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Recent Advancements in Orthopedic Implant Materials: A Short Review

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Abstract

In the modern day, as demand for automobiles rises, so does the frequency of accidents, and the need for advanced orthopedic implant materials also grows. Therefore, it becomes crucial to choose materials with excellent mechanical qualities, biocompatibility, osteointegration, non-bacterial adhesion, and non-colonization at the implantation site, among other qualities. Since the area is expanding quickly, periodic evaluations of our understanding of various materials and their evolution are required. In order to fulfill this need, this article offers a succinct overview of the many advanced orthopedic implant materials that have been employed, offering a thorough perspective on advancement material and potential future research areas.

1. Introduction to Distinct Advance Materials

The goal of enhancing patient outcomes and addressing the shortcomings of current materials is what drives the ongoing evolution of the area of orthopedic implant materials. Among the noteworthy recent developments are-

1.1. Nanotechnology

The engineering of matter at a very small, molecular scale is referred to as nanotechnology. In particular, "dimensions and tolerances of less than 100 nanometers" and "manipulation of individual atoms and molecules" are the focus of nanotechnology. Nanotechnology, which is the result of the collaboration of several scientific fields, has the potential to completely transform orthopedic surgery diagnosis and treatment. The application of nanotechnology in orthopedic implants has shown to be quite advantageous, enhancing the management of various bone abnormalities and orthopedic injuries. several materials have been studied and used, resulting in the utilization of several possible materials, each with special qualities and advantages of its own. Materials include polysaccharides like agarose, gelatin, bioactive ceramics, and biodegradable polymers. These nanomaterials' physical characteristics and nanoscale qualities enable them to support tissue regeneration and cell proliferation, which enables them to function effectively within the human body. Furthermore, implants made of nanoparticles have a larger surface area, which lowers infection rates and fosters a favorable environment for bone formation [1, 2]. Different surface alterations and drug delivery are brought about by nanotechnology, as will be covered below.

1.2. Surface Modifications

Implant surfaces can be altered using nanoparticles to promote osteointegration (the development of new bone) and decrease bacterial adherence. Examples are selenium nanoparticles and coatings made of hydroxyapatite. A thorough evaluation of the effects of Ti surface Nano topography on the behavior of bacteria and a variety of human cells was conducted by Miao et al [3]. The authors proposed that modifications to the Nano topography might facilitate the healing of soft tissues and bones. After polishing the smooth Ti surface (Smooth), it was possible to create micro-rough (Micro) and Nano-rough (Nano) surfaces using alkali-hydrothermal treatment, sandblasting, and acid etching, in that order [4]. Created a micro-nanostructured HA coating on Ti via MAO, and then added chitosan through dip-coating to enhance the antibacterial and surface biological qualities. Antibacterial activity has also been added to Ti surfaces by drug loading; these drugs, which are mostly broad-spectrum antibiotics including gentamicin, cephalothin, simvastatin, vancomycin, and tobramycin, have been applied using a variety of ways. Bioactive oxides, other bio-ceramics, and hydroxyapatite (HA) were among the bioactive implant coatings employed by the ifferent writers [5-7]. Due to its exceptional chemical stability, biocompatibility, and strong binding with the Ti alloy substrate, titanium dioxide has been widely used for surface modification of Ti alloy implants among the other bioactive oxide coatings currently in use, such as TiO_2, ZrO_2, $Al2O_3$, CuO, ZnO, and some other oxides [8, 9]. Furthermore, TiO2's photocatalytic qualities have a bactericidal impact, suggesting possible uses as an antibacterial implant coat-

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ing [10]. Other intriguing structures, such TiO_2 nanotubes, have been created and might be used for osteogenesis, anti-inflammatory purposes, and drug administration [11]. Zizhen et al. use surface modification approaches to create highly biocompatible HA no particles, manage the hydration layer and protein adsorption states on the surfaces under discussion, and create innovative bio ceramic nanoparticles for treating bone defects. For temporal implant applications, Moreno [12, 13]. Employed PCL and PLA top coats on a PEO-coated Mg3Zn0.4Ca alloy. The findings showed that HHC systems based on PLA or PCL increase corrosion protection by a factor of 10–12 at a magnesium alloy deterioration rate of 1.6–1.9 mm/year. Furthermore, medication delivery: Antibiotics or bone growth factors can be delivered to implants through the use of nanoparticles, which provide a targeted and continuous release for the purpose of preventing infections or promoting bone repair.

2. Biodegradable Materials

Anything that can be broken down by bacteria or other natural creatures without contributing to pollution is considered biodegradable. Biodegradable alloys have demonstrated better mechanical and biodegradation qualities, as well as increased biocompatibility, in recent decades. The next section discusses an example of biodegradable materials utilized in orthopedic implant applications.

2.1. Magnesium Alloys

Applications for magnesium alloys include orthopedics, cardiology, and tissue engineering. Over time, they spontaneously deteriorate, possibly removing the need for implant removal surgery. Additionally, their anti-tumor activities are promising. Novel magnesium alloys produced for biological applications were described [14]. In their investigation of the in vivo corrosion of several magnesium alloys [15]. Found that a buildup of biological calcium phosphates improved the osteointegration of all related metals. Numerous magnesium alloys used in biomedicine, including those based on zinc, calcium, for the purpose of creating magnesium alloys that degrade naturally, several research groups have looked at the magnesium-Si, magnesium-Sr, and magnesium-rare earth alloy bases in great detail [16-18]. Pure magnesium is known to corrode quickly, but when purity is increased by purification, the rate of corrosion is significantly decreased [19]. Magnesium frequently contains the impurities Fe, Cu, and Ni. The percentage of contaminants in magnesium greatly affects how quickly it corrodes. The mechanical characteristics of pure magnesium make it unsuitable for use in orthopedic applications. The current state of affairs indicates that magnesium-based implants have bright future possibilities.

2.2. Polymers and composites

In order to match bone strength and encourage tissue regeneration, new biodegradable polymers and composites with adjustable characteristics are being created. Some of the favored options for biodegradable materials include polymer compounds with both natural and synthetic bases [20, 21]. Natural-based polymers' poor mechanical strength, strong hysiological activity, repellency, and unclear rate of breakdown make them impractical for use in practical applications. Researchers have researched synthetic polymers with tailored design qualities to meet specific requirements, in an effort to overcome the limitations of natural polymers and imitate them. Since polymers are pliable at their glass transition temperature, it is imperative to render them biodegradable at temperatures higher than body temperature [22]. Polyglycolic acid (PGA), polylactic acid (PLA), poly-β-hydroxybutyrate (PHB), poly (lactic acid-co-glycolic acid) (PLGA), and poly-ε-caprolactone (PCL) are the biodegradable polymers [23]. Among these polymers, degradable sutures are made of PLA, PGA, and PLGA. The first known polymer to be utilized for sutures was PLA [24]. Natural materials like starch and maize were used to create PLA. Compared to amorphous PLA (DL-PLA), crystalline PLA (L-PLA) is less resistant to hydrolysis [25]. Due to hydrophilism, PGA, a synthetic polymer, has a rapid rate of breakdown, poor solubility, and high crystallinity. After implantation, PGA's mechanical strength decreases due to its fast rate of breakdown [26]. Medical implants commonly employ PCL, an aliphatic polyester with a difficult-to-control rate of deterioration. Because of its permeability and crystallinity, PCL is typically used as a medication delivery method and in the context of long-term implants.

3. Advanced Metals

All sectors are impacted by advanced materials as they not only help create new goods but also enhance the functionality of materials and products already on the market. The section below provides an example of various advanced materials and their uses in the orthopedic industry.

3.1. TNZS Alloy

With a low elastic modulus closer to bone, this innovative titanium alloy may lessen stress shielding and enhance implant function over the long run. The new Ti–Nb–Zr–Si (TNZS) alloy was created and contrasted with Ti–6Al–4V alloy and commercially pure titanium. Because silicide phases are present, electrochemical experiments showed that the TNZS has a higher corrosion resistance under all circumstances. To determine the created TNZS's level of biocompatibility, it was put to the test in preparation for further cell culture research. Based on the results, TNZS alloy appears to have potential as a competitive biomaterial in orthopedic applications. Researchers have demonstrated that Si has a function in stabilizing the crystalline phases in Si–Nb–based alloys, which may aid to increase corrosion resistance [27–30]. The unique characteristics and uses of TZNT alloy were described by Shima Nasibi et al. (2020) & Bordbar-Khiabani (2023) as a possible option for surgical and orthopedic implant applications [31-33]. The TNZS alloy by Michael Gasik et al. (2023) was created and contrasted with Ti–6Al–4V alloy and commercially pure titanium. In vitro, it demonstrated better cell-material interactions than Ti–6Al–4V. TNZS alloy may be a competitive biomaterial for orthopedic applications, according to the data [34].

3.2. Zirconium and tantalum

These metals are viable substitutes for titanium in some applications due to their superior corrosion resistance and biocompatibility. Tantalum has demonstrated significant promise in orthopedic and dental implant applications because to its attributes of corrosion resistance, biocompatibility, Osseo integration ability, and antibacterial qualities (2021) provide an overview of the most recent advancements and discoveries in the study of tantalum and its derivatives' Osseo integration and antibacterial qualities, as well as a summary of surface modification techniques used to improve these qualities. Tantalum has demonstrated a wide range of application potential in improving the stability and performance of implants in orthopedics and dentistry because of its exceptional corrosion resistance and biocompatibility [35]. At the moment, tantalum is most frequently used as an enhancer up cases of arthroplasty, tumors, and certain fractures, augmentations are used to fill up bone deficiencies. This material appears to permit bone ingrowth and successful biologic assimilation, and it may be manipulated to be very porous. A high level of intraoperative workability is paired with this biologic integration. Tantalum augments are frequently drilled in vivo and can be cut and drilled in the operating room. Among other applications, its advantageous features have made it a desirable option for complicated acetabular reconstruction. Tantalum's increased applications, such as tantalum fracture implants, are being discussed. Right now, not many people are using these programs [36]. Dense and adherent oxide layers occur on the surface of Zr alloy and improve its wear resistance (2015) described in the literature. Zr exhibits a lower magnetic susceptibility than SUS, Co-Cr alloy, and Ti, which makes it a good candidate for reducing artifacts in magnetic resonance imaging. The phase constitutions of the Zr alloys have an impact on their magnetic susceptibilities. Depending on the specifications for medical equipment under magnetic resonance imaging (MRI), magnetic susceptibility in addition to mechanical qualities might be modified by altering the composition [37]. Author reviewed the major characteristics of CP Zr and Zr -alloys as implant materials in the context of both the current 1.5 Tesla MRI and future high field strength (> 3 Tesla) MRI diagnostics. The effects of alloying elements, microstructures and mechanical characteristics, magnetic susceptibility, shape memory effect, super-elasticity, phase changes in Zr and its alloys, biocompatibility in both bulk and powder forms, and contemporary usage as implant alloys are some of these. In summary, Zr-alloys present exceptional prospects for orthopedic implant researchers to create a new class of alloys that can satisfy all important needs, such as wear resistance, biocompatibility, strength and ductility, modulus, and magnetic susceptibility for high field strength MRI diagnostics [38].

4. Antibacterial Materials

Antimicrobial materials are created to combat infections in order to address the limitations of antimicrobial therapy. Small molecules, macromolecules, polymers, ceramics, metals, or composites exhibiting microbicidal properties against bacteria, fungus, and viruses are known as antimicrobial materials. The antimicrobial substance consists of.

4.1. Stimuli-responsive Materials

These materials provide focused and regulated antibacterial activity by releasing antibiotics in response to particular stimuli, such as illness or temperature. Nanocomposite materials: To prevent infections linked to implants, silver nanoparticles or other antimicrobial compounds are included into implants. The rational design of adaptable biomaterials with bone healing and regeneration properties is covered [39]. Clarified are the distinct processes, therapeutic uses, and current constraints of the recently developed biomaterials. The most advanced smart orthopedic implant coatings were highlighted [40]. They also discussed how biomaterials create signals for their intended function, such as temperature, pH, light, etc., and the impact of smart coating stimuli on the cell microenvironment. The importance of biofilms, the method by which biofilms form, and the obstacles that must be overcome quickly in order to enable smart nanomaterials to efficiently target and cure implant biofilms are all covered [41].

4.2. Additive Manufacturing and Personalized Implants

4.2.1. Additive Manufacturing

Because of its features that allow for part customization, the creation of complex forms, waste reduction, design flexibility, and other advantages over traditional production processes, additive manufacturing, or AM, has become a widely used and powerful technology in the manufacturing industry. A new manufacturing technique called additive manufacturing (AM) creates three-dimensional items by layering on materials to a computer-aided design (CAD) model. Custom implants made to match each patient's anatomy are possible because to additive manufacturing, which may also improve fit and lower risk of problems [42]. Employed PLA material to create samples at various settings using an FDM 3D printer based on Taguchi's L-9 orthogonal array. Additionally, 316L stainless steel was applied to these samples by an inexpensive electric spray technique. Additionally, coated samples underwent tensile and flexural strength tests. Ultimately, the signal-to-noise ratio's analysis of variance was used to choose the best possible combinations of the parameters. Maximum tensile strength (29.51 MPa) and flexural strength (98 MPa) were attained at the optimal settings (A1B2C2: raster angle 30°, number of top and bottom layer 3, and coating thickness of 100 μm). The author further recommends conducting additional research on wollastonite and bioactive glass coating to evaluate their efficacy on polymeric materials.

4.3. Bioinks and Biocompatible Materials

The creation of biocompatible 3D printing inks opens the door to the printing of implants that include growth factors or live cells, enabling customized tissue regeneration. With an emphasis on their categorization, characteristics examined metallic and synthetic polymer implant biomaterials that can be used to fix load-bearing bone fractures because of their resistance to the body's mechanical loads and strains [43].

5. Challenges and Future Directions

Even though these developments are encouraging, there are still issues to be resolved, such as maximizing material qualities, guaranteeing long-term safety and durability, and getting past regulatory obstacles. Future studies will concentrate on.

5.1. Bioactive Materials

Implants that communicate with the body to support regeneration and healing [44]. Implants with sensors that track bone health and provide individualized care are known as smart implants. Integration with tissue engineering: For a more comprehensive rehabilitation of a joint or bone, implants are combined with created tissues.

6. Conclusion

The field of orthopedic implant materials is booming with innovation, driven by the desire to enhance patient outcomes and longevity. While challenges remain the recent breakthrough in orthopedic implant materials offer a glimpse into a future where implants seamlessly integrate with the body, promote healing and last a lifetime. This will not only improve patient quality of life but also reduce health care costs associated with revision surgeries and complications. In this study, the authors focus on the distinct advance materials so that this research could become the torchbearer for the futuristic researchers working in this area.

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