cations and particulate debris are liberated into the tissue surrounding them, potentially leading to an inflammatory response and bone loss/soft-tissue infection [13].

Peri-implant diseases have recently been highlighted the contribution to corrosion products. Titanium ions can affect the immune system by stimulating macrophage activity to yield pro-inflammatory cytokines and mediators causing bone resorption. Moreover, corrosion can affect the mechanical properties of the implant and might result in decreased stability or failure of the implant [14].

Peri-Implant Diseases: Connection to Corrosion

Peri-implant diseases such as peri-implant mucositis, and peri-implantitis are considered to be the main causes of implant loss. Peri-implant mucositis is an inflammatory process in the soft tissue around implants, with no loss of supporting bone [15]. In contrast, peri-implantitis combines inflammation of the surrounding soft tissue and bone. The principal cause is bacterial infection, but several studies have supported the involvement of corrosion-released titanium ions in the pathogenesis.

The liberated metal particles or ions into the peri-implant tissue may induce inflammation that causes tissue destruction and bone loss [16].

Current and Future Strategies for Mitigating Corrosion and Peri-Implant Diseases

To minimise corrosion and its consequences to the surrounding tissue, application of several approaches is under investigation, such as:

Surface Modifications: Techniques such as anodization, hydroxyapatite coating, and laser treatment can enhance the corrosion resistance of titanium implants. These modifications improve the oxide layer on the titanium surface, reducing the likelihood of corrosion under stressful conditions [17].

Alloy Development: The development of new titanium alloys with improved corrosion resistance and mechanical properties is an ongoing area of research. Alloys such as titanium-zirconium and titanium-niobium have been found to have better corrosion resistance than traditional titanium [18].

Biomaterial Coatings: The application of bioactive coatings, such as those made of ceramics or polymers, can help protect the implant surface from corrosion while enhancing osseointegration and promoting tissue healing [19].

Personalised Implant Designs: Patient-specific factors, such as immune response, mechanical loading, and anatomical differences, can be taken into account when designing titanium implants. Customisation based on these factors may reduce the risk of corrosion and improve long-term implant success [20]. Table 1 discusses the Current and Emerging Approaches to Mitigate Corrosion in Titanium Implants.

Table 1: Current and Emerging Approaches to Mitigate Corrosion in Titanium Implants

Approach	Description	Effectiveness	Challenges
Anodization	Involves electrochemical treatment to enhance the oxide layer on the titanium surface.	Increases corrosion resistance and surface roughness for better osseointegration.	Can be costly and time-consuming; may affect implant aesthetics.
Hydroxyapatite Coating	Coating the titanium implant with hydroxyapatite (HA) to promote bone integration and prevent corrosion.	Improves biocompatibility and reduces corrosion.	HA coatings can degrade over time, potentially affecting stability.
Titanium Alloys	Development of alloys like titanium-zirconium and titanium-niobium for enhanced corrosion resistance.	Superior corrosion resistance compared to pure titanium.	Higher costs and potential for reduced mechanical properties.
Biomaterial Coatings	Use of bioactive materials like polymers or ceramics to protect titanium implants.	It can significantly reduce corrosion and improve tissue interaction.	Long-term stability of coatings needs further validation.
Personalized Designs	Custom implants tailored to the patient's anatomical and physiological needs.	Potential for optimised implant performance and reduced complications.	Increased complexity and cost of production.

DISCUSSION:

Titanium implants are widely regarded for their excellent biocompatibility, mechanical strength, and long-term stability in orthopaedic and dental applications. However, as research continues to unveil, corrosion of titanium implants can contribute significantly to peri-implant diseases, compromising the overall success and longevity of these implants. The release of titanium ions from corroded surfaces can initiate inflammatory responses that lead to conditions such as peri-implantitis, posing a serious threat to implant survival [21].

In contrast to earlier studies that primarily focused on the clinical success of titanium implants, recent research has begun to explore the link between corrosion and peri-implant diseases. For example, a study by MD Soler et al. (2020) [22] highlighted the role of corrosion in exacerbating peri-implantitis, suggesting that titanium ions and corrosion particles contribute to inflammation and bone resorption. This aligns with the findings in the current review, which emphasizes the inflammatory cascade initiated by corrosion products. MD Soler's study, however, focused more on bacterial infection as the primary cause of peri-implant disease, only considering corrosion as an indirect factor. The present review offers a broader perspective by integrating corrosion as a central factor in implant failure.

Further, Messer RL et al. (2009) [23] examined the mechanical failure of titanium implants under stress, revealing that corrosion can significantly compromise the implant's structural integrity. This study also pointed out that certain conditions, such as high acidity in the oral cavity or excessive mechanical stress, could accelerate corrosion. While Kramer's research concentrated on the mechanical failure due to corrosion, the current review expands on these findings by incorporating the biological implications of corrosion and its role in triggering immune responses.

JCM Souza et al. (2020) [24] provided insight into the role of surface modifications in preventing corrosion, suggesting that anodization or hydroxyapatite coatings can improve corrosion resistance. This complements the findings in the review, which underscores the importance of surface treatments in mitigating corrosion-related complications. While Liu's work focuses on coatings as a method for enhancing biocompatibility, the review highlights a more comprehensive approach that combines surface modifications with advanced titanium alloys to improve both corrosion resistance and implant integration.

Lastly, Sharma A et al. (2021) [25] explored novel titanium alloys, such as titanium-zirconium, which demonstrate superior corrosion resistance compared to conventional titanium. This is consistent with the review's discussion on the role of material innovation in preventing corrosion. However, Sharma A's study primarily focused on the material properties, while the current review delves deeper into the broader implications of corrosion products on tissue inflammation and bone resorption.

CONCLUSION:

Titanium implants have changed clinical practice in orthopaedic and dental surgeries and offer long-term functionality for patients. Nevertheless, the problem of corrosion and its resulting complications, such as peri-implant diseases, is not entirely resolved. Surface modification, alloy development and custom implant design can all be used to reduce the potential of corrosion with better results. Deeper studies on the interaction between corrosion products and the surrounding biological environment of implants will be essential for future safety, improvement, as well as durability of titanium implants.

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Anchal Sood: Contributed to the literature review, data analysis, and manuscript writing.

Swantika Chaudhry: Contributed to data analysis and interpretation, and manuscript preparation.

Harsukhman Kaur: Assisted in the literature review and manuscript editing.

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Priyanka Pawar: Assisted in data collection, analysis, and manuscript writing.

ABBREVIATIONS USED IN THE STUDY:

a) **TDA:** Titanium Dental Implants

b) **TiO_2:** Titanium Dioxide

c) **HA:** Hydroxyapatite

d) **Ti-Zr:** Titanium-Zirconium

e) **Ti-Nb:** Titanium-Niobium

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