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Bioelectric Sensor and Its Application in Medical Signal Acquisition

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Abstract: As the cornerstone of the bridge between life science and mechatronics, bioelectrical sensors have made significant progress in various scientific fields in recent years. Despite some drawbacks, this sensor distinguishes itself from others in the sense of its revolutionary sensitivity and accuracy. This paper will start from summarizing their existing technologies in the fields of medical treatment, environmental monitoring, industrial manufacturing and agricultural production, and discussing their breakthrough achievements in frontier science. Then, this paper will focus on the analysis of the research results of bioelectrical sensors in the acquisition of ECG, EEG and EMG signals, respectively emphasizing their high-precision, high resolution and immediacy, which are essential for modern medicine to detect human signals. Additionally, the paper will briefly discuss some recentpopular technologies, such as enhancing the comfort of patients wearing ECG monitoring equipment, as well as the fields favored by cutting-edge science - brain computer interface and the new bionic structure of EMG sensors, giving a comprehensive understanding of bioelectric sensors.

Keywords: Bioelectric sensors, mechatronics, ECG, EEG, EMG

1. Introduction

With the gradual improvement of electromechanical integration and the in-depth study of micro and nano bionic structures, bioelectric sensors have become widely used in the medical field.

Bioelectric sensor is a device that can detect and convert bioelectric signals, which is utilized in the acquisition and analysis of electrocardiogram(ECG), electroencephalogram(EEG), electromyography(EMG) and other medical signals. By capturing human bioelectrical signals, these sensors provide real-time and accurate health data, supplying important support for early diagnosis, treatment and follow-up monitoring of diseases.

Bioelectric sensors offer unique advantages in medical signal acquisition. Unlike electrochemical sensors, which often rely on biological macromolecules like enzymes and antibodies, bioelectric sensors use cells, tissues, or even organs as biological recognition elements. This reliance on potential and biological impedance allows for high sensitivity and high precision for signal detection . Additionally, bioelectric sensors are typically small, portable, and energy-efficient, which makes them able to continuously monitor the physiological information of patients in various environments, and they are often combined with wireless communication technology to realize remote monitoring and data transmission, which greatly facilitates patients and medical staff [1].

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In recent years, with the progress of materials science and microelectronics technology, the performance of bioelectric sensors has been continuously improved. This paper introduces sensors based on emerging materials and flexible electronic technology, as well as more new micro nano sensing structures to adapt to the complex physiological environment of the human body. It alsohighlights the advantages of bioelectric sensors in improving the efficiency and accuracy of medical signal acquisition, and finally addresses some challenges of bioelectric sensors nowadays.

2. Overview of bioelectric sensors

2.1. Development history

The development history of bioelectric sensors can be traced back to the 1960s,when American scholar Leland C. Clark Jr. proposed the concept of enzyme electrode, which marked the birth of the first biosensor. Enzyme electrode uses enzyme as a biological recognition element to detect biochemical substances by electrochemical method. This innovation has laid a foundation for the development of bioelectric sensors [2].

Bioelectric sensors progressed rapidly through the 1970s and 1980s, incorporating biomolecules such as enzymes, antibodies, and cells as recognition elements. At the same time, physical and chemical transducers are also transforming into many types of bioelectric sensors[3]. In 1985, <biosensors>, an authoritative academic journal in the field of biosensors, was published and later renamed <biosensors&bioelectronics>.

In the 1990s, bioelectric sensor technology reached commercialization. In the 21st century, the introduction of nanotechnology has brought new development opportunities for biosensors. The high surface area and unique physical and chemical properties of nanomaterials have significantly improved the sensitivity and specificity of biosensors. For example, the use of quantum dots and nanowiresin the construction of biosensors. Today, bioelectric sensors hold promise in disease diagnosis, environmental monitoring, food safety and other fields.

In general, bioelectric sensors has developed through many stages, from concept to technological breakthrough, to commercial application and the introduction of nanotechnology, and will continue to expand their influence in the future.

2.2. Existing technology and Application

2.2.1. Medical field

The detailed measurement of bioelectrical signals in the medical field, especially the application in EEG, ECG and EMG, is the basis of modern disease nursing and preventive medicine.

ECG sensor is among one of the most widely used bioelectrical sensors, capable of diagnosing arrhythmia, myocardial infarction, and other cardiac conditions by detecting the heart's electrical activity. Modern ECG sensors are not only used in hospitals but also in home monitoring through portable devices. Unlike older, more invasive designs, these newer sensors—using specialized integrated circuits—offer a practical solution for patients outside of hospital settings, enabling them to monitor heart health in daily life, promptly detect abnormalities, and take timely measures. [2].

EEG sensor is also very important for diagnosing nervous system diseases. EEG sensors help doctors diagnose epilepsy, sleep disorders and other neurological diseases by recording the electrical activity of the brain. Another technology closely related to EEG sensors is brain computer interface(BCI), which has become a bridge between EEG signals and mechatronics. By embedding high-precision and high-sensitivity bioelectrical signal sensors, BCI technology converts the brain's intention into control instructions by collecting and analyzing signals, allowing for the control of external devices. EMG sensor is another important kind of bioelectrical sensor, primarily detects the

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electrical activity of muscle. Widely used in sports medicine and rehabilitation medicine, its functions include, but not limited to monitoring muscle dysfunction or neuromuscular signal transmission problems. It can diagnose muscle diseases such as myasthenia gravis and amyotrophic lateral sclerosis in clinical practice, and evaluate the muscle recovery of patients in rehabilitation medicine.

In addition, bioelectrical sensors also play an indispensable role in other medical fields - the continuous blood glucose monitoring system uses bioelectrical sensors to monitor the blood glucose level of patients in real time; During the operation, the depth of anesthesia monitoring sensor can help the anesthesiologist adjust the amount of anesthetic; In the intensive care unit, bioelectrical sensors are used to monitor heart rate, respiratory rate, blood oxygen saturation and other key vital signs to help medical staff handle critical situations in time

2.2.2. Environmental monitoring

In environmental monitoring, bioelectric sensors provide high sensitivity and often use biological recognition elements like enzymes or antibodies to detect specific pollutants. However, these sensors are sensitive to environmental conditions and require a mild environment to ensure the high activity of the identification element. In some environment with extreme temperature oracid-base environment, biological proteins are at risk of deactivation.

Joshua T. Atkinson's real-time bioelectronic sensor can detect a variety of molecules by using the genetic circuit of Escherichia coli, and then use these chemicals to trigger the synthesis of color proteins, so as to generate detectable optical signals. DNA molecules in genetic information are more stable than ordinary protein molecules, and the synthesized electron transporter chain is also rapid in response. This sensor shows the advantages of low power consumption, high sensitivity and high accuracy in monitoring thiosulfate, an anion that causes microbial bloom. Despite the slower response time, synthetic biology and material engineering improvements have reduced detection time to minutes [3].

2.2.3. Industrial manufacturing

In industrial production, bioelectric sensors are essential for monitoring and controlling fermentation process, enzyme reaction and other biochemical processes. These sensors can provide real-time data to help optimize the production process, improve production efficiency and product quality. For instance, conductive materials immobilized with oxidoreductase enable bioelectrocatalytic sensors, facilitating green manufacturing processes Composite conductive materials are mainly carbon materials such as graphene and carbon nanotubes, and composites formed by metal oxides, conductive MOF and polymers [4].

2.2.4. Agricultural production

Bioelectric sensors are used in precision and smart agriculture to measure soil moisture, pH, nutrient content, and pollutants, improving crop quality and food safety[5].

As for agricultural products, when there is a need to determine the characteristic parameters of a certain kind of livestock (such as broiler hens), the bioelectric sensor can use its impedance technology to simplify the original cumbersome steps. Studies have shown that abdominal fat deposition in broiler breeders is closely related to the development and maturity of the reproductive system and the performance of reproductive function [6]. Nutrients used for fat deposition in the laying period will affect the laying rate, egg quality, and the maintenance time of the peak period of laying, reduce the production performance[7], and at the same time, it will cause fatty liver syndrome, leading to the increase of the mortality rate of chicken flocks, which will seriously affect the breeding efficiency. The measurement method of abdominal fat content of broiler breeders can be accurately measured by bioelectrical impedance technology, avoiding the traditional slaughter anatomy method, and further improving the efficiency [8].

3. Frontiers in bioelectric sensor research

Bioelectric sensors are on the forefront of biomedical technology revolution. Its ultimate mission is to integrate electronic circuits, organic biology and medical model.

The organic matter sensor with the most power consumption is about to create a new generation of pulse meter. Elsamnah et al reported the development of new organic optoelectronic devices for pulse oximeter. The device carries out innovative and rapid medical diagnosis by measuring the rate of rhythmic contraction and expansion of the artery synchronized with the viscera[9].

One of the most promising and attractive fields is the combination of physical and electrical sensors and physical and electromagnetic medical preventive measures, which is a kind of therapy for wound healing with the help of external electric field - electrical simulation. Lagoumintzis et al. reported wireless line microcurrent stimulation (WMCs) In essence, the stress of WMCs in series can reverse the electrical leakage related to injury, short circuit the skin, and restore the physical electric field and ionization current of the affected tissue[10].

4. Application of sensor in medical signal acquisition

4.1. Electrocardiogram (ECG)

4.1.1. High precision ECG signal acquisition technology

ECG, as a non-invasive detection method, can assess the heart health by recording cardiac electrical activity. However, due to the weak and easily disturbed nature of ECG signal, the realization of high-precision ECG signal acquisition needs to overcome a variety of technical challenges.

Traditional high-precision ECG systems rely on equipment with high input impedance and low noise characteristics to ensure accuracy and signal stability. Preamplifiers usually use high-precision operational amplifiers, such as opa2333, to provide the necessary gain and noise suppression. In addition, a high common-mode rejection ratio (CMRR) is essential to effectively filter out power frequency interference and other environmental noise.

Recently, a hygroscopic sensor electrode for contact ECG signal acquisition has attracted widespread attention. This technology does not require direct skin contact, instead, it embeds a fabric electrode in a super absorbent organic polymer layer. This setup provides humidity for capacitive coupling, ensures strong coupling, and allows the measurement of stable and clear biomedical signals with a high signal-to-noise ratio [11].

4.1.2. Development of wearable ECG monitoring equipment

With the rapid development of Internet of things, big data, cloud computing and artificial intelligence, Wearable ECG monitoring equipment has gradually become the mainstream of cardiovascular disease monitoring and management. Real-time, continuous, and long-distance ECG monitoring is now crucial in the smart medical field.

These devices usually use advanced bioelectric sensing technology and Microelectronic Materials to capture and record precise ECG signals and transmit data to the medical platform in real time through mobile communication technology [2]. The high sensitivity and accuracy of bioelectrical sensors not only improve the accuracy and reliability of ECG monitoring, but also support telemedicine and home monitoring.

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4.2. Electroencephalogram (EEG)

4.2.1. High-resolution acquisition of EEG signals

The high-resolution acquisition of EEG signals has benefited significantly from the advent of ECoG sensors. Unlike traditional EEG devices that record cerebral cortex activity through scalp electrodes with limited spatial resolution, high-resolution ECoG sensors place electrode arrays directly on the cortex, allowing them to capture more detailed brain electrical activity.High resolution ECoG sensor can record EEG signals with higher spatial resolution through the electrode array directly placed on the surface of cerebral cortex. These sensor arrays are usually composed of hundreds to thousands of tiny electrodes, which can capture more subtle changes in electrical signals. For example, the latest research shows that the ECoG sensor array with 1024 or 2048 electrodes can achieve 100 times higher resolution than the traditional EEG [12]. This high-resolution recording ability not only improves the capture accuracy of EEG signals, but also provides surgeons with a more detailed brain function map during surgery, which helps to accurately locate the lesion area and reduce the damage to healthy brain tissue. At the same time, the emergence of micromachining technology enables multi electrode arrays (MEAs) to be used at the cellular level of neural interfaces. For example, the Michigan probe - a silicon based depth MEA for neural recording - has demonstrated a sufficient signal to noise ratio for single neuron resolved action potential discrimination [13].

4.2.2. Application of Brain-Computer Interface (BCI) technology

In practical applications, bioelectrical signal sensors are added more in the form of flexible electronic devices to obtain better mechanical properties compatible with the brain, and thus derive various human-computer interaction functions [14]. For example, EEG signals can be used to control prosthetics and other assistive devices to help paralyzed patients recover some motor functions, while biological limbs can transmit tactile feedback such as temperature and pressure back to neural pathways, thus simulating the input and output information of native limbs.

4.3. Eelectromyography (EMG)

4.3.1. Real time monitoring and analysis of EMG signal

There are two ways to obtain EMG signals: 1. Using needle electrodes to directly record the action potential of motor units in muscle fibers[15]; 2. Surface electromyography (sEMG) signals were obtained by surface electrodes. Modern bioelectrical sensors mostly adopt miniaturization technology, which can closely fit the skin and provide high-quality signal acquisition.

In rehabilitation medicine, by monitoring the EMG signal of patients in real time, doctors can evaluate muscle function and rehabilitation progress, and adjust the treatment plan in time. In sports medicine, similarly, athletes can assess their fatigue states and optimize training plans by wearing these sensors, so as to avoid the injury caused by overtraining.

4.3.2. New bionic structure of EMG sensor

sEMG is widely used in human machine interface (HMI) owing to its advantages of non-invasive signal acquisition and simple operation. However, the traditional wet conductive gel silver/silver chloride (Ag/AgCl) used to obtain sEMG actually has many limitations [16], such as weak signal strength and noise, electrode pads are easy to fall off from the skin with the drying of the gel, etc. In this regard, Zhou Xiao and others reported an ultra sensitive self powered motor sensor based on bionic friction nano generator (TENG) for muscle triggered communication HMI applications[17]. The sensor has high sensitivity (54.6 mv/mm), high intensity signal (± 700 MV) and wide sensing

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range (0 – 5 mm). The signal intensity is 206 times that of the traditional biopotential electromyography method. The inspiration of the device comes from the amplification effect of the vocal capsule when the male frog calls, with the generation of electrical signal determined by the physical friction performance. This dry design also just makes up for the shortage of traditional ones easily falling off. After the device is organically combined with the machine learning algorithm, it will realize the stable communication assisted HMI application and perfectly break through the bottleneck of the traditional EMG signal sensor.

5. Conclusion

Since their inception in the 1960s, bioelectric sensors have evolved significantly, supported by advances in synthetic chemistry and nanomaterials. Today, bioelectric sensors are indispensable for medical signal acquisition, offering high sensitivity, accuracy, and real-time monitoring capabilities. As commercialization and industrialization progress, bioelectric sensors are expected to reach new heights in both application and development.

To sum up, as the preferred sensor for collecting, processing and transforming all kinds of physiological information, biosensors have been supported by synthetic chemistry, nanomaterials and other technologies since their advent in the 1960s, and have a place in the academic community. Whether in terms of existing applications or cutting-edge scientific and technological achievements, it has demonstrated its unshakable position and great potential in the sensor industry. Especially in the field of medical signal acquisition, the high sensitivity and accuracy of bioelectrical sensors and its ability of real-time monitoring are indispensable. It is firmly believed that its commercialization and industrialization will push its development to a climax in the future.

References

[1] Kintzios, S. (2020). Bioelectric sensors: On the road for the 4.0 diagnostics and biomedtech revolution. Biosensors, 10(8), 96.

[2] Koyappayil, A., & Lee, M. H. (2020). Ultrasensitive materials for electrochemical biosensor labels. Sensors, 21(1), 89.

[3] Sharma, S. K., Sehgal, N., & Kumar, A. (2003). Biomolecules for development of biosensors and their applications. Current Applied Physics, 3(2-3), 307-316.

[4] Fuchs, B., Vogel, S., & Schroeder, D. (2002). Universal application-specific integrated circuit for bioelectric data acquisition. Medical engineering & physics, 24(10), 695-701.

[5] Atkinson, J. T., Su, L., Zhang, X., Bennett, G. N., Silberg, J. J., & Ajo-Franklin, C. M. (2022). Real-time bioelectronic sensing of environmental contaminants. Nature, 611(7936), 548-553.

[6] S.Z.Wang, K.L.Liu, S.Y.Wang, L.Jiang, L.X.Duan, Y.Xiong, & Z.H.Ji .(2021).Research progress in immobilization of oxidoreductase on novel materials. Journal of Fuzhou University, 49(4).

[7] R.J.Wang. (2024). Agricultural sensors: research progress, challenges and prospects Smart agriculture, 6(1), 1.

[8] Zhang.Y,et al. (2022).Study on the distribution and deposition of body fat in Wenchang Chicken. Journal of Tropical Biology, 13(3): 297-299.

[9] Y.L.Li. (2016). Correlation between fat deposition and reproductive performance in different stages of Beijing Fatty Chicken (Master'sthesis , Chinese Academy of Agricultural Sciences). https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201701&filename=1016174596.nh

[10] J.Liu, J.H.Wu, P.F.Zhu, W.Chen,& G.H.Ten. (2024). Prediction of abdominal fat content of broiler breeder hens based on bioelectrical impedance technology .Chinese poultry.

[11] Elsamnah, F., Bilgaiyan, A., Affiq, M., Shim, C. H., Ishidai, H., & Hattori, R. (2019). Reflectance-based organic pulse meter sensor for wireless monitoring of photoplethysmogram signal. Biosensors, 9(3), 87.

[12] Lagoumintzis, G., Zagoriti, Z., Jensen, M. S., Argyrakos, T., Koutsojannis, C., & Poulas, K. (2019). Wireless direct microampere current in wound healing: clinical and immunohistological data from two single case reports. Biosensors, 9(3), 107.

[13] Fong, E. M., & Chung, W. Y. (2015). A hygroscopic sensor electrode for fast stabilized non-contact ECG signal acquisition. Sensors, 15(8), 19237-19250.

[14] Zhang.M.R. (2022). The sensor array records brain signals with the highest resolution, which provides a new possibility for the medium and long-term brain computer interface research, https://www.cas.cn/kj/202201/t20220120_4822955.shtml

[15] Pochay, P., Wise, K. D., Allard, L. F., & Rutledge, L. T. (1979). A multichannel depth probe fabricated using electron-beam lithography. IEEE Transactions on Biomedical Engineering, (4), 199-206.

[16] Tang, X., Shen, H., Zhao, S., Li, N., & Liu, J. (2023). Flexible brain–computer interfaces. Nature Electronics, 6(2), 109-118.

[17] H. Tankisi, D. Burke, L. Cui, M. de Carvalho, S. Kuwabara, S.D.Nandedkar, S. Rutkove, E. Stalberg, M. van Putten, A. Fuglsang-Frederiksen, Clin. (2020). Neurophysiol, 131, 243.

[18] G.S Meltzner, J.T. Heaton, Y.B. Deng, G. De Luca, S.H. Roy, J. C. Kline, J. (2018), Neural Eng, 15,046031

[19] H. Zhou, D. Li, X. He, X. Hui, H. Guo, C. Hu, X. Mu, Z. L. Wang, (2021). Bionic Ultra-Sensitive Self-Powered Electromechanical Sensor for Muscle-Triggered Communication Application. Adv. Sci, 8, 2101020.