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BIOCOMPATIBILITY AND OSSEOINTEGRATION OF BIOMATERIALS USED IN PRE-IMPLANT BONE RECONSTRUCTION

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Abstract

Pre-implant bone reconstruction plays a crucial role in the success of dental implants, requiring the use of biomaterials capable of restoring bone volume and facilitating osseointegration. The choice of the optimal biomaterial is based on factors such as biocompatibility, osteoconductivity, osteoinductivity, and mechanical stability. Autografts are considered the gold standard due to active osteogenesis, but alternatives such as allografts, xenografts, and synthetic biomaterials are frequently used due to their extensive availability and osteoconductive properties. Recent studies focus on improving osseointegration through nanostructural modifications of biomaterials, the use of 3D scaffolds, and the integration of growth factors, such as bone morphogenetic proteins (BMPs). Bioactive biomaterials and nanotechnology also open up new perspectives for optimizing bone regeneration and reducing healing time. Future research directions include the use of stem cells, smart biomaterials with controlled release of osteoinductive factors, and the development of antibacterial materials for the prevention of postoperative complications. Continuous progress in the field of biomaterials contributes significantly to improving clinical outcomes, ensuring faster and more efficient integration of dental implants.

Keywords: Biomaterials, osseointegration, bone regeneration, dental implants, 3D scaffolds

Introduction

Pre-implant bone reconstruction is an essential stage in the oral rehabilitation of edentulous patients who have bone deficiencies that prevent the stable insertion of dental implants. The process of post-extraction bone atrophy, periodontal disease, trauma, and other systemic conditions can lead to the resorption of the alveolar bone, compromising the support necessary for implantation. In these situations, the use of biomaterials for bone augmentation becomes a fundamental solution, having the role of facilitating regeneration and restoring adequate bone volume [1-3].

The biocompatibility of biomaterials used in pre-implant bone reconstruction is a defining characteristic, representing their ability to interact with host tissues without causing adverse reactions, chronic inflammation, or rejection. In addition, osseointegration, defined as the process of direct connection between the surface of the biomaterial and the newly formed bone, is crucial for the long-term success of dental implants. The choice of materials used in bone augmentation is based on rigorous criteria, including osteoconductivity (the ability to allow bone cell proliferation on the surface of the biomaterial), osteoinductivity (stimulation of mesenchymal cell differentiation into osteoblasts), and osteogenesis (active formation of new bone) [1-4].

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Depending on their origin and properties, biomaterials used for pre-implant bone regeneration can be classified into four broad categories: autografts, allografts, xenografts, and synthetic biomaterials. Autografts, harvested from the same patient, are considered the gold standard due to active osteogenesis, but they have the disadvantage of morbidity at the donor site. Allografts, taken from individuals of the same species, are processed to remove antigenicity and preserve osteoinductive potential. Xenografts, derived from animal sources, are widely used due to their structure similar to human bone and excellent osteoconductivity. Synthetic materials such as hydroxyapatite (HA), tricalcium phosphate (TCP), and bioglass provide safe alternatives with variable resorption rates and controlled bone integration capacity [2-4].

The success of bone reconstruction depends not only on the choice of biomaterial but also on its interaction with the biological environment. The osseointegration process is influenced by factors such as local vascularization, mechanical stability of the graft, the surface area of the biomaterial, and the presence of growth factors. In this sense, current research focuses on the development of bioactive biomaterials capable of stimulating bone regeneration through the controlled release of osteoinductive factors and by modifying the nanostructure to optimize the interaction with bone cells [2-5].

This review aims to analyze in detail the biocompatibility and osseointegration of biomaterials used in pre-implant bone reconstruction, highlighting the advantages and limitations of each category of materials, the biological mechanisms involved, and the current research perspectives in this field.

Properties of biomaterials used in pre-implant bone reconstruction

The success of pre-implant bone reconstruction depends on the properties of the biomaterial used, which must be biocompatible, osteoconductive, osteoinductive, and have adequate mechanical characteristics. The choice of the optimal material is essential to ensure an efficient bone regeneration process and to achieve a stable integration of the dental implant [3-5].

Biocompatibility is the fundamental criterion of any biomaterial used in bone augmentation, defining its ability to interact with host tissue without inducing chronic inflammatory reactions, toxicity, or immunological rejection. An ideal biomaterial must allow the proliferation of bone cells and facilitate the formation of new bone, avoiding phenomena such as fibrosis or encapsulation. The degree of biocompatibility is influenced by the chemical structure, porosity, and surface of the biomaterial, factors that determine the interaction with bone cells and its integration into the receptor tissue [1,3-5].

Osteoconductivity refers to the ability of the biomaterial to function as a skeleton (scaffold) on which bone cells can attach and proliferate, allowing new tissue to grow. Osteoconductive materials are essential in guided bone regeneration, having the role of supporting osteoblasts and ensuring a gradual integration of the graft into the host bone. Hydroxyapatite, tricalcium phosphate (β-TCP), and demineralized xenografts are examples of osteoconductive biomaterials with wide applicability in implantological surgery [4,5].

Osteoinductivity is the ability of the biomaterial to stimulate the differentiation of mesenchymal stem cells into active osteoblasts, initiating the formation of new bone. This property is present in particular in allografts and biomaterials enriched with growth factors such as bone morphogenetic proteins (BMPs). Osteoinductive biomaterials are used in situations where natural bone regeneration is limited, providing an additional biological stimulus for bone matrix formation [3-6].

The mechanical stability of the biomaterial is essential for maintaining volume and providing adequate support for osseointegration. The materials used in augmentation must have sufficient strength to prevent the collapse of adjacent bone structures, but also optimal porosity to allow vascular and cellular infiltration. Hydroxyapatite and tricalcium phosphate are examples of materials with high mechanical stability, frequently used in combination with other biomaterials to optimize the regeneration process. The resorption of the biomaterial is an important characteristic, determining its ability to be progressively replaced by newly formed bone. A balance between the rate of resorption and the speed of bone regeneration is essential for the long-term success of reconstruction. Slow-resorption materials, such as hydroxyapatite, are preferred in situations where prolonged bone volume maintenance is required, while tricalcium phosphate and bioglass, with faster resorption, are used to stimulate accelerated bone remodeling [5-7].

The choice of biomaterial used in pre-implant bone reconstruction must take into account biocompatibility, osteoconductivity, osteoinductivity, mechanical stability, and resorption rate. The development of advanced biomaterials, capable of combining these properties, represents an essential direction of research in modern implantology, aiming to improve the success rate of bone regeneration and optimize the osseointegration of dental implants [6-10].

Table 1. The table presents the key properties of biomaterials used in bone reconstruction, detailing their role in osteointegration. It includes biocompatibility, osteoconductivity, osteoinductivity, mechanical stability, porosity, and bioactivity, along with examples of commonly used biomaterials such as hydroxyapatite, tricalcium phosphate, bioglass, autografts, and allografts [4-10].

Property	*Description*	*Examples of biomaterials*
Biocompatibility	The ability of the biomaterial to interact with host tissue without causing adverse reactions.	Autografts, allografts, hydroxyapatite (HA), tricalcium phosphate (TCP)
Osteoconductivity	The property of the biomaterial allows osteoblast proliferation and attachment for new bone formation.	HA, TCP, xenografts (Bio-Oss), bioglass
Osteoinductivity	The ability of the biomaterial to stimulate the differentiation of mesenchymal stem cells into osteoblasts.	Demineralized freeze-dried bone (DFDBA), BMP, functionalized biomaterials
Mechanical stability	The mechanical strength of the biomaterial, important for maintaining bone volume and preventing collapse.	Dense HA, composite biomaterials (HA + TCP), biopolymers
Porosity	The degree of porosity of the biomaterial, essential for nutrient diffusion and vascular network formation.	Bioglass, 3D scaffolds, porous hydroxyapatite
Resorption rate	The time required for the biomaterial to degrade and be replaced by newly formed bone.	TCP (fast resorption), HA (slow resorption), bioglass
Vascularization	The ability of the biomaterial to allow the formation of new blood vessels to support bone regeneration.	HA, bioglass, nanostructured biomaterials with angiogenic factors
Interaction with bone cells	The way the biomaterial interacts with osteoblasts and osteocytes to initiate osteogenesis.	Functionalized biomaterials with osteoinductive peptides, 3D scaffolds
Bioactivity	The ability of the biomaterial to stimulate biological processes, such as bone mineralization.	HA, bioglass, biomaterials doped with calcium and phosphate ions.
Tissue integration	The degree to which the biomaterial is accepted by the body and incorporated into existing bone tissue.	Autografts, allografts, xenografts, nanostructurally modified synthetic biomaterials

Types of biomaterials used in pre-implant bone reconstruction

Pre-implant bone reconstruction is based on the use of biomaterials capable of compensating for bone loss and providing adequate support for the osseointegration of dental implants. The biomaterials used in this process are classified into autografts, allografts, xenografts, and synthetic biomaterials, each with specific characteristics in terms of biocompatibility, osteoconductivity, osteoinductivity, and resorption rate [6-10].

Autografts are considered the gold standard in bone regeneration, due to their active osteogenic potential and the absence of immunological risks. They are harvested from the same patient, the most common donor areas being the iliac crest, the mandibular ramus, and the maxillary tuberosity. The main advantage of autografts is active osteogenesis, but limitations include rapid resorption and discomfort caused by harvesting bone tissue. In the case of extensive bone defects, where the autograft volume is insufficient, the use of alternative biomaterials is preferred [7-10].

Allografts, derived from individuals of the same species, are processed to eliminate antigenicity and reduce the risk of transmission of pathogens. They are available in various forms, including freshly frozen bone, freeze-dried demineralized bone (DFDBA), and freeze-dried mineralized bone (FDBA). Allografts offer good osteoconductivity and, in some cases, osteoinductivity, but their integration can be influenced by the degree of processing [7-11].

Xenografts, from other species, are frequently used in implant surgery due to their structural similarity to human bone. They are processed by specific methods to remove organic components, reducing the risk of immunological reactions. The most widely used xenografts are those of bovine origin, such as Bio-Oss®, recognized for their excellent osteoconductivity and long-term volumetric stability. However, incomplete resorption and slower bone integration may be limitations in certain clinical situations [8-11].

Synthetic biomaterials have been developed to provide a safe and predictable alternative to natural bone grafts. Among the most used synthetic materials are hydroxyapatite (HA), tricalcium phosphate (β-TCP), and bioglass, each of which has specific properties that determine their applicability in bone regeneration. Hydroxyapatite is a bioactive material with high osteoconductivity and slow resorption, being preferred for maintaining bone volume. Tricalcium phosphate exhibits a faster resorption rate, favoring gradual replacement with newly formed bone, but provides less mechanical stability. Bioglass, an innovative material in bone regeneration, stimulates bone formation through the controlled release of bioactive ions, having an important role in stimulating osteogenesis [9-11].

A distinct category of biomaterials is represented by composite materials, which combine the advantages of several types of grafts to optimize osseointegration. For example, combinations of hydroxyapatite with β-TCP allow adjustment of the resorption rate and improve the interaction between the biomaterial and the host bone. In addition, recent research focuses on the development of bioactive scaffolds, functionalized with bone morphogenetic proteins (BMPs) or growth factors, to stimulate bone regeneration in a controlled manner [7,9-11].

The choice of the optimal biomaterial for pre-implant bone reconstruction depends on multiple variables, including the size of the bone defect, the need to maintain volume in the long term, the resorption time, and the ability of the biomaterial to interact with bone cells. Autografts offer the best osteogenic potential, but are limited by the low availability and morbidity of the donor site. Allografts and xenografts are frequently used due to their osteoconductivity, but osseointegration can vary depending on their processing. Synthetic biomaterials are a versatile and safe solution, allowing the adjustment of mechanical and resorptive properties according to clinical needs [9-11].

Factors influencing the osseointegration of biomaterials

The osseointegration of biomaterials used in pre-implant bone reconstruction is an essential process that determines the success of augmentation and the long-term stability of dental implants. This complex process depends on the interaction between the biomaterial and the host bone tissue, being influenced by biological, mechanical, and chemical factors [9-12].

The surface of the biomaterial plays a crucial role in osseointegration, having a direct impact on the adhesion of osteoprogenitor cells and the formation of the bone matrix. The porous and rough texture of biomaterials favors cell proliferation and vascularization, facilitating osteoconductivity and osteoinductivity. Hydroxyapatite and tricalcium phosphate are materials with bioactive surfaces that interact favorably with the biological environment, stimulating the formation of new bone. Currently, research focuses on nanomodification of surfaces and the integration of osteoinductive factors to optimize cellular response [10-13].

Local vascularization is another essential factor, as it provides the supply of oxygen and nutrients necessary for bone regeneration. Porous biomaterials, with pore sizes between 150 and 500 μm, allow the formation of new blood vessels and faster graft integration. Poor vascularization can lead to necrosis and failure of regeneration, which is why recent strategies include the use of angiogenic growth factors, such as VEGF, to stimulate the formation of an adequate capillary network [11-14].

The mechanical stability of the biomaterial significantly influences osseointegration, especially in the early stages of bone healing. Excessive micro-movements can cause fibrous tissue to form instead of osteogenesis, compromising implant integration. Materials with high mechanical strength, such as dense hydroxyapatite, are used to maintain bone volume in high-load areas. In contrast, absorbable materials, such as tricalcium phosphate, require initial structural support until complete replacement with mature bone [8,11-14].

Biochemical factors also play a key role in osseointegration. Bone morphogenetic proteins (BMPs) and other osteoinductive molecules are used to stimulate the differentiation of mesenchymal cells into osteoblasts, accelerating bone regeneration. Biomaterials functionalized with such factors can significantly improve the integration rate, providing active biological support for the formation of new bone [10,12-14].

Recent studies and future directions in the use of biomaterials for pre-implant bone reconstruction

Current research on biomaterials used in pre-implant bone reconstruction focuses on improving osseointegration, optimizing mechanical characteristics, and accelerating the bone regeneration process. Recent studies have demonstrated that surface modifications, the addition of growth factors, and the use of nanotechnology can significantly increase the efficiency of biomaterials, reducing the time it takes to form mature, functional bone [13-15].

An important area of research is represented by bioactive biomaterials, capable of actively stimulating bone regeneration. They are functionalized with bone morphogenetic proteins (BMPs), endothelial growth factors (VEGF), or osteoinductive peptides, which accelerate the osteogenesis process. Hydroxyapatite and tricalcium phosphate, widely used in bone regeneration, are now being developed in nanostructured forms to provide better interaction with bone cells and improve osteoconductivity. Studies show that the use of nanostructured biomaterials results in better cell attachment and an increased rate of bone formation compared to conventional materials [15-17].

Also, research in the field of three-dimensional scaffolds has shown that 3D printed porous structures, made of biopolymers and ceramic materials, offer an optimal architecture for bone regeneration. These structures allow for rapid vascularization, facilitating the formation of new bone and the integration of biomaterials into the host tissue. An emerging trend is the use of smart biomaterials, capable of responding dynamically to the biological environment by the controlled release of growth factors or by adapting mechanical properties according to the needs of bone regeneration [16-18]. In parallel, clinical trials on resorbable biomaterials confirm that materials with controlled degradation rates can improve bone regeneration without compromising graft stability. Composite biomaterials, which combine hydroxyapatite with tricalcium phosphate or bioglass, are used to simultaneously optimize osteoconductivity and resorption rate. These materials allow a natural bone remodeling, being progressively replaced by mature bone, without requiring additional interventions [16-18].

Future research directions include the use of stem cells and tissue engineering technologies to create personalized biomaterials tailored to the needs of each patient. Integrating mesenchymal cells into porous biomaterials and stimulating them with growth factors could revolutionize bone regeneration, providing superior solutions for complex bone defects. In addition, the development of antibacterial materials, capable of preventing postoperative infections, represents another promising direction for improving the success of pre-implant bone reconstruction [17-19].

Advances in biomaterials focus on improving osseointegration, accelerating bone regeneration, and developing personalized solutions for patients. Advances in nanotechnology, tissue engineering and 3D bioprinting open up new perspectives for optimizing bone reconstruction, reducing complications and increasing the success rate of dental implants [18-20].

Conclusions

Pre-implant bone reconstruction is an essential field in implant surgery, and its success depends on the choice of a suitable biomaterial, capable of restoring the necessary bone volume and facilitating osseointegration. Biocompatibility, osteoconductivity and mechanical stability are critical factors influencing the efficiency of biomaterials used in bone regeneration.

Autografts remain the ideal option due to active osteogenesis, but are limited by donor site morbidity and low availability. Allografts and xenografts offer viable alternatives, having good osteoconductivity and greater volumetric stability, while synthetic biomaterials allow precise control of mechanical and resorptive properties. New generations of bioactive and nanostructured biomaterials have shown promising results in accelerating osseointegration and improving bone regeneration.

Factors influencing osseointegration, such as biomaterial surface, local vascularization and mechanical stability, play a crucial role in the long-term success of bone regeneration. Recent research has highlighted the importance of functionalizing biomaterials with growth factors and using 3D printed three-dimensional scaffolds to improve osteoconductivity and optimize their integration into host tissue. Future directions in the use of biomaterials for pre-implant bone reconstruction focus on the development of customized solutions through tissue engineering, the use of stem cells, and the integration of smart biomaterials with controlled release of osteoinductive factors. In addition, emerging technologies, such as nanobiomaterials and antibacterial materials, open up new perspectives for increasing the success rate of bone augmentation and reducing postoperative complications.

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