Introduction to nano-biosensors

The Fundamental Science of Nanotechnology Assignment 1

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Since the start of the 21st century, the integration of nano-materials with biological materials, in creation of electronic elements for specific biosensing purposes, has undergone significant advances. This integration of nanotechnology in biosensors can confer considerable improvements to the sensitivity, efficiency, and range of applications of instruments in the field. This has been reflected by a continued growth in development of nano-biosensors, fostering considerable advancements in the technology in recent years. With a focus on detection principles of biosensors, the basic mechanisms and functionality of nano-biosensors are outlined in this report, alongside illustrative examples of applications in the field.

I Introduction to (nano)-biosensor:

Biosensors are analytical devices designed to detect and quantify the presence of specific biochemical molecules. The functionality of a biosensor is grounded in employing biomaterials such as DNA, peptides, proteins and cells, which are widely used to exhibit electron transfer properties. [6] So-called nano-biosensors are biosensors which combine such biomaterials with nanomaterials that also have electronic properties, such as carbon nanotubes or metallic nanoparticles. [10] The sensitivity and performance of a biosensors can be greatly improved with the introduction of nanotechnology. Many new biosensor designs are being made possible by recently developed novel bioelectronics and submicron-scaled systems. Today, the development of nano-biosensors is being established as an emerging interdisciplinary field encompassing bioscience, physics, chemistry, materialogy, electronics and nanotechnology. [15]

II Components and their functions of (nano)-biosensors:

(Nano)-biosensors consist of three main functional components: the bioreceptor, transducer, and detector [9]. An understanding of the basic mechanisms of nano-biosensors can be gained by considering the functionality of each component in turn.

II.1 Bioreceptor (material which analyses):

The bioreceptor is the component that is specifically tuned to the detection of the target bioanalyte. [9] The target bioanalyte can be a substance or chemical constituent undergoing bioanalysis, such as antigen, antibody or any other bioactivators. The selectivity of the bioreceptor will determine the specificity of the biosensor. This specificity is additionally often reciprocal; for instance, the detection of an antibody might be achieved with an immobilised antigen in the biosensor and vice versa.

II.2 Transducer (signal conversion):

The transducer is responsible for signal conversion of a biochemical input quantity, resulting from the interaction between the bioreceptor and its target bioanalyte, into an electrical output. [9] Transducers vary in the specific signals that they are sensitive to, with the most suitable transduction method being that which most accurately quantifies the biochemical activity of the bioreceptor in response to the bioanalyte, across the range of possible concentrations of the bioanalyte. The transducer element can be considered a 'labeller', in charge of converting the biological recognition interaction into a type of signal that we are able to observe and measure. Examples of analysed signals, resulting from the bioreceptor's interaction with the bioanalyte, include an electrical charge, a magnetic field or a colour change.

II.3 Detector (reproducible response):

The electrical output provided by the transducer is finally amplified and analysed by the detector, providing a quantified measure indicative of the concentration, or degree of confidence in presence, of the bioanalyte. [3] The detector system receives the electrical signal from the transducer component and amplifies it appropriately so that the corresponding response can become more readable. In a complete system, the detector cooperates with a display consisting of the elements in charge of adapting and showing corresponding signals allowing the operator to interpret the detected response. [14]

III Different detection principles:

(Nano)-biosensors have various detection principles, which can be determined by the detection process of their transducer components. Based on the differences in potential signal sensitivity, four main types of transducers can be identified, sensitive to electrochemical, optical, thermal and piezoelectric changes in the bioreceptor [4]. Some detection mechanisms result solely from the congregation of nanomaterial properties, such as biosensors with transducers sensitive to piezoelectric changes. Nevertheless, the different types of transduction are vastly improved by an array of different properties of nanomaterials, such as in optical and thermal transducers.

III.1 Electrochemical biosensors:

The first and the most common detection principle is electrochemical, applied in several varieties of nano-biosensors. These sensors essentially work to facilitate or analyse the biochemical reactions with the help of electrical particles and metallic nanoparticles, which can be divided into two groups: amperometric and potentiometric-based biosensors. [9]

III.1.1 Potentiometric-based biosensor

Carbon and silicon are utilised as field-effect transistors (FETs) nanomaterials in semiconductor devices. Such FETs function by modulating conductance between the source and drain terminals from 'off' to 'on' states is achieved by a gate electrode coupled to the semiconductor. [8] The incorporation of this threshold dependency in FETs makes them ideal for implementation in biosensors that require detection of electrical signals, facilitating their application in a wide range of different biosensors specialised for detection of distinct bioanalytes. [13]

III.1.2 Amperometric-based biosensor

While research has often focused on the potential applications of detecting cations, anions, gases, and platinum electrodes in electrically-based nano-biosensors [1, 17], a parallel development has been the utilisation of measuring the current in redox reactions, as an alternative mechanism for biorecognition [13].

To highlight one example, Wang et al. [16] outline a nano-biosensor that electrochemically assays for adenosine, exploiting interactions between gold nanoparticles and Ruthenium (II) tris(bipyridine). [11] The aptamer developed in this instance is in a double-stranded form, capable of detecting adenosine in single-strand DNA with a high degree of sensitivity. The accuracy and selectivity of the complex are additionally shown by the insensitivity of the aptamer to related nucleoside molecules of guanosine and cytidine. [5] Such methods show considerable promise as feasible techniques, demonstrating a combination of structural simplicity (underpinning their low cost) and high-quality response characteristics.

III.2 Piezoelectric biosensor:

Another detection principle is piezoelectric detection. Biosensors that utilise this principle are capable of producing an electrical signal when stressed mechanically. An example can be seen in the vibrating silicon crystal transducer. [9] Referred to as piezoelectric crystals, these transducers serve as a demonstration of the piezoelectric effect more generally. The working principle is that when the crystal is deformed by an external stress, electric charges appear on certain portions of the crystal's surfaces; and when the direction of the strain reverses, the polarity of the electric charge is reversed.

III.3 Optical biosensor:

Optical detection is achieved with the use of an immobilized reagent, able to interact with the analyte to produce a complex with distinctive optical properties, which the biosensors are sensitive to changes in. [18] One example is seen in DNA fluorescence technology. While DNA is perhaps best known for storing genetic information, artificially synthesised DNA can also be used to exploit the molecule's structural and material properties. When synthesised DNA is placed in water, it acquires a strong negative charge. It has been established that this property of DNA can be used to increase the precision of a biosensor. [7] This technology has two parts, artificially synthesised antibodies to interact with and capture the target proteins, and signal converters to measure whether the proteins have been captured or not. The artificial antibody and the signal converter are based heavily on the structure of DNA. The fluorescent dye is added, and when the antibody captures its target protein, the fluorescent pigment goes dark. From changes in the degree of the fluorescence, the system can quickly and accurately measure whether the protein is present, and can be used to infer in what concentration the protein is present. [18]

III.4 Thermal biosensor:

Most biocatalytic reactions generate heat. It follows that accurate measurements of this heat generation, combined with biological elements, can be used to build biosensors sensitive to a range of materials which are involved in such biocatalytic reactions. In essence, the thermal transducer is a small calorimeter, with a highly sensitive thermometer which can normally detect a temperature change in the scale of a millidegree. [9] Such efficient measurement of changes in temperature can significantly improve the sensitivity of a biosensor. For example, 'Heatsens' is an ultra-sensitive technology born from research on the nanomaterials of gold nanoprisms. [12] These gold nanoprisms show interesting properties in certain contexts. When exposed to a source of energy in a given frequency, they convert almost 100% of light energy into heat, such that biosensors which use these gold nanoprisms as a label can achieve much higher sensitivity in their calorimeters, and much greater sensitivity to their target bioanalytes as a holistic system. [2]

IV Future development:

The combination of nanotechnologies and biotechnologies is at the frontier in the development of biosensors, and is currently a considerable 'hotspot' in research. Nanomaterials have been broadly applied in biomedical and diagnostic contexts, with a clear possibility of industrialisation in the field of nano-biosensors. Future research in areas such as biomedical treatments, biosafety of nanomaterials, biochip technology and nanobots are expected to receive more focus in coming years. Integration of nanomaterials in biosensors will lead to new breakthroughs in the development of novel nano-biosensors, with applications in a wealth of fields.

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