Application of Biosensors in Cancer Diagnosis

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Abstract. Prostate cancer is one of the most prevalent malignant neoplasms in males, and early detection is of paramount importance for improving patient survival rates. In recent years, nanobiosensors have demonstrated considerable promise in the domain of early cancer detection, largely due to their exceptional sensitivity and specificity. This paper presents a review of the research progress made in the field of nanobiosensors for the early detection of prostate cancer. It includes an examination of the selection of nanomaterials, sensor design, and innovations in detection techniques. This paper discusses the composition and function of biosensors, cancer diagnosis, and the detection of tumor markers. It also discusses the design and advantages of nanosensors, the challenges in clinical application and future development, as well as their potential impact in promoting personalized medicine and early intervention. In summary, nanobiosensors provide new ideas for the early detection of prostate cancer. Future research should focus on improving the stability and throughput of the sensors to achieve wider clinical application.

Keywords: Nanobiosensor; cancer biomarker; early diagnosis.

1. Introduction

Prostate cancer has become one of the most prevalent malignant neoplasms in men globally, and early detection is of paramount importance for enhancing treatment efficacy and patient survival. Conventional detection techniques, such as prostate-specific antigen (PSA) testing, are commonly employed; however, they are not without limitations in terms of specificity and sensitivity. In recent years, nanobiosensors have emerged as a prominent area of research in the field of early cancer detection, driven by their superior performance and diverse application prospects. The specificity of nanomaterials enables biosensors to achieve efficient detection at very low biomarker concentrations, which has fueled innovation in early screening methods for prostate cancer. This study aims to review the latest advancements in nanobiosensors for the early detection of prostate cancer and explore their potential applications and future development directions.

2. Biosensors and Cancer Diagnostics

2.1. Biosensor

An apparatus that is sensitive to biological materials and can detect them by converting their concentration into an electrical signal is called a biosensor. It is an analytical tool or system that includes immobilized biosensitive materials as signal amplification devices, suitable physicochemical transducers (such as oxygen electrodes, photosensitive tubes, field effect tubes, piezoelectric crystals, etc.), and recognition elements (such as enzymes, antibodies, antigens, microorganisms, cells, tissues, nucleic acids, and other biologically active substances).Biosensors are both transducers and receivers. A conversion component (transducer) and a molecular recognition component (sensitive element) make up the composition structure of the biosensor. The primary functional component that can result in a physical or chemical change is the molecular recognition component that identifies the target to be measured. The selective identification of biosensors, which are physical or chemical transducers (sensors) that translate signals from physiologically active expression into electrical signals, is based on the molecular recognition component.

Biosensors generally have three functions. Firstly, the first one is detection, by extracting biological materials, including biological tissues, microorganisms, organelles, enzymes, antibodies, antigens, nucleic acids, DNA, etc., in which plants and animals play a perceptual role. Enabling mass production of biomaterials or biomaterial-like materials, reusing them repeatedly, and reducing the difficulty and cost of testing. The second is conversion, i.e., converting the continuous, regular information sensed by biological material into information that people can understand. The last one is to present information to people through optical, piezoelectric, electrochemical, temperature, and electromagnetic means to provide a basis for decision making.

2.2. Cancer Diagnosis

Cancer diagnosis generally includes preliminary diagnosis and pathological diagnosis. Pathological diagnosis is the gold standard of diagnosis, through which the diagnosis of cancer can be further confirmed.

Initial diagnosis of cancer is mainly made by various imaging methods, such as CT examination, which detects tiny lesions in the human body by transmitting the measured data to a computer to form cross-sectional and three-dimensional images of the part of the human body being examined through the different transmittance and absorption rates of X-rays by different tissues of the human body. In addition, ultrasound can be used to examine the body's organs through ultrasound. However, the above is only a preliminary determination of the tumour and may be subject to some error.

Pathological diagnosis is mainly through puncture biopsy or surgical excision, etc., the cells of the possible lesion site are taken, and the excised part of the tissue is examined in detail to determine whether malignant tumour is present. It is through these steps that the final and correct judgement of the tumour can be made.

2.3. Common Cancer Markers and Their Associated Cancers

Cancer markers are a class of substances that are characteristically present in, or abnormally produced by, malignant tumour cells, or produced by the host in response to a tumour stimulus, and that reflect tumourigenesis and progression, and monitor the tumour’s response to treatment. Cancer markers are present in the tissues, body fluids and excretions of patients with tumours and can be detected by immunological, biological and chemical methods.

These are a few typical cancer indicators along with the diseases they are linked to. The MUC16 gene encodes the glycoprotein CA-125, sometimes referred to as mucin-16, which is found in epithelial ovarian carcinoma antigen and may be bound by the monoclonal antibody OC125.CA-125 has not been extensively utilized for screening in women who do not exhibit any symptoms, and its potential relevance in the early diagnosis of ovarian cancer is debatable. Prostate cancer screening is the main purpose of the PSA test. The prostate-specific antigen (PSA) level in the blood is determined by this test. The prostate is a tiny gland in men that sits just below the bladder. Both malignant and non-cancerous tissues of the prostate produce PSA.There is usually a small amount of PSA circulating in the bloodstream.PSA testing can detect high levels of PSA, which may indicate the presence of prostate cancer.Carcinoembryonic antigen CEA is a glycoprotein found in mucosal cells. Normally oncoproteins are produced in the gastrointestinal tissues during foetal development, but the substance is no longer produced after birth. Therefore healthy adults usually have very low levels of oncoproteins in their blood (about 2-4 ng/ml). However, patients with certain types of cancer have elevated levels of carcinoembryonic antigen in their blood, which means that carcinoembryonic antigen levels can be used as an indicator when people are being screened for cancer. Heavy smokers are also likely to have elevated levels of carcinoembryonic antigen in their blood. Levels of these markers may vary depending on individual differences, cancer type, and stage of disease, so they are often used in conjunction with other tests and clinical information.

2.4. Detecting Cancer Markers

Imaging tests are certain types of imaging tests, such as X-rays, ultrasounds, or CTs, that your doctor will perform when he or she first suspects cancer. For example, a chest X-ray may be performed on a person with a chronic cough and weight loss. A CT or MRI of the brain may be performed on people with recurrent headaches and vision problems. Although the presence, location, and size of an abnormal mass can be determined by these tests, they are unable to verify that cancer is the cause.

Biopsy refers to the identification of cancer by obtaining a sample of the tumour with the help of a puncture biopsy or surgery and examining the sample from the suspected area with the help of a microscope to find the cancer cells. Usually, the sample must be a piece of tissue, although sometimes a blood test is sufficient. Obtaining a tissue sample is called a biopsy. A biopsy can be performed by cutting off a small piece of tissue with a scalpel, although quite commonly a hollow needle is used to obtain a sample.

Blood tests, which are the most common method, measure specific markers by drawing a blood sample. For example, PSA, CA-125 and CEA can be detected in the blood.

Urine testing is where certain cancer markers can be detected in the urine, such as some metabolites or specific antigens in the urine.

3. Application of Prostate Cancer Detection and Its Characteristic Advantages

There are many applications of biosensors in cancer diagnostics, including novel molecularly imprinted biosensors for cancer biomarker detection [1]; electrochemical biosensors for the detection of tumour markers in breast cancer[2]; and nano-biosensors for the early detection of prostate cancer[3].

The application of nanobiosensors in the early detection of prostate cancer was proposed by Zhao Bin et al[3].In their paper, the team investigated nanosensing modalities for prostate cancer marker detection’s is considered the most sensitive indicator for the diagnosis of prostate cancer in modern science, and is mainly used with the early diagnosis, treatment, monitoring and prediction of recurrence of prostate cancer. Early diagnosis of prostate cancer has always been a challenge to be overcome in the medical field, and the combination of nanotechnology and biosensors to build nanobiosensors provides important help for both early diagnosis and treatment of prostate cancer, the authors of this paper investigated the nanosensing mode of the nanobiosensors for the detection of prostate cancer markers. The key technologies for this biosensor are nano-bioprobe design and nano-interface signal transduction.

3.1. Nanobiosensor

The design of the nanobioprobe is mainly composed of nanogold, carbon nanomaterials and quantum dots.

Nanogold a has advantages such as good biocompatibility and stable and reliable coupling chemistry. In 2003 Nam et al[4] invented a nanogold-based bio-strip assay technique BCA for the ultra-sensitive detection of PSA, in which the authors showed how nanoparticles enhance the sensitivity and specificity of the assay, allowing effective identification of proteins even at low concentrations. This technology has the potential for a wide range of applications in biomedical research and diagnostics. Yan et al[5] invented NanoRCA, a nanorolling amplification technology based on nanogold composite probes, for ultra-high sensitivity analysis of cancer markers by integrating RCA, a DNA roll-over amplification technology, with nanogold composite probes with each other. Because the extremely high amplification capacity of RCA results in the loading of a large number of signaling molecules into the analytical system, it provides ultra-high sensitivity for the detection of PSA molecules at 30aM in serum. In this way, researchers are able to efficiently detect low concentrations of proteins in complex biological samples. This technology has important applications in early disease diagnosis and biomarker discovery.

The carbon nanomaterials used in the design of the nano-bioprobes are called carbon nanotubes CNTs, a one-dimensional carbon nanomaterial with a special structure that is characterised by excellent electrical properties and a large specific surface area. Yu et al[6] invented an electrochemical immunosensor combining a multi-walled carbon nanotube composite probe and a single-walled carbon nanotube forest for the highly sensitive detection of PSA in biological samples, and then co-assembled the HRP signalling molecule and the secondary antibody onto the multi-walled carbon nanotubes to prepare a multi-labelled multi-walled carbon nanotube composite probe, which resulted in a substantial increase in the sensitivity of the assay. By utilising the highly sensitive detection technology of carbon nanotubes, PSA can be detected at an earlier stage, enabling early diagnosis and intervention. This is of great significance in improving the therapeutic effect of prostate cancer and improving the prognosis of patients. There is also graphene, a two-dimensional carbon nanomaterial based on a single layer of carbon atoms. Because graphene flakes have good electrical conductivity and a large specific surface area, they can be used to achieve highly sensitive detection of PSA with good reproducibility and stability.

Quantum dot QDs, a new type of fluorescent marker with the advantages of broad excitation and narrow emission, high photostability, high resistance to photobleaching as well as ease of diversification, are ideal nanobioscopes.

3.2. Nano-Interfacial Signal Transduction

Consists of field effect transistors, microcantilever beams, plasma nanosensors and DNA nanotechnology.

3.2.1 Field Effect Transistor

A field effect transistor, also known as a field effect tube, is a semiconductor device that controls the magnitude of the output current by controlling the electric field effect of the circuit input. In recent years, FET biosensors using nanomaterials, such as nanowires and nanotubes, as sensing elements have received more and more attention due to their advantages of no labeling, real-time detection, high sensitivity and easy integration and miniaturization. Kim et al[7] reported a reduced graphene oxide FET biosensor for highly sensitive detection of PSA-ACT. The method has a wide dynamic range and good linear response, which is favorable for prostate cancer monitoring. Especially in the early stage, this test not only improves the accuracy of the test, but also may reduce the cost and simplify the operation process, which has important clinical application value for the early diagnosis and monitoring of prostate cancer.

3.2.2 Microcantilever Beam

A Microcantilever beam is a device that transfers to nanomechanical signals and works by converting surface molecular interactions into mechanical deformations or resonant frequency changes. It is characterized by its small size, fast response time, high sensitivity as well as easy integration. Such devices have been used in a variety of bioanalytical fields, including DNA hybridization, single-base mismatch detection, and detection of tumor markers. Wu et al [8] were the first to report the microcantilever beam sensing technique applied to PSA detection. Since PSA is an important indicator for early diagnosis of prostate cancer, PSA detection using microcantilever beam technology is of great clinical importance. This novel sensor not only realizes high-sensitivity detection, but also simplifies the operation process and reduces the detection cost, providing an effective tool for early screening and monitoring of prostate cancer.

3.2.3 Plasma Nanosensors

Plasmonic nanosensor is an optical sensor built on the localized surface plasmon resonance LSRP effect based on metal nanoparticles. As a new type of optical sensor, it has shown an increasingly wide range of applications in the aspect of cancer diagnosis, and is of great clinical significance for the early detection of prostate cancer as well as the diagnosis of predicting recurrence after surgeryRodríguez-Lorenzo et al [9] reported a metal plasma nanosensor for early diagnosis of prostate cancer.In prostate cancer detection, important biomarkers such as PSA are usually present at very low concentrations. The enzyme-directed crystal growth plasma nanosensor technology proposed in this article enables highly sensitive detection of these low concentration markers. The application of this technology may significantly improve the early detection of prostate cancer, which in turn may improve the prevention of late-stage and therapeutic outcomes for patients.

3.2.4 DNA Nanotechnology

An emerging frontier cross-cutting field in recent years refers to nanotechnology based on the physicochemical properties of DNA. This technology utilizes DNA with its unique physicochemical properties as well as the superiority of DNA replication to build precise bottom-up nano-architectures, which are used in several applications, including the detection and treatment of cancer markers. The advantages and benefits of this technology are high sensitivity and high specificity, the nanorolling amplification technology based on nanogold composite probes can detect PSA at very low concentrations as well as the ability to detect PSA in prostate cancer tissue samples that are indistinguishable from conventional immunohistochemical staining. This is crucial for the early diagnosis of prostate cancer. Wen et al [10] reported a method for miRNA analysis of prostate cancer markers. miRNAs play an important role in the development and progression of prostate cancer; therefore, rapid and sensitive detection of these miRNAs can provide valuable information for early diagnosis and surveillance. By Wen et al [11] , a rolled-loop amplified DNA molecular machine was developed for the ultrasensitive detection of multiple miRNAs This method can effectively detect miRNA markers that identify prostate cells and cancer cells. Ultrasensitive detection of miRNAs associated with prostate cancer and improved early diagnosis and monitoring of prostate cancer can be achieved by utilizing the DNAzyme rolled-loop amplification technology in this study.

4. Challenges of current technologies and future developments

The current nano-biosensors for prostate cancer detection methods have not been all unified standards, standardization is not unified by may affect the diagnosis and treatment of clinical medicine. In addition, although a wide variety of technologies provide critical references for the early diagnosis of prostate cancer, there is still a need for a large number of long-term studies and trials to refine the objectivity and utility of nanobiosensors in the early diagnosis of prostate cancer.

Looking ahead, as nanotechnology and sensor designs continue to be optimized, their sensitivity, specificity and stability will continue to improve. Combining sensors with artificial intelligence may lead to clearer data analysis and reporting of results. Through continuous scientific and technological innovation and clinical experiments, the application of nano-biosensors in the early diagnosis of prostate cancer has a very broad prospect, and there is a great hope to provide a brand-new method for the early diagnosis of prostate cancer.

5. Conclusion

This paper reviews the applications of biosensors, cancer diagnostics, and marker detection.The design and progress of nanobiosensors for early diagnosis of prostate cancer are discussed, demonstrating their high stability, sensitivity, and specificity. By combining the application of nanomaterials with the design of biosensors, it shows great potential in further improving the sensitivity and specificity, offering some possibilities for early diagnosis in prostate cancer. However, so far, a large number of clinical trials as well as scientific and technological innovations are still needed to prove the feasibility of nanobiosensors for the early diagnosis of prostate cancer. Perhaps the technology can also be gradually stabilized by changing the design of the nanomaterials, the nature of the biosensor, and other aspects.

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