Variation of Sensitivity of Biosensor Based on Carbon Nanotubes

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Abstract
In this work, a biosensor was designed and assembled from carbon nanotubes (CNTs) structure for biomedical applications. The characteristics of this biosensor were determined after the optimization of the performance parameters on synthetic species. In practical use, the sensitivity of the biosensor was determined as a function of the CNTs size and it was found to decrease exponentially with increasing the size of CNTs.

Keywords*:* carbon nanotubes; Biosensors; Functional materials; Biomedical applications
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1. Introduction

Carbon nanotubes (CNTs) have emerged as one of the most promising nanomaterials in the field of biosensing due to their exceptional mechanical, electrical, and chemical properties. Their high surface area, excellent electrical conductivity, and ability to interact with biomolecules at the nanoscale make them ideal candidates for enhancing the sensitivity and functionality of biosensors. This article explores the design principles of CNT-based biosensors, evaluates their performance characteristics, and highlights their diverse applications [1-3].

Biosensors are analytical devices that convert a biological response into an electrical signal. A typical biosensor comprises a bioreceptor (such as an enzyme, antibody, or DNA probe), a transducer, and a signal processor [4,5]. CNTs can serve as the transducer material or as a platform for immobilizing bioreceptors, significantly improving the sensor's sensitivity, response time, and limit of detection [6].

CNTs are categorized as single-walled (SWCNTs) or multi-walled (MWCNTs) based on the number of graphene layers rolled into cylinders. Both types have been extensively explored in biosensing, with SWCNTs offering better electronic properties and MWCNTs providing greater surface area and ease of functionalization [7-9].

To interact with biological molecules, CNTs must be functionalized, either covalently or non-covalently. Covalent functionalization involves attaching functional groups directly to the CNT surface via chemical reactions (e.g., oxidation to introduce carboxyl groups). This provides strong binding sites but can disrupt the CNT's electronic structure. While non-covalent functionalization utilizes π–π stacking, van der Waals forces, or hydrophobic interactions to bind biomolecules, preserving the CNT’s electrical properties [10-12].

The versatility of CNTs has led to their application in numerous fields. In medical diagnostics, glucose monitoring and enzyme-based sensors using CNTs for diabetic glucose control offer real-time, highly sensitive readings [13]. For cancer biomarkers, CNT-FET sensors detect specific cancer markers such as PSA (prostate-specific antigen) or CEA (carcinoembryonic antigen) at ultralow concentrations [14]. For infectious diseases, CNT immunosensors detect viral or bacterial pathogens like HIV, H1N1, or SARS-CoV-2 quickly and accurately [15]. In the environmental monitoring, CNT biosensors are used to detect environmental toxins, heavy metals (like lead or mercury), and pesticides with high sensitivity, aiding in pollution control and public health protection [16]. In food safety, pathogen detection can be performed by identifying bacteria such as *E. coli* or *Salmonella* in food products [17]. Toxin monitoring can be carried out by detecting aflatoxins or other chemical residues in agricultural produce [18]. In biowarfare and security, CNT-based biosensors can be engineered to detect biological warfare agents like anthrax spores or nerve agents, providing rapid alerts in military or public safety scenarios [19]. In wearable and implantable devices, the integration of CNT sensors into flexible substrates and textiles enables real-time health monitoring in wearable devices. CNTs’ biocompatibility also opens the door to implantable biosensors for long-term physiological tracking [20].

CNT-based biosensors outperform many traditional sensors due to parameters such as the sensitivity as CNTs provide a large surface area-to-volume ratio and superior electron transport, enabling the detection of extremely low concentrations of analytes—often down to femtomolar levels. Second parameter is the selectivity where the use of highly specific bioreceptors (e.g., antibodies, aptamers) ensures strong selectivity [21]. Additionally, surface modifications and nanocomposites (e.g., CNT-metal nanoparticles) can further enhance specificity. Third parameter is the response time as the fast electron transfer and nanoscale proximity of the recognition element to the transducer result in rapid detection, often within seconds to minutes. Stability and reusability are important because CNT biosensors are stable over a wide range of temperatures and pH conditions. However, long-term stability and reusability depend on the bioreceptor's durability and the sensor's anti-fouling characteristics. Owing to their nanoscale dimensions, CNT biosensors can be miniaturized for integration into portable or wearable devices, facilitating point-of-care testing and continuous monitoring [22].

Despite their potential, CNT-based biosensors face several challenges. Toxicity and biocompatibility, while CNTs are generally biocompatible, their safety profile depends on size, purity, and functionalization. Long-term effects in vivo remain under investigation. Manufacturing scalability as producing uniform and defect-free CNTs at industrial scale is still a technical bottleneck. Sensor reproducibility because ensuring consistent performance across batches is difficult due to variability in CNT properties. However, ongoing research in nanofabrication, surface chemistry, and machine learning for signal processing is rapidly advancing the field. Hybrid materials—such as CNTs combined with graphene, polymers, or metal-organic frameworks (MOFs)—offer promising avenues for multifunctional and multiplexed sensing platforms [23].

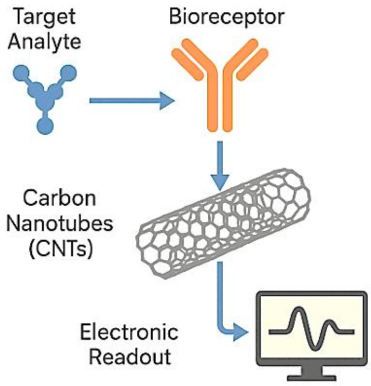
2. Experimental Part

Depending on the target analyte, CNT biosensors incorporate various bioreceptors such as enzymes used in glucose and urea sensors, antibodies used for detecting pathogens or proteins (immunosensors), nucleic acids employed in detecting DNA/RNA sequences and mutations, and aptamers synthetic oligonucleotides offering high affinity for a broad range of targets. Figure (1) schematically and photographically explains the contents of a CNTs-based biosensor.

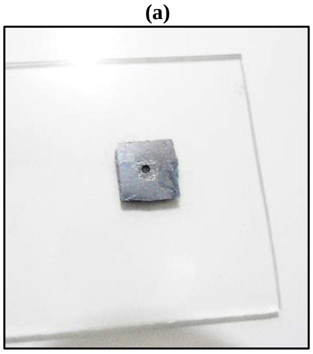
CNTs enable multiple modes of signal transduction. Electrochemical is the most common method, measuring changes in current, potential, or impedance. Field-effect transistors (FETs) where CNTs act as the semiconducting channel; changes in conductivity occur upon binding of the analyte. Optical fluorescence or Raman signals are modulated by interactions with analytes. Piezoelectric detects mass change upon analyte binding (less common for CNTs).

3. Results and Discussion

Figure (2) illustrates an inverse relationship between the size of carbon nanotubes (CNTs) and the sensitivity of CNT-based biosensors. As the size of CNTs increases, the sensitivity decreases. This trend arises because smaller CNTs have a higher surface area-to-volume ratio and better electronic properties, enabling more effective interaction with target analytes and faster electron transfer. Smaller CNTs also facilitate tighter binding of bioreceptors and improve signal transduction. Consequently, optimizing CNT size is crucial in sensor design to maximize performance. However, practical considerations like fabrication complexity and biocompatibility must also be taken into account when selecting CNT dimensions.



(a)



(b)

Fig. (1) (a) Schematic explanation, and (b) a photograph of the fabricated CNTs-based biosensor

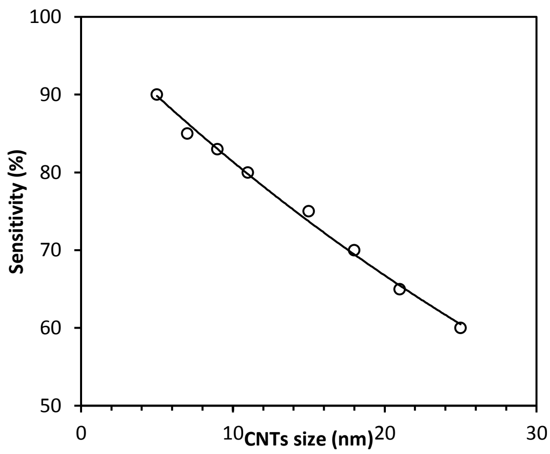


Fig. (2) Variation of biosensor sensitivity with CNTs size

4. Conclusion

Carbon nanotubes have revolutionized the design and capabilities of modern biosensors. Their unique physicochemical properties allow for the development of highly sensitive, selective, and compact sensing devices that span a wide range of applications from healthcare to environmental monitoring. As fabrication techniques improve and biocompatibility is better understood, CNT-based biosensors are poised to become integral to next-generation diagnostic and analytical tools.

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