Advancements in Electrode Materials for Brain-Computer Interface Technology

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Abstract: BCI technology become highly focus with the delevopment of neuroscience. It uses biology signal in brain to cure diseases. Despite of the input scale, the electrode material has been divided into non-invasive electrodes, semi-invasive electrodes and invasive electrodes. Non-invasive electrodes is safe but weak in spatio-temporal resolution; Semi-invasive electrodes are implant by injection using special rheoligical preperties; Invasive electrodes can ensure the strength and the quality of EEG signals but the surgery is risky. People still find it hard to deal with the biocompability problems. This paper talking about three kinds of electrodes, their features, the materials they're using and the reason. Due to these information BCI materials is widely use in the field of medical and aerospace. They start the discussion on optimizing material formulations and manufacturing processes, improving material multifunctionality, solving material degradation and infection problems, and developing materials integrated with energy harvesting and storage functions. This paper aims to give a general and specific view of the materials BCI electrodes are using, and inspire people to dig out other complex and useful materials in the future.

1 INTRODUCTION

Nowadays, with the development of high-standard technology, people pay attention not only to building up intelligent machines but to using technology to feedback on the human body. As the action center of the human body, the study of the brain has become famous.

BCI (Brain computer input) is a field major in using electrical devices to detect brain signals, which aims to treat pathological symptoms by interfering with brain behavior using bio-electrical signals, how to create a safe and sufficient material to avoid harm to the brain and the decreases of the number of active electrodes checkpoints caused by BCI implant and develop signal strength at the same time have become a focus. Multiple implant material choices are available, including non-intrusive dry electrodes, wet electrodes, and semi-dry electrodes. The dry electrode is more efficient than the wet electrode and has more flexible changes in materials. However, it results in a relatively high skin contact impedance. Wet electrode has good signal quality and is not sensitive to motion artifacts. However, the preparation before use is cumbersome, there are health risks and it is prone to short circuits. Semi-dry electrodes combine the advantages of wet and dry electrodes. However, there are problems such as complex molding and large volume. Each electrode has its advantages, but none of them have a relatively comprehensive performance.

Scientists have studied finding new materials and have some experimental products. Truly effective and scalable electrodes have yet to be developed. The biocompatibility may become an evaluation standard when discussing the electrode, and new electrode ingredients are needed to raise the biocompatibility scales. This article aims to discuss the advantages and disadvantages of different types of electrodes, and further summarize the current application status, problems, and optimization directions of these electrodes, to put forward feasible optimization suggestions for the future development of BCI electrodes.

2 DIFFERENT TYPES OF ELECTRICAL MATERIALS

BCI electrodes work inside the brain, and others work for physical things. That's why it's necessary to put a

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strong cut-off between them. Normal electrodes develop to face increasing facility needs. To strengthen the transmission efficiency, high elastic modulus, and high density are needed, and they will ignore the low bio-compatibility in some cases, for they only need to make sure people won't be harmed by touching them by hand. But BCI electrodes are different. As a natural part of human beings, the brain is born wildly and surely will resist things outside. What's even worse is that the electrode is made of conductive material which is a build-up of ingredients with a large difference compared with the brain. That's why the BCI electrode with low elastic modulus, high porosity wet softness, and good bio-compatibility is needed (He, et al.,2020). This paper will focus on this in further detail by dividing the types of electrodes by the scale of input.

In conclusion, as the degree of implantation increases, the collected signals become more precise. As the degree of implantation decreases, biocompatibility is becoming better and safer, and the rejection reaction is weaker. The degrees of implantation ranging from low to high are classified as non-intrusive electrodes, semi-invasive electrodes, and invasive electrodes.

2.1 Non-Intrusive Electrodes

They have low risk and high safety, with good biocompatibility, wearability, and low energy consumption. And they are developing towards being more flexible, compact, lightweight and comfortable. However, they are weak in spatio-temporal resolution, wake-up response sensitivity, stability and anti-interference ability. Due to the distance of signal selecting, they have poor and unstable signal quality.

Non-implantable electrodes are mainly used for signal acquisition on the skin surface. The flexibility, conductivity, and biocompatibility of the materials are crucial. Polymer materials such as polyimide and polyurethane have low stiffness and can conform well to the skin, increasing the contact area with the skin, reducing contact resistance, and minimizing motion artifacts. Carbon-based materials, such as carbon nanotubes and graphene, not only have excellent electrical conductivity, which can efficiently conduct bioelectrical signals, but also possess good flexibility and chemical stability, contributing to the improvement of electrode performance. Nanomaterials like nanocellulose, with their abundant sources, low cost, high biocompatibility, and unique micro-structures, also play an important role in non-implantable electrode materials. They can endow the electrodes with good mechanical properties and biocompatibility, enabling non-implantable electrodes to meet the comfort requirements for long-term wearing while ensuring the quality of signal acquisition (He et al., 2020)

2.2 Dry Electrode

Dry electrode includes mems electrodes, non-contact electrodes and ordinary contact electrodes. Dry electrodes using dry electrode microneedles pierce the stratum corneum. The signal quality is high but there is discomfort and infection risk. Non-contact electrodes collect signals from a distance. They are lightweight but easily affected by motion artifacts. Ordinary contact dry electrodes directly contact the scalp. They have diverse structures and adapt to the contact between hair and scalp through special designs (Yuan et al., 2021).

2.3 Wet Electrodes

Conductive paste is needed to reduce impedance. It has good signal quality and is insensitive to motion artifacts. However, the preparation before use is cumbersome, may cause skin discomfort, there is a risk of short circuit, and the gel will affect stability (Kim et al., 2017).

2.4 Semi-Dry Electrode

Combining the characteristics of wet and dry electrodes, it contains electrolytes and releases them during use. This avoids the problems of high impedance of dry electrodes and cumbersome preparation of wet electrodes. However, it has shortcomings such as complex molding and large volume. It is a current research hotspot and has development potential (Bates, 2017).

2.5 Semi-Invasive Electrodes

Semi-invasive electrodes using injection to implant electrodes to reduce patient pain and avoid acute immune response during implantation. Compared with traditional invasive surgery, this minimally invasive operation can accurately position the electrode in a specific brain region with minimal damage to surrounding tissues. They can improve the strength and quality of electroencephalogram (EEG) signals. However, some accidents still may happen. Like the material does not move smoothly in the needle tube and is prone to folding or tangling; Or Local bursting may occur during injection.

The materials for semi-implantable electrodes need to balance injectability and biocompatibility (Li, et al., 2018). Hydrogel-based materials are widely used due to their unique rheological properties. Under external stimuli, hydrogels can undergo a state transition, changing from a sol state that is easy to inject to a stable gel state, enabling precise injection into specific brain regions. Their three-dimensional porous network structures are not only conducive to the exchange of nutrients to maintain cell viability but also provide abundant sites for cell adhesion. They mimic the extracellular matrix environment, which can induce the growth of neurons and their synapses towards the electrode sites and achieve close binding, effectively reducing the rejection reaction and ensuring the long-term stable operation of the electrodes in the brain environment.

2.6 Invasive Electrodes

Invasive electrodes can ensure the strength and quality of EEG signals with high spatial resolution, high signal-to-noise ratio and wide frequency range. They are able to be used for a long time and are less affected by motion artifacts and external noise. They are the most risky experiment (Shen, et al., 2021). Surgical procedures are expensive and cumbersome and safety remains a major issue. They meet difficulties in electrode size design, which may compress nerves or lead to high impedance. They may also cause immune response problems.

Implantable electrodes need to be directly implanted into the brain, so the materials are required to have excellent biocompatibility, mechanical properties, and stability. Natural biomaterials, for example, have elastic and shear moduli similar to those of brain tissue, which can effectively reduce mechanical damage to the brain, as if they are tailor-made for the brain. Their porous structures are beneficial for cell adhesion and growth. It's like providing a suitable habitat for neurons, promoting the integration of the electrodes with nerve tissues and reducing the risk of immune reactions. Meanwhile, some smart materials such as shape-memory polymers possess unique shape-memory effects and variable modulus properties. During the implantation process, they can change their shapes under external stimuli for easy implantation. After implantation, they can return to their preset shapes and closely adhere to the brain tissue, providing a guarantee for long-term and stable signal acquisition and stimulation.

3 APPLICATIONS

BCI, as the name goes, is a technology that works on the brain and aim to cure brain diseases. So it mainly focuses on medical area. It builds up a new connection between brain and the machine through detecting brain signals. In this way, it helps people with physical disability. Like the paralyzed young man who wore an exoskeleton using BCI technology to detect active signals in brain and kick the football without an external order successfully in 2014 (Chih, et al., 2010).

Non-invasive electrode is used for preliminary EEG signal monitoring, such as the initial diagnosis of epilepsy. Its high safety, without the need for brain implantation, reduces the risk of infection and other hazards, making it suitable for frequent use in daily medical scenarios and highly acceptable to patients.

Semi-invasive electrode is used for in-depth research on brain nerve activities, such as exploring the signal transmission mechanism between neurons. Semi-invasive electrodes can accurately locate specific brain regions to obtain high-quality nerve signals. At the same time, it avoids the significant damage and immune responses that invasive electrodes may cause, providing a more reliable research tool for researchers.

It also plays a role in the treatment of some nervous system diseases, such as deep-brain stimulation treatment for Parkinson's disease. It can accurately place the electrodes in the target brain region, provide more precise stimulation, and reduce the impact on surrounding normal tissues, improving the treatment effect and reducing side effects.

Invasive electrode is suitable for the treatment of severe nervous system diseases, such as the restoration of motor function in paralyzed patients (Spüler, 2017). Invasive electrodes can directly obtain deep-brain nerve signals, with high signal quality and stability. They provide more precise movement control signals for paralyzed patients, helping them regain some motor abilities.

In some high-end brain-computer interface (BCI) experiments and applications, such as developing prosthetics capable of complex motion control. Invasive electrodes can provide richer and more accurate nerve signals, enabling prosthetics to more precisely simulate natural human movements and improving patients' quality of life.

Moreover, the skills of detecting brain technology not only work on medical field. It can also work in the place that is not suit to use normal connecting method, like in the aerospace industry. BCI can both work on helping astronauts to finish complex task and monitoring their mental health (Gianluca et al., 2019)

4 DISCUSSION

In the realm of BCIs, the selection of materials holds utmost importance in dictating the performance of electrodes. Currently, although a variety of electrode materials exist, each with its own set of advantages and drawbacks, continuous research efforts are driving the evolution of BCI material precursors towards enhancing biocompatibility, optimizing signal acquisition and transmission capabilities, and augmenting material multifunctionality.

Biomimetic materials, such as hydrogels, have shown great potential in the BCI field. Their three-dimensional porous network structures and hydrateGd environments similar to the extracellular matrix contribute to promoting neuron growth and reducing rejection responses. In the future, researchers will focus on refining the formulation and fabrication processes of biomimetic materials. By modifying natural biomaterials, they aim to replicate the extracellular matrix's physical structure more accurately and endow the materials with more precise biological activity-regulating functions. For example, the introduction of specific bioactive molecules like nerve growth factors and cell adhesion peptides into hydrogels can guide the oriented growth and differentiation of neurons, strengthening the integration between electrodes and nerve tissues and further enhancing biocompatibility.

Intelligent biomaterials, like shape-memory polymers, can change their shapes and moduli in response to external stimuli, meeting the diverse needs of BCI electrodes during implantation and operation. Future developments in this area will likely lead to materials with faster response times and more diverse response mechanisms. Scientists may create materials that respond simultaneously to multiple stimuli, such as temperature, electric fields, and magnetic fields. This multi-responsiveness will enable precise control of electrode performance. For instance, during implantation, an external magnetic field can soften the material for easy insertion into specific brain regions, and a subsequent temperature change can restore it to its original rigid state, ensuring close contact with brain tissues and stable signal acquisition.

Carbon-based materials, including carbon nanotubes and graphene, have excellent electrical conductivity, flexibility, and chemical stability, and are already used in BCI electrodes (Li et al., 2023). In the future, these materials will see innovations in preparation techniques and structural designs. Advanced nanomanufacturing technologies will be employed to create carbon-based materials with tailored morphologies and structures. For example, graphene materials with hierarchical porous structures can increase the specific surface area, improving signal acquisition efficiency, while also enhancing flexibility and breathability to minimize adverse effects on the skin or brain tissues. Researchers will also explore new ways to combine carbon-based materials with other substances, such as polymers and biomaterials, to enhance their overall performance synergistically.

With the progress of quantum technology, quantum materials are emerging as potential new precursors for BCI electrodes. Quantum materials possess unique quantum properties, such as the quantum tunneling effect and the quantum Hall effect, which hold great promise for significantly improving electrode signal transmission speed and sensitivity. Quantum dot materials, capable of single-photon-level signal detection, can be used in BCIs to precisely capture subtle electrical signal changes in the brain. Although the application of quantum materials in the BCI field is currently in its early stages, continued research is expected to bring revolutionary advancements to BCI technology.

Material degradation and infection are common issues during the use of BCI electrodes. Future BCI materials are expected to integrate self-healing and antibacterial functions. By incorporating self-healing groups, like polymers with disulfide bonds, and antibacterial components, such as metal nanoparticles, these materials can repair themselves when damaged. The disulfide bonds can reform under certain conditions, restoring the material's integrity, and the metal nanoparticles can inhibit bacterial growth, reducing the risk of infection. This dual-function design will extend the electrode lifespan and enhance the reliability of BCI systems (Lin, et al., 2023).

To ensure the long-term stable operation of BCI devices and reduce their dependence on external power sources, integrated materials for energy harvesting and storage will be a research focus. Scientists may develop BCI electrode materials based on thermoelectric materials and supercapacitors. These materials can convert the body's heat energy into electrical energy and store it. For example, thermoelectric coatings on the material surface can utilize the temperature difference between the body and the environment to generate electricity, which is then stored in built-in supercapacitors. This energy-self-sufficient design will improve the portability and practicality of BCI devices, making them more suitable for various applications.

5 CONCLUSION

In conclusion, the field of BCI electrodes is at a crucial juncture of development. Currently available non-intrusive, semi-invasive, and invasive electrodes all have their own sets of advantages and disadvantages, and no single type can fully meet all requirements. Non-intrusive electrodes offer safety and comfort but suffer from poor signal quality; semi-invasive electrodes balance signal quality and safety to some extent but face challenges like material injection issues; invasive electrodes provide high-quality signals but carry significant risks. Continuous research is promoting BCI material precursors in the direction of enhancing biocompatibility, optimizing signal acquisition and transmission capabilities, and increasing material versatility.

Looking ahead, future research should focus on several key aspects. Biomimetic materials, such as hydrogels, can be further optimized to better mimic the extracellular matrix and precisely regulate biological activity, thus enhancing biocompatibility. Intelligent biomaterials like shape-memory polymers hold promise for achieving more precise control of electrode performance through multi-responsive capabilities. Carbon-based materials are expected to see breakthroughs in preparation techniques and structural designs to improve signal acquisition efficiency and reduce adverse effects. Quantum materials, despite being in the early stage of application, may revolutionize BCI technology with their unique quantum properties. Additionally, developing materials with integrated self-healing and antibacterial functions, as well as those for energy harvesting and storage, will be essential for enhancing the reliability and portability of BCI systems. By addressing these aspects, people can expect to overcome the current limitations of BCI electrodes and bring about more efficient, safe, and user-friendly BCI technologies, which will not only benefit patients with neurological disorders but also find wider applications in various fields such as aerospace and entertainment.

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