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Advanced Applications of Nanotechnology in Laboratory Diagnostic Methods: A Comprehensive Overview

[1]- Fahad Mesfer Alotaibi,[2]- Ahmad Mohammed Alomai,[3]-Mohammed Shafi Alanazi,[4]-Abdulwahab Saeed Alzahrani,[5]- Ahmed Abdurrazaq Hayjan,[6]-Hamsa Rabia Saad Alquatany,[7]-Sulaiman Ahmed Salem Alhassan,[8]-Basem Mohammed Mousa Safhi ,[9]-Essa Mohamed Ahmed Kinani,[10]- Ahmed Ali Daghriri,[11]-Hussain Dyab Ahmed Hamzi,[12]- Abdu Hadi Hamoud Gharwi,[13]- Aishah Ali Ali Sharahili,[14]-Abdulmajeed Mohsen Ali Khawaji,[15]-Nader Munaji Abdu Suwayyid

King Saud University Medical City
King Saud University Medical City
King Saud University Medical City
King Saud University Medical City
King Saud University Medical City
Ksa, Ministry Of Health, Wadi Al-Dawasir General Hospital
Ksa, Ministry Of Health, Alradifa Phc
Ksa, Ministry Of Health, Abu Arish General Hospital
Ksa, Ministry Of Health, Central Laboratory And Blood Bank
Ksa, Ministry Of Health, Samtah General Hospital
Ksa, Ministry Of Health, Abu Arish General Hospital
Ksa, Ministry Of Health, Sabya General Hospital
Ksa, Ministry Of Health, Jazan Genral Hospital
Ksa, Ministry Of Health
Ksa, Ministry Of Health, Jazan Genral Hospital

Abstract

Background: The rapid identification of infectious diseases is critical for improving public health outcomes and therapeutic efficacy. Traditional diagnostic methods often suffer from limitations in sensitivity and speed, necessitating the exploration of innovative approaches. This review focuses on the integration of nanotechnology in developing advanced diagnostic tools, emphasizing its potential to enhance detection accuracy and reduce costs.

Methods: A comprehensive analysis of various nanotechnology-based diagnostic techniques, including biosensors, immunoassays, and molecular diagnostics, is presented. Methods employed involve the synthesis of nanostructured materials and their application in biosensing platforms, highlighting their superior sensitivity and specificity.

Results: Results indicate that nanotechnology significantly improves the performance of diagnostic assays, enabling rapid and reliable disease detection. For instance, nanobiosensors demonstrate enhanced interaction with target biomarkers, leading to quicker diagnostic results compared to conventional methods.

Conclusions: The review concludes that the incorporation of nanotechnology into diagnostic practices not only streamlines the detection process but also has the potential to revolutionize point-of-care testing. Future research should focus on addressing the challenges associated with the practical application of nanodiagnostics in clinical settings, including regulatory considerations and safety assessments. Overall, the findings underscore the transformative impact of nanotechnology on the field of diagnostics, paving the way for more effective disease management strategies.

Keywords: Nanotechnology, Diagnostics, Biosensors, Infectious Diseases, Point-of-Care Testing.

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Introduction

The swift detection of infectious diseases in their first stages is crucial for enhancing public health and achieving effective therapeutic results. The prompt and precise identification of an illness is a crucial component of effective medical intervention. illness diagnosis is a procedure that involves determining the type and etiology of an illness, assessing the patient's history, and analyzing pertinent test data [1]. Medical diagnosis must be expeditious, precise, and specific, with a reduced likelihood of 'false outcomes.' Highly sensitive and precise diagnostic techniques facilitate the early identification of diseases and enhance prognostic outcomes. The advancement of medical diagnostic technology directly influences public healthcare, making progress in this field a paramount priority of applied research [2].

Recently, much scientific study in biotechnology has concentrated on creating rapid, precise, portable, and cost-effective diagnostic equipment that patients may use independently to monitor their health. A variety of assays and procedures are accessible for diagnosis, including immunoassays, genetic testing, medical imaging, and biosensing. Commonly used diagnostic bioassays include polymerase chain reaction (PCR) based genetic tests, enzyme-linked immunosorbent assays (ELISA), and staining assays for viral and bacterial infections, such as Gram and Giemsa stains [3]. Traditional diagnostic procedures have drawbacks such as inadequate sensitivity, low specificity, and sluggish speed. Nanotechnology's use in diagnostic tool creation has been transformative due to improved sensitivity, specificity, and functionality of these instruments [4,5].

Biomarker detection often entails significant expenses, prolonged waiting periods, and is conducted utilizing advanced automated analyzers in centralized facilities. Cost-effective, expedited, and more resilient technologies could ideally replace laborious laboratory diagnostics to advance point-of-care diagnosis [6]. Nanostructured materials provide significant potential for the advancement of sophisticated diagnostics. Nanotechnology combined with genomics, proteomics, and molecular machine systems may facilitate the development of efficient, dependable, and rapid onsite medical diagnostics. Nanotechnology has revolutionized these modalities by facilitating the manufacturing of innovative materials for the development of medical diagnostic instruments [7].

Traditional diagnostic techniques need the use of huge, costly apparatus and intricate, laborious processes. Nanotechnology has the ability to redirect the medical field into better trajectories [8]. The use of nanoscience to regulate, manipulate, and integrate atoms and molecules to create nano-dimensional (1–100 nm) structures and components facilitates various techniques in diagnostic device development. Their diminutive structures and elevated surface area to volume ratio enable them to demonstrate very advantageous features. Nanotechnology primarily aims to improve traditional diagnostic procedures by improving process efficiencies and increasing the reusability of nanomaterials, hence reducing the total cost of diagnostics [9].

The current need is to create a rapid and sensitive instrument for illness diagnostics with nanotechnological technologies, which will eventually evolve into the new area known as nanomedicine. The integration of nanotechnology in diagnostics gives a unique opportunity for the advancement of world health. This combination may provide promising new medicines and diagnostic tools for many ailments. Biomedical applications, such as medication delivery, tissue scaffolds, implantable materials, and nano-devices like biosensors, have extensively used diverse nanomaterial architectures [10]. Nanotechnology is progressively assuming a significant function in the advancement of biosensors owing to its heightened sensitivity and performance. Biosensors that integrate biological, physicochemical, or mechanical characteristics of transducers have significant potential in healthcare, food safety, agriculture, and biodefense systems.

Biosensors

Biosensors are analytical instruments consisting of three components: a bio-receptor or recognition element, a transducer, and a signal reading device [11,12]. Biosensors, as defined by the International Union of Pure and Applied Chemistry (IUPAC), are self-contained devices that deliver quantitative or semi-quantitative information by integrating a bio-receptor and a transducer, which directly convert detected biological reactions into measurable signals [13].

The bio-receptor in a biosensor might consist of an enzyme, a receptor, a full microbial cell, nucleic acid fragments, antibody fragments, plant or animal tissues, or polysaccharides, among others. The transducer may detect changes in many physico-chemical characteristics, namely. current, electric potential, mass, temperature, viscosity, conductance, impedance, etc. Biosensors may be classified as affinity types, where the bio-receptor forms a complex with the analyte, or as catalytic types, where the bio-receptor interacts with the analyte [14]. Affinity biosensors are classified into three categories: DNA or geno-sensors, immunosensors, and receptor sensors. DNA or geno-sensors use natural or manufactured nucleic acids as biological receptors [15-19]. Various DNA sensors using peptide nucleic acids, DNA and RNA aptamers, synthetic nucleic acids, and denatured single-stranded DNA (ssDNA) as bio-receptors have been documented. Immunosensors use immobilized antigens or antibodies as bio-receptors and are recognized as quick detection devices. Catalytic biosensors, such as enzyme-based sensors, use enzymes as bio-receptors, and upon recognizing their particular substrates, the resultant product creation is documented. Numerous enzyme-based catalytic biosensors have been documented [20-23].

Categories of biosensors

Biosensors are categorized into many categories based on the transducers used. A transducer enables the conversion of a signal from one form (chemical, physical, or biological) to another (electrical) with great sensitivity [24]. A variety of transducer systems have been created and continue to advance. Common biosensor types, categorized by the transducer system used, include optical, piezoelectric, calorimetric, and electrochemical (Figure 1).

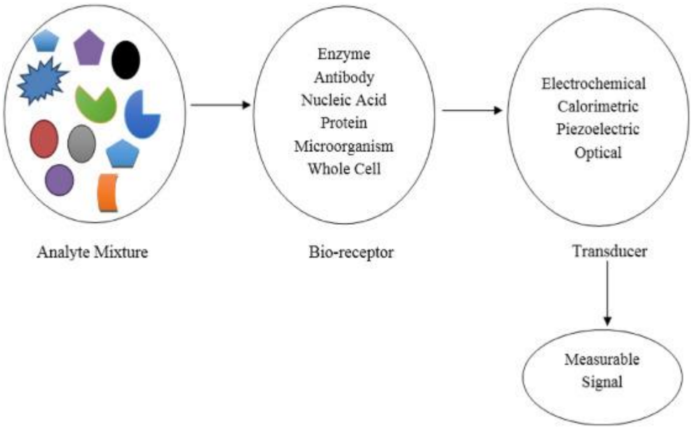

Figure 1. Biosensor types.

Optical biosensors monitor light emitted or absorbed due to biological reactions between a bio-receptor and an analyte. Additional optical characteristics, including bio/chemiluminescence, fluorescence, Raman scattering, and refraction, are used as transducers in several optical biosensors [25,26]. Optical biosensors provide real-time detection and are extensively used in medical diagnostics [27,28]. Fluorescence and surface plasmon resonance (SPR) biosensors are the most prevalent optical biosensors [29]. The SPR biosensor utilizes electromagnetic waves to identify alterations caused by the interaction between an immobilized bio-receptor and the analyte. These have been used for real-time, label-free detection of DNA point mutations and hybridization [30-32]. Additional benefits include the direct use of smaller sample volumes, expedited processing, high-throughput analysis, enhanced sensitivity, and the capacity to mitigate interference, all of which are characteristics of SPR biosensors [33]. Surface Plasmon Resonance (SPR) based biosensors are used to identify infectious microorganisms and diagnose several disorders [34].

Fluorescence-based optical biosensors have been developed to detect DNA hybridization between analytes and bio-receptors and are said to be widely used in environmental monitoring [35,36]. Optical fiber-based biosensors provide great sensitivity, enhanced safety, and are free from electromagnetic interference [37]. They have been extensively used in the detection of nucleic acids and antigens in various capacities [38].

Piezoelectric biosensors use piezoelectric materials, such as quartz, as transduction components. The surface of the piezoelectric material, covered with the bioreceptor or sensing material, vibrates at its natural frequency when subjected to an electric field. The reaction of the analyte with the sensor element on the piezoelectric material results in a change in the material's inherent frequency. The change in natural frequency may be quantified and associated with the mass of the analyte in question. There are several varieties of piezoelectric crystals, including. Zinc oxide, potassium sodium tartrate, lithium niobate, gallium arsenide, barium titanate, lead titanate, lithium tantalate, langasite, and lead zirconate titanate may be used; however, quartz and its equivalent salts are mostly employed. Numerous dependable modifications of piezoelectric biosensors are recognized for the label-free detection of analytes [39].

Piezoelectric biosensors are primarily categorized into two types: surface acoustic wave (SAW) and bulk wave (BW), each possessing distinct benefits and drawbacks depending on the specific applications [40]. Surface acoustic wave (SAW) biosensors are used in applications for monitoring physical parameters, including temperature, pressure, and viscosity, as well as for detecting diverse biological constituents. In these biosensors, the contact between the analyte and the sensing element alters the frequency of acoustic waves traversing the surface of the piezoelectric material, facilitating the detection of minor mass changes on the surface [41]. In bulk wave (BW) sensors, the acoustic wave propagates through the piezoelectric material, generating vibrations throughout the material when an alternating electric field is applied to the electrodes positioned on its sides. The vibration frequency is contingent upon the dimensions and density of the piezoelectric materials, among other factors. [42] Advanced piezoelectric biosensors with high sensitivity have been developed for the detection of cholera toxin, hepatitis, and foodborne infections [43-46]. Low sensitivity and specificity, together with interference reduction and challenges in the fixation of non-specific chemicals, remain notable drawbacks of piezoelectric biosensors [47].

Calorimetric biosensors measure heat variations in a reaction that correlate with the concentration of the analyte in question [48-50]. The first calorimetric biosensors used enzymes paired with heat detectors (thermistors), leading to the early development of several glucose biosensors under the calorimetric biosensor category [51,52]. A calorimetric biosensor using microfluidic channels for real-time measurement of thermal variations has been documented [53]. A novel calorimetric biosensor for the detection of cancer cells has been disclosed [54]. The use of calorimetric biosensors in environmental monitoring and the food business has been delineated by Kirchner et al. [55]. Numerous researchers have shown fast DNA hybridization detection via calorimetric biosensors [56,57].

When an analyte interacts with a bioreceptor or biosensing element, the electrochemical characteristics of the solution are modified. Electrochemical biosensors assess these electrochemical characteristics and relate them to the analyte concentration. Electrochemical biosensors use oxidation-reduction processes and are regarded as straightforward, sensitive, cost-effective, and quick analytical procedures [58,59].

Electrochemical biosensors may be categorized into amperometric, potentiometric, impedimetric, conductometric, and capacitive forms based on the nature of the measured electrochemical change. Amperometric biosensors have lately attained significant prominence among diverse electrochemical biosensors and are used in several applications for disease diagnostics [60].

Amperometric biosensors quantify current variations in a solution caused by biochemical interactions between an analyte and the amperometric transducer, correlating these variations to analyte concentration. Electrochemical biosensors use a three-electrode system, including a working electrode (often made of carbon, gold, or platinum), a reference electrode (constructed from silver or silver chloride), and a counter or auxiliary electrode (fabricated from noble metals) for analytical purposes. Amperometric biosensors are often developed for diverse purposes [61-65].

The oxygen electrode created by Clark in 1962 is regarded as the most basic kind of amperometric biosensor [66]. Amperometric biosensors are categorized into three generations: first, second, and third. In first-generation amperometric biosensors, electrons are immediately transferred to the electrode via product production in a process. In second-generation amperometric biosensors, electrons are sent to the electrode via specific mediators, such ferrocene, toluidine blue, prussian blue, or methylene blue. Mediators in amperometric biosensors facilitate operation at low voltage. Third-generation amperometric biosensors operate without mediators, depending only on the interaction between the bioreceptor and analyte to elicit a response [67-70].

Amperometric biosensors detect analytes by immobilizing the recognition element on the electrode surface. Diverse techniques are used for this immobilization. A straightforward method involves physical adsorption via non-covalent bonding [71]. Covalent bond immobilization of bioreceptors is the predominant approach, ensuring the stability of the immobilized bioreceptor for an extended duration [72]. Bioreceptor immobilization by cross-linkers is an alternative technique that guarantees robust chemical bonding [73]. Additional techniques used include entrapment, microencapsulation, affinity immobilization, and electro-polymerization [74-76].

Prospective opportunities and obstacles

Biosensors are widely used in healthcare, pharmaceutical sectors, and biological research for biomarker identification and illness diagnosis. Recent breakthroughs in biotechnology, nanotechnology, and innovative immobilization methods have rendered nanobiosensors more effective instruments in illness diagnostics. This chapter summarizes the discussion of numerous biosensor types, including immunosensors, genosensors, piezoelectric biosensors, and optical biosensors. An overview of the many kinds of nanomaterials used is provided, facilitating their comparison in the development of pertinent sensors. Nanobiosensors provide a conclusive method in analytical applications because to their superior sensitivity, reliability, and specificity. The technology of nanobiosensors seeks to commercialize innovative, accurate diagnostic gadgets and gain consumer trust.

Summary

Nanobiosensors are essential instruments for the transformative lab-on-a-chip technology used in the diagnosis of human and animal biomarkers, as well as the identification of food pathogens and adulterations. Nano-engineered physiologically active components and nanodevices significantly improve functionality owing to their intracellular accessibility, heightened sensitivity, and mobility. Nevertheless, several nanobiosensors that operate well in laboratory settings may not perform optimally in practical applications or clinical trials owing to different physical limitations. Numerous health hazards are associated with the handling and administration of nanoparticles. The use of nanomaterials as biosensors for disease detection is a very promising area of future study. Experts and engineers from several pertinent fields must collaborate to develop and market this very promising technology.

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التطبيقات المتقدمة لتقنية النانو في طرق التشخيص المختبري: نظرة شاملة

الملخص

الخلفية: يعد التعرف السريع على الأمراض السارية أمرًا حيويًا لتحسين نتائج الصحة العامة وفاعلية العلاج. غالبًا ما تعاني طرق التشخيص التقليدية من قيود من حيث الحساسية والسرعة، مما يستدعي استكشاف أساليب مبتكرة. تركز هذه المراجعة على دمج تقنية النانو في تطوير أدوات تشخيصية متقدمة، مع التأكيد على قدرتها على تعزيز دقة الكشف وتقليل التكاليف.

الطرق: تم تقديم تحليل شامل لمختلف تقنيات التشخيص المعتمدة على تقنية النانو، بما في ذلك البيوسينسور، والاختبارات المناعية، والتشخيص الجزيئي. تشمل الطرق المستخدمة تخليق مواد نانوية وهياكل نانوية واستخدامها في منصات البيوسينسنج، مع تسليط الضوء على حساسيةها العالية ودقتها.

النتائج: تشير النتائج إلى أن تقنية النانو تحسن بشكل كبير من أداء الاختبارات التشخيصية، مما يمكّن من الكشف السريع والموثوق عن الأمراض. على سبيل المثال، تُظهر أجهزة استشعار النانو تفاعلات محسنّة مع المؤشرات البيولوجية المستهدفة، مما يؤدي إلى نتائج تشخيصية أسرع مقارنةً بالطرق التقليدية.

الخاتمة: تستنتج المراجعة أن دمج تقنية النانو في الممارسات التشخيصية لا يقتصر على تبسيط عملية الاكتشاف فحسب، بل لديه أيضًا القدرة على إحداث ثورة في الاختبارات في نقطة الرعاية. يجب أن تركز الأبحاث المستقبلية على معالجة التحديات المرتبطة بالتطبيق العملي للتشخيصات النانوية في الإعدادات السريرية، بما في ذلك الاعتبارات التنظيمية وتقييمات السلامة. بشكل عام، تبرز النتائج التأثير التحويلي لتقنية النانو على مجال التشخيص، مما يمهد الطريق لاستراتيجيات أكثر فعالية في إدارة الأمراض.

الكلمات المفتاحية: تقنية النانو، التشخيصات، أجهزة الاستشعار البيولوجية، الأمراض السارية، الاختبارات في نقطة الرعاية.