REVIEW

A brief report on orthopaedic implants with bioactive-coatings to improve their effectiveness

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ABSTRACT

Orthopaedic implants, though widely used in modern medicine, continue to face several critical challenges such as microbial contamination, mechanical wear and tear, limited biocompatibility, and the absence of bone-mimicking characteristics. Traditionally, metals and metal alloys, particularly titanium and its derivatives, have been the preferred choice for replacing damaged bones and joints due to their strength and corrosion resistance. However, these materials are not without drawbacks, as they often fail to provide intrinsic antibacterial activity and may not integrate effectively with surrounding tissues, thereby compromising long-term success. To overcome these limitations, recent research has focused on functional coatings that can impart additional beneficial properties to implants. This article highlights significant advancements in coating technologies, including metals, polymers, ceramics, biomolecules, and modified silk fibroins. By providing an overview of these developments, it aims to encourage the design of novel biomimetic nanomaterials that can improve implant performance, minimize infections, and enhance patient outcomes.

Keywords: orthopaedic implants, bioactive coatings, antimicrobial, polymer, metal and metal alloys, bioglass.

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INTRODUCTION

In orthopaedic implants, many advancements have been made to improve the biocompatibility, load bearing strength improvement, minimizing wear and tear as well as resist microbial attack. Surface coatings with different types of metals, alloys, polymers, biomolecules, ceramics and ceramic composites, and modified silk fibroin has been recently employed to overcome the limitations. Figure 1 shows the different types of functional coatings that are been employed for orthopaedic implants.

This perspective discusses about some recent findings on surface coatings of orthopaedic implants.

KEY EVIDENCE

Increased use of antimicrobial metal and alloy surfaces, along with coatings, reduce the biomaterial-related infections risk. Despite significant research and progress in developing

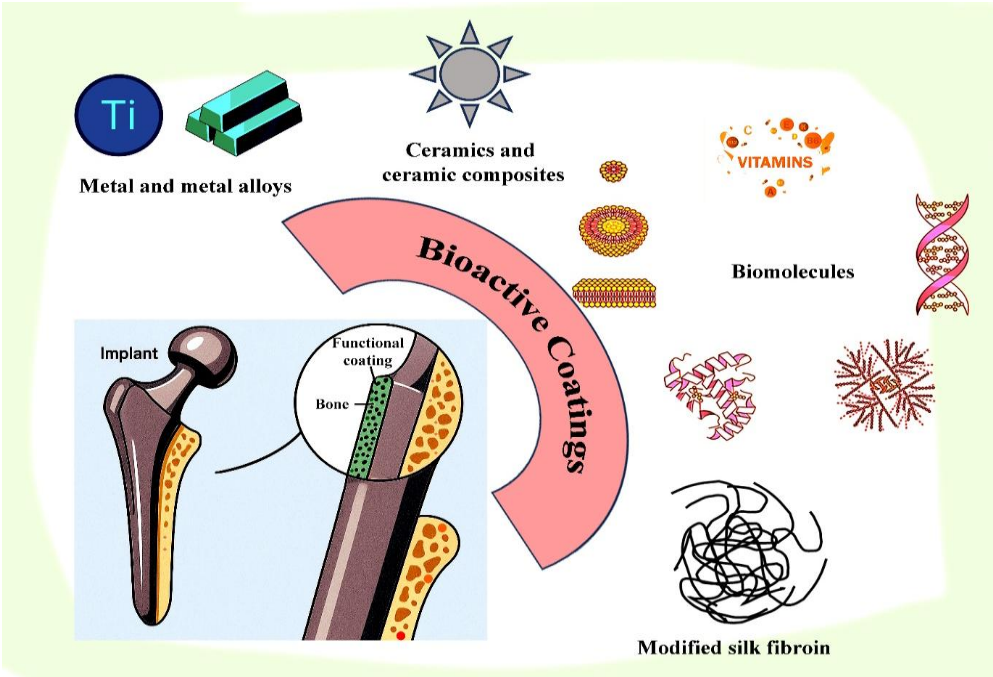

Figure 1. The various types of functional bioactive coatings used to improve the characteristics of orthopaedic implants.

metals and alloys-based biomaterials, infection rates remain on the rise. Designing antimicrobial biomaterials becomes challenging due to numerous factors that influence antimicrobial effectiveness while also impacting the implant's biotoxicity. These factors comprise surface characteristics such as chemistry, topography, and physiochemistry, as well as the implant's location within the body (e.g., in a closed or open environment). Additionally, surface, and biological factors affect how the biomolecules and proteins from the adjacent environment deposit and orient themselves on the implant's surface. The interaction between the material and its environment also impacts the rates of corrosion of metals and alloys. Moreover, variations in bacterial genus and species, also determines the antimicrobial efficacy of the biomaterial. Researchers have reported of how the surface properties of metals and alloys affect microbial adhesion, as well as their antimicrobial and biotoxicity characteristics [1-3]. Aslan *et al*. applied multilayer tantalum nitride (TaN) coatings on CoCrMo biomedical alloys, widely used in orthopaedic implants for their mechanical strength but limited by toxic metal ion release during in vivo use. To overcome this, a closed-field unbalanced magnetron system was used to deposit TaN multilayers, enhancing corrosion resistance and minimizing ion release. Potentiodynamic polarization and static immersion tests in simulated body fluid over 45, 60, and 90 days confirmed the coating's protective effect. Inductively coupled plasma mass spectrometry revealed a significant reduction in metal ion release, with electrochemical tests indicating 93% corrosion protection. These results highlight the coated alloy's potential as a superior implant material

[4]. The clinical use of metallic zinc (Zn) and its alloys present challenges for the healing of bone fractures due to their irregular degradation patterns, the burst release of Zn2+ ions, and inadequate osteo-promotion and osteo-resorption regulation [5]. A metal-organic hybrid nanostick was developed using Zn^{2+} coordinated with zoledronic acid (ZA) and HEDP, which was then incorporated into a zinc phosphate (ZnP) solution to form a uniform micro-patterned hybrid coating on a Zn substrate. This coating significantly reduced localized corrosion and Zn^{2+} release while enhancing osteo-compatibility and osteo-promoting effects both in vitro and in vivo, due to the combined bioactivity of Zn ions, ZA, and the unique micro/nanostructure [6]. To further address rapid degradation and limited strength in Mg-based alloys, direct current magnetron sputtering was employed to apply zirconium (Zr)-doped coatings. These coatings improved corrosion resistance, maintained biocompatibility, and enhanced mechanical strength without affecting osseointegration. The Mg–Zr coatings exhibited liquid-loving behaviour, stable Young's modulus (~80 GPa), and increased hardness, making them strong candidates for biodegradable temporary bone implants [7].

Camargo *et al*. evaluated the biocompatibility of ISO 5832-9 steel and Ti6Al4V alloy coated with electrospun poly(methyl methacrylate) (PMMA) nanofibers, materials commonly used in acetabular and femoral prosthetic components. After surface pretreatments (sanding and acid etching), nanometric PMMA fibers were uniformly deposited, showing excellent adhesion and biocompatibility with fibroblast cultures. To further enhance cell-material interaction, hydroxyl radicals were introduced into PMMA via Electrospinning Induced Surface Activation (EISA), producing hydroxylated PMMA (PMMA-OH) nanofibers. These promoted denser cell monolayers, improved adhesion, and enhanced cellular functions such as growth, migration, and extracellular matrix synthesis. This two-step method effectively created bioactive, OH-functionalized PMMA coatings that significantly improved the cellular response on metallic implants [8].

In a study on enhancing titanium (Ti) implant integration, researchers developed transcript-activated coatings using chemically modified mRNA (cmRNA) encoding bone morphogenetic protein 2 (BMP2). Three biocompatible materials—poly-D,L-lactic acid (PDLLA), fibrinogen, and fibrin—were used to coat Ti surfaces for localized protein production with osteoinductive properties. The coatings delayed cmRNA release, significantly improving transfection efficiency, with fibrinogen showing the highest performance. Lower PDLLA and thrombin concentrations yielded better transfection outcomes for PDLLA and fibrin, respectively. All coatings enhanced cell viability and proliferation, with fibrinogen-coated surfaces demonstrating superior results, including increased BMP2 production, alkaline phosphatase activity, and mineralization. These findings identify fibrinogen as the most effective matrix for cmRNA delivery, promoting improved transfection, osteogenesis, and implant integration [9].

Nilawar *et al*. reviewed the use of bioactive ceramic coatings on degradable orthopaedic implants to enhance healing and bio-integration through controlled degradation. These ceramics form chemical bonds with surrounding tissues, promoting integration of polymeric or metallic implants, and some also offer antibacterial properties to reduce infection risk. Recent advances include mechanical surface treatments to improve bio-corrosion resistance while preserving biocompatibility. Additionally, surface nano-crystallization enhances biomechanical performance, durability, and functionality. The review highlights commonly used bioactive ceramics and their influence on the biological, mechanical, and corrosion properties of degradable implants [10].

Zhu *et al*. investigated bioactive ceramic composite coatings on Zn–Mn–Mg alloy by applying calcium phosphate (CaP) coatings over micro-arc oxidized zinc using hydrothermal treatment (HT), inspired by bone-derived CaP minerals. By adjusting HT duration, they achieved a uniform micro-CaP coating that enhanced cell viability and adhesion of MC3T3-E1 preosteoblasts and L-929 cells. Compared to untreated samples, the coated materials showed reduced cytotoxicity, higher cell density, and preserved morphology, with longer HT improving cell distribution. Additionally, the CaP coating reduced zinc ion release during degradation. These findings suggest that CaP coatings effectively enhance cytocompatibility and control degradation, making Zn-based biomaterials more suitable for biomedical applications [11].

Researchers explored hexafluoro-isopropanol (HFIP)-based silk fibroin (SF) coatings on AZ31 magnesium alloys to address their corrosion susceptibility in aqueous environments. Unlike conventional aqueous SF coatings that require pretreatment, the HFIP-based coating was applied directly and stabilized using ethylene glycol diglycidyl ether (EGDE) for enhanced chemical crosslinking. Morphological and nano-scratch analyses confirmed a more compact structure and stronger adhesion compared to aqueous coatings. Electrochemical and in vitro degradation studies showed significantly improved corrosion resistance. Additionally, tests using MC3T3-E1 cells demonstrated enhanced cell adhesion, cytoskeleton structure, and biological activity, indicating the coating's potential for biomedical applications [12]. A novel protein-based coating for magnesium alloys was developed by incorporating calcium and strontium ions into silk fibroin using a binary solvent system, which significantly increased the β-sheet content to 45.4%. This structural enhancement intensified the nanoscale "labyrinth effect," leading to a three-order-of-magnitude reduction in corrosion current density compared to uncoated alloys. The Ca^{2+} and Sr^{2+} ions were carefully doped to chelate with the amorphous regions of silk fibroin, enabling their controlled release. This ion release activated the Wnt signalling pathway, promoting osteogenic activity. Overall, the coating simultaneously improved both corrosion resistance and osteogenic potential, making it a promising strategy for magnesium-based biomedical implants [13].

CONCLUSION

Bioactive coatings on orthopaedic implants play a crucial role in enhancing the performance, longevity, and biocompatibility of the orthopaedic implants. These coatings are engineered to improve osseointegration, reduce wear and tear, and resist infection, addressing common post-surgical complications. Bioactive coatings, such as hydroxyapatite or bioglass, mimic the natural mineral content of bone and accelerates bone cell attachment and growth. Antibacterial coatings incorporating silver, zinc oxide, or antibiotic-releasing systems aids in inhibiting biofilm formation and reduce the risk of implant-associated infections. Additionally, surface modifications using polymers, drug-leaching materials, or nano-structured layers can provide controlled drug release, anti-inflammatory activity, and improved corrosion resistance. A few coatings are fabricated to be biodegradable, gradually resorbing by our body as new bone tissue regenerates. Innovations in functional coatings also encompasses smart materials responsive to physiological conditions, further accelerating the therapeutic outcomes. Overall, these coatings not only extend the life of the implant but also enhance patient recovery, making them a critical component in modern orthopaedic implant design.

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