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Review

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Advanced review on biodegradable materials for bone repair: polymers, magnesium-based metals, and ceramics

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ABSTRACT

Biodegradable materials have garnered substantial attention in the field of bone repair due to their potential to eliminate the need for secondary surgeries, reduce patient pain, and decrease economic costs associated with orthopedic interventions. This review systematically summarizes the current knowledge, recent advancements, and clinical applications of three major categories of biodegradable bone repair materials: magnesium-based metals, polymers and ceramics. The physicochemical properties, degradation mechanisms, mechanical behaviors, and biocompatibility of these materials are discussed in depth. Additionally, this review highlights the challenges and future directions in the development of next-generation biodegradable bone implants, providing insights for researchers and clinicians aiming to optimize biomaterial selection for specific clinical applications.

Keywords: Biodegradable materials, bone repair, polymers, magnesium alloys, ceramics, biocompatibility, degradation mechanisms

INTRODUCTION

Bone repair materials are crucial in orthopedic surgery, trauma repair, and dentistry due to the increasing incidence of bone defects arising from trauma, infection, and tumor resection. Traditional bone grafts include autografts, allografts, and synthetic materials. Autografts remain the gold standard; however, they are limited by donor site morbidity, secondary surgical requirements, immune rejection, and the risk of disease transmission.[1]

Consequently, synthetic biodegradable materials have become a focal point of research, offering design flexibility, controlled degradation rates, and the potential to reduce patient morbidity.[2]

Biodegradable materials are generally categorized into bio-inert and bioresorbable (biodegradable) types. Bio-inert materials, such as titanium and stainless steel, have a long history of clinical success but remain permanently in the body unless removed surgically. In contrast, biodegradable materials gradually transfer mechanical load to healing tissue, thereby mitigating stress shielding and eliminating the need for secondary surgery.[3]

The primary classes of biodegradable biomaterials are polymers, magnesium-based metals, and ceramics.[4]

This review presents an in-depth discussion of their physicochemical properties, degradation mechanisms, mechanical characteristics, biocompatibility, and current clinical and experimental applications.

BIODEGRADABLE MAGNESIUM-BASED METALS

Overview

Magnesium (Mg) and its alloys are promising biodegradable metals due to their favorable density, elastic modulus, biocompatibility, and bioactive degradation products.[5]

Mg-based metals corrode in vivo, producing Mg^{2+} ions that are absorbed or excreted by the body. Their mechanical properties surpass those of polymers and ceramics, making them suitable for load-bearing applications. Despite their excellent biocompatibility, the rapid corrosion rate of Mg alloys limits their clinical applications.[6]

Current Studies on Magnesium Alloys

Commercial alloys:

AZ31B, AZ91, and WE43: Commercial alloys such as AZ31B, AZ91, and WE43 were initially developed for engineering purposes. While biocompatible, some alloys release Al and rare earth elements, raising toxicity concerns. Pure

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Mg exhibits uniform degradation but limited mechanical strength.[7]

MgeCa alloys: Calcium-containing alloys (Mg-Ca) provide densities similar to bone and release Mg^{2+} and Ca^{2+} ions to enhance osteogenesis. Mg-Ca alloys exhibit good biocompatibility, promoting osteoblast and osteocyte activity.[8]

MgeZn alloys: Zinc addition improves corrosion resistance and mechanical strength. Mg-6% Zn alloys demonstrate tensile strength of 279.5 MPa and elongation of 18.8%, with controlled degradation in vivo and minimal cytotoxicity.[9]

MgeRE alloys: Rare earth element alloys such as Mg-Y, Mg-Gd, and Mg-Nd show enhanced corrosion resistance and mechanical performance. Mg-Nd alloys exhibit slower degradation, making them promising for long-term implants.[10]

Degradation Mechanisms

Mg alloys corrode via electrochemical reactions producing $Mg(OH)_2$ and H_2 gas. Chloride ions accelerate corrosion through pitting, while phosphate, carbonate, and protein layers can inhibit corrosion. Stress corrosion cracking is a critical concern for load-bearing applications.

Applications in Bone Repair

Mg alloys are investigated for screws, plates, and porous scaffolds. Their use in load-bearing bones is limited by rapid degradation, gas evolution, and mechanical weakening. Surface modifications such as anodization, micro-arc oxidation, electrodeposition, and biomimetic coatings are explored to enhance corrosion resistance.

BIODEGRADABLE POLYMERS

Overview

Biodegradable polymers are widely used in tissue engineering and bone repair implants due to their versatility and processability. Polymers can be natural or synthetic. Natural polymers, such as collagen, fibrin, chitosan, and hyaluronic acid, are biocompatible but often have limited mechanical strength, unpredictable degradation rates, and potential immunogenicity. Synthetic polymers, including polylactic acid (PLA), polyglycolic acid (PGA), polycaprolactone (PCL), and polyhydroxybutyrate (PHB), allow precise control over mechanical properties and degradation kinetics.[11]

Polymers consist of macromolecules with covalently bonded monomeric units, which can be arranged linearly, branched, or cross-linked. They may exhibit amorphous, crystalline, or semi-crystalline regions, which influence their mechanical behavior and degradation. Temperature-dependent properties such as the glass transition temperature (Tg) are critical, with Tg values above physiological temperature preferred to maintain structural integrity in vivo.

Common Biodegradable Polymers

Polycaprolactone (PCL): PCL is a hydrophobic aliphatic polyester with lower degradation rates than PLA or PGA due to its high crystallinity. It possesses excellent flexibility, drug permeability, and machinability, making it suitable for long-term implants and drug delivery systems.[12] PCL can be processed via extrusion, injection molding, and 3D printing.

Polyglycolic acid (PGA): PGA is a highly crystalline aliphatic polyester synthesized via ring-opening polymerization. Its hydrophilicity results in rapid hydrolytic degradation, reducing tensile strength to approximately 50% within 14 days post-implantation. PGA is frequently copolymerized with PLA to form PLGA, which provides tunable degradation rates suitable for surgical sutures and bone repair applications.[13] PLGA-based materials include Vicryl® and Polyglactin 910, widely utilized in clinical practice.

Polylactic acid (PLA): PLA is among the most extensively studied biodegradable polymers. Derived from renewable resources such as corn starch, PLA can exist in L-PLA (mostly crystalline) and DL-PLA (mostly amorphous) forms. Crystalline L-PLA exhibits slower hydrolysis and higher mechanical strength, whereas DL-PLA degrades more rapidly.[14] PLA has been employed in sutures, screws, rods, and scaffolds, demonstrating biocompatibility and FDA approval for clinical use.

Poly-para-dioxanone (PDS): PDS is a synthetic biodegradable polyester with high mechanical flexibility, biocompatibility, and bioabsorbability. Commonly used in fracture fixation and controlled drug delivery, PDS degrades over months in vivo, allowing gradual transfer of mechanical load to regenerating bone.[15]

Polyhydroxybutyrate (PHB): PHB is a highly crystalline biopolymer produced by bacterial fermentation. Its excellent stereoregularity and absence of catalyst residues make it an ideal model material for polymer studies. However, its brittleness and narrow processing window limit direct clinical application.[16] PHB is often blended with other polymers to improve mechanical properties and decrease brittleness.

Physicochemical and Mechanical Properties

Polymer properties such as tensile strength, elongation at break, and modulus depend on stereochemistry, molecular weight, and processing history. PLLA exhibits higher mechanical strength and slower degradation than PDLA, making it suitable for load-bearing applications. PLGA offers tunable properties by adjusting the ratio of lactide to glycolide units.[17]

Degradation Mechanisms

Polymers degrade primarily through hydrolysis and enzymatic action. Ester bond cleavage converts macromolecules to oligomers, eventually yielding carbon dioxide and water. Degradation rates are influenced by crystallinity, molecular weight, stereochemistry, and the local physiological environment.

Applications in Bone Repair

Polymers are used in screws, pins, plates, and scaffolds for non-load-bearing and partially load-bearing bones. Biodegradable polymers reduce stress shielding, avoid secondary surgeries, and can be combined with bioactive molecules to promote osteogenesis. Clinical products include Lactosorb® (PLGA) and Natureworks PLA®.

BIODEGRADABLE/BIORESORBABLE CERAMICS

Overview

Ceramics, including hydroxyapatite (HA), tricalcium phosphate (TCP), and bioactive glasses, are used for bone and dental defect repair.[18] They are categorized as bio-inert, bioactive, or bioresorbable based on interactions with tissue.

Common Bioresorbable Ceramics

Hydroxyapatite (HA): Synthetic HA is highly crystalline with composition $Ca_{10}(PO_4)_6(OH)_2$, closely resembling bone mineral. HA is osteoconductive, biocompatible, and can act as a carrier for osteoinductive factors. Clinical use is primarily in non-load-bearing bone defects.

Tricalcium phosphate (TCP) ($Ca_3(PO_4)_2$): TCP is resorbable, with higher degradation rates than HA. Implants facilitate bone ingrowth and are resorbed by osteoclastic activity.[19]

Bioactive glass-ceramics: Bio-glass forms HA microcrystals on surfaces, providing strong bonding with bone. It is used in craniofacial reconstruction, bone defect filling, and dental applications. Bio-glasses maintain superior mechanical strength compared with others.[20]

Physicochemical and Mechanical Properties

Bioresorbable ceramics generally exhibit lower mechanical strength than bio-inert ceramics. Non-porous HA and cerabone A/W glass-ceramics show the highest strength among bioactive materials but remain less fracture-resistant than ZrO_2 ceramics.

Degradation Mechanisms

Bioresorbable ceramics degrade via solution-driven and cell-mediated processes. Osteoclasts, mesenchymal cells, and macrophages facilitate resorption, which is influenced by implantation site and protein interactions. Gradual replacement by lamellar bone occurs during physiological remodeling.

Applications in Bone Repair

Bioresorbable ceramics are applied in cranial, maxillofacial, and dental reconstruction, as well as in joint and periodontal repair. Commercial products include Depuy Spine Conduit® (TCP), Medtronic MasterGraft® (HA/TCP), Stryker Vitoss® (TCP), and Stryker Cortoss® (bioactive glass).

SUMMARY AND FUTURE PERSPECTIVES

Biodegradable polymers, Mg-based metals, and bioresorbable ceramics each offer unique advantages in bone repair applications. Polymers provide tunable degradation and flexible processing but may exhibit limited mechanical strength. Mg alloys offer load-bearing capacity and bioactive degradation products but require corrosion control.[21] Ceramics provide excellent osteoconductivity but are brittle and mechanically weaker.[22]

Future research should focus on optimizing material properties, degradation kinetics, and bioactivity.[23] Composite materials combining polymers, metals, and ceramics may harness the advantages of each class. Surface modifications, alloying strategies, and doping of ceramics can enhance mechanical and biological performance. Personalized approaches, including 3D-printed scaffolds and patient-specific implants, are expected to improve clinical outcomes.

CONCLUSION

As a result, the development of biodegradable materials for bone repair continues to advance rapidly, offering new opportunities for safer, more effective, and patient-specific orthopedic treatments. Continued interdisciplinary research integrating materials science, biology, and clinical practice is essential to translate these materials into widespread clinical application.

ETHICAL DECLARATIONS

Peer Review Process

This review was externally peer-reviewed.

Conflict of Interest

The authors declare no conflicts of interest.

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Author Contributions

The author is solely responsible for the conception, data collection, analysis, and writing of this manuscript.

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