Current Study on Dry and Wet Electrodes in the Field of Non-Invasive Brain-Computer Interface

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Abstract. Brain-computer Interface (BCI) technology is an innovative field of technology that enables the human brain to communicate directly with computers or other electronic devices. This technology uses principles from neuroscience, computer science, and engineering to control external devices or software by interpreting electrical signals from the brain, without the use of traditional input devices such as keyboards and mice. This paper compares the principles and development trends of different electrodes in non-invasive brain-computer interface (BCI) systems, and discusses the advantages and disadvantages of dry electrodes and wet electrodes in the application of non-invasive BCI systems, aiming to improve system performance and optimize user experience. Wet and dry electrodes are key components for signal acquisition, and their physical properties, comfort level, and adaptability in different application scenarios directly affect the overall performance of BCI systems. Wet electrodes provide high-quality signals by enhancing skin-electrode contacts using conductive gels. However, dry electrodes are favored for ease of use, although they may face challenges in signal quality. Studying the performance impact of electrodes, is helpful in developing more efficient signal processing methods and improving the accuracy of BCI systems. The comprehensive analysis of wet and dry electrodes shows that each electrode type has its unique advantages and applicable scenarios. Future research should focus on addressing the limitations of existing electrodes through the use of new materials, design innovations, and the application of integrated circuit technology to optimize BCI technology to provide solutions that better match the needs of users.

Keywords: Wet Electrodes, Dry Electrodes, EEG Signal Processing, Non-invasive.

1 Introduction

In the evolving field of neuroscience and biomedical engineering, Brain-Computer Interfaces (BCIs) represent a significant technological frontier, enabling direct communication pathways between the human brain and electronic devices. Unlike traditional interaction mechanisms that rely on physical inputs like keyboards and mice, BCIs interpret neural signals directly, facilitating control and interaction

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without physical exertion. This capability not only opens new avenues for medical rehabilitation but also expands the horizons of how humans interact with technology. The efficacy of these systems heavily depends on the type of electrodes used to detect neural signals—primarily categorized into wet and dry electrodes. This paper aims to dissect the operational principles, application benefits, and limitations of these electrodes within non-invasive BCIs, striving to enhance system performance and user engagement.

Wet electrodes, traditionally favored in clinical and research settings for their high signal fidelity, utilize conductive gels to enhance the interface between the electrode and the skin, thereby reducing impedance and improving signal quality. This type of electrode is crucial for applications requiring precise signal detection, such as in diagnostic and therapeutic settings for neurological disorders. However, the application of conductive gel can be cumbersome and uncomfortable for users, often leading to limitations in long-term usability and user satisfaction.

Conversely, dry electrodes offer a more user-friendly alternative, eliminating the need for conductive gels and thus reducing preparation time and improving comfort. These electrodes are designed with advanced materials and novel architectures that attempt to maintain good signal quality while enhancing user comfort. Despite these advancements, dry electrodes often face challenges related to higher impedance and susceptibility to noise, which can affect the reliability of the signal during dynamic activities or over extended periods.

Recent innovations have led to the development of semi-dry and flexible electrodes, which merge the benefits of both dry and wet technologies. Semi-dry electrodes utilize a minimal amount of gel, which can help in maintaining lower impedance like wet electrodes while not compromising on the comfort typical of dry electrodes. Flexible electrodes, made from innovative conductive polymers and flexible substrates, conform closely to the skin, offering reduced preparation time and enhanced signal stability without the rigidity of traditional electrodes.

This paper will explore how these different types of electrodes impact the overall functionality of BCIs, considering their physical properties, comfort levels, and adaptability across various application scenarios. Furthermore, we will delve into the latest advancements in electrode materials and designs, aimed at addressing the current limitations of conventional electrodes. By integrating insights from recent research and case studies, the analysis will highlight how innovative electrode technologies can significantly improve both the performance of BCIs and the user experience.

By examining the comparative benefits and potential drawbacks of wet, dry, and semi-dry electrodes within non-invasive BCIs, this discussion aims to provide actionable insights for researchers and practitioners in the field, guiding future innovations and applications of BCI technology. The ultimate goal is to foster developments that enhance the integration of BCIs in everyday applications, making them more accessible and effective for a broader range of users.

2 Related Research Works

2.1 Wet Electrodes

In the early days, people proposed to use silver foil electrodes taped to the head of the experimenter with a bandage and record EEG signals [1]. Through experiments, we know that the lower the impedance between the electrode and the skin, the better the quality of the EEG signal. So now a better option is to use wet electrodes, which use a conductive gel or paste to increase the conductivity between the ions in the wet electrode and the skin [2]. Low electrode-skin impedance will help to reduce power line interference, and the impact of motion artifacts on EEG signals will be greatly reduced [1]. The most commonly used wet electrodes are silver/silver chloride (Ag/AgCl) electrodes. These Ag/AgCl electrodes have excellent electrophysiological recording properties because Ag/AgCl electrodes have a very low half-cell potential [3], which means better noise performance and drift during DC and low-frequency measurements. The conductive gel can be used as a conductive medium for the current of the human body example due to its abundant Cl ions [3]. At the same time, the gel can maximize the area of contact with the skin, effectively reduce the contact impedance of the electrode, and act as a buffer for the electrode movement. So the conductive gel, the electrolyte gel, will form a conductive path between the electrode and the skin, thus reducing the skin-electrode impedance. Of course, the advantages will have disadvantages. Although conductive gel has the ability of Angle infiltration and stable electrochemical site [4]. However, when using gel, to ensure a stable connection between the electrode and the skin of the head, a certain amount of conductive gel will be applied to each electrode. At the same time, the acceptable range of impedance reduction (5-20KΩ) of the wet electrode will be observed [1], and skin abrasion is required to remove part of the epidermis [3], which can reduce the contact impedance of the electrode. Although the electrolyte gel is almost harmless, the process will take time, make participants uncomfortable, and even cause allergic reactions in some, and because of the sticky product, the contact area will become dirty. The most serious is the non-durability of the conductive gel because the water in the conductive gel will continue to evaporate over time, that is, when the electrode impedance in the conductive gel reaches a value that can be used for experiments, the water in the conductive gel will slowly evaporate until it dries. In this process, the gel will dissipate into a more uniform layer and the impedance of the wet electrode will increase over time [2]. An increase in impedance only allows the signal quality of the EEG to decrease and motion artifacts to increase. Fig. 1 showed the structural differences between wet electrodes (left) and dry electrodes (right) when in contact with the skin.

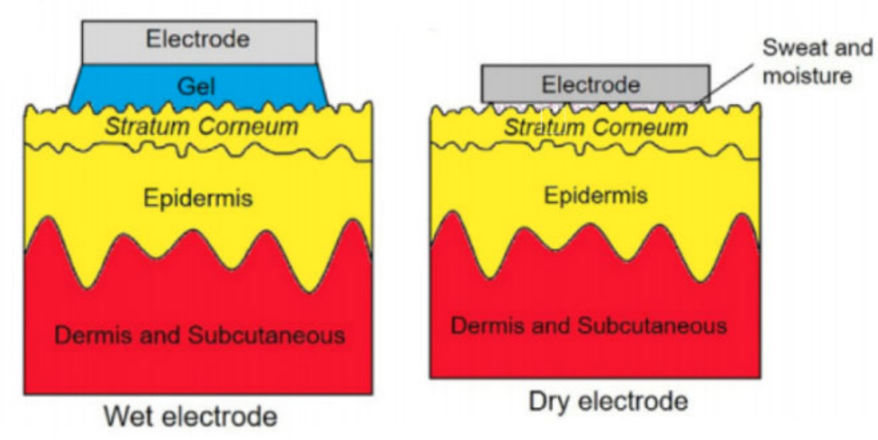

Fig. 1. The illustration shows the structural differences between wet electrodes (left) and dry electrodes (right) when in contact with the skin [1]

2.2 Dry Electrodes

To overcome the problems highlighted by the wet electrode above, such as laborious scalp preparation, time-consuming [1], etc. Dry electrodes are beginning to be mentioned as an alternative to long-term EEG recording [5]. Dry electrodes are mainly divided into contact electrodes, non-contact electrodes or insulating electrodes due to different methods such as pointed, capacitive, non-contact, and other methods [1]. The contact electrode scalp will be in direct contact with the electrode surface, which is composed of metal spikes. Sometimes it is even possible to Pierce the cuticle (SC) for better electrical attachment and mechanical fixation to the scalp, resulting in better electrical properties and mechanical stability. In non-contact dry electrodes, namely non-intrusive surface dry electrodes, the chassis is made of metal, and capacitive coupling is carried out through an insulator [6]. Usually has a higher impedance than the microneedle electrode. Insulating electrodes, which use insulating material as the base plate of the electrode, also operate on a capacitive coupling basis. In EEG applications, dry contact electrodes are more commonly used because they have a slightly lower impedance compared to the other two types. The electrical model of the electrode-skin interface is shown below. The wet electrode is modeled as a resistive capacitance circuit due to the addition of conductive gel, and the impedance can be less than 1KΩ, while the dry electrode is in contact with the skin (SC-stratum corneum), and the resistance will be higher due to the absence of conductive gel. And dry electrodes are still problematic.

The principle of the nanoneedle and microneedle methods is to be able to bypass the SC and enter the inner layer of the skin with low impedance [5]. However, microscopic results often split, resulting in infection and impedance mismatch between electrodes. In 2012, Forvi E. et al. conducted a technical evaluation of the microneedle dry electrode. In the experiment, once the electrode pierced the SC, the impedance at this time was only 12 kΩ. No problems such as tip failure occurred after the experiment. So this week the dry electrode method of nano or microneedle can also replace the wet electrode. They have the capability of low electrode impedance, high mechanical stability, fewer motion artifacts, long-term measurements, and fast setup. However such electrodes can be relatively expensive to produce. A dry electrode consisting of 180 conical needles, which were treated with titanium and gold to reduce impedance and prevent oxidation, was fabricated using a 3D printer with micron resolution [3]. This will allow fast, low-cost, high-precision production. The advantage is that, because of the micrometer needle, EEG measurements can be performed in hair-bearing areas without compromising the hardness and invasiveness of the needle. However, the disadvantage is that because the mill needle does not Pierce the SC, the contact/attachment to the skin is insufficient, which may produce motion artifacts.

So the dry electrode is still problematic. First, since there is no conductive layer, the impedance will be very high (even up to several MΩ at 50/60Hz), so a lot of noise and interference will be observed in the EEG recording leading to a higher incidence of motion artifacts. To reduce the noise of interference, this needs to be done by shielding dry electrodes and using a passive electrode (unshielded cable) connection does not ensure good signal quality. Instead, choose an active electrode, which amplifies the scalp EEG and reduces the impact of noise. The need for shielded cables to maintain signal quality is also reduced. This will be a good feature for wearable devices. Second, if the microneedle array is convenient, it can also be used for real-time and long-term EEG recording [5]. However, the strength of the microneedle will be an important issue. When the needle is broken, it will lead to an impedance mismatch between differential measurement and infection. However the risk rate of infection will be reduced if proper sterilization is performed before the experiment begins. Also, the microneedle dry electrode fixation was not always specified and was not evaluated in areas covered by hair [5]. Another is that the size of the tip must maintain a balance between invasiveness, reliability against fracture, and ability to accomplish SC puncture.

2.3 EEG Signal Processing

The key to the quality of EEG electrode signals, whether wet or dry, is the electrochemical properties of the materials and coatings used to form the electrodes. Brain-computer interface (BCI) is a device that connects the brain to a computer [7]. Intelligent systems generally decipher brain signals through five steps: signal acquisition, preprocessing, feature extraction, classification, and control interface. The human brain is roughly divided into three main parts based on function: the cerebellum, which deals with physical skills, the limbic system, which deals with situations, and the cortex, which deals with mental processing and analysis [7]. The cortex is responsible for critical thinking, perception, memory storage, and visual data processing. However, BMI can be divided into two categories in signal acquisition, namely invasive BMI and non-invasive BMI. The main difference between the two techniques is that invasive implants electrodes in the cerebral cortex, while non-invasive relies on recording from the skull. On the non-invasive side, the most commonly used neural recording technique is electroencephalography (EEG), where electrodes are placed at specific points on the scalp to record the average neuronal signal across different cortical areas. The biggest advantage is that the system is portable. They have good temporal resolution because they measure neural activity directly, and lack spatial resolution because the signal must pass through many physical barriers, including the skull, scalp, and cerebrospinal fluid.

3 Effects, Advantages and Disadvantages

In order to monitor high-quality signals, EEG electrodes must have excellent signal acquisition capabilities [8]. Most bioelectrical signals have several characteristics in common: low signal intensity (the increase of bioelectrical signals is usually less than 5mV) [6]; Randomness and instability (various external or internal stimuli can cause corresponding changes in human signals) Low signal-to-noise ratio (SNR) is also susceptible to interference. Therefore, to obtain high-quality and stable EEG signals the detection process should try to meet the following requirements [9, 10]: 1) The impedance between the electrode and the skin should be minimized to ensure sufficient signal amplitude for recording. 2) The electrodes should provide sufficient and stable contact interfaces to reduce motion artifacts during the detection process. In general, Ag/AgCl wet electrodes with excellent electrical properties can provide accurate and stable EEG signals. The conductive gel in the wet electrode can reduce the interface impedance between the skin and the electrode, thus providing good bioelectrical signals. The electrode represents the connecting interface between ion charge transport on the surface and electron charge transport in the external detection device.

In electroencephalogram (EEG) signal acquisition, the contact between skin and electrodes can be described by a circuit model. The characteristics and principles of wet electrodes are clearly shown in Fig. 2.

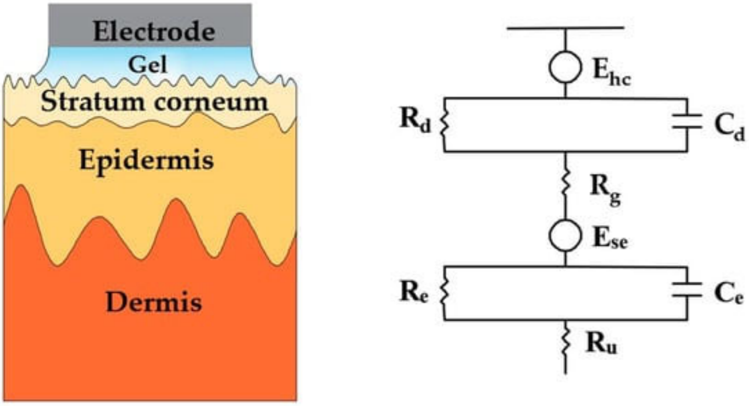

Fig. 2. The illustration on the left shows the structure of a wet electrode in contact with the skin, including the electrode, conductive gel, stratum corneum, epidermis, and dermis layers [6]

This model consists of resistors and capacitors, reflecting the electrical impedance and capacitance properties of human skin. Specifically:

1) Ehc represents the potential difference generated by the electrical activity of the brain, which is the voltage source in the circuit.

Rd and Cd are connected in parallel and represent the resistance and capacitance of the stratum corneum, the layer of skin that contributes the most to the overall impedance.

2) Rg and Ese represent resistance and potential sources located in deeper layers, such as the epidermis and dermis, reflecting the resistance properties of these layers.

3) Ce is the capacitance in parallel with Rg and Esc and represents the capacitive nature of these skin layers.

4) Ru is the resistance representing the contact between the electrode and the amplifier.

It can be easily seen that the wet electrode circuit has lower contact impedance due to the conductive gel, thus having better signal quality and reducing motion-induced artifacts; As traditional EEG electrodes, wet electrodes have mature methods and benchmark data. However the disadvantages of wet electrodes include long preparation time; The conductive gel may cause patient discomfort and inconvenient cleaning, and the dehydration and condensation of the conductive gel during the process can lead to an increase in impedance, which may increase detection noise and degrade signal quality.

To overcome these problems with wet electrodes, dry electrodes that do not use conductive gels have the potential to solve these problems. The characteristics and principles of dry electrodes are clearly shown in Fig. 3.

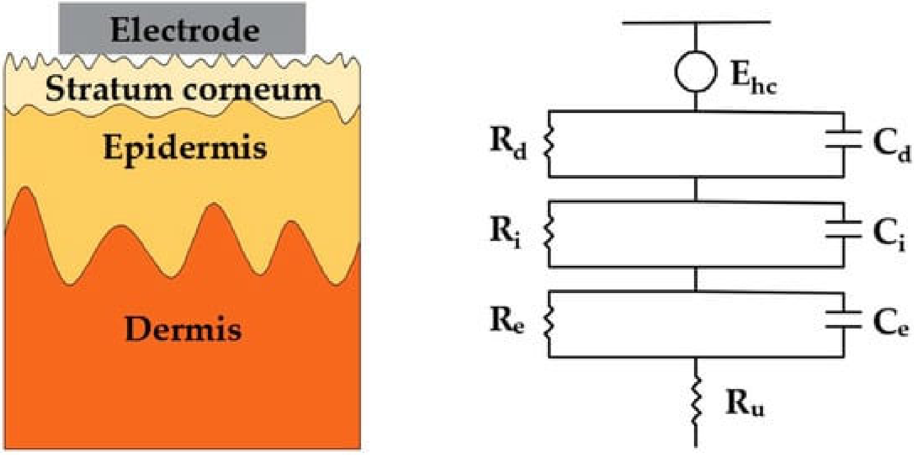

Fig. 3. The illustration on the left depicts the structure of a dry electrode in contact with the skin, including the electrode, stratum corneum, epidermis, and dermis layers [6]

Non-invasive dry electrodes provide higher impedance than wet or microneedle electrodes without causing discomfort to the human body This circuit diagram simulates the contact interface between the skin and a dry electrode, where the electrode senses signals generated by electrical activity in the brain through the multi-layered structure of the skin:

1) Ehc is the potential difference generated by the electrical activity of the brain, which can be regarded as the voltage source of the circuit

2) Rd and Cd represent the resistance and capacitance of the stratum corneum, which is the most resistive part of the skin and has an important influence on signal transmission.

3) Ri and Ci represent the resistance and capacitance of the epidermal layer, which is located below the stratum corneum and is the middle layer of the skin.

4) Re and Ce correspond to the resistance and capacitance of the dermis, which contains blood vessels and nerves and also affects signal transmission.

5) Ru represents the contact resistance between the electrode and the measuring device, which is usually related to the material and fit of the electrode.

It can be seen that compared to wet electrode circuits, dry electrode circuits have higher impedance, but the advantage of dry electrodes is that they are easy to use, more suitable for long or repeated use, no gel, so there is no messy problem, reducing the preparation and cleaning time. However high impedance can still lead to increased noise in the signal. Compared to wet electrodes, dry electrodes may provide less stable signals over long periods of recording or under different environmental conditions.

4 Discussion

In the field of non-invasive electroencephalography (EEG), both dry and wet electrodes face several technical challenges, while new research continues to push the technology forward.

On the opposite side of technology, both dry and wet electrodes have advantages and disadvantages, and it is more important to reduce the impact of disadvantages, such as:

1) Signal quality of dry electrodes: Since dry electrodes are in less close contact with the skin than wet electrodes, they usually suffer from lower signal strength and higher noise. The challenge is how to design the electrode and the accompanying circuit to improve the signal acquisition quality of the dry electrode and reduce noise and artifacts.

2) Comfort and stability of wet electrodes: Although wet electrodes can provide high-quality signals, long-term use will lead to degradation of signal quality due to gel drying and may cause skin discomfort. Researchers are seeking to improve gel formulations or develop new wet electrode types to improve long-term wear comfort and signal stability.

In the future trend, the brain interface technology mainly focuses on the following three points:

1) Use of new materials: To address the aforementioned challenges, researchers are exploring new materials such as conducting polymers, nanomaterials, and flexible materials to improve the performance and experience of using electrodes.

2) Design innovation: Dry electrode design innovation, such as the introduction of microstructure, can improve the mechanical adhesion of the electrode to the skin, reduce motion artifacts, and improve the quality of the signal.

3) Application of integrated circuit technology: In order to improve the overall performance of dry electrode systems, integrated circuit (IC) technology is being applied to electrode design. This includes developing miniaturized, low-power circuits that integrate signal amplification, filtering, and transmission functions.

5 Conclusion

This study's detailed comparison between dry and wet electrodes in non-invasive brain-computer interfaces has highlighted their unique advantages and inherent limitations, which are critical for refining BCI technology. Dry electrodes are appreciated for their ease of use and minimal preparation, making them ideal for prolonged applications. However, they often encounter challenges with signal integrity due to increased impedance and susceptibility to environmental noise, which can compromise the accuracy of data interpretation.

On the other hand, wet electrodes deliver superior signal clarity owing to their lower impedance facilitated by conductive gels. This feature makes them indispensable in clinical settings where precision is paramount. Nevertheless, the gel application process can be cumbersome and uncomfortable for users, limiting their suitability for long-term monitoring.

Emerging technologies like semi-dry and flexible electrodes are promising innovations that seek to merge the convenience of dry electrodes with the high-performance characteristics of wet electrodes. These developments aim to improve user comfort and signal stability, potentially broadening the applicability of BCI technologies in both medical and consumer electronics.

Looking ahead, future research should concentrate on optimizing the materials and structural designs of electrodes to minimize the trade-offs between user comfort and signal quality. Advancements in nanotechnology and materials science could lead to significant improvements in electrode functionality, paving the way for more robust and user-friendly BCI systems. Pursuing such innovations will be crucial in overcoming current limitations and fulfilling the vast potential of brain-computer interfaces.

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