Transactions on Materials, Biotechnology and Life Sciences
ISSN: 2960-1932, eISSN: 2960-2319 | Volume 7
MISBP 2024

Carbon Nanotube-Based Glucose Biosensor: Preparation and Application

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Abstract. Glucose biosensor is one of the most important sensors for converting glucose concentration into measurable signal. The use of biosensors for monitoring glucose has significant value in healthcare. It has attracted much attention in recent years because of its excellent real-time detection ability, high stability, minimally invasive and easy operation. Carrier and electron transport medium are important factors which affect the selectivity and sensitivity of biosensors. Therefore, the search for carriers with high specific surface area and excellent electrical conductivity is the key to promote the performance of glucose biosensors. Carbon nanotubes (CNTs) are excellent candidates for the modification of glucose biosensors due to their unique structure and excellent properties. In this paper, glucose biosensors are introduced briefly. The components, development, classifications and working principle of biosensors are introduced in detail. The biosensors used for detecting glucose are also outlined, including their composition, principles, development, and modifications. Especially the CNT-based sensors, which are formed by modifying the electrodes with CNTs, are described in detail. It is shown that CNTs combined with other nanomaterials could form composite materials which is very useful for improving the detection performance of glucose sensors. This work will promote real-time monitoring of glucose concentration.

Keywords: Biosensors; Glucose Biosensors; Carbon Nanotube; Electrochemical sensors.

1. Introduction

Biosensors represent a promising multidisciplinary intersection of life sciences, analytical chemistry, physics, information science, and related technologies. With their advantages of high sensitivity, selectivity, and real-time monitoring capabilities, biosensors have addressed the limitations of conventional instruments that struggle with slow diagnosis and real-time detection. Consequently, they have found widespread application across various domains, notably in healthcare, drug discovery, food safety, homeland security, pharmaceutical research, and environmental monitoring.

The use of biosensors for monitoring glucose has significant value in healthcare. Glucose biosensors occupy a pivotal position in the evolution of biosensor technology due to the fundamental role of glucose [1]. These biosensors, predominantly enzyme-based, adeptly convert the chemical reaction between glucose and oxygen into a quantifiable electrical signal, enabling precise measurement of glucose concentrations in solution. Their unparalleled attributes of high selectivity, sensitivity, speed, and reversibility underscore the immense potential of glucose biosensor development across diverse domains.

One of the important means to improve glucose biosensors is to use new nanomaterials for modification [1-3]. Carbon nanotubes (CNTs), as a new type of nanomaterial, have excellent properties. Carbon nanotubes, as quantum carbon materials, possess a distinctive structure and exceptional properties that have garnered substantial attention from scientists worldwide since their initial discovery by Japanese electron microscopist Iijima. These nanostructures are comprised of one or more layers of graphene sheets seamlessly rolled into cylinders, exhibiting an exceedingly high aspect ratio. Carbon nanotubes boast remarkable tensile strength, elasticity, electrical conductivity, fatigue resistance, and chemical stability. Owing to these characteristics, carbon nanotubes demonstrate immense potential for diverse applications. In the realm of renewable energy, they can serve as hydrogen storage materials, enabling efficient and secure hydrogen storage and

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transportation. Within biomedicine, carbon nanotubes function as drug carriers, biosensors, and cell imaging probes, playing a pivotal role in drug delivery systems, disease diagnosis, and treatment modalities. Carbon nanotubes (CNTs) have garnered significant attention as carriers for immobilizing biomolecules in glucose biosensors, owing to their exceptional surface-to-volume ratio, electrical conductivity, and biocompatibility. These attributes significantly enhance the sensitivity, selectivity, and overall performance of the sensors. Consequently, CNT-based glucose biosensors have found widespread applications in medical diagnosis, health management, environmental monitoring, and food safety. These biosensors leverage either enzymatic or non-enzymatic reaction mechanisms to achieve efficient and reliable glucose detection. Therefore, this work aims at this research topic. Biosensors are introduced in this work. Subsequently, glucose biosensors are discussed in detail. Besides, the application of CNTs-based glucose biosensors is also discussed.

2. Biosensors

In the healthcare realm, biosensors enable the detection of physiological parameters such as blood glucose, blood pressure, and heart rate [4, 5]. Meanwhile, biomolecules such as pathogens and tumor markers can also be detected by biosensors. Therefore, biosensors can assist in the precision medicine and health monitoring. It is well known that environmental monitoring is crucial for healthcare. In environmental monitoring, biosensors could facilitate the detection of critical indicators. Water quality, air quality, and soil pollution can be monitored by biosensors, providing vital data to environmental protection agencies. Furthermore, biosensors play a pivotal role in ensuring food safety, advancing agricultural practices, and supporting biological researches.

2.1. Overview of Sensors

A sensor is a detection device which is capable of measuring and perceiving information from a target object. It can subsequently transform this perceived information into electrical signals or other forms of output in accordance with a predefined principle. A biosensor is an instrument which is highly sensitive to biological substances. It is capable of detect their concentration or presence by converting them into photoelectric signals. Its operational principle relies on the specific interaction between the biosensitive material and the analyte. The resulting biological information is transduced into optical or electrical signals through a physicochemical converter, thereby facilitating the detection and analysis of the target substance.

2.2. The Components of Biosensors

Biosensors comprise two essential components which are the sensitive membrane and the transducer. The sensitive membrane serves as the recognition element and directly determines the functionality and quality of the sensors. The transducer is responsible for converting diverse biological, chemical, and physical signals into electrical signals. These components work in unison to accomplish the identification of the analyte, signal conversion, amplification, and output.

2.3. The Classification of Biosensors

There exist diverse classifications in the realm of biosensors. Biosensors primarily encompass three major categories.

Firstly, biosensors are categorized based on their molecular recognition element, which is also known as the sensing element. This classification segregates them into enzyme sensors, microbial sensors, cell sensors, tissue sensors, and immunosensors.

Secondly, biosensors are differentiated according to their transducer, which serves as the signal converter. This classification encompasses bioelectrode sensors, semiconductor biosensors, optical biosensors, thermal biosensors, and piezoelectric biosensors.

Lastly, biosensors are further classified based on the nature of interaction between the target analyte and the molecular recognition element. Biosensors can be divided into biophilic biosensors and metabolic biosensors. The biophilic biosensors rely on affinity-based interactions, while the metabolic biosensors harness metabolic processes for detection.

This refined classification system offers a more nuanced and academic perspective on the biosensors, facilitating a deeper understanding of their underlying principles and applications.

3. Glucose Biosensor

In the healthcare sector, glucose biosensors are invaluable tools that furnish diabetic patients and healthcare practitioners with accurate and prompt blood glucose readings, facilitating the customization and refinement of treatment protocols. Furthermore, the continuous monitoring of glucose levels holds promise for early screening and alerting of certain medical conditions. Wu et al. reported a glucose biosensor modified with various nanomaterials using glucose oxidase (GOD). Specific detection and rapid response for glucose can be achieved. It can effectively filter out interfering substances in the matrix [1].

Within the food industry, glucose biosensors contribute significantly to product quality control by enabling swift and accurate determination of glucose content in food products, thereby ensuring food safety and compliance with regulatory standards.

The researches which focused on glucose biosensors have fueled continuous innovation and advancement in sensor technologies [6]. Concomitant with breakthroughs in disciplines such as bioengineering, nanotechnology, and microelectronics, glucose biosensors have witnessed remarkable improvements in their performance, sensitivity, and user-friendliness. Notably, the advent of non-invasive or minimally invasive sensors has mitigated the discomfort associated with traditional testing methods, enhancing patient compliance and satisfaction.

3.1. The Composition of Glucose Biosensors

Glucose biosensors accurately measure glucose concentrations through the enzymatic oxidation of glucose [4]. It is primarily catalyzed by glucose oxidase (GOx) [7]. This biochemical process results in the conversion of glucose to gluconic acid, accompanied by the generation of hydrogen peroxide (H_2O_2) or the consumption of dissolved oxygen. In this intricate mechanism, receptors and transducers play pivotal roles.

Receptors, which are consisted of membranes imbedded with glucose oxidase enzymes, function as biocatalysts, facilitating the specific oxidation of glucose molecules. Meanwhile, transducers, typically aerobic or amperometric electrodes, convert the biochemical output into measurable electrical signals.

3.2. The Principles of Glucose Biosensors

Understanding the working principle of glucose biosensors is crucial. The working process of glucose biosensors is mainly divided into four stages.

In the enzyme-catalyzed reaction stage, the glucose oxidase receptors act as biocatalysts. It could specifically recognize and catalyze the oxidation of glucose molecules in the presence of oxygen, yielding gluconic acid and hydrogen peroxide. This reaction serves as the foundation for glucose concentration detection.

In the hydrogen peroxide detection stage, contemporary glucose sensors detect the current generated by the electrochemical oxidation of hydrogen peroxide at the electrode surface, thereby circumventing interference from oxygen concentration fluctuations.

Afterwards, it turns to the current shift detection stage. Subsequently, hydrogen peroxide undergoes an electrochemical decomposition reaction at the electrode interface. The liberated electrons are conducted through the electrodes, generating a measurable current. The magnitude of this current is directly proportional to the concentration of glucose, thus providing a quantitative indicator of glucose levels.

When it comes to the measurement and conversion stage, the sensor converts the detected current magnitude into a corresponding glucose concentration value, employing electronic circuitry for signal amplification.

3.3. The Evolution of Glucose Biosensors

The evolution of glucose biosensors has spanned four significant advancements. The first generation is the oxygen electrode-based sensors which relied on the consumption of oxygen during glucose oxidation for detection. However, they suffered from accuracy limitations due to the influence of background oxygen concentrations. The second generation uses the introduction of mediators such as thionine and ferrocene to accelerate the oxidation of hydrogen peroxide at the electrode. It enhances the sensitivity and stability of the sensor. Nevertheless, mediator leaching from the electrode surface posed challenges to long-term stability. The third generation is the dielectric-free sensors. It achieved direct electron transfer between the enzyme and electrode through innovative electrode materials or structures, further improving sensor selectivity and stability. The fourth generation is the enzyme-free sensors which utilize catalysts such as noble metals to mimic enzymatic functions, overcoming the limitations of enzyme-based sensors and paving the way for the continued advancement of glucose biosensors.

4. CNT-Based Glucose Biosensors

Carbon nanotubes (CNTs) primarily consist of carbon atoms arranged in hexagonal lattices, interconnected through covalent bonds to form one or multiple layers of coaxial tubes. They maintain a consistent interlayer distance of 0.34 nm, and they exhibit diameters ranging from 2 to 20 nm. CNTs can be classified into sawtooth, armchair, and spiral configurations, based on the orientation of the carbon hexagons along the axial axis.

Originating from the rolling of graphene sheets, carbon nanotubes are categorized into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs possess a solitary graphene layer, leading to smaller diameters typically between 1.3 and 2 nm, accompanied by well-defined nanostructures and high uniformity. In contrast, MWCNTs consist of multiple coaxial graphene layers, with diameters spanning from 2 nm to 50 nm. MWCNTs may comprise hundreds of layers.

There exist three primary methodologies for synthesizing carbon nanotubes. The arc discharge method is a pioneering approach which still be used today. It involves utilizing a vacuum chamber filled with an inert gas or hydrogen at a specified pressure. Graphite electrodes doped with catalysts undergo arc discharge, during which the anode graphite evaporates, while carbon nanotubes deposit on the cathode. This method is simple in equipment and cost-effectiveness. However, it needs high reaction temperatures. It may yield carbon nanotubes with increased impurities and reduced purity.

The laser evaporation method involves positioning a metal-graphite target wrapped in a long quartz tube within a heating furnace. Upon reaching a predetermined temperature, an inert gas is introduced, and a laser focuses on the target. The resulting carbon and catalyst particles are transported from the high-temperature zone to the lower-temperature region by the gas flow, depositing carbon nanotubes on the substrate and chamber walls under the catalysis of the embedded metals. This method excels in producing carbon nanotubes with high purity and quality, but it suffers from low yield and expensive equipment, which limit its widespread application.

The chemical vapor deposition (CVD) is the most prevalent technique for carbon nanotube synthesis. It involves passing a carbon-containing gaseous compound over a catalyst, which decomposes to release carbon atoms and facilitate the growth of carbon nanotubes on the surface of the catalyst. This method is favored for its lower temperature requirements, ease of parameter adjustment, and high yield.

The modification of glucose biosensors by using CNTs is a research hotspot. By utilizing the excellent conductivity of CNTs to modify the electrodes of the sensor, the detection sensitivity can be improved. Zhu et al. reported a enzyme-free glucose biosensor by using CNTs. This type of sensor is directly grown on the substrate. A large number of CNT arrays were used to achieve high-sensitivity detection of glucose [2].

Combining CNTs with other nanomaterials to form composite materials is also a good method for electrode modification [6]. Gold nanoparticles are often used in combination with CNTs to improve the conductivity of electrodes. Jia et al. prepared a thin film containing a mixture of CNTs and gold nanoparticles (AuNP). This film is formed on a glassy carbon electrode. This modified electrode has been proven to improve the detection stability of glucose sensors [3].

5. CNT-Based Glucose Sensors

5.1. Working Principles

CNTs as carriers in glucose biosensors demonstrate immense potential in both enzyme-based and non-enzymatic configurations. In enzyme-based glucose sensors, glucose oxidase (GOx) serves as the primary catalyst. However, immobilization onto electrode surfaces can alter its morphology, causing denaturation, inactivation, and subsequent degradation of catalytic performance. This directly impacts the biosensor's lifespan. Incorporating CNTs as carriers addresses this issue by coordinating with the enzyme structure to enhance GOx loading and stability, rendering them superior substrates for enzyme immobilization. Furthermore, the exceptional electrical conductivity of CNT facilitates direct electron transfer between the enzyme and electrode surface, resulting in reduced operating potentials, improved longevity, heightened sensitivity, and faster response times.

In non-enzymatic glucose sensors, the catalytic effect stems from nanomaterials, such as metals, metal oxides, or metal-organic frameworks (MOFs) integrated with CNTs. The integration of CNTs with other materials further augments sensor performance. For instance, precious metals (Pt, Au, Ni, Cu, etc.) in sensor construction may encounter interference from substances like amino acids and creatinine in the presence of chloride ions. Conversely, synthesized nanoscale noble metals increase the specific surface area and roughness of the metals, thereby enhancing the sensitivity and selectivity of the glucose sensors. In MOF-based sensors, such as ZIF-67, the combination with CNTs significantly boosts catalytic reactions and detection capabilities through their high porosity and extensive specific surface area. Conductive polymer-based sensors, when combine with CNTs, yield high-performance nanocomposites that offer superior enzyme immobilization efficiency, sensing performance, and enhanced mobile electron availability.

5.2. Applications

Carbon nanotubes (CNTs), a prominent exemplar of nanotechnology, have ushered in a new era in the realm of biosensors through their exceptional physical and chemical properties, exhibiting unparalleled potential, particularly in glucose monitoring. This nanomaterial boasts remarkable electrical conductivity, ensuring the precision of sensors in detecting minute currents. Meanwhile, it also results in a vast specific surface area, which furnishes ample binding sites, rendering it an ideal platform for biologically active molecules like glucose oxidase (GOx). Leveraging these advantages, CNTs significantly amplify the sensitivity and stability of glucose biosensors, thereby revolutionizing diabetes management strategies.

In the context of minimally invasive glucose monitoring, CNTs address the challenges of biocompatibility and inflammatory reactions commonly encountered by conventional sensors in vivo. Through innovative designs, including meticulously crafted functionalized CNT helical fiber bundles, gradient-structured hollow fiber membranes, and microneedle sensor arrays, researchers have achieved long-term, continuous monitoring of blood glucose levels. These advancements not only enhance measurement accuracy but also alleviate patient burden and facilitate personalized diabetes care.

Moreover, CNTs have played a pivotal role in non-invasive glucose monitoring. With the ascendancy of wearable technology, CNT-based sensors for detecting sweat, saliva, and other body surface fluids have emerged. These sensors mitigate the pain and infection risks associated with invasive procedures, enabling real-time monitoring and remote transmission of glucose levels due to their superior flexibility and conductivity. From wearable sweat sensors to MXene-based composite sensors, to innovative products such as smartwatches and smart diapers, CNTs are progressively infiltrating various aspects of daily life, offering unprecedented convenience in health management.

6. Conclusion

As the broaden of the application horizons, researches concerning with glucose biosensors would yield more significant outcomes. The modification of CNT-based glucose sensors will also be further enriched. The combination of CNT-based glucose sensors with materials which have recognition functions would be a promising modification method.

References

[1] Wu B Y, Hou S H, Yin F, Amperometric glucose biosensor based on layer-by-layer assembly of multilayer films composed of chitosan, gold nanoparticles and glucose oxidase modified Pt electrode, Biosensors & Bioelectronics 22 (2007) 2854 - 2860.

[2] Zhu Z G, Garcia-Gancedo L, Chen C, Enzyme-free glucose biosensor based on low density CNT forest grown directly on a Si/SiO2 substrate, Sensors and Actuators B Chemical 178 (2013) 586 - 592.

[3] Jia F, Shan C, Li F, Carbon nanotube/gold nanoparticles/polyethylenimine-functionalized ionic liquid thin film composites for glucose biosensing, Biosensors & Bioelectronics 24 (2009) 945 - 950.

[4] Wang J, Glucose biosensors: 40 years of advances and challenges, Sensors Update 10 (2002) 107 - 119.

[5] Yoo E H, Lee S Y, Glucose biosensors: an overview of use in clinical practice, Sensors 10 (2010) 4558 - 4576.

[6] Briza Pérez, Martin Pumera, Manel del Valle, Glucose biosensor based on carbon nanotube epoxy composite, Journal of Nanoscience and Nanotechnology 5 (2005) 1694 - 1701.

[7] Wooten M, Karra S, Zhang M, On the direct electron transfer, sensing, and enzyme activity in the glucose oxidase/carbon nanotubes system, Analytical Chemistry 86 (2014) 752 - 758.