http://www.jourmag.org/index.php/jma

Journal of Magnetism and Its Applications

Received December 25th 2025 received in revised December 28th 2025 accepted December 30th 2025

Research articles

Magnetic Materials in Biomedical Engineering: From Drug Delivery to MRI Contrast Agents

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Article info
Keywords:
magnetic materials,
magnetic nanoparticles,
targeted drug delivery,
MRI contrast agents,
biomedical engineering,
nanomedicine,
magnetic hyperthermia,
medical imaging

Abstract
Magnetic materials have emerged as a transformative component in biomedical engineering due to their unique magnetic responsiveness, nanoscale properties, and biocompatibility. These materials are widely applied in medical diagnostics, targeted drug delivery systems, and imaging technologies. Magnetic nanoparticles, particularly iron oxide-based nanomaterials, allow precise control of therapeutic agents using external magnetic fields, enabling site-specific drug delivery while minimizing systemic toxicity. Furthermore, magnetic materials have significantly enhanced the performance of magnetic resonance imaging (MRI) by serving as effective contrast agents that improve image clarity and diagnostic accuracy. Recent advances in nanotechnology have also enabled the development of multifunctional magnetic nanostructures capable of combining imaging, therapy, and monitoring within a single platform. This article explores the fundamental properties of magnetic materials, their synthesis techniques, biomedical applications in drug delivery and MRI imaging, and emerging research directions. The integration of magnetic materials with nanotechnology, biotechnology, and medical imaging systems is expected to revolutionize future healthcare solutions and personalized medicine.

Introduction

Biomedical engineering has increasingly benefited from advances in materials science, particularly through the development of magnetic materials with nanoscale dimensions. Magnetic nanoparticles possess unique physical and chemical properties such as superparamagnetism, high surface area, and tunable magnetic responses that make them suitable for medical applications. These materials can be manipulated using external magnetic fields, allowing researchers to control their movement and interaction within biological systems. One of the most significant advantages of magnetic materials in medicine is their ability to enable targeted therapy. Conventional treatments such as chemotherapy often affect healthy tissues along with diseased cells, leading to severe side effects. Magnetic nanoparticles can transport drugs directly to diseased areas, significantly improving therapeutic efficiency while reducing toxicity. In addition to drug delivery, magnetic materials have become essential components in diagnostic imaging. Magnetic resonance imaging (MRI) is one of the most widely used medical imaging techniques, and magnetic nanoparticles serve as contrast agents that enhance the visibility of tissues and abnormalities. The integration of magnetic materials into biomedical technologies has therefore created opportunities for more precise diagnostics and personalized treatment strategies.

Properties of Magnetic Materials for Biomedical Applications

Magnetic materials used in biomedical engineering are primarily based on iron oxide nanoparticles, particularly magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3). These materials are widely studied because of their excellent magnetic behavior, chemical stability, and relatively low toxicity compared with many other metallic nanoparticles. At the nanoscale, these particles typically exhibit superparamagnetism, a magnetic state in which the nanoparticles become strongly magnetized when exposed to an external magnetic field but lose their magnetization once the field is removed. This characteristic is particularly important in biomedical systems because it prevents permanent magnetic aggregation that could otherwise lead to particle clustering in blood vessels or tissues. As a result, superparamagnetic nanoparticles remain dispersed in biological fluids and can circulate safely within the body. Another critical property of magnetic nanoparticles is their large surface-to-volume ratio, which enables efficient surface modification and functionalization. Researchers can attach a wide range of biological molecules to the nanoparticle surface, including antibodies, peptides, DNA strands, and pharmaceutical drugs. These surface modifications enhance the interaction between nanoparticles and biological targets, allowing the development of highly specific therapeutic and diagnostic systems. For example, functionalization with tumor-targeting ligands allows nanoparticles to selectively bind to cancer cells, thereby improving drug delivery precision and minimizing damage to healthy tissues. Surface engineering also plays an important role in improving the biocompatibility and stability of magnetic nanoparticles. Bare iron oxide nanoparticles can be prone to oxidation or rapid recognition by the immune system. To address this issue, nanoparticles are often coated with protective layers such as polyethylene glycol (PEG), dextran, chitosan, silica, or phospholipid polymers. These coatings enhance particle stability in physiological environments, extend circulation time in the bloodstream, and reduce the likelihood of immune system clearance. Furthermore, polymer coatings can be designed to respond to environmental triggers such as pH or temperature, enabling controlled drug release in targeted regions of the body. Magnetic nanoparticles also possess unique magnetothermal and electromagnetic properties that make them suitable for advanced therapeutic applications. When exposed to alternating magnetic fields, certain nanoparticles can convert magnetic energy into heat through processes such as Néel and Brownian relaxation. This heat generation capability forms the basis of magnetic hyperthermia, a treatment method that selectively raises the temperature of tumor tissues to damage or destroy cancer cells. Because the heat can be generated locally within tumors, surrounding healthy tissues remain largely unaffected. Another important advantage of magnetic nanoparticles is their ability to be remotely controlled using external magnetic fields. This property allows physicians to guide nanoparticles toward specific locations in the body, enabling noninvasive manipulation of therapeutic agents. Such control mechanisms are highly valuable in minimally invasive medicine and personalized therapy. In addition, magnetic nanoparticles can simultaneously serve as diagnostic probes and therapeutic carriers, creating multifunctional systems often referred to as theranostic platforms. Advances in nanotechnology have also enabled the development of core–shell magnetic nanostructures, where a magnetic core is combined with additional materials such as gold, silica, or polymers. These hybrid structures can incorporate imaging capabilities, targeted therapy, and biosensing

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DOI: 10.53533/JMA.v2i1.27

functions within a single nanoparticle system. For instance, magnetic-gold nanoparticles can be used for both magnetic resonance imaging and photothermal therapy, demonstrating the potential of magnetic materials to support integrated biomedical technologies.

Magnetic Nanoparticles in Targeted Drug Delivery

Targeted drug delivery has become one of the most significant areas of research in nanomedicine, and magnetic nanoparticles play a key role in advancing this field. Conventional drug delivery methods often distribute therapeutic compounds throughout the entire body, which can lead to severe side effects and reduced treatment efficiency. Magnetic nanoparticle-based systems offer a solution by allowing drugs to be delivered directly to diseased tissues with high precision. In these systems, therapeutic molecules are attached to or encapsulated within magnetic nanoparticles, which are then guided to specific locations using externally applied magnetic fields. The use of magnetic guidance enables researchers to control the spatial distribution of drugs within the body. For example, a magnetic field generated by an external magnet can concentrate drug-loaded nanoparticles at tumor sites, significantly increasing the local drug concentration while reducing systemic exposure. This approach improves the therapeutic effectiveness of anticancer drugs and minimizes damage to healthy organs. In addition, magnetic targeting can be particularly useful in treating tumors located in difficult-to-reach areas where conventional drug delivery methods may be less effective. Controlled drug release is another major advantage of magnetic nanoparticle systems. After nanoparticles accumulate in the target tissue, drugs can be released through various stimuli-responsive mechanisms. These mechanisms may involve pH-sensitive coatings that dissolve in the acidic microenvironment of tumors, temperature-responsive polymers that release drugs when heated, or enzymatic triggers that activate drug release in specific biological environments. Such controlled release strategies ensure that therapeutic agents are delivered precisely when and where they are needed. Researchers have also developed ligand-targeted magnetic nanoparticles that recognize specific cellular receptors. Many cancer cells express unique surface markers that distinguish them from normal cells. By attaching antibodies, peptides, or small molecules that bind to these receptors, nanoparticles can selectively attach to cancer cells and deliver drugs directly to them. This receptor-mediated targeting significantly improves drug uptake by diseased cells while reducing toxicity to surrounding tissues. Magnetic nanoparticle drug delivery systems are currently being explored for a wide range of medical conditions. In cancer therapy, they are used to transport chemotherapeutic drugs, gene therapy vectors, and immunotherapeutic agents directly to tumors. In cardiovascular medicine, magnetic nanoparticles are being investigated for targeted delivery of drugs to treat atherosclerosis and vascular inflammation. In neurological disorders, researchers are studying magnetic nanoparticle systems capable of crossing the blood–brain barrier to deliver therapeutic molecules for diseases such as Parkinson's and Alzheimer's. Recent developments in multifunctional nanomedicine have further expanded the capabilities of magnetic drug delivery systems. Modern nanoparticles can integrate drug delivery, imaging, and therapeutic functions within a single platform. For instance, magnetic nanoparticles used for drug delivery can also serve as contrast agents in MRI scans, allowing physicians to track the distribution of therapeutic particles in real time. This integration of diagnosis and therapy provides a powerful tool for personalized medicine and precision healthcare. Despite these promising developments, several challenges remain before magnetic drug delivery systems can be widely used in clinical practice. These challenges include optimizing particle size for efficient circulation, preventing rapid clearance by the immune system, ensuring long-term safety, and achieving scalable manufacturing methods. Continued research in nanotechnology, materials science, and biomedical engineering is expected to overcome these limitations and pave the way for advanced magnetic nanoparticle therapies in the near future.

Magnetic Materials as MRI Contrast Agents

Magnetic resonance imaging (MRI) is one of the most advanced noninvasive diagnostic imaging techniques used in modern medicine. It relies on powerful magnetic fields and radiofrequency pulses to generate high-resolution images of internal organs, soft tissues, and physiological structures. The quality and clarity of MRI images can be significantly improved through the use of contrast agents that modify the relaxation behavior of hydrogen protons in surrounding water molecules. Magnetic nanoparticles have emerged as highly effective MRI contrast agents because of their strong magnetic properties and nanoscale dimensions, which allow them to interact efficiently with biological environments. Among the most widely used materials for MRI contrast agents are superparamagnetic iron oxide nanoparticles (SPIONs). These nanoparticles alter the transverse relaxation time (T2) of nearby protons, leading to a decrease in signal intensity in MRI images. As a result, tissues containing these nanoparticles appear darker on MRI scans, which improves the visibility of abnormalities such as tumors, inflammatory regions, and vascular disorders. Because of their high magnetic susceptibility, iron oxide nanoparticles produce strong contrast effects even at relatively low concentrations. The nanoscale size of these particles provides several advantages in biomedical imaging. Their small dimensions allow them to circulate through the bloodstream and penetrate biological tissues, enabling imaging of internal structures that might otherwise be difficult to observe. Additionally, nanoparticles can be engineered with surface coatings that enable them to accumulate selectively in certain organs or disease sites. For example, magnetic nanoparticles coated with targeting ligands can bind to tumor cells, allowing MRI to visualize cancerous tissues with higher specificity. Another important aspect of magnetic nanoparticle contrast agents is surface functionalization, which enhances their stability and biocompatibility in biological systems. Coating materials such as dextran, polyethylene glycol (PEG), silica, and phospholipids are commonly used to prevent nanoparticle aggregation and improve circulation time in the bloodstream. These coatings also reduce recognition by the immune system, allowing nanoparticles to remain active in the body long enough to perform their imaging functions. Recent advances in nanotechnology have led to the development of multimodal imaging nanoparticles, which combine magnetic materials with other imaging components such as fluorescent dyes, quantum dots, or radioactive isotopes. These hybrid nanoparticles allow simultaneous imaging using multiple diagnostic techniques, including MRI, fluorescence imaging, and positron emission tomography (PET). Such integrated imaging systems provide complementary information about tissue structure, metabolic activity, and molecular interactions, significantly improving diagnostic accuracy. Furthermore, researchers are exploring smart MRI contrast agents that respond to biological stimuli such as pH, enzyme activity, or temperature changes. These responsive nanoparticles can enhance contrast selectively in diseased tissues, providing more precise diagnostic information. For example, pH-sensitive magnetic nanoparticles can become more active in the acidic microenvironment of tumors, improving tumor detection during imaging procedures. Despite these promising developments, challenges remain in optimizing MRI contrast agents for clinical use. Issues related to long-term biocompatibility, toxicity, and nanoparticle clearance must be carefully addressed. Continued research in nanomedicine and materials engineering aims to develop safer, more efficient magnetic contrast agents that can support early disease detection and personalized medical diagnostics.

Magnetic Hyperthermia and Cancer Therapy

Magnetic hyperthermia has emerged as a promising therapeutic technique that utilizes magnetic nanoparticles to selectively generate heat within tumor tissues. This method takes advantage of the ability of certain magnetic nanoparticles to convert electromagnetic energy into thermal energy when exposed to an alternating magnetic field. The heat generated by these nanoparticles can raise the temperature of tumor tissues to levels that damage or destroy cancer cells while minimizing harm to surrounding healthy tissues. The heating mechanism in magnetic hyperthermia is primarily governed by two physical processes known as Néel relaxation and Brownian relaxation. These mechanisms describe how magnetic moments within nanoparticles respond to alternating magnetic fields, resulting in energy dissipation in the form of heat. The efficiency of heat generation depends on several factors, including nanoparticle size, magnetic anisotropy, field frequency, and particle concentration within the tumor tissue. Typically, temperatures between 42°C and 45°C are sufficient to induce cellular stress in cancer cells. At these temperatures, tumor cells experience protein denaturation, disruption of cellular membranes, and damage to DNA structures. Because cancer cells are generally more sensitive to heat than healthy cells, magnetic hyperthermia can selectively target tumors without causing significant damage to surrounding tissues. Magnetic hyperthermia can also be combined with other treatment methods to improve therapeutic outcomes. For example, combining hyperthermia with chemotherapy can enhance the uptake of anticancer drugs by tumor cells, making treatments more effective. Similarly, the application of hyperthermia alongside radiotherapy can increase tumor sensitivity to radiation, leading to improved cancer cell destruction. Another advantage of magnetic hyperthermia is its potential for localized treatment. By injecting magnetic nanoparticles directly into tumor tissues or guiding them using external magnetic fields, clinicians can concentrate heating effects precisely where they are needed. This targeted approach reduces systemic side effects and allows for minimally

invasive cancer therapy. Recent clinical studies have shown encouraging results in the use of magnetic hyperthermia for treating certain types of cancers, including brain tumors and prostate cancer. For instance, iron oxide nanoparticles have been used in clinical trials to treat glioblastoma, one of the most aggressive forms of brain cancer. Early findings suggest that magnetic hyperthermia can significantly enhance survival rates when used in combination with conventional therapies. Nevertheless, further research is needed to optimize nanoparticle design, heating efficiency, and treatment protocols. Scientists are currently investigating new materials with improved magnetic properties and developing nanoparticle delivery systems that can achieve better tumor targeting and heat distribution.

Future Trends and Challenges in Biomedical Magnetic Materials

The rapid development of nanotechnology has significantly expanded the potential applications of magnetic materials in biomedical engineering. Magnetic nanoparticles are increasingly being integrated into advanced medical technologies that combine diagnosis, treatment, and monitoring within a single platform. These multifunctional systems, often referred to as theranostic nanoplatforms, represent a major step toward personalized and precision medicine. One of the key research directions involves the development of multifunctional magnetic nanoparticles that can simultaneously perform imaging, drug delivery, and therapeutic functions. For example, nanoparticles designed with magnetic cores and biocompatible shells can carry therapeutic drugs while also serving as contrast agents in MRI scans. This integration allows clinicians to monitor drug delivery in real time and evaluate treatment effectiveness using imaging technologies. Artificial intelligence and machine learning are also expected to play an important role in the future of magnetic biomedical technologies. AI-based image analysis systems can improve the interpretation of MRI data obtained using magnetic nanoparticles, enabling earlier detection of diseases and more accurate diagnosis. In addition, computational models can assist researchers in designing nanoparticles with optimized magnetic and biological properties. Despite these promising advancements, several challenges remain before magnetic materials can be widely implemented in clinical practice. One major concern is ensuring the long-term safety and biocompatibility of nanoparticles within the human body. Although many iron oxide nanoparticles are considered relatively safe, understanding their long-term accumulation, metabolism, and elimination is essential for regulatory approval and clinical use. Another challenge involves achieving precise control over nanoparticle synthesis. The size, shape, crystal structure, and surface chemistry of nanoparticles strongly influence their magnetic properties and biological interactions. Variations in these parameters can affect circulation time, targeting efficiency, and therapeutic performance. Therefore, developing reproducible and scalable synthesis techniques remains a key research priority. In addition, large-scale manufacturing and regulatory approval processes present practical challenges for the commercialization of magnetic biomedical technologies. Producing nanoparticles with consistent quality and ensuring compliance with medical safety standards require advanced manufacturing techniques and rigorous testing procedures. Looking ahead, continued progress in nanomaterials science, biomedical engineering, and medical imaging technologies is expected to accelerate the development of next-generation magnetic biomedical devices. These innovations have the potential to revolutionize healthcare by enabling earlier disease detection, more effective therapies, and personalized treatment strategies tailored to individual patients.

Summary

Magnetic materials have become an essential component of modern biomedical engineering, offering innovative solutions for both diagnosis and therapy. Magnetic nanoparticles enable targeted drug delivery, reducing side effects and improving treatment precision. They also play a critical role in medical imaging technologies such as MRI, where they function as contrast agents that enhance diagnostic accuracy. Furthermore, emerging techniques such as magnetic hyperthermia demonstrate the therapeutic potential of magnetic materials in cancer treatment. Advances in nanotechnology and materials engineering are enabling the development of multifunctional systems that integrate imaging, drug delivery, and therapy. Although challenges related to biocompatibility, toxicity, and large-scale production remain, ongoing research continues to address these issues. The future of biomedical engineering is expected to be strongly influenced by magnetic nanomaterials, leading to more personalized, efficient, and minimally invasive healthcare technologies.

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