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BIORESORBABLE SCAFFOLDS IN BONE TISSUE ENGINEERING

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Abstract

Bioresorbable scaffolds play an essential role in bone tissue engineering, providing temporary support for bone regeneration and eliminating the need for secondary intervention for removal. The materials used, such as biodegradable polymers (PLA, PLGA) and bioactive ceramics (HA, β-TCP), must ensure biocompatibility, osteoconductivity, and a controlled degradation rate. Advanced manufacturing techniques, such as 3D printing and electrospinning, allow optimized structures to be obtained, and functionalization with growth factors and the integration of nanomaterials improve osteogenesis and vascularization. Applied in orthopedics, dental implantology, and cranio-maxillofacial reconstruction, these scaffolds have demonstrated effectiveness in preclinical and clinical studies. However, challenges related to degradation, mechanical stability, and tissue integration require innovative solutions. Future research focuses on the development of smart and personalized scaffolds, based on nanotechnology and bioengineering, to optimize bone regeneration and improve clinical outcomes.

Keywords: Bioresorbable scaffolds, bone regeneration, osteoconductivity, 3D printing, biodegradable polymers, bioactive ceramics, bone tissue engineering.

Introduction

Bone tissue engineering is an essential direction in regenerative medicine, aiming to restore bone structures affected by trauma, infections, or degenerative diseases. Bioresorbable scaffolds play a key role in this strategy, providing temporary support for osteogenic cells and facilitating bone regeneration through their gradual degradation, synchronized with the formation of new tissue. Unlike permanent implants, these structures eliminate the need for secondary surgery for removal, reducing the associated risks and costs [1-3].

The materials used for scaffolds must be biocompatible, bioactive, and exhibit a controlled resorption rate, avoiding premature collapse or excessive persistence. In addition, optimal porosity is essential for vascularization and cell infiltration, and the mechanical properties must be adapted to the targeted anatomical area. The development of these structures involves a combination of biodegradable polymers, bioactive ceramics, and advanced

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manufacturing technologies, such as 3D printing and electrospinning, aimed at improving the architecture of scaffolds and accelerating bone regeneration [2,3]. The interest in bioresorbable scaffolds has increased significantly, due to their potential in orthopedic surgery, dental implantology, and the treatment of complex bone defects. Current research is aimed at optimizing the composition of materials and integrating growth factors or stem cells to improve osteoinduction. This review analyzes the latest advances in the field, highlighting the advantages, challenges, and prospects of using bioresorbable scaffolds in bone regeneration [1-4].

An essential aspect in the use of bioresorbable scaffolds is their interaction with the biological microenvironment. The optimal integration of a scaffold into the host bone depends on its ability to support the proliferation and differentiation of osteoblastic cells, as well as to stimulate angiogenesis, a process essential for the formation of viable bone tissue. The materials used must provide controlled degradation so that the resulting products do not induce inflammation or adverse reactions. For example, biodegradable polymers, such as polylactic acid (PLA) and PLGA copolymers, are used due to their progressive bioresorption, but can sometimes generate an acidic environment through their degradation products, affecting osteogenesis [2-4].

In contrast, bioactive ceramics, such as hydroxyapatite (HA) and tricalcium phosphate (β-TCP), exhibit superior osteoconductivity but increased brittleness, limiting applicability in areas with high mechanical stresses. To compensate for these limitations, current research focuses on the development of polymer-ceramic composites and the use of advanced 3D printing technologies to create biomimetic structures. Thus, the optimization of bioresorbable scaffolds remains a major challenge, being essential for the advancement of regenerative therapy in critical bone defects [3-6].

Ideal properties of bioresorbable scaffolds

Bioresorbable scaffolds intended for bone regeneration must meet essential criteria to support the osteogenetic process and allow optimal integration into the host tissue. Biocompatibility is a fundamental condition, ensuring that the material does not induce inflammatory or immune reactions that could compromise regeneration. In addition, scaffolds must be bioactive, facilitating cell attachment and osteogenic differentiation by interacting with extracellular matrix proteins and bone progenitor cells [4-7].

An essential feature is the controlled rate of degradation, which must be synchronized with the formation of new bone. If the resorption is too fast, the scaffold cannot support tissue regeneration, and if it is too slow, the remaining structure can interfere with local physiological processes. Biodegradable polymers such as PLA, PGA, or PLGA copolymers are used due to their degradation by enzymatic hydrolysis, while bioactive ceramics, such as HA and β-TCP, undergo a progressive dissolution and direct integration into the bone matrix [6-10].

The mechanical properties of the scaffolds must mimic the characteristics of native bone, providing sufficient structural strength to support the regenerated tissue. In areas of mechanical loading, the materials used must exhibit optimal rigidity to prevent premature collapse without interfering with bone remodeling. For example, polymer scaffolds may require hardening with ceramic nanoparticles to improve rigidity and maintain structural stability [7-10].

Table 1. The table presents the ideal properties of bioresorbable scaffolds used in bone regeneration, including biocompatibility, osteoconductivity, controlled degradation, and vascularization. Descriptions of each feature are highlighted, along with examples of materials used, such as biodegradable polymers, bioactive ceramics, and polymer-ceramic composites [4-10].

Property	*Description*	*Examples of materials*
Biocompatibility	The material must be compatible with human tissue, without inducing inflammatory or immune reactions.	Collagen, chitosan, HA, β-TCP
Bioactivity	The scaffold's ability to interact with cells and extracellular matrix proteins stimulates osteogenesis.	HA, β-TCP, bioactive glass
Controlled degradation	The scaffold must degrade at a rate that allows bone formation without compromising the newly formed structure.	PLA, PLGA, HA, β-TCP
Mechanical properties	It should mimic the mechanical properties of native bone to support regenerated tissue, preventing premature collapse.	Polymer-ceramic composites, HA reinforced with nanomaterials.
Optimal porosity	Pores should be interconnected, with sizes between 100-500 μm, to allow cell migration and vascularization.	3D printing with biodegradable polymers and HA
Osteoconductivity	The material's ability to support osteoblast adhesion and proliferation for integration into the host bone.	HA, β-TCP, bioactive glass
Osteoinductivity	The scaffold's ability to stimulate the differentiation of stem cells into the osteoblastic lineage.	BMP-2, osteoinductive peptides
Vascularization	The scaffold structure should allow blood vessel formation to support the metabolic needs of bone tissue.	VEGF, scaffolds functionalized with stem cells
Biological functionalization	The possibility of integrating growth factors, bioactive peptides, or stem cells to enhance bone regeneration.	Scaffolds impregnated with BMP-2, TGF-β.
Processability	The material must be processable through modern techniques (3D printing, electrospinning, laser sintering) to obtain optimized structures.	PLA, PLGA, 3D-printed bioceramics
Controlled release of growth factors	The scaffold should allow the gradual release of osteogenic factors to accelerate the healing process.	Scaffolds loaded with BMP-2, TGF-β, FGF-2

The porous structure plays a decisive role in the success of bone regeneration, influencing cell migration, vascularization, and nutritional exchanges. The porosity must be interconnected, with dimensions between 100-500 μm, to facilitate the proliferation of osteoblasts and the infiltration of blood vessels. Advanced technologies, such as 3D printing and electrospinning, allow precise control of the porous architecture, optimizing the microstructure of the scaffold to improve osteoinduction and osteoconductivity [7-11]. Another important factor is the ability of scaffolds to stimulate osteogenesis through the controlled

release of growth factors or bioactive ions. Materials functionalized with bone morphogenetic proteins (BMPs) or bioactive peptides can accelerate the bone formation process, enhancing the effectiveness of regenerative therapy. In this context, smart scaffolds, capable of responding to biological or mechanical stimuli, represent a promising direction in tissue engineering [8-11].

The ideal bioresorbable scaffolds must be biocompatible, mechanically stable, with adequate porosity and a controlled degradation rate, facilitating efficient bone regeneration. Optimizing these properties remains a major challenge, and future research will continue to improve the performance of these biomaterials by integrating nanotechnologies and molecular engineering [8-12].

Materials used for bioresorbable scaffolds

The materials used in the manufacture of bioresorbable scaffolds must be biocompatible, biodegradable, and support osteoconductivity. They are divided into three main categories: polymers, bioactive ceramics, and polymer-ceramic composites. Natural and synthetic polymers are commonly used due to their flexibility and ability to control degradation. Natural polymers, such as collagen and chitosan, promote cell adhesion and mimic the extracellular matrix, but have low mechanical strength. Synthetic polymers, such as polylactic acid (PLA), polyglycolic acid (PGA), and PLGA copolymers, offer controlled resorption and can be processed into complex structures. However, their degradation products can acidify the microenvironment, affecting osteogenesis [10-14].

Bioactive ceramics, such as hydroxyapatite (HA) and tricalcium phosphate (β-TCP), are used due to their similarity to the mineral phase of bone, conferring osteoconductivity and osteoinducibility. HA degrades slowly and favors bone integration, but it is fragile. β-TCP has a faster resorption, facilitating bone remodeling. Both materials are often used in the form of powders, granules, or sintered porous structures [8,11-14].

Polymer-ceramic composites combine the advantages of polymers (flexibility, controlled resorption) with those of ceramics (rigidity, bioactivity). The integration of HA or β-TCP nanoparticles into polymers improves mechanical and osteoinductive properties, reducing the risk of premature collapse. Such composites are frequently used in 3D printed scaffolds to create biomimetic structures with optimized porosity. The choice of material depends on the clinical application, the architecture of the scaffold, and the desired regeneration rate. Combining these materials remains a promising strategy, optimizing degradation and stimulating bone formation [12-14].

Manufacturing techniques of bioresorbable scaffolds

The manufacture of bioresorbable scaffolds involves advanced techniques designed to ensure optimal porosity, adequate mechanical strength, and a controlled degradation rate. The methods used are divided into conventional and advanced, each with specific advantages. Conventional methods, such as freeze-drying, gas foaming, and mold casting, allow porous structures to be achieved, but have limited control over the final architecture. Freeze-drying creates scaffolds with interconnected porosity by removing a frozen solvent, and is frequently used for natural and synthetic polymers. Gas foaming produces porosity by generating gas bubbles in the molten material, but it can lead to uneven pore distributions. In-mold molding is

simple and efficient, but provides little freedom in customizing the geometry of the scaffolds [10,12-14].

Advanced technologies such as 3D printing, electrospinning, and selective laser sintering (SLS) enable the creation of custom structures with well-defined porosity. 3D printing uses techniques such as extrusion, sintering, or light-curing to build scaffolds layer by layer, providing precise control over the architecture and composition of materials. It is ideal for combining polymers with ceramic nanoparticles, improving osteoconductivity. Electrospinning, based on the application of an electric field to a polymer solution, produces nanometric fibers that mimic the extracellular matrix and is used for small-scale bone regeneration. Selective laser sintering (SLS) allows the manufacture of ceramic scaffolds with controlled porosity, but the high temperature required limits the use of heat-sensitive polymers [12-15].

The choice of technique depends on the material used and the desired application. Conventional methods are effective for mass production, while advanced technologies provide customization and superior performance. The integration of these methods in the manufacture of bioresorbable scaffolds continues to evolve, optimizing bone regeneration through advanced biomimetic solutions [12-14].

Clinical applications and preclinical studies

Bioresorbable scaffolds are used in the regeneration of critical bone defects, orthopedic surgery, and dental implantology, demonstrating promising results in preclinical and clinical studies. They provide temporary support for osteogenic cells, facilitating bone regeneration without requiring surgical removal [13-15].

In orthopedic surgery, scaffolds are used for the treatment of complex fractures, post-traumatic bone defects, and joint reconstruction. Polymer-ceramic composites are preferred due to the balance between rigidity and controlled degradation, allowing for gradual bone integration. Studies in animal models have demonstrated that scaffolds in HA and β-TCP support osteoconductivity and vascularization, accelerating healing [13-16].

In dental implantology, bioresorbable scaffolds are used for the regeneration of alveolar ridges and peri-implant defects. The combination of biodegradable polymers and ceramic nanoparticles promotes bone formation and implant integration. Clinical studies have shown that scaffolds functionalized with growth factors, such as BMP-2, improve the success rate of bone regeneration. In cranio-maxillofacial surgery, scaffolds are used to reconstruct bone defects caused by tumors, congenital malformations, or trauma. 3D printing revolutionized this field, allowing the manufacture of customized scaffolds, adapted to the shape and size of the defect [16-18].

Preclinical studies indicate increased efficiency of bioresorbable scaffolds, but challenges remain related to degradation control and mechanical stability. Future research aims to integrate stem cells and nanomaterials to improve osteoinduction and vascularization. Thus, bioresorbable scaffolds continue to represent a promising solution for bone regeneration in clinical practice [16-20].

Conclusions

Bioresorbable scaffolds are a promising solution in bone regeneration, providing temporary structural support and facilitating the formation of new functional bone. Compared to permanent materials, they eliminate the need for secondary intervention, reducing postoperative risks and speeding up patient recovery.

The materials used, such as biodegradable polymers and bioactive ceramics, are selected according to the clinical application, but challenges persist in terms of degradation control, mechanical stability, and osteoinduction. Polymer-ceramic composites and advanced technologies, such as 3D printing, allow these properties to be improved, generating structures optimized for bone integration. Preclinical and clinical studies confirm the effectiveness of bioresorbable scaffolds in orthopedics, dental implantology, and cranio-maxillofacial reconstruction. However, insufficient vascularization and limitations of current materials require innovative solutions, such as functionalization with growth factors, integration of nanomaterials, and the use of stem cells.

The future of bioresorbable scaffolds depends on advances in bioengineering, nanotechnology, and artificial intelligence. The development of smart scaffolds, capable of responding dynamically to the biological microenvironment, will revolutionize regenerative medicine, offering personalized treatments for complex bone defects.

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