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Development of electrochemistry-based biosensors in medical field

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ABSTRACT

Electrochemical biosensors are a significant field that examines the electrical properties and energy conversions of chemical reactions used to determine or sense biologically and environmentally substantial analytes in laboratory settings. Electrochemical biosensors sophisticated based on these principles have recently occurred as wearable and portable biosensors, point-of-care devices that everlastingly monitor target analytes in a real-time environment and alert target users to abnormalities. Thanks to its high sensitivity, low cost, portability, and quick response times, it submits a wide series of applications in many areas, especially in medicine. These sensors, capable of showing amperometric, potentiometric, and conductometric measurements, make use of electrode materials such as gold, silver, carbon, and platinum. Electrochemical biosensors, which first entered clinical use in glucose testing, are now broadly used in the detection of cholesterol, cancer biomarkers, and other critical molecules. Developments in nanotechnology and artificial intelligence have further enhanced the sensitivity, specificity, and clinical applicability of these systems. Integration with wearable and portable devices is making a remarkable contribution to the improvement of personalized health monitoring systems. This mission aims to evaluate the historical development of electrochemical biosensors, their current medical applications, and their future potential within an extensive framework.

Keywords: Electrochemistry, Biosensor, Nanotechnology.

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INTRODUCTION

Electrochemistry is a scientific discipline that examines the electrical features of chemical phenomena and is of critical significance to many disciplines, primarily the basic sciences, additionally engineering and health sciences. With advancing technology today, electrochemistry, which has accomplished a substantial place in modern technology, has the potential to produce solutions to global challenges such as energy, the environment, and medical diagnostics.[1–3] This discipline, which studies the interaction between electrical and chemical processes, plays a central role in the progress of biomedical devices and biosensor technologies. Electrochemical sensors enable the chemical detection of molecules in biological samples such as blood, urine, saliva, and tears, and are broadly used in clinical applications.[4]

The first applications of electrochemistry in the field of medicine date back to the mid-20th century, and the development of a glucose sensor based upon glucose oxidase in 1960 marked a milestone in the diagnosis of diabetes. Blood glucose meters, which are broadly used in healthcare today, are one of the most prevalent medical applications of electrochemical technologies. Furthermore, electrochemical methods are also used in areas such as DNA analysis, detection of cancer biomarkers, and measurement of many biochemical parameters. Advances in nanotechnology have significantly in enhanced the sensitivity and selectivity levels of electrochemical sensors, contributing to the widespread use of DNA-based biosensors in modern diagnostic methods. Electrochemistry maintains to increase its impression in medical diagnosis, treatment, and biotechnology applications today.[5,6] Consequently, the integration of smart technology, nanotechnology, and artificial intelligence with electrochemistry performs an innovative and strong potential for the prognosis, early diagnosis, and treatment of deadly diseases in the future.

ELECTROCHEMICAL BIOSENSORS

Electrochemical biosensors are analytical systems that integrate biosensing processes occurring at the electrode surface with electrochemical measurement techniques that rely on changes in voltage, current, conductivity, or impedance. The high specificity of these sensors arises from the selective binding of biorecognition elements to their target molecules, which significantly minimizes interference from matrix components. These platforms are capable of detecting very low concentrations of analytes in biological samples.[7]

In electrochemical biosensors, biorecognition events directly modulate the electrochemical behavior of the electrode surface, forming the basis of the detection mechanism. These mechanisms include enhanced or restricted access of species to the electrode surface, alterations in the transport of ions or charge carriers, and modulation of redox probe interactions with biorecognition elements through electrostatic affinity or intercalation. Electrochemical biosensors are classified as amperometric/voltammetric, potentiometric, conductometric, or impedimetric sensors based on their signal transduction mechanisms and the electrochemical detection principles they employ.[8]

Compared to other biosensor technologies, optical biosensors submit advantages owing to their simple detection methods and the ability to observe results with the naked eye without requiring expensive, complex equipment.[9] On the other hand Paper-based biosensors possess notable advantages such as biocompatibility, flexibility, and low cost.[10] Electrochemical biosensors stand out for their high sensitivity and selectivity. As used in combination with different sensor technologies, they may generate substantial synergy in terms of multi-signal detection, increased accuracy, and the progress of portable, economical sensing platforms.

Electrochemical Biosensors Based on Biological Recognition Elements

Electrochemical biosensors are categorized according to the type of bioreceptor or biological recognition element used.[11] This classification involves enzyme sensors, DNA sensors, immunosensors, and aptamer sensors.

- **Enzyme-Based Sensors;** Thanks to its high specificity and catalytic activity advantages, it enables the quick and certain detection of target molecules even at low concentrations. Enzymes can generate powerful analytical signals in a short time by catalyzing the reactions of small molecules. However, the sensitivity of enzymes to environmental conditions and the costly nature of extraction and purification processes are notable limiting factors in the use of these sensors.[12]
- **DNA Sensors;** It is based on base pairing between the target DNA sequence and the complementary probe. The ability to privatize DNA probes according to target sequences notably enhances the selectivity of these sensors. Moreover, when combined with amplification techniques such as PCR, DNA sensors can detect nucleic acids even at very low concentrations with high sensitivity.[13]
- **Immunosensors;** It works by utilizing the natural specificity of antigen-antibody interactions. The lack of need for signal amplification in high-concentration samples makes these sensors convenient for highly efficient and cost-effective analyses.[14]
- **Aptamer-Based Sensors;** represents the new generation of biosensor technologies. Aptamers are selected to demonstrate high specificity against specific target molecules and enable the detection of a wide range of analytes, including proteins, cells, ions, and small molecules. Their important advantages include being easier to produce compared to antibodies, being more resistant to environmental conditions, and being convenient for various chemical modifications.[15]

Electrochemical Principles and Medical Applications

Understanding electrochemical principles, both theoretical research and clinical applications, is of great significance. Electrochemistry is an analytical method that uses potential, current, or charge measurements to detect the concentration of an analyte or characterize its chemical reactivity, and is based on the study of electron transfer in oxidation–reduction reactions.[16,17] Advances in technology have improved the development of more sensitive, selective, and reliable electrochemical biosensors. The first grand step in the use of electrochemistry in healthcare was taken in the 1950s, laying the foundation for sensor technologies in this sector and paving the way for the development of numerous different biosensors in subsequent years. Today, using enzyme, antibody, DNA, or cell-based biological recognition elements to interact with analytes, it is used in many areas, including cancer diagnosis, diabetes management, and detection of environmental toxic agents.[18] Based on the principle of converting chemical energy into electrical energy, these cells have gained a notable place in modern medical applications in diagnosis and treatment processes. With advancing technology, the potential of these systems in the healthcare field gradually is increasing.

Electrochemical Approaches in Medical Diagnosis

The use of electrochemical approaches in medicine began in 1950 with Clark's development of the first biosensor, which measured oxygen by utilizing the glucose oxidase enzyme to oxidize glucose, thereby producing hydrogen peroxide. This technology revolutionized diabetes management by enabling the development of portable glucose meters in the 1960s.[5] The development of amperometric biosensors for cholesterol analysis has also provided quick, low-cost, and movable solutions in diagnostic processes.[19] Because of the high mortality rate of cardiovascular diseases, measuring cholesterol and other cardiac markers using quicker and more economical methods is clinically significant.[20,21]

Cancer is one of the leading causes of mortality worldwide, and early diagnosis is of vital significance. In clinical applications, the measurement of protein-based biomarkers offers a more affordable option compared to genetic markers, and electrochemical biosensors provide an influential alternative in this field.[22] Today, biosensor applications, which started with glucose sensors, have expanded into many areas of medical diagnosis, such as genetic testing, protein biomarkers, and the analysis of metabolic markers.

Electrochemistry in Treatment Methods

Biopharmaceuticals are complex drug products manufactured using biotechnology, and electrochemical principles play a central role in the controlled release systems of these drugs. Thanks to advances in nanotechnology, new-generation drug delivery systems have been enhanced that activate with electrochemical stimulation, control release rates, and enable targeted treatment.[23]

These systems;

- Targeted cancer therapy for tumor tissue,
- Drug delivery in neurological diseases using brain implants,
- Controlled antibiotic release in infections,
- Electrochemical bandages that release antiseptic substances during wound recovery is used in many clinical applications.[24]

Nevertheless, the limitations of traditional drug delivery systems, such as systemic toxicity, have increased the need for new-generation controlled drug delivery mechanisms. Microfluidic-based systems enable more delicate, reliable, and patient-friendly treatment approaches through liquid control at the nano/micro level.[24]

Wearable and Portable Electrochemical Devices

Wearable systems that operate on electrochemical principles have occurred as a notable innovation in personalized health management. These devices can quickly detect target analytes by operating on amperometric, potentiometric, or impedimetric principles.[25]

Wearable electrochemical sensors;

- Glucose monitoring in diabetic patients,
- Lactate measurement and performance evaluation in athletes,
- Monitoring pH and electrolyte balance is widely used in many areas.[5,26] Smartwatches, Holter monitors, antiseptic-releasing electrochemical bandages, and skin-compatible sensor surfaces have become significant components of modern health technologies.

The Future of Electrochemistry: Integration with Artificial Intelligence and Nanotechnology

The quick progress of artificial intelligence and nanotechnology has the potential to enhance the clinical performance of electrochemical systems. Early diagnosis and risk prediction in heterogeneous and complex diseases such as cancer are becoming more trustworthy with artificial intelligence-supported analyses.[27,28]

Artificial intelligence algorithms in electrochemical sensors:

- Noise reduction,
- Automatic calibration,
- Pattern recognition in multi-data analysis,
- Disease prediction can successfully perform such crucial functions.

This integration enables the development of quicker, more responsive, and clinically more effective biosensor systems.

CONCLUSION

Nanotechnology and AI-enabled electrochemical biosensors are poised to significantly transform the early diagnosis and treatment of high-mortality diseases such as cancer. The growing adoption of non-invasive diagnostic approaches is driven by the development of nanoscale and highly sensitive sensors capable of enabling early and rapid disease detection. Moreover, the integration of artificial intelligence into electrochemical data analysis enhances diagnostic accuracy and enables faster prediction of high-risk disease states. Collectively, these advancements highlight the substantial potential of electrochemical biosensing technologies to reshape future clinical practice.

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