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Comparative Analysis of Biomaterials Used in Dental Implants: Osseointegration, Biocompatibility and Clinical Performance

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SUMMARY:

This article provides a comparative analysis of the main biomaterials used in dental implants, highlighting their properties related to osseointegration, biocompatibility and clinical performance. Classic materials, such as titanium and its alloys, as well as emerging alternatives, such as zirconia, are discussed. Based on a critical review of recent scientific studies, the interaction of these biomaterials with bone tissue, their immunological responses and clinical implications are discussed. The work emphasizes the role of surface modifications and technological advances in optimizing results in implantology. The data presented aim to contribute to the informed choice of the ideal material in current clinical practice.

Keywords: Biomaterials, Dental implants, Titanium, Zirconia, Osseointegration, Biocompatibility.

ABSTRACT:

This article presents a comparative analysis of the main biomaterials used in dental implants, highlighting their properties related to osseointegration, biocompatibility, and clinical performance. Classic materials such as titanium and its alloys are discussed, as well as emerging alternatives like zirconia. Based on a critical review of recent scientific studies, the article examines the interaction between these biomaterials and bone tissue, their immunological responses, and clinical implications. The study emphasizes the role of surface modifications and technological advancements in optimizing outcomes in implant dentistry.

The presented data aims to support evidence-based decision-making in the selection of the most appropriate material for contemporary clinical practice.

Keywords: Biomaterials; Dental implants; Titanium; Zirconia; Osseointegration; Biocompatibility.

1. INTRODUCTION -

Implantology represents one of the most significant advances in modern dentistry, especially with regard to the functional and aesthetic rehabilitation of patients with tooth loss. Since the consolidation of osseointegration proposed by Branemark (1969), the clinical success of dental implants has been largely associated with the interaction between the biomaterial used and the surrounding bone tissue. This biological integration depends fundamentally on the chemical, mechanical and physical properties of the biomaterial, which makes the choice of material a crucial aspect for the longevity of the implant (Albrektsson et al., 1981).

The most widely used material for manufacturing dental implants is titanium, whose corrosion resistance, lightness and biocompatibility properties have made it the gold standard in implantology (Jemat et al., 2015). However, limitations regarding aesthetics due to metallic coloring and possible adverse reactions have motivated the development and investigation of alternative materials, including zirconia, a ceramic that combines high mechanical resistance with a coloration similar to natural teeth, in addition to a favorable biological profile (Scarano et al., 2003; Piconi & Maccauro, 1999).

The field of biomaterials for dental implants is constantly evolving, with advances related not only to the materials themselves, but also to their surfaces, which can be modified to optimize osseointegration and minimize the risk of complications such as peri-implantitis (Wennerberg & Albrektsson, 2009). Nanotechnology and bioactive coatings have gained prominence in modulating the biological response, enhancing cell adhesion and bone formation around implants (Zhao et al., 2016).

This article proposes a detailed comparative analysis of the biomaterials used in dental implants, considering the aspects of osseointegration, and provides an updated and critical view that helps dental professionals in making clinical decisions based on robust scientific evidence.

A deep understanding of the biological mechanisms that govern the interaction between biomaterial and bone tissue, as well as the influence of the physical and chemical properties of the materials, is essential for the improvement of implantology techniques and for the continuous improvement of clinical results. Thus, this study will contribute to the advancement of scientific knowledge and to the development of more effective and safer clinical strategies.

Finally, it is emphasized that the choice of the ideal biomaterial should not only consider its isolated properties, but also the clinical context, patient characteristics and associated technologies, which makes comparative analysis a valuable instrument for contemporary dental practice.

2. Titanium in Dental Implants: Properties, Osseointegration and Clinical Performance

Titanium and its alloys are widely recognized as the gold standard for the manufacture of dental implants due to the unique combination of mechanical, chemical and biological properties that favor osseointegration and the long-term success of implants. The element has high corrosion resistance, low specific weight and excellent biocompatibility, characteristics that have been extensively studied and documented in research since the 1970s (Branemark et al., 1977; Albrektsson et al., 1981).

Osseointegration, a concept defined as the direct union between bone tissue and the implant surface, depends significantly on the ability of titanium to form a passive layer of titanium oxide on its surface, which protects the implant against corrosion and favors cell adhesion (Le Guéhennec et al., 2007).

Studies conducted by Anselme (2000), published in the Journal of Biomedical Materials Research, demonstrated that the topography and chemistry of the titanium surface are decisive in modulating the cellular response, directly influencing osteoblast proliferation and bone mineralization.

Furthermore, surface modifications, such as sandblasting with alumina particles and acid treatment, have been widely applied to increase titanium roughness, promoting a larger contact area and better biological fixation. According to Wennerberg and Albrektsson (2009), published in Clinical Oral Implants Research, these topographical changes improve primary stability and accelerate osseointegration, reducing the time required for prosthetic loading.

The biocompatibility of titanium has also been the subject of in-depth investigation, especially in relation to immunological and inflammatory responses. Research conducted by Hallab et al. (2001), published in Biomaterials, indicated that particles released by corrosion or wear of titanium can induce local immune responses, but that, under appropriate clinical conditions, these effects are minimal and do not compromise bone integration. Even so, such studies highlight the importance of maintaining precise surgical techniques and avoiding excessive micromovements of the implant.

From a clinical perspective, the longevity and success rates of titanium are widely documented. A long-term prospective study conducted by Pjetursson et al. (2012) and published in the European Journal of Oral Sciences analyzed more than 10 years of follow-up on titanium implants, reporting success rates of over 90%, even in challenging conditions such as the posterior maxilla. This data reinforces the reliability of titanium as a biomaterial, despite the constant search for aesthetic and functional alternatives.

Finally, recent advances have focused on further optimizing the properties of titanium, with the development of special alloys such as Ti-6Al-4V and nanotechnological surface treatments that seek to improve cell adhesion and mechanical resistance without compromising biocompatibility (Zhao et al., 2016). Such innovations indicate that, despite aesthetic limitations, titanium remains the solid basis for the development and evolution of modern implantology.

3 Zirconia in Dental Implants: Characteristics, Biocompatibility and Applications Clinics

Zirconia , or zirconium dioxide (ZrOÿ), is a ceramic material that has been gaining increasing prominence in implantology due to its superior aesthetic properties and high biocompatibility. Unlike titanium, which has a metallic color, zirconia has an opaque white hue that resembles the natural color of teeth, a fact that makes it particularly attractive for use in aesthetic areas of the dental arch, especially in the anterior sectors, where implant visibility is greater (Piconi & Maccauro, 1999).

This aesthetic characteristic, combined with the absence of metal ions in its composition, minimizes the risk of allergic reactions or sensitivities in susceptible patients, expanding its field of clinical application. In addition, zirconia ceramics have high mechanical strength, abrasion resistance and low thermal conductivity, factors that contribute to their stability in intraoral environments subject to different types of loads and thermal variations.
(Scarano et al., 2003).

Experimental studies conducted by Scarano et al. (2003), published in the Journal of Biomedical Materials Research, evaluated the mechanical resistance of zirconia and demonstrated that, despite being a ceramic, the material supports load levels comparable to those of titanium, resisting mechanical fatigue induced by repetitive chewing cycles. This resistance is attributed to the stabilized tetragonal crystalline structure of zirconia, which presents a phase transformation mechanism that prevents the propagation of cracks, increasing the durability of the material. The research also highlights that, under controlled laboratory conditions, zirconia implants presented satisfactory mechanical performance for clinical use, which has encouraged the development of increasingly sophisticated commercial models suitable for functional load in the oral cavity.

In terms of biocompatibility, zirconia has a favorable biological profile, with a low tendency to induce inflammatory reactions or adverse immune responses, unlike some metals that can release ions that cause chronic inflammation.
Kohal et al. (2012), in a clinical study published in Clinical Oral Implants Research, observed that zirconia implants exhibited less inflammatory infiltration in the peri-implant region and better integration of peri-implant soft tissues when compared to titanium implants, suggesting a more stable biological environment conducive to healing.
These data are essential for the prevention of peri-implantitis, a condition that represents one of the main causes of failure in dental implants. Therefore, the use of zirconia may represent a viable alternative for patients with a history of exacerbated inflammatory responses. However, the osseointegration of zirconia is still the subject of intense study, since
since its ceramic surface is naturally smoother and less bioactive than that of titanium, which can hinder initial cell adhesion and bone mineralization.

To overcome these limitations, several surface modification techniques have been developed, such as particle blasting, laser treatments and the application of bioactive coatings based on hydroxyapatite or calcium phosphate. Faria et al. (2016), in an article published in the journal Materials Science and Engineering C, demonstrated that nano
texturing the surface of zirconia significantly increases the adhesion, proliferation and differentiation of osteoblasts, cells responsible for bone formation, promoting a
faster and more effective osseointegration. These modifications are essential to ensure the

primary and secondary stability of the implant, especially in regions with low bone density.

In the clinical setting, zirconia has a more recent history and a smaller longitudinal data set compared to titanium. However, prospective studies conducted by Osman et al. (2014), published in the International Journal of Oral and Maxillofacial Implants, indicate success rates close to those of metal implants, with percentages above 90% in follow-ups of up to five years. These results show that, despite initial concerns regarding mechanical resistance and osseointegration, zirconia implants are capable of providing satisfactory clinical results, especially in patients with aesthetic needs and contraindications to the use of metals. In addition, the absence of electrochemical corrosion reduces long-term complications.

Despite the advances and benefits of zirconia, there are still technical and economic challenges to be overcome for its widespread clinical adoption. The inherent fragility of ceramics, especially under excessive loads or lateral impacts, demands technical precision in the manufacturing and installation of implants, increasing costs compared to titanium. In addition, the complexity of production and the lower commercialization volume still limit the supply in the market. However, the continuous development of reinforced ceramic alloys, as well as improvements in manufacturing processes and surface treatment, point to a promising future in which zirconia may consolidate itself as a standard biomaterial for aesthetic implants, maintaining high functional and biological performance (Sailer et al., 2018).

4. Special Alloys in Dental Implants: Mechanical Properties, Biocompatibility and Clinical Applications

Special alloys, especially those based on titanium, such as the Ti-6Al-4V alloy (titanium, aluminum and vanadium), represent an important advance in biomaterial technology for dental implants, seeking to improve mechanical properties without compromising biocompatibility. This alloy offers greater mechanical strength, ductility and toughness compared to pure titanium, and is widely used in orthopedic and dental implants. that require greater structural performance (Geetha et al., 2009).

The main advantage of Ti-6Al-4V is its combination of fatigue resistance, corrosion resistance and lightness, which allows the production of thinner implants with complex shapes, favoring anatomical adaptation and primary stability. According to Rupp et al. (2018), in an article published in Materials Science and Engineering C, the microstructure of this alloy, composed of alpha and beta phases, provides superior mechanical properties, reducing the risk of fractures and deformations during implant installation and function.

In terms of biocompatibility, despite the inclusion of the elements aluminum and vanadium, which may be toxic under certain conditions, the passive layer of titanium oxide that forms on the surface of the alloy acts as an effective barrier against the release of metal ions, maintaining a safe biological profile for bone and mucous tissue (Niinomi, 2008). Toxicological studies conducted by Geetha et al. (2009), published in the Journal of Biomedical Materials Research, indicated that the cytotoxicity of Ti-6Al-4V is comparable to that of pure titanium, provided the integrity of the passive layer is maintained.

Osseointegration of Ti-6Al-4V presents satisfactory clinical results, with success rates similar to those observed for commercially pure titanium, but the alloy allows the development of surfaces that are more resistant to wear and deformation. Surface modifications, such as anodizing, sandblasting and bioactive coatings, are applied to improve the roughness and bioactivity of the alloy, as demonstrated in recent research, including the work of Elias et al. (2013), published in the Journal of the Mechanical Behavior of Biomedical Materials.

In addition to Ti-6Al-4V, other special alloys, such as Ti-13Nb-13Zr (titanium, niobium and zirconium), have been investigated to reduce potential biological risks associated with traditional metals, while maintaining excellent mechanical properties. A study by Geetha et al. (2013), published in Acta Biomaterialia, indicated that Ti-13Nb-13Zr has a lower modulus of elasticity, closer to that of human bone, which favors load distribution and reduces the risk of bone loss due to excessive stress.

In the clinical setting, special alloys are especially indicated for implants in regions that support high masticatory loads, or in patients with challenging bone conditions, such as osteoporosis. The application of these alloys is directly related to the increase in the longevity and functionality of implants, ensuring resistance and integrity even in adverse situations. Future prospects include the development of hypoallergenic alloys and nanotechnological coatings to optimize biological integration, as pointed out by Liu et al. (2019) in the Journal of Materials Science: Materials in Medicine.

5. Immunological and Biological Response of Biomaterials in Dental Implants: Mechanisms and Clinical Implications

The interaction of biomaterials used in dental implants with the body's immune system is a crucial factor for the clinical success and longevity of implants. When inserted into bone and mucosal tissue, implants trigger a series of biological responses, ranging from initial cell adhesion to complex bone remodeling processes and possible inflammatory reactions (Gomes et al., 2014). Understanding these mechanisms is essential for the development of biomaterials that promote integration efficient and minimize complications.

The initial immune response to the implant is characterized by the activation of the innate immune system, mainly through the action of macrophages and neutrophils, which recognize particles and residues released from the implant surface as potential aggressive agents. As highlighted in the study by Hallab et al. (2001), published in Biomaterials, the release of metal ions and wear particles, especially in titanium implants, can induce the activation of these cells, resulting in the release of pro-inflammatory cytokines that modulate the healing process.

This acute inflammatory phase is necessary to initiate tissue repair, however, if exacerbated or prolonged, it can lead to peri-implantitis processes and implant failure. According to the study by Schwarz et al. (2018), published in the Journal of Clinical Periodontology, peri-implantitis is associated with a dysregulated immune response, with increased

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production of inflammatory mediators that promote bone resorption around the implant, compromising its stability. Thus, biomaterials that minimize the release of residues and present bioinert surfaces tend to reduce the incidence of this complication.

The biocompatibility of materials is also related to their ability to induce a tolerogenic immune response, that is, one that favors the acceptance of the implant by the body. Recent research, such as that by Chen et al. (2017), published in Acta Biomaterialia, shows that surfaces modified with nanotechnology and bioactive coatings can modulate macrophage activity towards an anti-inflammatory phenotype, promoting bone regeneration. and adequate healing of peri-implant tissues. This strategy represents an important line of research to optimize the biological integration of implants.

In addition to the immune response, the biological response also includes the interaction with the soft tissues surrounding the implant, such as the gingival mucosa, which plays a protective role against bacterial invasion. The quality of this interface is essential to prevent infections and ensure the durability of the implant. A study by Buser et al. (2017), published in Clinical Oral Implants Research, emphasized that implants with surfaces that favor cell adhesion gingival mucosa have a lower risk of peri-implant pocket formation and chronic inflammation.

Another relevant aspect refers to the influence of the physicochemical characteristics of the biomaterial in modulating the immune response. Topography, roughness, surface charge and chemical composition directly affect the adsorption of plasma proteins, which in turn regulate the adhesion and activation of immune cells. As described by Anselme et al. (2010) in the Journal of Biomedical Materials Research, nanotextured surfaces provide an environment that is more favorable to colonization by osteogenic cells and less conducive to bacterial proliferation, reducing the risk of infection and inflammation.

In summary, understanding the immunological and biological mechanisms related to biomaterials in dental implants allows the development of materials and surfaces that optimize osseointegration, minimize adverse inflammatory responses and promote long-lasting integration. Continued research in this field is essential to improve the predictability and success of implant treatments, contributing to the improvement of patients' quality of life (Gomes et al., 2014; Hallab et al., 2001; Chen etal., 2017).

6 Clinical Performance and Comparative Analysis of Biomaterials in Dental Implants: Recent Evidence and Future Perspectives

The clinical performance of biomaterials used in dental implants is assessed through longitudinal studies that analyze success rates, longevity, bone integration, incidence of complications and patient satisfaction. Comparison between the main materials — titanium, zirconia and special alloys — allows identifying specific advantages and limitations, assisting in personalized selection according to the clinical profile and aesthetic needs (Albrektsson et al., 2012).

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Titanium remains the gold standard due to its proven osseointegration capacity and mechanical robustness. Global epidemiological studies, such as that of Buser et al. (2017), published in Clinical Oral Implants Research, show success rates of over 95% in 10-year follow-ups, with low rates of peri-implant complications when accompanied by rigorous clinical protocols. The material also stands out for its
versatility in manufacturing, cost-effectiveness and surface adaptations to optimize bioactivity.

On the other hand, zirconia implants have shown significant growth in the dental market, driven by aesthetic demand and patients with metal sensitivity.
Recent clinical research, such as the systematic review by Kohal et al. (2020), published in the International Journal of Implant Dentistry, indicates success rates ranging from 85% to 95% in studies with follow-up of up to five years. Although the results are promising, the shorter time of clinical use and mechanical challenges still limit widespread adoption.
requiring continuous monitoring for long-term validation.

Regarding special titanium alloys, the literature indicates that they provide significant improvements in mechanical properties and fatigue resistance, especially in cases of high load. A study by Liu et al. (2019), in the Journal of Materials Science: Materials in Medicine, demonstrates that implants manufactured with Ti-6Al-4V present clinical performance comparable to pure titanium, with advantages in structural strength and functional stability.
However, biocompatibility remains a critical aspect, requiring maintenance
of the passive layer to avoid adverse reactions.

In addition to the mechanical and biological aspects, clinical success is directly related to the surgical technique, prosthetic planning and control of peri-implant health. The multicenter study by Schwarz et al. (2018), published in the Journal of Clinical Periodontology, reinforces that factors such as oral hygiene, control of bacterial plaque and periodic monitoring are decisive for the maintenance of implants, regardless of the material used.
This shows that the biomaterial is just one component within a context.
multidisciplinary that involves the patient and the professional.

Comparative analysis also points to the accelerated development of nano surfaces
technological advances and advanced treatments that seek to optimize osseointegration and minimize inflammatory responses. As reviewed by Anselme et al. (2010), these technological advances promise to improve the clinical performance of implants, regardless of the base material, by providing biocompatible microenvironments that favor cell adhesion and bone regeneration.

Finally, future prospects for biomaterials in implantology point to the combination of ceramic and metallic materials, hypoallergenic alloys and smart surfaces that respond to the biological environment. The integration of technologies such as personalized 3D printing, bioengineering and nanotechnology should transform the field, enabling more effective, personalized and long-lasting treatments (Osman et al., 2019).
Therefore, continuous clinical evaluation and research are essential to consolidate these advances and to offer safe and efficient therapies to patients.

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Final Considerations

This analysis demonstrated that the choice of biomaterial for dental implants plays a central role in therapeutic success, directly impacting osseointegration, biocompatibility, immunological response and, consequently, long-term clinical performance. Titanium, due to its consolidated history and mechanical robustness, remains the most widely used and studied material in implantology, supporting its status as the gold standard through scientific evidence demonstrating a high rate of bone integration and fatigue resistance. Titanium's ability to form a passive oxide layer that ensures its chemical stability and biological tolerance is one of the main factors justifying its wide clinical acceptance, as described in classic and recent studies (Albrektsson et al., 2012; Geetha et al., 2009). However, aesthetic limitations and specific cases of metallurgical hypersensitivity motivate the search for alternatives.

In this context, zirconia emerges as a promising option, especially for patients with high aesthetic demands and sensitivity to metals. The white color of zirconia, similar to tooth enamel, allows for a visually superior result without compromising biocompatibility. In addition, zirconia has a low affinity for bacterial adhesion and reduced immune response, which may reduce the risk of peri-implantitis (Kohal et al., 2020). However, the mechanical resistance and inherent fragility of some types of zirconia still represent challenges to be overcome for its widespread and safe use in all cases.
clinical trials. Therefore, zirconia is an evolving biomaterial that requires more longitudinal clinical studies to consolidate its safety and efficacy profile.

Special titanium alloys, such as Ti-6Al-4V, offer a technical alternative that combines the properties of pure titanium with improved mechanical strength, enabling their use in clinical situations that require greater durability and wear resistance. Scientific research shows that these alloys maintain an adequate biocompatibility profile when properly treated, ensuring the integrity of the passive layer and minimizing the release of potentially toxic ions (Elias et al., 2013; Liu et al., 2019). The evolution of these alloys
points to the manufacture of implants with optimized geometry and surfaces, capable of withstanding more intense masticatory loads, expanding clinical indications for patients with different functional profiles.

In addition to the physicochemical properties of biomaterials, the study highlighted the importance of the immune response in implant integration. Modulating this response through nanotechnological and bioactive surfaces represents a significant advance, as it promotes a balance between stimulating bone regeneration and controlling local inflammation (Chen et al., 2017; Anselme et al., 2010). Balanced activation of the immune system prevents complications such as peri-implantitis, which has been one of the main causes of implant failure, as evidenced in recent clinical studies (Schwarz et al., 2018). Thus, the development of biomaterials that interact positively with the biological microenvironment is a trend that should direct implantology in the future.

From a clinical perspective, it is essential to highlight that the performance of implants is intrinsically linked to a multidisciplinary and individualized approach, which goes beyond the biomaterial used. Success depends on factors such as surgical technique, planning, adequate prosthetic equipment, the patient's general and oral health, and rigorous postoperative monitoring (Buser et al., 2017; Schwarz et al., 2018). This means that even the best biomaterial can have its potential compromised if these elements are not respected, reinforcing the need for an integrated and evidence-based clinical practice.

Finally, the future of biomaterials in implant dentistry points to the convergence between technological innovation and regenerative biology. The combination of ceramic and metallic materials, combined with smart surfaces and personalized treatments through 3D printing and nanotechnology, offers promising prospects for the development of increasingly durable, aesthetic and biocompatible implants (Osman et al., 2019). For these innovations to be incorporated into clinical practice safely and effectively, it is essential to continuation of rigorous scientific studies that evaluate not only technical performance, but also the biological impact and long-term patient response. In this way, the improvement of biomaterials and associated techniques will contribute significantly to the evolution of implantology, raising the quality standards of treatments and patient satisfaction on a global scale.

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