Sensors and Actuators B 237 (2016) 167–178

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Novel passive ceramic based semi-dry electrodes for recording electroencephalography signals from the hairy scalp

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ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form 25 May 2016
Accepted 6 June 2016
Available online 7 June 2016

Keywords:
Dry electrode
Dry sensor
Dry biopotential electrode
Electrode/scalp impedance
EEG recording

ABSTRACT

This study reports on a novel passive ceramic-based semi-dry electrode prototype for electroencephalography (EEG) applications. With the help of capillary forces of the porous ceramics pillars, the semi-dry electrodes build a stable electrode/scalp interface by penetrating hair and releasing a small amount saline in a controlled and sustained manner. The semi-dry electrode/scalp impedances were low and stable (44.4 ± 16.9 kΩ, $n = 10$), and the variation between nine different positions was less 5 kΩ. The semi-dry electrodes have shown non-polarization characteristics and the maximum difference of equilibrium potential between eight electrodes was 579 μV. The semi-dry electrodes demonstrated long-term stability, and the impedance only increased by 20 kΩ within 8 h. EEG signals were simultaneously recorded using a 9-channel gel-based electrode and semi-dry electrode arrays setup on ten subjects. The average temporal cross-correlation between them in the eyes open/closed and the steady state visually evoked potentials (SSVEPs) paradigm were 0.938 ± 0.037 and 0.937 ± 0.027 respectively. Spectral analyses revealed similar response patterns with expected functional responses. Together with the advantages of quick setup, self-application and cleanliness, the result suggests the semi-dry electrode is suitable for emerging real-world EEG applications, such as brain-computer interfaces and wearable EEGs.

1. Introduction

Electroencephalography (EEG) is nowadays the most widely used non-invasive brain imaging technique due to its excellent temporal resolution, high portability and relative low cost [1]. In recent years, the emerging EEG-based brain-computer interface (BCI) applications and wearable devices have attracted extensive attention from academic and industry circles. Compared to the requirements of electrode sensors used in traditional clinics and laboratories, more attention has been paid to friendly and convenient use in real-world application scenarios such as physiological monitoring [2–4], neuro-feedback training [5,6] and neuro-marketing [7,8], etc. However, despite all the recent technological advances in acquisition electronics and signal processing, convenient and reliable EEG electrodes still remain an important technological challenge.

Detecting high quality EEG signals depend on a reliable electrical path between electrode and scalp, which requires non-polarizable electrodes with low and stable electrode/scalp impedance. Neural signals are carried by ionic currents to the scalp surface via the body fluid, then recorded by the electrodes placed on the scalp. The electrode converts ionic current to electronic current, before sending the signals to an amplifier and subsequent signal processing. Here, conductive gel plays an important role of carrying bioelectrical signals (weak ionic current impulse) and builds an electronic/ionic interface at the electrode surface (referred to as the double layer). Conductive gels assist electrodes to form a stable electrode potential, minimize electrode polarization and reduce electrode/scalp interface impedance.

So far, gel-based electrodes have become the main choice for recording EEG in clinics and research laboratories due to theirs excellent signal to noise ratio and high reliability [9,10]. Non-polarizable silver/silver chloride (Ag/AgCl) electrodes and conductive gels or pastes containing chloride ions are often used in these applications and referred to as 'wet' electrodes. The conductive gel forms an ionic path and constructs a non-polarizable electric double layer on the electrode surface, which minimizes the polarization potential and ensures smooth baseline in EEG signal recording. Moreover, the gel-based electrode/scalp impedance has been proved to be very stable and tolerant of head movement, because the conductive gel can penetrate the hair, then conform

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http://dx.doi.org/10.1016/j.snb.2016.06.045
0925-4005/

to the scalp surface and wetting of the high impedance skin stratum corneum, even possibly penetrate into the inner layer of skin through sweat glands and pores. However, the setup of gel-based electrodes usually is time-consuming, including skin preparation (i.e. cleaning and abrasion of the skin) and conductive gels application [11]. Even worse, conductive gels dirty and mess the hair, and may cause discomfort for the users [12,13]. Therefore, these inconvenience and discomfort issues severely limit emerging EEG-based applications.

To overcome these problems, many efforts have been made to develop gel-free electrodes in recent years. The gel-free electrodes, usually referred to as 'dry' electrodes, consist of an electronic conductor with no conductive gel between electrode and scalp, such as inert metallic pins or tips [14–18], comb-like conductive polymer elastomer [19,20] and flexible metal-coated bristles [21,22]. These dry electrodes actually still maintain a very tiny amount of electrolyte such as perspiration and moisture at the electrode/scalp interface. Nevertheless, as no conductive gel or paste application is needed, the 'dry' electrodes are bringing a significant improvement over the 'wet' electrodes for its quick setup, self-application, and cleanliness.

However, the absence of the conductive gel always leads to relative high impedance (i.e. several hundreds kΩ or higher), due to the less effective ionic conductive path and interface double layer. A Multi-tips based dry electrode of the size of a US 5¢ coin was proposed by Matthews et al., with the contact impedance between the scalp and each tip being as high as 10 MΩ [18]. A flexible, low-cost electrode made of polymer silver-coated bristles approximately the size of a toothbrush developed by Cristian et al. and an initial impedance of 80 kΩ was reported that deteriorated to 150–200 kΩ after 10 months of use [21]. Cognionics Inc. claims that the contact impedance of their flexible dry EEG electrodes is in the range of 100–2000 kΩ [23]. The motion artifact often arises from the disturbance at the electrode/skin interface [13]. Therefore, dry electrodes of high impedance are more sensitive to motion artifacts because of lack of enough electrolyte at the electrode/skin interface. In addition, the high impedance also tends to lead to an unstable electrode potential. All of these cause poor signal quality [24–28].

Active dry electrodes with high input impedance preamplifiers inside were developed to alleviate the poor signal [14,16,19,29–31]. Since the active electrodes can convert the high electrode/skin impedance into a low impedance output, the signal quality is less dependent on the electrode/skin impedance [32]. Although active electrodes are less affected by environmental noise, they are still susceptible to movement artifacts. In addition, the active electrodes are usually bulky and expensive [25].

In order to overcome the problems of 'wet' and 'dry' electrodes, the 'quasi-dry' electrode concept was developed [25,33]. The working principle of 'quasi-dry' electrodes is to release electrolyte fluid by imposing a pressure on a saline reservoir instead of the present of conductive gels. Although the 'quasi-dry' electrodes demonstrate several merits over 'dry electrodes', but there are still some technical problems as follows. Firstly, it needs an additional pressure to enable continuously releasing the electrolyte fluid; secondly, electrode deterioration, such as electrode deformation and electrode coating failure, can happen under long-term pressure applications. Moreover, it is very difficult to achieve uniform pressure. The non-uniform pressure will bring uncontrolled, unexpected moistener release, thus leading to signal instability [25]. Finally, it is noteworthy that the EEG test results were not very sound, as the reported data were from only one participant. An alternative solution was proposed by Martins et al. to avoid the pressure related issues, which was similar to "felt-pen" concept [34]. The concept employed a specifically developed polymer wick to achieve continuous and stable delivery of liquid without external pressure. Unfortunately, the electrochemical performance and EEG signal quality has not been reported.

In this study, we proposed a novel porous ceramic-based semi-dry electrode prototype aiming to overcome the problems of the 'quasi-dry' electrode. The semi-dry electrodes consist of sintered Ag/AgCl electrode and saline in reservoir, which ensure a stable non-polarization electrode interface and an ionic conductive path. Similar to the "polymer wick" electrode concept, the semi-dry electrodes enable release a small amount of saline solution in a controlled and sustained manner, which achieve by the assistance of capillary forces in the porous ceramic pillars. It is clear that the semi-dry electrodes eliminate the inconvenience of using conductive gel. Further, the semi-dry electrodes retain the non-polarizable electrode/electrolyte interface, which can minimize polarization potential, then allows a smooth baseline in EEG recording. It also facilitates DC coupling of an amplifier.

To systematically evaluate the performance of the proposed semi-dry electrode, we conducted a series of electrochemical investigations including electrode/scalp impedance and electrode polarization performance. The performance was further assessed in a human EEG study: 10 subjects were recruited to participate in several classical EEG paradigms such as the eyes open/closed, as well as the SSVEPs.

2. Materials and methods

2.1. Semi-dry electrodes and headset

The design of the semi-dry electrode prototype is illustrated in Fig. 1A and B. The semi-dry electrode includes five porous ceramic pillars (i), a built-in reservoir (ii), ~500 μL 3.5% saline solution (iii) and sintered Ag/AgCl electrode (iv). The aluminum oxide (Al_2O_3) ceramic pillars were purchased from Suzhou Greentek (China), considering its character of excellent mechanical properties (i.e. wearability, resistance to compression) and good hydrophilic and permeability performances. The physical dimensions of the porous ceramic pillars are Φ1.2 mm × 7.0 mm with a few micrometer pores structure (Fig. 1C). Using the capillary force of the porous ceramics, the semi-dry electrode enables continuous release of saline solution from the built-in reservoir at the rate of 10–20 μL/h. Sintered Ag/AgCl (Φ6.0 mm, 1.0 mm thick, Greentek, China) was chosen as electrode material, considering its character of non-polarization, electrode potential stability, and low noise properties.

In the present study, the semi-dry electrodes were assembled into a customized 9-channel headset (shown in Fig. 1D) for a series of *in-vivo* measurements including the electrode/scalp impedance tests and EEG signal recording. The semi-dry headset consists of ten semi-dry electrodes placed at O1, Oz, O2, P3, Pz, P4, C3, Cz, C4 and Fz (as ground electrode). A comparison test was conducted between the semi-dry and the conventional 'wet' electrodes that consisted of sintered Ag/AgCl electrodes and conductive gel (Greentek, China). A 'wet' electrode cap was worn and the semi-dry electrode headset was placed over the 'wet' electrode cap.

2.2. Subject and ethical information

Ten subjects (four females, age between 21 and 34 years) were enrolled in the study. All of them were free of medication, had normal vision or vision corrected to normal, and no history of central nervous system abnormalities. The study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee of Wuhan University. All subjects participated in the semi-dry electrode/scalp impedance tests first, followed by the EEG signal evaluation tests. Two of them also participated in an 8 h electrode/scalp impedance test to evaluate the long-term stability.