Biosensors and Nanotechnology: Tools for Advanced Diagnostics

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Abstract

Incorporating nanotechnology into biosensors has resulted in more accurate diagnostics, faster test outcomes and lower costs. Many research studies showed that the presence of gold nanoparticles, carbon nanotubes and quantum dots in biosensors increased both how sensitive they were and how small the amounts they could detect. Using nanoparticles in their sensors allowed researchers to find both viral and bacterial pathogens in the body before most other methods could detect them. Using graphene and polymer-based nanomaterials, sensors could measure glucose, lactate and electrolytes in the body continuously and accurately. With the use of nanostructured biosensors, early detection and improved judgment of prognosis became possible for PSA, CEA and HER2, whose amounts were measured in such small units. With multiplexed nanosensors, researchers could detect different analytes from one sample which cut down the testing time and improved how many results could be processed in the same run. Implanted biosensors produced from biodegradable nanostructures remained secure and did not show any significant change in response from the nearby tissues for a prolonged time. While these improvements were achieved, differences in performance resulting from the environment and the short lifespan of a few nano-sensors were observed. However, the results prove that nanotechnology-based biosensors can offer fast, sensitive and accurate diagnostics for different purposes.

Keywords: Nanobiosensors, Medical Diagnostics, Wearable Sensors, Personalized Medicine

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Introduction

The quick development of healthcare and diagnostics has led to a strong need for technology that is accurate, efficient, lightweight, movable and usable in different situations. Because people are now living longer, the healthcare sector must meet the demands for efficient detection, continuous monitoring and personal treatment measures. As more chronic diseases, outbreaks and health risks appear, it is more important than ever to use new diagnostic techniques that provide accurate and helpful findings. Using the standard approaches may be effective, but they generally do not work well with the many demands we face today. Integrating biosensors and nanotechnology is now considered a groundbreaking solution for dealing with the challenges mentioned above (Nakhjavani et al., 2024).

New medical technology has revolutionized the way diseases are spotted and looked after. Biosensors and nanotechnology are now important tools in advanced diagnostics. A biosensor detects biological signals by converting them into quantities, giving more precise and sensitive output when looking for different biomarkers (Kaya et al., 2022). Nanotechnology helps achieve improvements in biosensors by allowing for superior sensitivity, a smaller size and continual detection. A biosensor includes a bioreceptor that recognizes certain molecules, along with a transducer that changes these interactions into signals in optical or electrochemical form. Since the first introduction of biosensors in 1962 to detect oxygen with enzymes, they have been developed into their modern sophisticated forms. As a result of their high sensitivity, selectivity, affordable cost and easy miniature design, they are often used today for drug analysis as well as for detecting heavy metals and environmental pollutants (Malik et al., 2023).

Basically, biosensors detect substances by the combined action of a bioreceptor and analyte which is then converted by a transducer using electrochemical, optical, magnetic or electrical methods. Such biosensors are grouped by their recognition components as immunosensors, apt sensors and Geno sensors, while other groups define biosensors by function as affinity, chemical and catalytic types (Nakhjavani et al., 2024). Moreover, scientists are investigating new ways like wearable biosensors which promise to make it possible to diagnose testing results instantly on site. Nanotechnology is important for enhancing biosensors because it uses the unique features of nanomaterials, for example their high ratio of surfaces to volume, quick reaction rate and electronically and optically changeable qualities. With these features, it becomes possible to develop modern tools for diagnostics that are easier to carry and more accurate. Nanotechnology linked to biosensors has made possible new systems in healthcare such as wearable, multipurpose and implanted biosensors for use in infection control, cancer monitoring and monitoring food safety (Hammond et al., 2016).

The chapter covers in detail biosensors, applications of nanotechnology in diagnostics and their use in advanced medicine. It demonstrates how examining different principles and real-life uses shows how these technologies are advancing personalized medicine and healthcare, coping with worldwide health problems and driving important changes in diagnostics.

2. The Role of Nanotechnology in Advancing Biosensor Design and Performance

Developments in nanotechnology have enabled the creation of nanodevices that directly interact with the biomolecules or analytes for which the biosensors used. These new biosensors are unique in that they have their own magnetic, electrical and optical qualities, greater conductivity, and more sensitivity and respond much faster than traditional biosensors. As a result, these types of biosensors have roles in drug delivery applications (Mao et al., 2018). There is evidence that nanotechnology has a strong impact on the medical field when it comes to finding diseases by using resonance, electrochemical, magnetic and electromechanical methods (Karikalan et al., 2016).

Biosensors have seen big progress recently due to important developments in transducers, nanotechnology and ways to amplify signals. Even so, biosensors typically experience irregular signal noise. A number of biosensors need to depend on aptamers or antibodies as bioreceptors which shortens their shelf-life and leads to unstable sensing over time. Generally, commercial development of biosensors is limited by how accurate and reliable they are (Chandra et al., 2017). In many possible ways, researchers are devoting great effort to improving the performance of biosensors. There have been a number of studies that examine machine learning (ML) techniques for looking at sensing data. ML makes it possible for biosensors to address current issues by changing standard biosensors into smart ones which can anticipate what type or quantity of analyte they detect using an algorithm (Bhaiyya et al., 2024). Other research teams have centered chemometrics on the analysis of how a biosensor responds. Chemometrics is a popular method for chemical analysis that uses math or statistics to get the most from chemical data and improve the design of experiments (Banerjee et al., 2021; Cui et al., 2020; Deepa et al., 2022).

Fabrication includes nanoparticles and the resulting devices are recognized as nano-biosensors. Nanomaterials are especially important in bioanalytical sciences due to the many bio-imaging, diagnostic, medication and treatment activities they support (Munawar et al., 2019; Tran et al., 2015). Amperometric devices are applied to investigate enzyme reactions, but fluorescent QD devices are preferred for testing the binding ability and use of conjugated nanoparticles in immunolabeling and analyzing interactions between different biomolecules. Nanoparticles are promising for biosensing because they naturally have optical qualities and can be joined to fluorescent markers. By using electro/chemiluminescent, fluorescent and bio-FET tests, nanomaterials like CNTs or rGO, graphene and graphene sheets can be produced. Fluorescent detectors rely on quenching properties of graphene in fluorescent-based assays (Rasheed et al., 2019; Singh et al., 2016) and different measurement methods make carbon nanomaterials adopt several forms (Ramesh et al., 2022).

3. Types of Biosensors

3.1 Electrochemical Biosensors

These sensors measure the amount of an analyte by reacting with it and producing an electrical signal that represents that amount. The structure of a typical electrochemical sensor has a working electrode as the sensing element and a reference electrode in contact with an electrolyte. Most of the time, a three-electrode system is chosen, where the reference connects to a high-impedance potentiate and the counter electrode finishes the circuit for charge flow. Many applications in biosensing use electrochemical tools, including potentiometric (by measuring the open circuit potential changes and biological field-effect transistors), amperometry (by monitoring reduction/oxidation reactions through current measurements) and impedimetric (by detecting changes in system impedance when biolayers are added to the electrode surface). Although other electrochemical techniques can be applied to biosensing, their significance is not as high. A main benefit of electrochemical biosensors comes from their basic design. Electrodes with low cost allow sensors to be built simply and used quickly in small, portable systems. Detecting the amount of an analyte inside a complex sample at the point-of-care in near real-time is highly useful for medicine, handling current diseases and monitoring the environment. In particular, amperometry biosensors are common in helping people with diabetes quickly and accurately test their glucose levels from only a small drop of blood taken by a prick of a finger. The introduction of carbon nanotubes and graphene into electrochemical biosensors is lowering LOD values much further than before which helps drive the development of creative biosensing solutions (Hammond et al., 2016). Table 1 provides an overview of different types of biosensors and their integration with nanoparticles. It categorizes biosensors based on their biorecognition elements, such as antibodies in immunosensors, aptamers in apt sensors, and DNA/RNA in Geno sensors. It highlights the role of nanoparticles in enhancing the performance of these biosensors by improving sensitivity, amplifying signals, and enabling miniaturization. For instance, nanoparticles help in the rapid detection of pathogens and biomarkers, increasing the efficiency of diagnostics. Additionally, other biosensor types like paper-based, microfabricated, and capacitive sensors benefit from nanoparticle incorporation, offering advancements in low-cost, portable, and multiplexed detection systems.

3.2 Optical Biosensors

Optical biosensors make it possible to detect many biological and chemical materials directly, in real time and without using labels which is more advantageous than conventional techniques. Advantages of these methods are their great accuracy, sensitivity, small size and low cost. Various modern methods from engineering and biology including microelectronics, MEMSs, micro/nano-technologies, molecular biology, biotechnology and chemistry are used to develop new optical biosensors. Over the last decade, there has been fast growth in research and development of optical biosensors. Most efforts in optical biosensor research and development have been put into healthcare, environmental fields and biotechnology. Biosensors find many uses in medicine, the environment and biotechnology and each of these fields has specific requirements for the analytes measured, required accuracy, sample concentration, reaction period, recycling time and how to clean the biosensor (Dey & Goswami, 2011).

Table 1: Types of Biosensors and use of Nanoparticles

Biosensor Type	Biorecognition Element	Use of Nanoparticles	Examples/Applications	References
Immunosensors	Antibodies	Nanoparticles enhance binding efficiency, signal amplification, and sensitivity.	Pathogen detection, biomarker identification.	(Chen et al., 2023)
Apt sensors	Aptamers	Nanomaterials improve sensor performance by increasing surface area and reaction sites.	Cancer biomarker detection, nucleic acid analysis.	(Hosseinzadeh & Mazloum-Ardakani, 2020)
Geno sensors	DNA/RNA	Nanoparticles can improve the sensitivity of nucleic acid detection by increasing conductivity or optical properties.	Genetic disease diagnosis, pathogen identification.	(Babaei et al., 2022)
Paper-based Biosensors	Various biological recognition elements	Nanoparticles enable low-cost and portable diagnostic tests with enhanced sensitivity.	Point-of-care diagnostics, rapid tests for infections.	(Nguyen & Kim, 2020)
Microfabricated Biosensors	Varied bioreceptors (enzymes, antibodies)	Nanoparticles facilitate miniaturization, signal amplification, and multi-analyte detection.	Lab-on-a-chip applications, multiplexed detection.	(Blair & Corrigan, 2019)
Capacitive Biosensors	Surface-bound bioreceptors	Nanoparticles improve the sensitivity and increase the capacitance of the sensor.	Real-time monitoring of pathogens and biomarkers.	(Canfarotta et al., 2018)

The optical class of biosensors is the one reported most frequently. By exploiting interactions between the optical field and biorecognition elements, we can detect biological changes. Optical biosensing is generally split into two main ways: label-free and label-based. Without a label, the detector measures the signal that comes up as the focused molecule contacts the transducer. With label-based sensing, labels are attached and then the optical signal forms due to colorimetric, fluorescent or luminescent approaches. Label-free sensing can detect glucose using enzymes during an oxidative reaction. Biosensors have found their biggest success yet in the developing type of device for checking blood glucose, used by diabetics. Yet, in a few cases, for example, when an antibody and antigen interact and one of the bio reactants carries a tag, labeling may affect binding and introduce unwanted mistakes into the analysis (Damborský et al., 2016).

3.3 Magnetic Biosensors

Modern bioanalytical tools and biomedical care depend on particles, from nanometers to micrometers in size, made of magnetic materials. Many diagnostic and therapeutic procedures in healthcare, environmental science and biotechnology use their diverse functions and special magnetic properties. Magnetic detection is distinguished by low background noise relative to the usual problems of signal noise and contamination from the environment seen with optical and electrical detection. As a result, magnetic methods are highly appealing for producing assays that are both highly sensitive and specific (Lee et al., 2015).

Due to their ability to adapt and work easily, different types of magnetic particles are developed as signal markers, separation platforms, force gauges and sensors. Many diagnostic tests use magnetic particles to isolate particular proteins, nucleic acids or cells from complex body fluids. With magnetic separation, testing miniaturized devices such as microfluidics becomes both more accurate and efficient (Chircov et al., 2019). It is also possible to use magnetic particles as labels in bioassays and by measuring them with a magnet, results can be quickly and precisely determined without using bulky optical devices. Apart from diagnosis and labeling, magnetic particles are used for various purposes in imaging and medical therapies. Many doctors use SPIONs as contrast agents in MRI to help see tissues clearly and spot small abnormalities accurately. In addition, particles in a magnetic field heat up which is the basis for magnetic hyperthermia, used to kill specific cancer cells while nearby healthy tissue remains unharmed (Yang et al., 2022). Magnetic particles are also finding their way into new drug delivery systems. After adding targeting molecules and drugs to their surface, they can be driven to chosen parts of the body with the help of external magnets, delivering treatment without a surgical procedure. Magnetic particles are used creatively to study the interactions of biomolecules. Hooking a magnetic tag to a biomolecular combination, like an antibody-antigen or DNA-protein set, enables investigators to see its binding response in different circumstances. Molecular dynamics help researchers create better tools for diagnosis and treatment. Now, these tools can detect biomarkers for diseases like sepsis and influenza in a simple, reliable way at the patient's bedside (Haghayegh et al., 2024). In addition, test kits using magnetic particles are being used for environmental surveillance. They support the discovery and estimation of heavy metals and toxins within water samples, making the process simpler, more convenient and more sensitive (Chen et al., 2017).

3.4 Piezoelectric Biosensors

Piezoelectric materials are found in a wide range of technology and are typically part of many electronic devices. Oscillators on a piezoelectric system, piezoelectric materials respond by motion whenever a surface flows across them and are thus highly suitable for measuring affinity between particles in biosensors (Pan et al., 2024). A great number of anisotropic materials can generate a piezoelectric effect. Both inorganic and organic substances, as well as nucleic acid, exhibit electric charge under mechanical stress. On the other hand, biosensors are built with only a limited number of materials and quartz crystal is the most typically used due to its dependability. In the future, even more changes are expected because of progress in chemical synthesis and nanomaterials development. The best way to take advantage of piezoelectric biosensors is to make direct measurements with the analyte without needing any labels. For this reason, antibodies and antigens promise to work seamlessly with a piezoelectric sensor (Pohanka, 2017).

4. Nanotechnology in Diagnostics

The multidisciplinary technique of nanotechnology works by applying molecules made on a nanoscale. Nanotechnology is considered a pioneering and fast developing field where objects are manufactured, processed and applied using control over features smaller than a nanometer. From the Greek word nano, we get the term nanotechnology which means dwarf technology. Objects called nano-particles are considered single, with dimensions that do not exceed 100 nm (Prasad et al., 2021). Specific characteristics of nano-particles are due to their small size and their chemical and physical features. When materials are altered, the resulting products gain versatility and effectiveness which makes them desirable for both industrial and medical fields. These nanotechnologies and nano-materials are used so widely that their particles end up in the environment (Ahmeda et al., 2017).

Types of Nanomaterials Used in Diagnostics

Over the last few years, the development and testing of nanoparticles has increased and their possible uses for diagnosis and therapy have become very popular. Even though diagnostic nanoparticles are being suggested, only iron oxide nanoparticles have been used in routine clinics at present. This problem arises mainly because it is hard to obtain appropriate pharmacokinetic qualities and to manufacture uniform nanoparticles every time. People are also concerned about their ability to be broken down, eliminated and their toxicity. The greatest number of nanomedicines currently used in the clinic are meant for therapeutic action. Through using these modified nanoparticles, researchers aim to bring the (chemo-) therapy drug directly to the diseased site while protecting healthy organs and tissues, usually by counting on the enhanced permeability and retention (EPR) effect. Additionally, because they can mix various diagnostic and treatment features, nanoparticles show excellent potential for theranostics and are considered highly valuable for designing individualized nanomedicine therapies (Baetke et al., 2015).

Several studies involving quantum dots confirm the usefulness of QDs for finding tumor cells early, imaging multiplexed tissues, labeling cells inside a sample and detecting markers in cells during immune histochemistry. Biologically modified QDs replace commonly used organic fluorescent dyes for single source excitation, a relatively narrow emission band, a higher quantum yield, longer fluorescence time and greater stability when exposed to light. The reason many QDs are unsuitable in biomedicine and the biological field is because they are toxic and do not mix well with biological molecules. To solve these problems, researchers use InP QDs instead of cadmium-based ones and take steps to passivate the surface. The latest developments in QDs give cause to believe cancer cells can be detected at an early stage. They are designed this way because polymers wrap them and antibodies or biomolecules are attached, so they can be used to intentionally treat certain cancer cells. Therefore, because of their high fluorescent strengths and the way their light emission depends on size, quantum dots may be applied in the development of highly sensitive in vivo research and treatment tools (Devi et al., 2022).

4.1 Carbon Nanotubes (CNTs)

Nanotechnology in biomedicine has made considerable progress over the years because of how promising nanomaterials are. The special attributes of carbon nanotubes (CNTs) have made them a useful choice in cancer diagnosis and therapy. They are seen as a promising family of nanomaterials that can both spot cancerous cells and deliver medicines or small therapeutic molecules to them (Saberi et al., 2024). During the past few years, CNTs have been tested in practically every cancer treatment approach, including methods for drug delivery, targeting the lymphatic system for chemotherapy, thermal treatments, photodynamic therapy and gene therapy (Murjani et al., 2022).

4.2 Nanowires

In the last ten years, silicon nanowire (SiNW) biosensors have been investigated as sensitive, label-free and electrical tools for finding biological molecules. Point-of-care (POC) devices for diseases could be realized using SiNW biosensors as these sensors have potential for being small and built into other devices (Namdari et al., 2016). The workflow of a nanobiosensor system begins with various sample sources, such as environmental, food, human, and cell culture samples. These samples are analyzed using different bioreceptors, including cells, bacteria, antibodies, DNA, and enzymes. The interaction between the samples and bioreceptors is detected through an electrical interface, incorporating electrodes, nanotubes, nanoparticles, and field-effect transistors. Signal transduction is performed using various transducer types, such as optical, acoustic, thermal, and electric. Finally, the processed signals are displayed and analyzed using a signal processor, enabling the detection and monitoring of specific biomarkers.

5. Benefits and Drawbacks of Nanotechnology in Diagnostics

Engineered nanomaterials help deliver drugs directly to afflicted areas, decreasing the harmful effects of many medications. Because of their very small size and high surface area, nanoparticles are now often used to deliver drugs. Because nanoparticles are so small, they deliver drugs more accurately within cells and throughout the body and their structure keeps the drug stable as it moves through the body. Essential benefits aside, using nanoparticles for drug delivery comes with many safety issues. Small guests are great, but there are a few issues they can bring. It is significant that new and lasting materials are being used to make the nanoparticles. A few nanoparticle types can induce inflammatory reactions and cause tissue scarring. Being small also means there is a large surface area capable of exposing more of what nano materials offer to cells. A further issue is how the nanoparticles are prepared and stabilized for drug delivery, since reducing agents and radiation can increase the level of toxicity in the cells (Anderson et al., 2016).

Conclusion

Ultimately, combining biosensors and nanotechnology is transforming diagnostics, allowing for quicker, more accurate and more sensitive detection of many diseases. Biosensors can be made smaller, work in real time and target specific biomolecules, so diagnostic devices are becoming wearable, implantable and available on lab chips. The use of nano-technology has made detection simpler for electrochemical, optical and magnetic biosensors. Consequently, the detection limits have improved and more testing methods are possible. Although there is great potential for change, issues such as stability, difficulties in making new substances, regulatory barriers and biocompatibility should be overcome for widespread use in medicine. AI-based changes to sensors and the development of green nanomaterials may help get around these challenges. Rising interdisciplinary work is preparing nano biosensors to make a big difference in personalized medicine and world healthcare.

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