Magnetic-Nanosensor-Based Diagnostic Chips: An Overview

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Abstract Magnetic nanosensors are showing great potential in detecting and treating numerous illnesses. They represent an effective way to administer drugs and transport contrast agents, making them ideal for use within the body. Furthermore, magnetic nanosensors can also be an external method for removing particular compounds from the bloodstream. This article examines the most recent developments in the field of magnetic nanosensors. It covers how they are created, how they have been made more compatible with biological systems, their clinical uses, and any associated risks. This chapter highlights the current advances in biosensors in nanotechnology, with particular emphasis on magnetic-nanosensor-based diagnostic chip synthesis, factors affecting this process, interaction with biomaterials, and the prospects of magnetic-nanosensor-based diagnostic chips. Nanomaterials' possible dangers and impacts in medical treatments involving magnetic nanosensors are also discussed.

Keywords Biosensors · Magnetic-nanosensors · Diagnostic chips · Biosynthesis

1 Introduction

Biosensors are increasingly used for disease diagnosis because they convert biochemical information into detectable signals [28]. Biosensors usually consist of biological recognition and physicochemical transduction parts, as described in the same article. The biological recognition part of a biosensor can be antibodies, aptamers, or other biomolecules that recognize and interact with target analytes. In contrast, the transduction part converts the recognition event into a measurable signal. The use of diverse biosensors for pathogen detection is gaining popularity due to their ease of use, rapid response time, and cost-effectiveness. As noted in a review by Cui

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et al., integrating nanomaterials into biosensors has shown promise in improving their analytical performance, including sensitivity, selectivity, and analysis speed, thus expanding their potential applications [6].

Additionally, biosensors are becoming increasingly popular as powerful diagnostic tools for various diseases [26]. Analytical devices can convert biochemical information into detectable signals such as optical, electrical, electrochemical, magnetic, or thermal signals. A biosensor typically consists of two parts: the biological recognition part and the physicochemical transduction part. The biological recognition part, such as antibodies and aptamers, recognizes and interacts with the target analytes, while the transduction part converts the recognition event into a measurable physicochemical signal [13].

The use of diverse biosensors for the detection of pathogens is gaining popularity due to their simple operation, fast response, and cost-effectiveness. The utilization of nanomaterials has also shown potential in improving the analytical performance of biosensors in terms of sensitivity, selectivity, and analysis speed, thus expanding the applications of biosensors.

Recent advancements in nanotechnology have paved the way for developing biosensors at the nanoscale level using various nanomaterials. These biosensors have direct interaction and contact with the biomolecules or analytes for which they are intended to be used. As a result, they possess stand-alone properties such as customized magnetic, electrical, and optical properties, enhanced electrical conductivity, high sensitivity, and a low response time compared to traditional biosensors. Therefore, biosensors have gained importance in different bioengineering applications, including drug delivery [22, 40].

For instance [22], developed a three-dimensional porous nickel framework anchored with cross-linked $Ni(OH)_2$ nanosheets, which showed high sensitivity as a nonenzymatic glucose sensor. Similarly [40], developed a nonenzymatic wearable sensor for electrochemical analysis of perspiration glucose using nanomaterials.

Biosensors are emerging as powerful diagnostic tools for various diseases. These analytical devices can convert biochemical information into detectable signals, including optical, electrical, electrochemical, magnetic, or thermal signals [4, 12]. A typical biosensor consists of two parts: the biological recognition part and the physicochemical transduction part. The biological recognition part, such as antibodies and aptamers, interacts with the target analytes, while the transduction part converts the recognition event into a measurable physicochemical signal [2, 23, 25].

Diverse biosensors are being adopted to detect pathogens due to their simple operation, fast response, and cost-effectiveness [19, 33]. The utilization of nanomaterials has also shown the potential to improve the analytical performance of biosensors in terms of sensitivity, selectivity, and analysis speed, thus expanding the applications of biosensors [23, 34].

Magnetic nanoparticles have become an increasingly important class of materials in recent years due to their unique magnetic properties and potential applications in various fields. These nanoparticles typically have dimensions of 1–100 nm and can be synthesized using different physical, chemical, and biological methods.

Physical synthesis methods involve using physical forces such as heat, pressure, or magnetic fields to create the nanoparticles. For example, thermal decomposition, solvothermal synthesis, and high-energy ball milling are all physical methods that can be used to develop magnetic nanoparticles.

Chemical synthesis methods involve the use of chemical reactions to produce nanoparticles. These methods often involve the reduction of metal salts or oxides in the presence of surfactants or other stabilizing agents. Examples of chemical synthesis methods include co-precipitation, thermal decomposition, and hydrothermal synthesis.

Biological synthesis methods involve using living organisms or their products to produce nanoparticles. These methods can be more environmentally friendly and sustainable than traditional chemical methods. Biological synthesis methods can include using bacteria, fungi, plants, or even human cells to produce magnetic nanoparticles, as seen in Fig. 1a. Magnetic nanosensors are an emerging sensing device class that utilizes magnetic nanoparticles to detect and quantify specific analytes with high sensitivity and selectivity. The principles of magnetic nanosensors rely on the unique magnetic properties of nanoparticles and their ability to be functionalized with specific ligands or functional groups.

The synthesis of magnetic nanoparticles involves carefully selecting precursor materials, followed by a series of physical, chemical, or biological steps to create nanoparticles with desired properties such as size, shape, and magnetic behavior. The surface of these nanoparticles can then be coated with a layer of organic or inorganic material to improve their stability and biocompatibility.

In addition to coating, magnetic nanoparticles can be functionalized with linking groups or spacer molecules that facilitate the attachment of specific agents such as

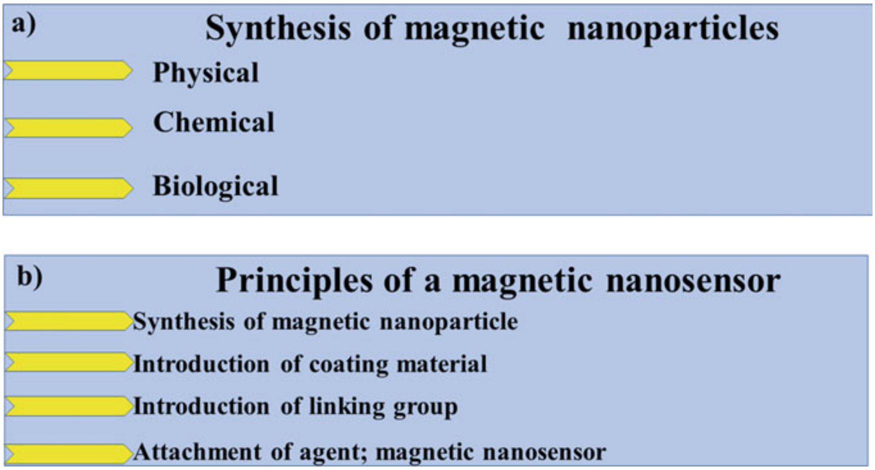

Fig. 1 **a** Types of synthesis of magnetic nanoparticles. **b** The main principles of magnetic nanosensors

ligands or biomolecules. These agents can then bind to specific target analytes in the sample, leading to changes in the magnetic properties of the nanoparticles that can be detected and quantified.

The attachment of these agents to the surface of magnetic nanoparticles forms the basis of magnetic nanosensors. The specificity and sensitivity of these sensors can be improved by carefully selecting the linking group and agent used and optimizing the conditions for the binding reaction.

In all cases, synthesizing magnetic nanoparticles requires careful control of the reaction conditions to achieve the desired particle size, shape, and magnetic properties. Once synthesized, these nanoparticles have many potential applications, including drug delivery, magnetic resonance imaging (MRI), environmental remediation, and data storage. Therefore, the synthesis of magnetic nanoparticles using physical, chemical, and biological methods is an active area of research with significant potential for future development.

Overall, magnetic nanosensors offer a promising avenue for detecting and quantifying a wide range of analytes, with potential applications in fields such as medical diagnostics, environmental monitoring, and food safety. The combination of the unique magnetic properties of nanoparticles and the ability to functionalize them with specific agents provides a powerful tool for developing susceptible and selective sensing devices.

2 Type of Magnetic-Nanosensor-Based Diagnostic Chips

Magnetic-nanosensor-based diagnostic chips have gained significant attention in recent years as a promising technology for the early and accurate detection of various diseases [21, 36]. Integrating magnetic sensors with microfluidic systems has enabled the development of compassionate and specific diagnostic tools to detect biomarkers at low concentrations in biological fluids [24].

Magnetic nanoparticles are used in magnetic nanosensors to specifically bind to biomolecules of interest, which magnetic sensors can then detect [35]. This approach offers several advantages over traditional diagnostic methods, including faster analysis time, reduced sample volume, and increased sensitivity [27].

An antibody or an aptamer can be added to magnetic nanosensors to detect disease markers or biomarkers in bodily fluids. When these nanoparticles bind to the targeted molecules, they generate a detectable signal that can be measured by magnetic sensors [15, 39].

This technology has been applied in diagnosing various diseases, such as cancer, infectious diseases, and cardiovascular diseases.

Magnetic nanosensors eliminate the need for large volumes of bodily fluids and provide faster and more accurate results compared to traditional diagnostic techniques.

As the technology develops, magnetic nanosensors are expected to become even more versatile and widely used in clinical applications, providing clinicians with a powerful tool for early disease detection and personalized medicine.

Magnetic-nanosensor-based diagnostic chips have gained significant attention in recent years for their potential to revolutionize the field of medical diagnostics. These chips integrate magnetic sensors with microfluidic systems to develop highly sensitive and specific diagnostic tools that detect biomarkers at low concentrations in biological fluids [32, 39]. The detection of disease markers or biomarkers in bodily fluids is possible by using magnetic nanoparticles that are functionalized with specific biomolecules, such as antibodies or aptamers [8, 9, 21].

Compared to traditional diagnostic methods, magnetic-nanosensor-based diagnostic chips offer several advantages, including faster analysis time, reduced sample volume, and increased sensitivity [15, 37]. They have been used to diagnose various diseases such as cancer, infectious diseases, and cardiovascular diseases. For instance, in a recent study, magnetic nanosensors were used for the early detection of colorectal cancer, achieving a high sensitivity and specificity [3, 10, 16].

As the technology develops, magnetic nanosensors are expected to become even more versatile and widely used in clinical applications. Magnetic-nanosensor-based diagnostic chips have the potential to provide clinicians with a powerful tool for early disease detection and personalized medicine. Further research and development could enable earlier diagnosis, better disease monitoring, and improved patient outcomes.

Using magnetic nanosensors as diagnostic chips, it is possible to detect biomolecules in complex biological samples faster and more accurately than ever before.

Magnetic nanoparticles are often chosen as the primary magnetic nanosensors for diagnostic chips due to their biocompatibility and ability to selectively bind to target biomolecules. MNPs can also be used for in vivo imaging due to their small size and ability to pass through cell membranes [1, 16].

Magnetic nanowires have shown promise as highly sensitive and specific nanosensors due to their high aspect ratio, which results in a high magnetic moment and sensitivity [6, 31]. MNWs can be integrated into microfluidic channels for rapid and sensitive detection of target biomolecules in biological samples.

Magnetic quantum dots have unique magnetic and optical properties that make them useful for biosensing applications [16, 17]. For sensitive and selective detection of target biomolecules in biological samples, they can be functionalized with biomolecules and integrated into microfluidic channels.

Magnetic microbeads have been widely used in diagnostic chips due to their ease of functionalization and ability to be manipulated by magnetic fields [11]. MMBs can be separated from biological samples using a magnet, making them suitable for point-of-care testing.

In conclusion, magnetic-nanosensor-based diagnostic chips are promising for early and accurate disease detection. They offer several advantages over traditional diagnostic methods and have been utilized to diagnose various diseases with high sensitivity and specificity. As the technology continues to develop, magnetic nanosensors are expected to become even more versatile and widely used in clinical applications, revolutionizing the field of medical diagnostics.

3 Characterisation Techniques

Characterization techniques are essential for evaluating the performance and sensitivity of magnetic-nanosensor-based diagnostic chips. Various methods have been used to characterize the magnetic nanoparticles and the sensors, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), vibrating sample magnetometry (VSM), and magnetic force microscopy (MFM) [5].

SEM and TEM techniques have been used to investigate the size and shape of the magnetic nanoparticles and their distribution within the microfluidic channels. XRD is used to determine the crystal structure and phase of the magnetic nanoparticles. VSM is used to measure the magnetic properties of the nanoparticles, including magnetic moment, coercivity, and remanence [16]. MFM is used to image the magnetic fields of the nanoparticles and their distribution within the microfluidic channels.

Moreover, the electrical and magnetic properties of the magnetic sensors can be evaluated using impedance spectroscopy, AC susceptometry, and Hall effect measurements [29]. These techniques are used to investigate the sensitivity and signal-to-noise ratio of the magnetic sensors.

In summary, characterization techniques are essential for evaluating and optimizing magnetic-nanosensor-based diagnostic chips. These techniques allow researchers to investigate the physical, electrical, and magnetic properties of the magnetic nanoparticles and sensors, leading to the development of more sensitive and specific diagnostic tools.

4 Physical and Chemical Characteristics of Magnetic-Nanosensor-Based Diagnostic Chips

Magnetic nanosensors possess unique physical and chemical properties, making them a promising diagnostic chip platform. Some of the key characteristics of magnetic nanosensors used as diagnostic chips are discussed below:

Magnetic Properties: The strong magnetic properties of magnetic nanosensors make them detectable in low concentrations using magnetic sensors. Nanosensors' magnetic properties depend on their size, shape, and composition. Iron oxide (Fe3O4) and nickel (Ni) are the most commonly used magnetic materials in magnetic nanosensors due to their high magnetic moments and good biocompatibility [35].

Surface Functionalization: The surface of magnetic nanosensors can be functionalized with various molecules to enable their specific binding to biomolecules such as proteins, antibodies, or nucleic acids. The functionalization can be achieved through various chemical reactions such as covalent bonding, electrostatic interaction, or physical adsorption. The surface functionalization is critical for the specificity and sensitivity of the nanosensors in detecting target molecules [4, 7].

Biocompatibility: Magnetic nanosensors used in diagnostic chips must be biocompatible to prevent harmful effects on cells or tissues. Iron oxide-based nanosensors have been shown to exhibit good biocompatibility, low toxicity, and minimal inflammatory response in vivo [35].

Detection Sensitivity: Magnetic nanosensors can detect target molecules in low concentrations, typically in the picomolar range. This high sensitivity is due to the amplification effect of the magnetic signal generated by the nanosensors [11].

In conclusion, magnetic nanosensors have unique physical and chemical properties, making them a promising diagnostic chip platform. Their strong magnetic properties, surface functionalization, biocompatibility, and high detection sensitivity make them a powerful tools for early disease detection and personalized medicine.

5 Application and Impact of Magnetic-Nanosensor-Based Diagnostic Chips

Magnetic nanosensors used as diagnostic chips significantly impact various fields, including medical diagnostics, drug discovery, environmental monitoring, and point-of-care testing.

Disease diagnosis: Magnetic nanosensors have been utilized to diagnose various diseases, including cancer, cardiovascular diseases, and infectious diseases, as mentioned earlier [37, 38]. A study demonstrated the use of magnetic nanosensors for the early detection of pancreatic cancer by detecting a specific biomarker in the blood [19].

Drug discovery: Magnetic nanosensors have been used for drug discovery by screening compounds for their ability to bind to a target molecule. A study demonstrated the use of magnetic nanosensors to identify novel inhibitors of the protein tyrosine phosphatase 1B, a target for treating diabetes and obesity [5, 6].

Environmental monitoring: Magnetic nanosensors have potential applications in environmental monitoring by detecting pollutants and contaminants in water and soil. A study demonstrated the use of magnetic nanosensors for detecting arsenic in water samples with high sensitivity and specificity [18].

Point-of-care testing: Magnetic nanosensors have shown great promise in point-of-care testing by enabling rapid and sensitive detection of biomarkers at the point of care. A study demonstrated magnetic nanosensors in a handheld device for detecting HIV RNA in plasma samples with high sensitivity and specificity [26, 40].

6 Conclusion

Magnetic nanosensors are highly sensitive and precise tools for disease diagnosis. Using magnetic nanoparticles and surface functionalization agents can specifically target biomolecules for detection. The detection of changes in the magnetic field generated by magnetic nanoparticles can be carried out using a magnetometer or MRI. With further advancements in technology, magnetic nanosensors have great potential for widespread use in diagnosing and treating diseases.

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