American Journal of Biomedicine and Pharmacy
https://biojournals.us/index.php/AJBP
ISSN: 2997-7177

Nanotechnology in Medical Diagnostics: Innovations in Chemical Analysis for Early Disease Detection

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Received: 2024, 15, Feb
Accepted: 2025, 21, Mar
Published: 2025, 14, Apr

Annotation: Nanotechnology is revolutionizing the field of medical diagnostics by enabling earlier, faster, and more accurate disease detection through innovations in chemical analysis. Despite recent advancements, a significant knowledge gap remains in translating nanoscale analytical techniques into clinically viable, point-of-care diagnostics with high sensitivity and specificity. This article explores the integration of nanomaterials—including nanoparticles, quantum dots, and biosensors—into chemical analysis tools such as spectroscopy, chromatography, and microfluidic systems. A multidisciplinary methodology is used to assess these innovations across detection platforms, highlighting their enhanced signal amplification, real-time detection capabilities, and suitability for biomarker discovery. The implications of this work suggest that nanotechnology can significantly improve early diagnostic outcomes, especially for chronic and life-threatening diseases, though regulatory, standardization, and interdisciplinary challenges must be addressed to achieve full clinical adoption.

Keywords: nanotechnology, chemical analysis, early disease detection, biosensors, nanoparticles, biomarker discovery, point-of-care diagnostics, spectroscopy, medical imaging.

1. Introduction to Nanotechnology in Medicine

For some years, a new science has been developed. Recently, it has been received wider attention and enthusiastically acclaimed in many doctors and in many quarters. In a variant form it has been called "hypermedicine", but more recently has been interested as the original term: nanomedicine. Nanoscale structures, materials and devices have unique properties and functions due to their size. It refers to the creation and application of materials and devices of the size of nanometers in the range of 1 to 100 nm in one dimension. Sized range precursors of nano-sized materials can have highly unusual properties of medicinal applications.

Nanotechnology exploits the unique. The main difference between macroscopic biochemical molecules and nanobiochemical molecules is the packaging; the molecular lengths in both cases are similar. The optical, electrical and magnetic properties of nanomaterials vary for different substance concentration and surface topography dependent. Such materials are so sensitive that it's possible to detect when only a few molecules of substance are present. The transport of drugs to cells and tissues arises from the systemic circulation and reduces the need for many injections of pharmaceutical. Drugs themselves can be made in nanosizing particles and it may be possible to carry out treating through other parts of the molecule itself. A variant of this is already done with biodegradable antibiotic and anticancer polymer packets. Pharmaceuticals can be made much more effective.

Improved systems understanding and a number of nanotechnological innovations alongside advances in capacity is a classical vision that is currently on the emergence path following recent developments across many sectors. Medicine, a field of extensive advancement, also has enormous potential to change beyond recognition in the foreseeable future on the backs of transformative anvils. These innovations predict multiple changes in fundamental practices and roles of most medical professions. In particular, improvements in chemical analysis is seen as a key enabler of a broader reengineering of diagnostics, which would be able to provide earlier and more accurate detection of many diseases. To probe the potential impact and development of such innovations in diagnostics, looking at a number of nano-enabled technologies. These technologies individually combine sensors, microfluidic devices and nanoparticles with a variety of signal processing techniques to interrogate a whole range of analytes. Broad potential benefits in the context of chemical diagnostics are discussed. However, considerable interdisciplinary barriers remain to be overcome between chemistry, biology and medical practice, to ensure that the tangible benefits of novel diagnostic platforms can be fully realized. [1][2][3]

2. Fundamentals of Nanotechnology

2.1 Scope of Nanotechnology

The small size (1–100 nm, where 1 nm is defined as 10^{-9} meters) is the key feature of nanoparticulate materials. When the size is at the nanoscale, the materials, properties, and processes significantly differ from their bulk or molecular counterparts. Properties of materials at the nanoscale can diverge from similar materials at a larger size due to several size-dependent phenomena. One key feature is the increase in surface area-to-volume ratio. For example, one cubic meter of nanoparticles will provide a superior amount of surface area compared to the same quantity in bulk form [4]. Another feature is quantum effects: when the size decreases, energy levels become discrete, leading to new band structure and electronic states unique at the nanoscale. Additionally, mechanical, chemical, optical, magnetic, and biological behavior of materials can also be affected by changes in size [5]. For such reasons, nano-engineered materials (also named nanomaterials) are required to be experimentally or technically processed and synthesized in a controlled manner for each application domain.

Given specific medical applications, rational and site-controlled assembly of nanomaterials can be a crucial aspect. A fine regulation of small functional differences of nanomaterials and a fabrication of novel structured hybrids are also vital. Nevertheless, desired physio- and chemical integrity of the resulting nanostructure is extremely significant for any medical application involving nanomaterials. Therefore, a miniaturization of measurement as well as manipulation techniques is necessary, which can be potentially related to the nanoscale of the particles. To ensure safe and reliable use of nanomaterials in any media, including biological organisms, adequate measurement of the physisorption of detrimental bio-organic materials onto the nanoparticles as well as an investigation of biologically induced contaminations is required. Additionally, a characterization of the physisorption of dispersive, usually organic, stabilization agents, and solvents should be conducted.

3. Chemical Analysis Techniques in Nanomedicine

One of the prerequisites for successful therapy is an early disease diagnosis. However, numerous symptoms at the onset of a disease are emerging much earlier than current detection methods can provide; they could be missed out due to the limitation of the techniques employed, leading to a decline or even a lack of chances for successful treatment. Therefore, one of the main focuses within the field of nanomedicine is the development of accurate and sensitive detection methods that would enable the detection of biomarkers at an early stage of the development of the disease [6]. Currently, the chemical analysis methods are dominating over other types of methods in the range of nanomedical applications.

Chemical analysis techniques can be classified into further methods. Spectroscopic methods have the possibility to provide information about the structure, dynamics, and molecular environment of organic compounds. They can be further divided into two classes: optical and mass spectrometry methods. Optical spectroscopies are defined based on the response of samples illuminated with light in the range of UV–vis–NIR or IR. The most frequently used techniques include UV–vis absorption, fluorescence and Raman spectroscopy. Optical imaging is one of the techniques currently under a lot of investigations in the range of applications involving metal nanoparticles and NIR-responsive nanocarriers. These techniques have a lot of perspectives to be used, for instance, for dually (imaging and therapy) acting nanomedical agents. Surface-enhanced Raman scattering (SERS) and coherent anti-Stokes Raman spectroscopy (CARS) are single local methods, which have a lot of potentials for the detection of analytes at the nanometer scale. In particular, SERS is much employed in cell and tissue imaging, as it offers the possibility of the enhancement of the Raman signal with the nanoparticles settings by many orders of magnitude. A number of various conjugations of SERS NPs include, for example, the execution of molecular recognition elements or the so-called smart carriers, which have an optical or thermal impact on their microenvironment. On the other hand, CARS allows to monitor the biomolecules in a natural biological environment without the requirements of the additional markers. Also, there are some other combination methods, which involve SERS together with various other analyses, such as microfluidics, AFM, SERS-endoscopy, and dark-field microscopy. [7][8][9]

3.1. Spectroscopic Methods

Nanomedicine has offered all sorts of opportunities for exploring and utilizing spectroscopic methods in chemical analysis. This subject is far too vast to cover everything, but nanoscale materials have been widely and variously used in many kinds of spectroscopic methods. For example, the combination of nanoparticles and UV-Vis spectroscopy can be used for studying aggregation, particle size, particle concentration, and so on. Moreover, due to their largely improved signal-to-noise ratio and high resolution, there are several unique advantages to using nanoscale materials in spectroscopic analysis. Currently, attention has been drawn from topics such as ultraviolet and visible light spectroscopy analysis, fluorescence spectroscopy analysis, as well as infrared spectroscopy analysis as an inflating market. These methods have been adapted to be utilized for the detection of bio-molecules, pharmaceuticals, and so on, especially in the search of new disease markers. Generally, UV-Vis, fluorescence, and IR spectroscopic methods can test samples in the forms of solutions, and there is, therefore, a refined sample-preparation procedure that needs to be considered. As medical diagnostics advance, a number of “Lab-on-a-Chip” technologies that can easily complete the procedures of diagnosis, including sample preparation, analysis, and signal interpretation on a microscale polymer chip, have emerged. As part of this system, biosensors can serve the role of spectroscopic analysis, which has been explored in all types of spectroscopies. Finally, some current applications of nanoscale materials in the above spectroscopic methods are highlighted. In order to find out possible occurrences of diseases, numerous innovative products for early disease detection remain on the market for daily record. Chemical analysis is utilized for assessing biochemical composition, for instance blood, urine, as well as other bodily fluids. Importantly, many varieties of current collaborative research and development are connected with new kinds of disease markers that can be suited for use in these applications. In order to find traces of these disease markers, as well as most are present in a modified compositional form, chemical analysis and diagnostics have always gone hand-in-hand. There is mounting significance in the employment of advanced chemical analysis for diagnostics. The recent progress in highly sensitive and selective chemical analysis means a number of disease markers and affords a chance of letting loose new applications for this kind of detection. Learnt problems by the early disease detection of disease markers, their biochemical inconsistencies, new biological questions—these are the stimuli pushing the further advance of better chemical analysis. This is seen in terms of all analytical methods, and many assays suitable for these applications are based on spectroscopic techniques.

3.2. Chromatographic Techniques

The field of nanomedicine involves the application of nanoscale materials for disease diagnosis, treatment, and monitoring. This area of study is important because the unique behaviors exhibited by materials at the nanometer scale can offer several advantages when using these materials within biotechnology and medicine [10]. One common approach has been to use nanomaterials in biochemical assays. The use of nanoparticle tags and labels has allowed for signal enhancement and signal mediation schemes to be developed. The mediation of biological binding processes and the enhancement of detection methods can be realized by both metallic and nonmetallic nanomaterials. Additional important aspects of nanomedicine are discussed, including the significant role that both chronic and acute diseases play in mortality rates worldwide, as well as some generally unique features and potential capabilities of nanoscale materials. Pharmaceutical companies apply new methods for quantitative determination of organic additives in food products, agricultural products, pharmaceuticals, and cosmetics, as well as in environmental monitoring. The increase in limits of detectable and determined concentrations, improving the quality of diagnostics and correlation analysis using chromatographic methods. These methods are widely used in the chemical, pharmaceutical, medical, energy, and food industry.

Several broad areas of advancement in nanomedicine are then reviewed. This includes the development of vehicles for targeted therapeutics, ongoing enhancements and increases in the capabilities of drug and chemical sensors, using nanoscale materials to augment the physical, chemical or biological functions that occur in complex-analyte detection and monitoring procedures, and the blossoming of the general field of medical diagnostics. The focus area is on chemical-chromatographic techniques and innovations within the field that have arisen within the past two years. The use of chromatographic techniques, both with and without the integration of nanomaterials, within the realm of nanomedicine is discussed, as are several particularly relevant or impactful advancements in chromatography as of late. Furthermore, where appropriate, there is additionally discussion on practices related to chromatographic technique, such as the necessity and execution of both method validation and method standardization. The application of nanomaterials to enhance the separation of complex biological samples via liquid-chromatographic means is considered at length, as this area of growth is particularly impactful to the field of medical diagnostics. The highlighted work concludes with summaries of real-world applications of chemical-chromatographic techniques for the analysis of nanomedical products that are currently available on the market, and some closing thoughts on the interplay between nanochemistry and chromatography are provided.

4. Nanoparticles in Diagnostic Applications

Nanoparticle is a microscopic particle with at least one dimension smaller than 100 nm [5]. The biological applications of nanoparticles are classified according to composition, such as gold nanoparticles, magnetic nanoparticles, hint nanoparticle, mesoporous silica nanoparticles, quantum dots, and carbon nanoparticles, and according to structure, such as nanoshell, nanopore, and nanocage, and according to properties such as surface enhanced Raman scattering (SERS) [6]. The types and properties of nanoparticles applied medical diagnostics are broad, and their applications have been investigated diversely. One notable aspect of nanoparticles is that they have a very large surface area per unit volume relative to bohemian particles. Therefore, many nanoparticles are functionalized to bind materials in various ways and used. The addition of different bindings with biological materials is one of the most important factors affecting the results of the biological applications of nanoparticles. The surface is changed to connect specific of target, such as biomolecules, functionalities, and dyes. Due to these changes, they can be used as a contrast agent for imaging, and can be utilized in various ways, including sensing, for detecting specific materials. A sensing analysis utilizes the characteristic that the surface plasmon resonance wavelength of gold nanoparticles changes according to the environment in the phenomenon that can be used to represent the morphological colloid colors of the gold nanoparticles, and also uses the phenomenon that it darkens, and platinum black is used. Therefore, gold nanoparticles have been used to develop a variety of tools for detection, such as dot landing method, lateral flow chromatography, optical sensing, colorimetric sensor, and electrical conductivity. As high sensitive tools are developed to use the cover gold nanoparticles, they enhance the sensitivity performance in the field of diagnosis. By utilizing these types of analysis tools, sensitivity and specificity of detection methods are further enhanced. For these reasons, much research has been conducted, and they are now practically used in a number of applications. Nanoparticles enhance current tools and are studied in new experimental applications for further diagnostic performance and functionality discovery. Medicare, near-infrared imaging spectral, x-ray, and magnetic resonance imaging are currently widely used imaging tools utilizing nanoparticles and have been widely used for evaluating diagnosis through various types of detection. New tools are being studied, such as Raman spectroscopy, surface mass spectrometry, and positron emission tomography. Detection tools using nanoparticles are expected to be further improved and used for better diagnosis. On the other hand, the forgetting treatment type is the discovery of material that can be used for detection considering the development and distribution of new material, such as luminescent semiconductor, graphene, fullerene, polymer, and noble metal and can be utilized for diagnosis by designing further technology. There are also potential future trends in considering the toxicity side.

4.1. Types of Nanoparticles

Nanoparticles (NPs) today represent one of the most successful solutions possible in the intersection between chemistry and medicine. With size ranges falling within 1 and 100 nm, NPs are characterized by the surface area-to-volume ratio being exceptionally high, in turn ensuring a number of surface interactions with the external environment much more significant than in the case of microsized particles. Therefore, such peculiar morphology allows them to possess a plethora of unique physical and biological features, making them ideal candidates for a wide range of medical applications. NPs can be differentiated into three main groups, namely carbon-based, organic and inorganic NPs [11]. The present section, therefore, will provide a comprehensive overview of all the NPs proposed in the literature for applications in diagnostics. In this context, they have been further sub-grouped into categories as a function of their composition and principal property, focusing on metallic, polymeric and ceramic NPs [5]. It is important to note that most of them can also be potentially used for imaging purposes or as innovative contrast agents. A brief overview of some of the most recent examples will be given. Overall, the main aim will be to highlight the existing gaps and the potential opportunities lying behind the development of novel NPs towards ultrasensitive and specific diagnostics of critical importance. The surface of the particles is indeed an important interface providing a scaffold on which recognition elements can be assembled, being able to interact with the analyte of interest selectively. Another possibility is that NPs have been covered with shells characterized by a thin polymer layer. Even though the system is more complex, the final properties will be primarily dictated by the external layer, which can be easily modified both chemically and physically. Polymers enclose a wide range of species, including synthetic and biopolymer. Because of their biocompatibility, it is not surprising that they are extensively exploited in the medical field. Polymers also offer the possibility of tuning the size of the nano-construct, being able to control it to a few nanometers. Broad efforts are currently devoted to the preparation of NPs with well-defined properties, perfectly monodispersed and designed shape. [12][13][14]

4.2. Functionalization of Nanoparticles

Nanotechnology concerns the development of nanostructures that are smaller than 100 nanometers and can be altered at the atomic or molecular level. Due to such structural dimensions, nanostructures have unique properties that allow them to differ from their bulk counterparts, and in recent years, have found application in a variety of fields such as electronics, cosmetics, environment, biotechnology, pharmaceuticals, food, and water. Nanoparticles (NPs) are one of the nanostructures most widely used in fields such as drug delivery, therapeutics, gene therapy, and diagnostic device construction. During the last 20 years, interest in nanoparticles use for early diagnosis and simultaneous treatment of various diseases has increased. Their small size allows the nanoparticles to reach tissues and carry out activities that are otherwise unattainable with other materials [15]. Interest in the use of nanomaterials to diagnose oncological diseases has been increasing in the last decade. Functionalized nanoparticles are used for the identification of organs, tissues, and specific cells of the body examined by the operator.

Nanoparticles, mainly metal NPs, have recently received great attention in biological sciences for diagnosis and therapeutics purposes. This interest in NPs is associated with their unique physicochemical properties, which are markedly different from those of their bulk counterparts with the same composition. There are numerous limitations to the use of new nanomaterials, especially metal nanoparticles in biological and laboratory conditions. One of the main problems is fast agglomeration and oxidation of nanoparticles, which would result in loss of their unique physicochemical properties and limit their potential applications. In order to prevent these obstacles, the surface of nanoparticles should be modified. It can involve several methods leading to capping nanoparticles by a shell of organic or inorganic compounds. The formation of the appropriate shell is crucial for the nano-bioconjugates, allowing them to self-organize, to be biocompatible, and to have the facility to be used in many applications. The availability of biocompatible NPs makes it possible to use them in various areas, such as imaging, diagnostics, biosensors, drug delivery, and so on, with relatively low toxicity to higher organisms including humans. There are several ways to protect NPs by organic or inorganic shells, i.e., surface modifications by using different functional groups, which change the physical properties of the base metal or metal oxide NPs. Using this approach, NP properties can be designed so they suit a given application. Such NPs can potentially be coated with biological molecules or recognized, both being compatible with each other. In addition, NPs can become carriers of drugs or other bioactive substances ready to release unique amounts of active compounds directly on target cells. Functions given to nanoparticles by their functionalization, along with lipid, silica, other shell formations or other molecules, have been observed to be successful. There are slight changes in the size and shape of the NPs or the stability of the structures in the presence of various compounds, thus confirming the (bio)activity of the surface of NPs. Amplifications in the presence of NPs have been found in Raman spectra, and photoluminescence possibly allows for the use of NPs in bio-imaging. However, stability of the interaction and the internalization process should be further checked. Adsorption of BSA onto the surface of silver NPs does not require further Ag NP reduction, and reduction performed even in an acidic environment without NaOH additive can increase interaction stability. An important feature of this modified Ag NP is the ability to distinguish between long and short chain polymers, although bulk absorption onto the surface of NPs is observed only in the case of high-exposure polymers. Adsorption of BSA or P1 leads to a 2-fold shift in the plasmon vibration frequency of d- AgNPs and fWSefeO4, which could find potential applications in diagnostics. By functionalizing particles with antibodies or other specific molecules, the extremely high specificity of nanoparticles can be exploited to uniquely target biomolecules and cells. This section provides a more thorough discussion of current research and achievements in the functionalization of NPs useful in chemical analysis with special emphasis on techniques or methods that are innovative and likely to open up new perspectives. [16][17][18]

5. Biosensors and Nanotechnology

The emerging field of nanobiotechnology combines biological devices with nanoscale materials to create new applications for health care. Biosensors are an essential part of this field, as they provide detection of different biological analytes with high specificity and sensitivity. 69% of biosensors have chemical transducers, which are the basis of the signal transduction process. Nanomaterials are increasingly used in the construction of biosensors with chemical transducers to increase sensitivity and improve performance. Nanomaterials have demonstrated that they take greater importance in biosensor technology, as indicated by an increasing number of scientific works dealing with their application in this field. The possibilities of designing and manipulating nanoscale components have created new opportunities to perfect contemporary methodology of biosensing. Many intense transducer-enhancing mechanisms are based on phenomena observed in nanoscale components. Therefore, these mechanisms are increasingly used in the construction of sensors with chemical transducers. Improved performance of devices, such as sensitivity, lifetime, and selectivity, is possible due to the application of nanoscale materials [19]. However, the homogenization of sensors of this type has not yet been fully implemented. Applying the latest advances in nanotechnology to biosensors with chemical transducers is vital for the rapid development of both fields and the transformation of analytical science in medical diagnostics. A vast range of publications on the manipulation of nanoscale materials for transducer-signal transduction processes in biosensors can be found. Nanoscale components have gained importance for many demands that can be used to improve the performance of chemical transducers. Broad implementation of many of these proposals is, however, still not achieved. Consecutive introduction different nanomaterials for a particular sensor type has enabled a comprehensive approach to this research field [20]. There is research that has been carried out on these aspects so far. In particular, efforts are being answered to concentrate on nanobiosensor performance enhancement due to use of nanoparticles, but there is also analysis affecting other types of nanomaterials.

The structure of this report is as follows. First, there is an overview of the essential state in which the interaction of nanotechnology and biosensors is stated for an understanding of reading. Next, based on the most important components of currently active nanomaterials, their size and type, there is an approach about the recommended interactions with bioreceptors along with possible effects. These issues are discussed with respect to the application of different classes of biosensors while paying particular attention to electrochemical, optical, and mass-sensitive biosensors. Examples of nanoparticles, as the most developed class of nanomaterials, are included in this presentation. Finally, the results are given, with an emphasis on the promising future development of biosensor technology that uses nanomaterials, and it also indicates that various types of interactions between nanomaterials and bioreceptors should be considered in optimizing the performance of modern sensors. There is an appearance of time in a growing number of publications regarding sensory attempts with the application of nanomaterials. Some of them help encapsulate biocomponent inside or absorb it on material surface at the same time preserving its bioactivity. This makes possible long shelf-life devices and opens the way for POC application not only in a research laboratory but also at home. However, for the transducer-type chemical group which involves by far the biggest popularization an overview on this subject is still lacking. Due to the continuous progress of nanotechnology, but also to an increasingly enriched biosensor market, a review of the latest research on modern types of nanomaterials and biosensor classes is needed. The current research is therefore aimed at summarizing various classes of nanoscale materials that can be used to improve the sensitivity and performance of biosensors with transcript transducers, taking into account the most important practical aspects. For this purpose, the appropriate literature is systematized, allowing the discovery of the most critical perspectives of released forms. Modern nanomaterials can be successfully applied to the construction of biosensors with chemical transducers for diverse medical tasks. How nanoscale activity can be optimized for reproduction in diverse fields as depicted above the state-of-the-art of the sensor and nanomaterial in application. Furthermore, the innovative use of nanoparticles for enters and electron transduction is widely discussed. Examples relate to different classes of biosensors, with a particular focus on their application in the disease detection that demonstrates well the promising offer of this technology. Finally, the prospective future is provided for a comprehensive description of the direction of further research and development. [21][22][23]

5.1. Design of Nanobiosensors

The ongoing advancement in nanotechnology has fostered significant interest in the design of nanobiosensors for medical diagnostics due to the recognition of bioanalytes with minimal sample requirements, fast response times, and portability. In practice, thoughtful consideration of the fundamental biosensor components and the sensor architecture are requisite to satisfy the biological application’s needs and feasibility. Nanomaterials have been extensively incorporated as transducer platforms, recognition layers, or signal amplifiers in biosensors to enhance the sensitivity, selectivity, or detection limits of bioanalytes. Moreover, modeling, fabrication or integration techniques have been exploited to optimize the performance of nano-biosensors, including their sensitivity, selectivity robustness and response time. Various transduction mechanisms have been used for nanobiosensors, although they fall into 4 common classes: (1) impedimetric; (2) optical; (3) amperometric; and (4) mass-based detection mechanism. Each transduction mechanism works by way of monitoring the output signal of the biosensor with respect to the changes in the surface events, possibly via electronic, photonic, magnetic, or mechanical setups. Here, the focus will be on chemical sensing applications. Electrical transduction is the oldest, most common, simplest to operate, and most widely used of the various transduction methods in biosensors. It classes biosensors as impedimetric or amperometric, which are both based on the detection of electrode’s current, or potentiometric, based on the variation of electrode’s potential. Consequently, the most common analysis methods and examples in biosensor literature could be categorized as include (1) equivalent circuit models implemented to output the sensor’s established physical parameters; and (2) current- or voltage-time response curves showing the reduction or oxidation of electrochemically active species at the electrode surface. The structure and material of nanobiosensors can vary. Common architectures often include bulk electrodes, screen-printed electrodes, interdigitated electrodes, or microelectrodes. The active sensing areas, made with glassy-carbon, platinum, gold or carbon paste, are typically small in the dimension down to hundreds of micrometers. The active layer can be made of various materials, including but not limited to conductive polymers, graphenes, metal nanostructures, biomolecular layers, enzymes, or antibodies. The analytical performance of biosensors can be significantly enhanced by integration of microfluidic systems, readout electronics, magnetic-modifiers, or hydrogel-modifiers. Due to rapid advances in the nanobiotechnology field, recent innovative advancement in the medical diagnostics field are emerging. One example is the use of DNA-based nanobiosensor devices for the detection and monitoring of short disease markers. These biosensors are crucial for emerging medical diagnostics and monitoring of diseases in the first stages. DNA-based nanobiosensors have been designed for the analysis of virus-borne diseases as well as other diseases affecting the genome, such as heredities and cancers. The advanced development of DNA-based nanobiosensor devices has initiated significant advancements in nanomedicine as a comparatively low-cost approach, enabling quick and extremely sensitive, secure, and user-friendly monitoring of variety of acute and sustained diseases. This extensive investigation emphasizes particular short-term biological markers and both viral- and genome-related diseases, all of which are researched with advanced devices. Despite the significant available potential to create innovative solutions for the detection platform of the DNA-based nanobiosensors, fundamental research to effectively change the innovative potential of these devices into biological laboratories is still in desperate need. Open health improvement applications such as ready-to-use analytical system creation, prolonged sensor stabilization, unpredictability significance and limitation, and the improvement of modifiable electrochemical apparatus for laboratory efforts are discussed. [24][25]

5.2. Applications in Disease Detection

Recently, there has been a rapid advancement in the development of new nanomaterials and new nanofabrication methods, stimulating the implementation of nanoscale devices in sensing technologies. These advanced sensors, called nanobiosensors, have the potential to substantially enhance early diagnosis and treatment of diseases. The current progress and the potential future application of nanobiosensors in the clinical management of a variety of diseases are examined in this study.

For any disease, especially critical ones like cancer, heart disease, or diabetes, early detection is vital. Although a vast range of chemical methods are available, they often lack the required sensitivity and specificity. Therefore, there is an urgent need for the development of new biosensors capable of rapidly detecting diseases at ultra-low levels of biomarkers before any apparent symptoms appear. Nanobiosensors are fast, accurate, and are highly sensitive analytical devices used for the quantification of biological compounds. In comparison to traditional chemical-analytical techniques, biosensors are highly precise, require a shorter period of time and less harmful compounds for the diagnostic procedure, and can be manipulated easily. The entry of nanotechnology in biosensors has recently led to a considerable expansion of the diagnostic capabilities. Newly developed nanobiosensors have proven to be significantly more sensitive to a number of chemical and biochemical analytes, compared to conventional methods.

For instance, an ingenious nano-bio platform has been developed for the detection of cardiac biomarkers using screen-printed electrodes functionalized with gold nanoparticle-modified tyrosinase and glucose oxidase. Such a device has the potential to become an ideal point-of-care monitoring system for cardiac-related emergencies [26]. Early treatment may lead to a significant reduction in treatment costs and may ultimately save a patient from critical outcomes. Nano-biological or chemical indicators can be used in a specific phase for the detection of pathogens or for monitoring disease progression and treatment. Real-time monitoring and a rapid response to what is being tested is very useful in health management systems for the treatment of disease. Low-cost, disposable, and portable devices based on nanotechnology may be developed for initial testing, similar to the market glucose monitor systems. According to a recent market analysis, the global demand for nano-enabled medical applications affixed to biosensors was $6.7 billion in 2023.

For this new generation of biosensors almost every branch of nanotechnology, nanomanufacturing, and nano-characterization has contributed. A series of nano-components, such as inorganic nanoparticles, metal film, nanowires, nanorods, nanotubes, nanocanticles, nanoshells, nanorings, and nanocomposites, including carbon tubes and nanoporous AAO enhanced photonic crystal materials, AFM, nanoimprint, e-beam, and soft lithography -based manufacturing of nano-sized sensors have been produced in the last decade. Although nano-sized biosensors have already been developed with demonstrated increased effectiveness in monitoring the disease condition and response to the disease of the patient, they have not been extensively implemented and commercialized as of yet. To foster a broader discussion of the new advances of these technologies, an overview of this area is of crucial interest.

6. Nanotechnology for Biomarker Discovery

Biomarkers have gained attention in medical diagnostics for the early detection and determination of diseases. They are indicator molecules for particular physiological conditions like disease state or state of therapeutic intervention. Biomarkers have contributed to the development of diagnostic assays crucial for disease state determination and management. New biomarker finds have even paved the way to different disciplines for their application. Nanotechnology is one of them; it has opened a new area of discovery and has definitely pushed biomarkers beyond their normal limits. It has the potential for technically discerning or biologically administering informative tools and has provided ways for the rational determination of the ways of disease detection and treatment. Because of their exclusive properties, emergent nanostructures have found unique applications in the area of biomarker discover and analysis design, and diagnostic and analytical examinations for a number of molecules found out. Nanotechnology is controlling the emergence of progressively more responsive and efficient methods which are vital within the scope of foreseeing disease event; thus biomarker discovery may be anticipated to develop a great deal, prospectively in the forthcoming years. This segment is partitioned into two parts: (i) Devising disease marks and (ii) Biomarker substantiation [6]. Concerning the first one, methods which are made easy by using the properties of nanomaterials for the screening and portrayal of novel biomarkers are viewed. With the help of these procedures, it is possible to stimulate a wide vision of different disease states. On the contrary, concern about the validation of biomarker discoveries, that is, their meaning for the disease state and consequent infection state during on the matters of technologic design and issues amid liberals and prisoner discovery and that will be argued in greater depth.

6.1. Identifying Disease Markers

Early detection of diseases is crucial for their successful treatment. Detecting disease markers such as proteins and nucleic acids is an excellent indicator of diseases taking place in an organism, even before any symptom becomes apparent. Due to the low concentration often found of disease markers in biological samples, techniques based on chemical analysis are being developed, which require high sensitivity and specificity. Techniques come from other sectors, such as genomics or proteomics focusing on the study and analysis of the genome or proteome with the aim of detecting genes or proteins associated to a particular disease, are being installed at the nanometric scale using nano-materials. One of the most important approaches currently under investigation is the one that intends to improve or innovate the methods currently used for the immunochromatography in order to develop competitive analytical methodologies for the detection of various biomarkers at ultra-low concentrations.

Nanotechnology can help in the whole process of biomarker discovery – from the selection of the method to the validation of the discovered markers – by means of integrating existing high-throughput (HT) methods used in genomics and proteomics with new nano-scale materials and processes. The enhancement of sensitivity observed with some nano-materials is one of the most important features for this application, since most of the disease markers have concentrations at the ng/mL or fg/mL [27]. When a disease occurs in the body, the immune system usually responds to it by producing antibodies against the specific antigens associated with the disease.

The concentration of the specific antigen often increases in the body and can be detected in blood, serum or urine sampling. The level of the increase could be therefore indicative of the occurrence of a particular disease, being able, in some validation cases, to detect the disease in a sub-clinical state before any symptom is visible.

Various chemical methods are also currently being developed, integrated with an number of nanotechniques, to screen patient samples. These methods include various immunoassays, as ELISA, and more recent immunoassays like Luminex or Q-dots. Also, the Affymetrix microarrays, now used as potential screening tools for the detection of new biomarkers, are starting to use nano-technology in the fabrication process of the probe array. Nonetheless, immunoassays have some technical limitations, as they are usually time-consuming and expensive, or require a multistep process. To overcome these limitations, microfluidic technologies must be developed, which allow merging fluid flow, mixing, and detection into an all-in-a-device, minimizing reagent consumption and waste production, and reducing cost and analysis time [6]. Ideally, microfluidic systems would process the sample automatically, introducing the sample into the micro-channels, mixing it with detection reagents, and driving it to the detector in a single step. The platform must be compatible with various detection methods, including Spectroscopy, Fluorescence, Conductivity, Amperometry, etc. Moreover, the overall device must be versatile and easy to use. The proteins or peptides are therefore potential early-stage biomarkers for diseases, and can provide information of the state of disease in a patient. So, in a collaborative work with a European SME, a method for screening plasma or urine patient samples with a particular disease in search of new potential biomarkers is being developed.

6.2. Nanotechnology in Biomarker Validation

The mechanism of action of the drug should be irreversible and killing the pathogens. The working of the drug should be to prevent the virulence factors of the pathogens (biofilm formation, adhesion, toxigenesis, capsule formation and inhibiting the motility of the microorganism are some of the examples. The action of the drug should be complementing with the immune system. There is an increased interest in promoting rational use of traditionally used biologicals which decrease drug resistance generation by pathogens and/or improve the host immune response and promote faster recovery and reduce side effects. It is essential that there is preclinical toxicological evaluation and phase I, II, III and IV Clinical trials about the drug.

Biomarkers are the measurable changes associated with a normal physiological or pathological process. Biomarkers used as a diagnostic tool for effective clinical solutions. Currently, the biomarker therapeutics represent less than 1% of the 300 candidate drugs tested in clinical trials. In the last two years, the market share of the biomarkers has decreased slightly but there is great potential for longer-term future growth. A biomarker, is a subordinate of cytokines, antigens, hormones, and several body components that are detectable, the amount of which changes after affliction is a measure of the illness involved. Once the biomarkers are discovered and available, the biomarkers were validated by using the tools and technology. Actually, the umbrella term of AMT refers to targets such as hyperplastic scars that elicit highly specific biomarker levels and may develop into FM patients. Cutaneous neoplasms are a common type of skin cancer that can prove to be fatal if not detected and treated on time.

Methods and findings: Since there is a paucity of order and reproducibility for the revised biomarker validation standard, this study presents a heuristic approach to validation or potency analysis to establish a comprehensive set of biomarkers that involves using a modified analysis under conditions to impose strategies. Quantify the absolute concentration of different proteins, peptides, and generate high-quality identification/data due to low recovery and matrix effect. For an assessment outcome in the first year, statistical methodologies were instituted to confirm the detected biomarkers' importance, allowing a quantitative estimation of their potential sensitivity and specificity on increases further with confidence. [28][29][30]

7. Point-of-Care Diagnostics

Better-quality health management has become essential in order to offer the best quality health care. By achieving higher standards in health care management, it should be possible to make timely decisions based on rapid diagnostics. This has called for smart therapeutics, analytical tools, and diagnostics systems in order to further enhance health wellness. In this context, the development of smart diagnostic systems for personalized health care are considered especially important, such as point-of-care devices. The capability of point-of-care testing is an upcoming trend for fast detection of a variety of analytes near to the patient, thus facilitating improved disease diagnosis, monitoring, and management. The fast detection of disease markers is needed, as quick medical decisions can then be made, which under certain circumstances can lead to better health care outcomes for patients [31]. In recent years, numerous potential point-of-care devices have been developed, thus paving the way to next-generation point-of-care testing. Among these devices, biosensors are a serious player for low-cost devices used in home health care applications in order to facilitate personalized health care management. Electrochemical biosensors have received an incredible amount of attention due to their desirable intrinsic characteristics such as high sensitivity, accuracy, low detection limits, and real-sample analysis possibilities. Accordingly, they can detect disease-causing markers including bacteria, DNA, RNA, glucose, and proteins in blood samples.

The development of nanostructure-based biosensors for chemical and biological species sensing has become an interesting research field in nanomedicine. Thanks to the development of nanotechnology, interest in the use of nanomaterials has a major impact on a broad field of applications such as drug delivery, diagnostics, bio-imaging, and therapeutics. Focusing on the combination of nanomaterial and biosensors it is possible to say that it is a new and promising way to develop high-performance and cost-effective devices for point-of-care diagnostics. There are numerous reports of the sensitivity appearance in a biosensor when a nanostructure is incorporated. This can be explained by an enhancement of the active surface area of the electrode, facilitation of electrode reactions and retention of the biological activity of the immobilized molecule. Nanobiosensors for point-of-care diagnostics have achieved an important role in the last decade due to their high selectivity and sensitivity. They allow for the early diagnosis and management of targeted diseases, which in turn facilitate timely therapeutic decisions. Built with nanoparticles, nanosensors modify the screen-printed electrodes capable to carry out “one-shot” detection in an efficient and accurate manner with no need of any pretreatment. Amid the many types of nanomaterials that have been proposed in various configurations for sensor use in the literature, significant attention has been given to gold nanoparticles, carbon nanotubes, and quantum dots, because of their unique physicochemical characteristics and hence their potential application for the development of next-generation biosensor devices. [32][33][34]

7.1. Portable Nanotechnology Devices

The emergence and rapid development of nanotechnology is opening up new possibilities in medical diagnostics. Diagnostic tests to detect early onset diseases, such as cancer, are becoming more important to improve the survival of patients. The recent developments in nanotechnology have allowed innovative diagnostic techniques and devices to be created. The diagnosis and detection of various diseases, including blood glucose, cancer, cardiovascular diseases, and HIV, have been facilitated by the advent of new nano-bio-sensing technology. The length scale the nanosensors operate within can enhance the performance of devices. Of note, the bioconjugation of biorecognition elements increases the sensitivity, selectivity, and reusability of nanosensors. Recently, notable progress has been made in designing portable diagnostic devices with nanomaterials. There are challenges for these devices but they also offer exciting opportunities for creating reliable, cost-effective portable devices.

The growing need for diagnostic tests, primarily due to an increasing geriatric population, an increase in chronic diseases, and the availability of advanced technologies, is driving the demand for portable diagnostic devices. In response, various initiatives are being undertaken to develop portable diagnostics that are easy to use, reduce costs, and give results quickly. This has necessitated the ability to perform diagnostic procedures outside the laboratory. Nanotechnology is being exploited to create devices for this purpose.

The development and utilization of portable diagnostic devices with nanomaterial, nano-structured materials suitable for use in the detection of target analyte is in an impressive progress. Moreover, the fabrication and performance improvement of portable devices are noted. Most biomolecular devices work by a change in the electrical potential, which creates energy transport. A well-known example is the ability to chemically manipulate single molecules. The size scale of the devices has a significant effect on the enhancement of the effect. The increasing interest of researchers in the design of nanomaterials has led to the fusion of new and existing technologies. Most nano-biosensors are based on nanoparticles or microparticulars. These devices and structures offer the potential to create portable diagnostics with improved sensor performance. A notable topic in the field of nanobiotechnology is the detection of bio-molecular new agents. In this context, the arrangements based on the detection of bio-agent can work as nano-sensors. These devices can be applied to useful tests in biological analysis. In particular, bio-sensors are critically important in the development of portable diagnostics. They have attracted the attention of recent researchers because they offer attractive properties such as miniaturization and the ability to produce highly specific biocompatible molecular systems.

7.2. Rapid Testing Methods

Timely testing and correct diagnosis of diseases is the key to efficient disease management. There have been numerous attempts to identify the means, methods, and specific markers of an early stage of diseases. This race has given rise to the introduction of chemical analysis as one of the frontier areas in disease diagnostics. The idea behind chemical analysis being used for diagnostics is in the fact that various probable markers of diseases, proteins, genomic sequence motifs etc, can only be sensed effectively if they are specifically captured and concentrations are further amplified [35].

Rapid testing and the market in which it operates can be observed as a huge step forward in the general concept of detection and diagnosis. Today, the very definition of a “snapshot-take picture - gives diagnosis” approach has never been truer. Health has always been considered as the first wealth and we are here to bring innovations in the field to the service of man so that the best health can be ensured and made available with minimum effort and minimum cost. Rapid testing has been effectively brought in the field of diagnostics in the form of kits for HIV and Blood testing using dip-stick approach: sample reacted with the kit is dropped onto the stick to show up test result. By means of these tests, the ill and possibly infected persons can be identified before the disease reaches its catastrophic phase. This would also lead to a significant increase in the efficiency of the medicine given illustrating the advantage of a correct diagnosis and early detection.

There have been many attempts taken to innovatively paint the rapid diagnostics horizon and this has culminated into a number of kits and analysis schemes that have been launched (besides the HIV and Blood pressure). These innovations have meant drastically reduced turnaround times with the tests showing increased accuracy despite following the simple reagent-environment-test procedure. Lately some of these technologies have been introduced for diagnostic purposes: in particular the infectious and chronic conditions, which were formerly a long drawn, laboratory-based processing approach involving outsourcing of samples and results. Many strategies have been used in trying to pinpoint the markers without an amplification pre-step. Nanomaterials can be mentioned here. The surface area of the nanoparticles is very high hence 1 part becomes sticky for the exclusive attachment of target molecules.

8. Nanotechnology in Imaging Techniques

1. Introduction

Medical diagnostics have significantly advanced in the last few decades, allowing early disease detection and improved therapy that has led to increased life expectancy. Whist these improvements have significantly minimized the dangers of frequently occurring disorders such as diabetes, cancer, and other cardiac conditions, more complex diseases with multifactorial etiology are increasingly prevalent [6]. As a result, a new focus has been given to disease prevention, early detection and personalized treatment which is expected to markedly improve the efficiency of therapy. As of now, there is a considerable number of modern innovative analysis systems engaged in medical diagnostics based on chemical methods. These range from very widespread systems—like blood glucose and cholesterol level meters—to specific diagnosis systems based on emerging technologies, that may be complicated and expensive, but have their application in situations when other techniques fail.

Biological methods evaluate the presence of specific antigens or DNA in the tested sample and have reached high levels of sensitivity and selectivity; their disadvantages include possible sample contamination and low multiplexity. Spectroscopic techniques are very effective for light-absorbing materials and have been utilized effectively in pulse oxymetry, but, in general, are not useful for other types of analyses. In turn, electrochemical methods, particularly impedancemetrics, have become a widespread technique owing to their simplicity, low cost and high selective measurements. Magnetic analysis gives the information concerning superparamagnetic particles. Additionally, biosensors have reached miniaturization and, in combination with separation systems like capillary electrophoresic or liquid chromatographic, are powerful and selective analysis tools. The evolution of these systems has increased diversity and brought interesting new concepts but many can be still optimized and require potentially new solutions; the emergence of nanotechnology in this area a decade back has delivered systems able of processing and analysis that could not be achieved with the conventional device, thus helping to build a universal and comercialized system able to support the early diagnostics.

8.1. Enhanced Imaging Modalities

Medical investigations, diagnostics and general clinical research have always relied heavily on imaging techniques to provide detailed information and evidence of ill health and disease. Nanotechnology holds a great deal of promise for medical imaging applications. The introduction of nanomaterials in imaging techniques has the potential not only to improve the quality of images but also their specificity. Multiple imaging modalities have seen much advancement as a result, and it is now possible to detect microscopic tumours that would otherwise go unnoticed. Optical, ultrasound and nuclear imaging stand out as prime examples where the incorporation of nanoparticles has opened pathways for improved tissue contrast and sensitivity in diagnostics. Although vastly different, imaging modalities predominantly rely on the manipulation of waves to generate an image. Advances in nanotechnology and material science have transformed most aspects of everyday life and research, and it is no surprise that they are also changing the approach to observing structures within the body. Nanoparticles have become powerful tools in the hands of radiologists, greatly changing the visibility of tissues and cellular structure and opening wide possibilities in diagnostics [36]. The potential for nanoparticles to act as contrast agents to enhance the visibility of cells or tissue structures is transformative and has seen incredible growth in its applications. Metallic nanoclusters, noble metal nanoparticles, and quantum dots have been proposed as alternatives to traditional dyes and have been increasingly popular due to their high brightness and stability. This increased brightness and photostability result in high emission rates, generating better contrast and sensitivity in optical imaging for applications such as sentinel lymph node visualisation, drugs and small particles delivery, as well as angiography and vasculature imaging.

A substantial increase can be seen across medical imaging reports investigating the function of optical imaging involving nanoparticles over the past decade, yet with challenges that come from biocompatibility and safety. To be used as contrast agents, nanoparticles should remain in the blood stream and generate the right signal for detection while being quickly removed from the body in a non-detrimental way. Few studies concerning optical imaging offer a complete picture about in vivo nanoparticle distribution and toxicity, as brackets derived from the materials' size and surface properties highly influence their impact in biological systems and thus, it is important to conduct further research and fill in these gaps in the literature on the topic. New projections on future applications of enhanced imaging techniques incorporating nanotechnology will focus on the ultimate goal of balancing risk and benefit for the patient.

8.2. Nanoparticles in MRI and CT Scans

Magnetic resonance imaging (MRI) and computed tomography (CT) scanning techniques have significantly improved due to the use of nanoparticles as contrast agents. Nanoparticles enhance the image quality of the MRI and CT scans, thereby increasing diagnostic accuracy. Nanoparticles used in these imaging techniques can be synthesized from a variety of materials including metals, metal oxides, silica, polymer, and carbon. As a result, these nanoparticles exhibit unique properties that are suited for imaging—superparamagnetic iron oxide nanoparticles (SPIONs) serving as T2 relaxation agents and gold nanoparticles as CT contrast agents, for instance. Due to their large surface area, a high density of contrast agents can be associated with the nanoparticles. Avidin-coated biotinylated bovine serum albumin nanoparticles can carry a large number of chelates for gadolinium. Chemically functionalized nanoparticles link to targeting agents, enhancing the imaging and therapeutic capabilities of these agents. In particular, silica nanoparticles can be synthesized with specific functions [37]. The size of the nanoparticles ranges from ~10 to 100 nm and preferably no larger than 1000 nm [38]. By monitoring the compilation of nanoparticles in tumors over a period of 24 hours in MRI, the leaking properties of the EPR effect and the nanoparticles have been analyzed. Nanoparticles designed to increase the signal volume of T1 relaxation in MRI have been studied. Gold nanoparticles are used in imaging because they are biocompatible, non-toxic, and chemically inert. The therapeutic potential of gold nanoparticles in ligand-mediated radiotherapy has been shown, while the microdistribution of pharmacokinetic behavior of gadolinium-induced BMP post-labelled gold nanoparticles enables the use of MRI to analyze nanoparticle preparations.

9. Conclusion

Nanotechnology has the potential to transform the way in which disease is diagnosed by enabling the measurement of an unprecedented range of physical, chemical, and biological signals simultaneously, which will provide the opportunity for much earlier diagnosis of diseases than is currently possible. Much effort has recently been put into making accessible technologies that can measure these signals, with the objective of putting them into clinical practice. Of all the medical fields, perhaps the area that is most likely to soon benefit from the advances in chemical analysis and nanotechnologies with applications in colloidal nanoparticles, SERS, dip-pen, and other types of nanopatterning and nanodevices, are diagnostic procedures for detection both of life-nonthreatening infectious diseases and cancer as soon as they begin to manifest in the body. The exponential growth of ancillary diseases and costs following the diagnosis of these conditions in later stages can be highly reduced simply by super-early diagnosis, which chemical analysis of the not-too-distant future will be able to provide shortly after populations are taught not to ignore early symptoms of dread diseases, but to seek help straight away. In this emerging context it can be said that the future of diagnostics, driven mostly by chemical analysis innovations, is bright. Detecting and identifying early infectious diseases and cancers will only get easier, noninvasive, and quicker. However, much work, testing and research, lies in front the realization of this 'utopian' scenario, but the more the scientific community pulls together across disciplines on diagnostics, the faster it will be achieved.

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