



Review Article

Medical Applications of Nanotechnology and Biomaterials

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Abstract

In the present era, biomaterials are defined as substances of natural, synthetic, or composite origin that are used to replace, regenerate, and support tissues that have lost their functional activity or have been damaged. The primary criterion for the efficacy of these materials is their high biocompatibility, defined as their capacity to induce minimal adverse reactions within the body. Despite the long-standing utilization of classic biomaterials (metal alloys, ceramics, and polymers) in medical devices, their mechanical incompatibility, corrosion potential, and limited biological activity at the cellular level have led to a significant demand for more advanced solutions. The application of nanotechnology offers a revolutionary approach to addressing these needs by enabling the control of material properties at the nanoscale (1-100 nm). Because of their high surface area/volume ratios, nanobiomaterials more closely resemble the cell microenvironment, which enables the development of sophisticated scaffolds and physiologically stimulating materials for tissue engineering. The classification of biomaterials, their mechanical and biocompatibility criteria, the contributions of nanotechnology to biomaterial development, and nano-assisted medical systems, including biosensors, biochips, and nano-carrier systems, are all thoroughly examined in this article.

Keywords: nanotechnology, biomaterials, biocompatibility, drug delivery, tissue engineering

1. Introduction

One of the most significant and rapidly evolving areas of medicine is biomaterials science [1]. Biomaterials are materials derived from natural, synthetic, or composite sources that are used in the human body to sustain, regenerate, and replace damaged or dysfunctional tissues [2]. They are widely used in dentistry (dental implants), orthopedics (artificial joints), cardiology (artificial vessels, stents), and cosmetology [3].

Biomaterials have been used since prehistoric times. For example, the Egyptians used animal muscle for sutures. Tissue engineering and materials science have recently contributed to the advancement of the modern biomaterials discipline, which is based on a synthesis of medicine, biology, physics, and chemistry. Biomaterials science has grown rapidly in the last decade thanks to advances in tissue engineering and regenerative medicine.

Biomaterial science is a multidisciplinary field whose successful application requires the integration of many important scientific disciplines. As shown in Figure 1 [4], this field is closely related to Materials Science (synthesis and characterization of new materials), Biological Sciences (cell-material interactions and tissue responses), Biomechanics (analysis of response to mechanical load), Toxicology Sciences (prevention of toxic effects of materials on the body), and Medical Sciences (clinical application needs and outcomes). The clinical efficacy of materials is also determined by engineering and human health considerations. Through this integration, fourth-generation nanomaterials that actively assist biological activity, going beyond materials that only have a passive replacement function, have become possible.

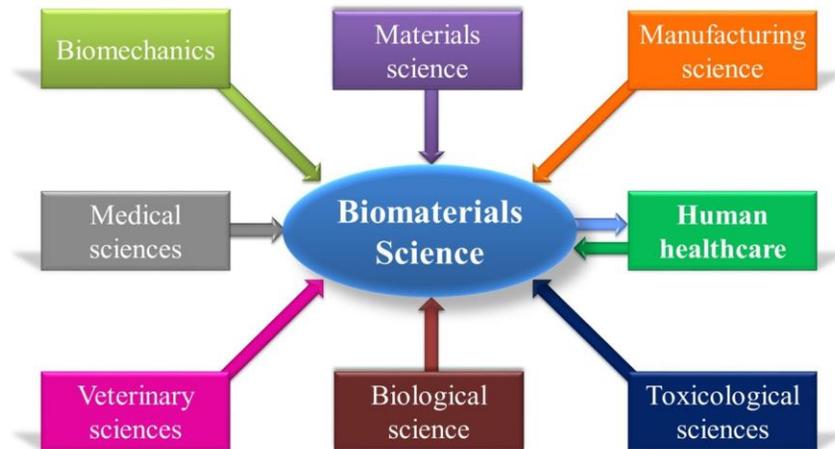


Figure 1. The relationship of biomaterials science with other sciences [4].

There are four primary generations in the history of biomaterial development: The goal of first-generation materials, such as passive polymers, was to reduce the immunological response while solely acting as passive substitutes. Certain bioceramics and other second-generation materials are bioactive, which means they interact favorably with tissue and encourage its integration [5]. Third-generation materials, such as scaffolds that promoted cell growth, were created for tissue engineering. The fourth generation considerably improves cellular functional activity while maintaining nanomaterials at the core of its development.

The mechanical strength of materials is not the only restriction caused by modern therapeutic requirements. Toxic ion leakage from metal corrosion following long-term implantation is one of the biggest issues with conventional biomaterials. The high risk of infection at the implantation site is another significant problem. A fibrous capsule forms around the implant as a result of the body's defensive response to the material surface's incompatibility with the normal biological environment. This significantly reduces the implant's functional success. These drawbacks are motivating scientists to develop a new class of biomaterials with great biocompatibility and the ability to replicate biological processes [6].

2. Classification of Biomaterials

Based on their mechanical characteristics and chemical composition, biomaterials are classified into four major groups (Figure 2) [1].

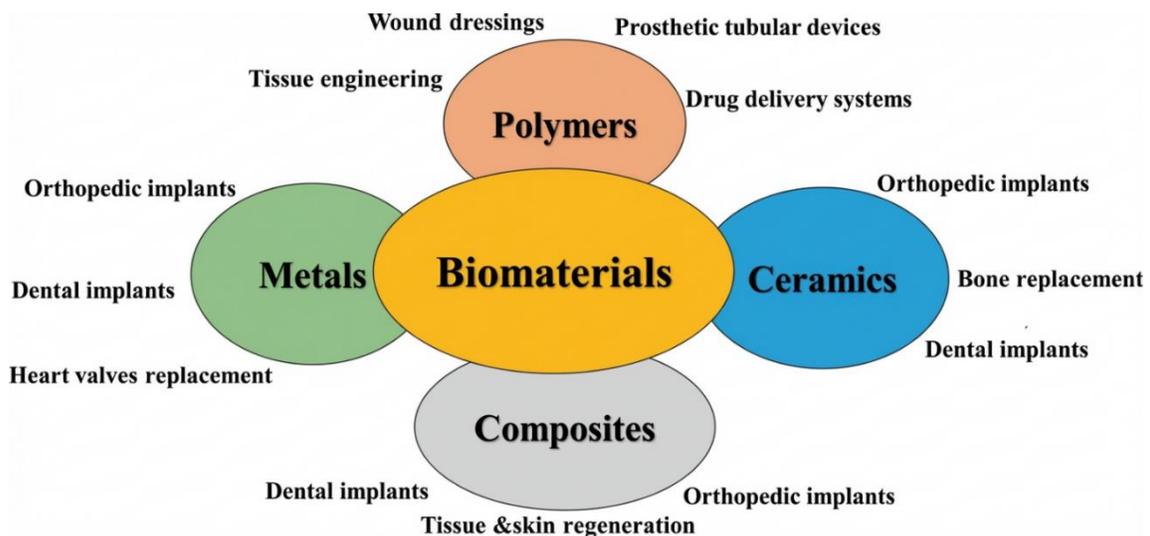
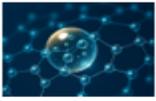


Figure 2. Basic Classification of Biomaterials [1].



2.1. Metallic Biomaterials

Because of their high strength, fatigue resistance, and durability, metallic biomaterials [7] (such as stainless steel, titanium alloys, and cobalt-chromium alloys [8]) are used in areas subjected to high mechanical stress, especially in orthopedic implants (hip-pelvic joints), dental implants, and stents in cardiology. The most popular metallic biomaterials are titanium alloys (Ti-6Al-4V) [9], in particular, due to their superior corrosion resistance and biocompatibility. However, the metal's high elastic modulus may cause issues with stress shielding, which would weaken bone tissue.

2.2. Ceramic Biomaterials

Bioceramic materials have both chemical stability and biocompatibility [10], such as calcium phosphates, which include aluminum oxide, zirconium dioxide, and hydroxyapatite (HAp). These substances can be classified as either bio-active (like HAp), which forms direct chemical connections with bone tissue, or bio-inert (like Al_2O_3), which functions passively. Because HAp replicates the mineral composition of bone tissue, it is essential in applications like implant coatings, bone fillings, and bone cements. Polymers are used to create composites in order to remove brittleness.

2.3. Polymeric Biomaterials

The most adaptable class of biomaterials is polymers since they can easily change the characteristics of the material [11]. These are either permanent (like silicone and polyurethane) or biodegradable (like PLA and PGA), which the body absorbs after a specific amount of time and permits tissue regeneration. Polymers are widely used in contact lenses, vascular grafts, soft tissue replacements, and controlled medication delivery systems.

2.4. Composite Biomaterials

Composite biomaterials, such as ceramic particles embedded in a polymer matrix, are made by combining two or more distinct kinds of materials. The combination of polymers and ceramics offers distinct advantages, including the flexibility of polymers and the bioactivity of ceramics, which are both absent in single materials. An exemplar of this phenomenon is polymer-HAp composites, which have been demonstrated to meet the mechanical and biological requirements of bone [12].

3. Biocompatibility and Mechanical Requirements

3.1. Cell-Material Interaction

The capacity of a material to interact properly with surrounding tissues while producing few negative reactions is known as biocompatibility. Body proteins absorb the material's surface in the initial seconds following implantation. The way fibroblasts and osteoblasts interact with the surface is determined by this layer of proteins. Bioactive materials encourage integration and tissue regeneration [13], whereas bioinert materials (such as certain metals) can cause fibrous encapsulation. To encourage cell adhesion, proliferation, and differentiation in tissue engineering, the material's surface energy, roughness, and chemical structure must be precisely tuned.

3.2. Mechanical Compatibility

An implant's ability to adapt to the mechanical circumstances of the application site is critical to its long-term effectiveness. Because orthopedic biomaterials are subjected to repetitive loads (walking, running) for years, they need to have a high fatigue resistance. Additionally, the elastic modulus of the material must be similar to the surrounding tissue. Stress shielding from metal implants with a modulus much greater than bone can result in implant loosening and bone atrophy [14]. Porous or nanostructured alloys with exceptionally low elastic modulus are being developed to address this issue.

4. Nanotechnology in Biomaterials and Medicine

By manipulating material properties at the atomic and molecular levels, nanotechnology has transformed the study of biomaterials. The biggest benefit of nanomaterials, which range in size from 1 to 100 nm, is their high surface area-to-volume ratio and capacity to interact on a comparable scale with biological systems (cells, proteins) [15], [16].

4.1. Nanostructured Surfaces

The biocompatibility and biological activity of biomaterials are greatly enhanced by nanoscale surface modification. Nanostructured surfaces, such as nanowires, nanofibers, and nanochannels, imitate the extracellular matrix (ECM), which is the natural habitat of cells. These biomimetic surfaces inhibit the colonization of bacteria that cause illnesses while simultaneously promoting cell adhesion, proliferation, and differentiation (particularly bone cells, or osteoblasts).

4.2. Nanocarrier Systems

In the area of nanomedicine, nanocarrier systems are crucial platforms for the targeted and regulated delivery of medications, genetic materials, and bioactive compounds. The main categories of nanocarriers are lipid-based, polymer-based, inorganic nanoparticles, drug-conjugate systems, and viral nanoparticles, as seen in Figure 3 [17].

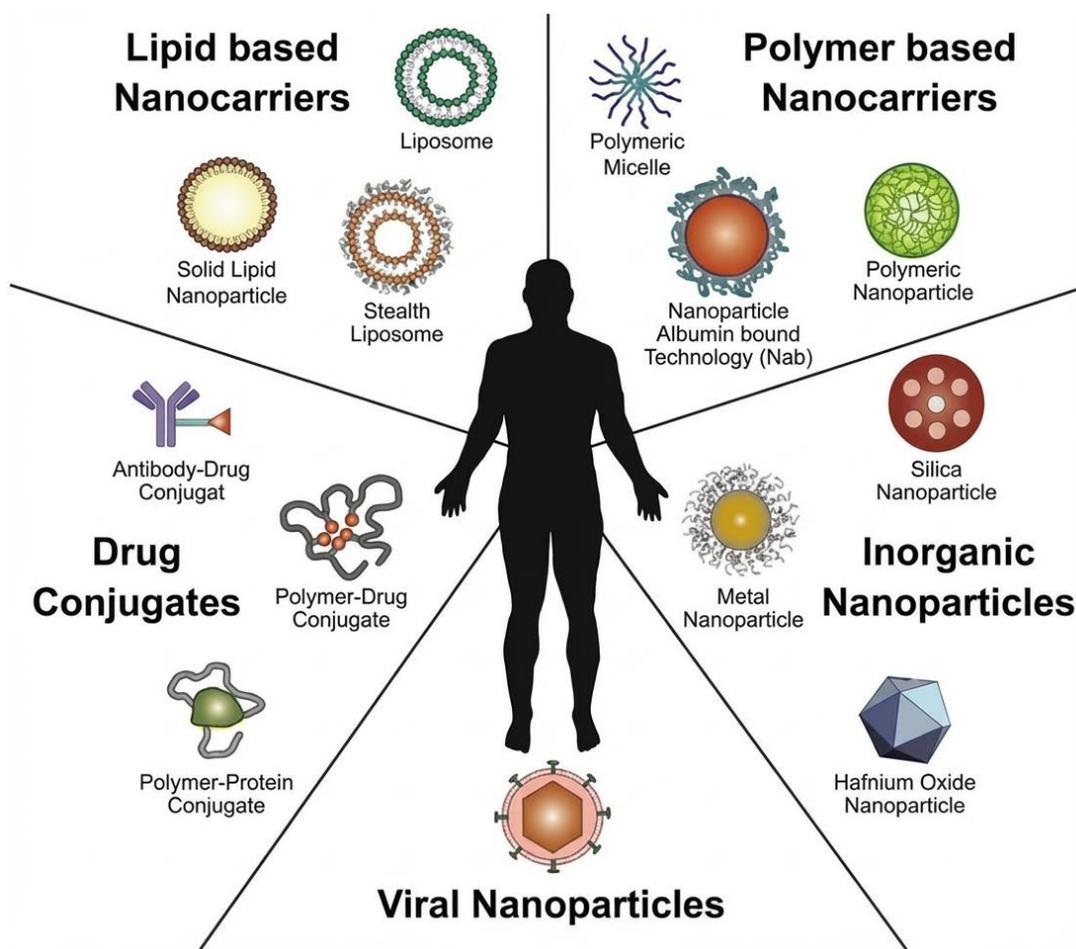


Figure 3. Application of nanomaterials in medicine [17].



Liposomes, solid lipid nanoparticles, and latent (PEG-coated) liposomes are examples of lipid-based nanocarriers. These systems prolong the drug's stay in the bloodstream, prevent enzymatic breakdown, and enable the simultaneous delivery of hydrophilic and hydrophobic medications. High stability, controlled release, and functional surface modification are the benefits of polymer-based nanocarriers, such as polymeric micelles, polymeric nanoparticles, and albumin-bound nanoparticles (Nab technology).

Metal, silicon, and hafnium oxide nanoparticles are examples of inorganic nanoparticles that are primarily employed in radiation, imaging, and combination therapies. Drug molecules attach to proteins, polymers, or antibodies in drug-conjugate systems to target certain cell receptors, greatly increasing the efficacy of targeted therapy. Because of their strong transcriptional capacity, viral nanoparticles are especially significant in gene therapy and vaccine technologies.

These nanocarrier systems reduce systemic toxicity and boost therapy efficacy by selectively depositing the medicine in tumor tissue, particularly in oncology treatment.

5. Nano-enabled Medical Systems

5.1. Biosensors

Biosensors based on nanomaterials offer extremely sensitive, real-time molecular diagnostic data gathering. Because of their high electrical conductivity and surface area, nanocarbon-based materials like graphene and carbon nanotubes make excellent sensor platforms for identifying biological substances, including proteins, DNA, and glucose. These sensors are crucial for both the ongoing monitoring of chronic illnesses (like diabetes) and the early detection of diseases [18].

5.2. Biochips

Micro and nanofluidic technologies are used in biochips, also known as micro-total analysis systems or laboratory-on-a-chip. On a tiny chip, they incorporate complex laboratory procedures including drug testing, cell analysis, and genetic testing. Reduced sample volume, quicker processing times, and lower costs are made possible via nanoscale channels and surface changes. This technology has a lot of promise for quick diagnoses, especially in places with limited resources or distant locations [19].

5.3. Nanorobots

Nanorobots are nanoscale robotic constructs that can carry out particular tasks in a biological setting. They are created at the nanometer scale (1–100 nm). Targeted medication delivery, identifying sick cells, molecular diagnosis, and minimally invasive medical procedures are their primary goals. An inner and an outer component make up the structure of nanorobots. The external component is robust enough to interact with the body's diverse chemical surroundings. The interior is a vacuum-sealed, fully enclosed space that permits fluid flow only when required. Through auditory impulses, nanorobots can interact with the physician and carry out instructions [20].

Cosmetics are another area where nanorobots are being used. Nanorobot-containing creams, for instance, can eliminate extra oil, exfoliate dead cells, and supply vital components for the skin. They can be combined with antiseptics in oral and dental care to eradicate bacteria and stop the development of plaque and tartar.

6. Clinical Applications and Future Perspectives

Many medical fields are already being revolutionized by nanobiomaterials:

Tissue Engineering and Regenerative Medicine: In the area of electricity, skin, bone, cartilage, and nerve tissue are regenerated using polymer scaffolds made by electrospinning. These scaffolds' nanostructures encourage optimal cell development.

Cardiology: Nanomaterial-modified biological stents speed up vascular tissue regeneration and decrease inflammation following insertion [21].

The goal of future research is to turn biomaterials into "responsive/intelligent" systems that manage drug release and react to changes in the body's environment, such as a drop in pH during an infection or a temperature rise. New biomaterials with desirable biological characteristics will be designed more quickly by incorporating AI and machine learning techniques into materials science. This will make it possible to develop treatments that are specific to each patient's needs and conditions.

7. Conclusion

It is helpful to examine the past and present before talking about future objectives in the field of biomaterials. In the past, the primary remedy for tissue injury or loss of function was tissue removal. Later, new fields of application developed with the discovery of antiseptics, penicillin and other antibiotics, hygiene, and vaccinations. The lifespan of implants is finite. When orthopedic prostheses are physiologically compatible with tissues, they last longer. Restoring tissue function, metabolic and biochemical activity, and biomechanical performance are all part of tissue regeneration. Nanorobots based on nanotechnology can eliminate dangerous compounds from the bloodstream, treat viral and bacterial infections, kill cancer cells, and monitor and diagnose a variety of illnesses.

Therefore, by creating materials that are compatible with biological structures, biomaterials research, a subfield of bioengineering, seeks to enhance our quality of life. Future studies should concentrate on creating biomaterials that allow for the remodeling of natural tissues and make use of or improve the body's ability to self-renew.

Author Contributions

The authors confirm responsibility for the conception, drafting, critical revision, and final approval of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the article.

Abbreviations

Titanium Alloys (Ti-6Al-4V), Hydroxyapatite (HAp), Aluminum Oxide (Al_2O_3), Polylactic Acid/ Polylactide (PLA), Polyglycolic Acid/Polyglycolide (PGA), Extracellular Matrix (ECM), Pegylated (PEG), Nanoparticle Albumin-Bound Technology (Nab Technology).



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