A Novel Bristle-shaped Semi-dry Electrode with Low Contact Impedance and Ease of Use Features for EEG Signal Measurements

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Abstract— Objective: **In this paper, we present a novel soft bristle-shaped semi-dry electrode for electroencephalography (EEG) recording. Because the bristle-shaped structure with electric conductivity could overcome the obstacle of hair and enable the direct connect to scalp, the semi-dry electrode could work with drinking water instead of saline water that widely used in previous semi-dry or water electrodes to improve its convenience. The electrode consisted of conductive bristles and a 3D printed casing. Carbon coated nylon conductive bristles could achieve low impedance and soft properties of the semi-dry electrode. The bristles could spread on skin and realize the larger contact area. The carbon coated conductive bristles could also continuously penetrate water into the corneum of skin to reduce contact impedance. The contact impedance of bristle-shaped semi-dry electrode was similar to traditional wet electrode, but much lower than dry electrode. Although the saline water had much lower impedance than drinking water, our electrode still achieved even lower skin-electrode contact impedance than previous semi-dry or water electrode with saline water. The alpha rhythms, P300 visual evoked potential and steady-state visual evoked potential were respectively measured to evaluate the electrode performance for EEG recording.**

***Index Terms*—EEG sensor; Semi-dry Electrode; Soft Electrode; Biopotential; Low Contact Impedance; Conductive Bristles**

I. INTRODUCTION

THE brain-computer interface (BCI) is a direct connection between human or animal brains (or cultures of brain cells) and external devices[1-3]. The application of BCI system needs an effective detection method of electroencephalography (EEG). At present, EEG signals used for BCI systems are mostly recorded by conventional wet electrode [4, 5], as shown in Fig. 1a. Although wet electrode has been applied to EEG measurement for several decades, there are still a number of inconveniences and performance flaws in the applications of wearable or daily BCI systems, including the professional skills and cumbersome processes required for the setup of wet electrode EEG cap [6], difficult cleaning of conductive gel after EEG recording, and the short endurance due to the dehydration of conductive gel over extensive time [7].

To overcome the drawbacks and inconveniences of wet electrode, various kinds of dry electrode have been studied by many research groups [8-13]. To overcome the obstacle of hair on scalp, pin-shaped structure was widely designed in dry EEG electrode (Fig. 1b). To transmit EEG signals, the pins were often fabricated from metal or soft conductive polymer [14-16]. Since the metal materials are rigid, they usually have a potential to cause a sense of pain or hurt even with spring structure design. The soft conductive polymer electrodes can reduce the feel of discomfort, but they usually have very large skin-electrode contact impedance with more than 1MOhm and need large pressure to reduce contact impedance [17].

Due to the high contact impedance, dry electrodes usually need an active electrode circuit to reduce the influence of common mode noise and signal attenuation [18, 19]. But the use of pre-amplifier is costly, which can also result in the attenuation of high frequency components and low frequency components in EEG signals. And the performance of dry active electrode had obvious gap compared with wet electrodes, although the active electrode with high contact impedance usually has a very similar signal compared with a low contact impedance passive electrode when viewed with the naked eye, it still needs a much bigger number of trials in a BCI test to achieve the same accuracy [20]. And there was generally more spectral power across all frequencies for the dry active electrode system compared with a traditional wet electrode system [27].

In recent years, many kinds of semi-dry electrode and water based electrode were designed to overcome the drawbacks of conventional wet electrode and dry electrode. Nowadays, semi-dry electrodes are usually fabricated from porous ceramics [21]. Fig. 1d shows the porous ceramics semi-dry electrode designed by G Li, et al. The porous ceramics and metal could allow small amount of electrolyte diffuses into skin from the electrodes and reduce the impedance of the corneum. This kind of semi-dry electrodes were often designed to be pin-

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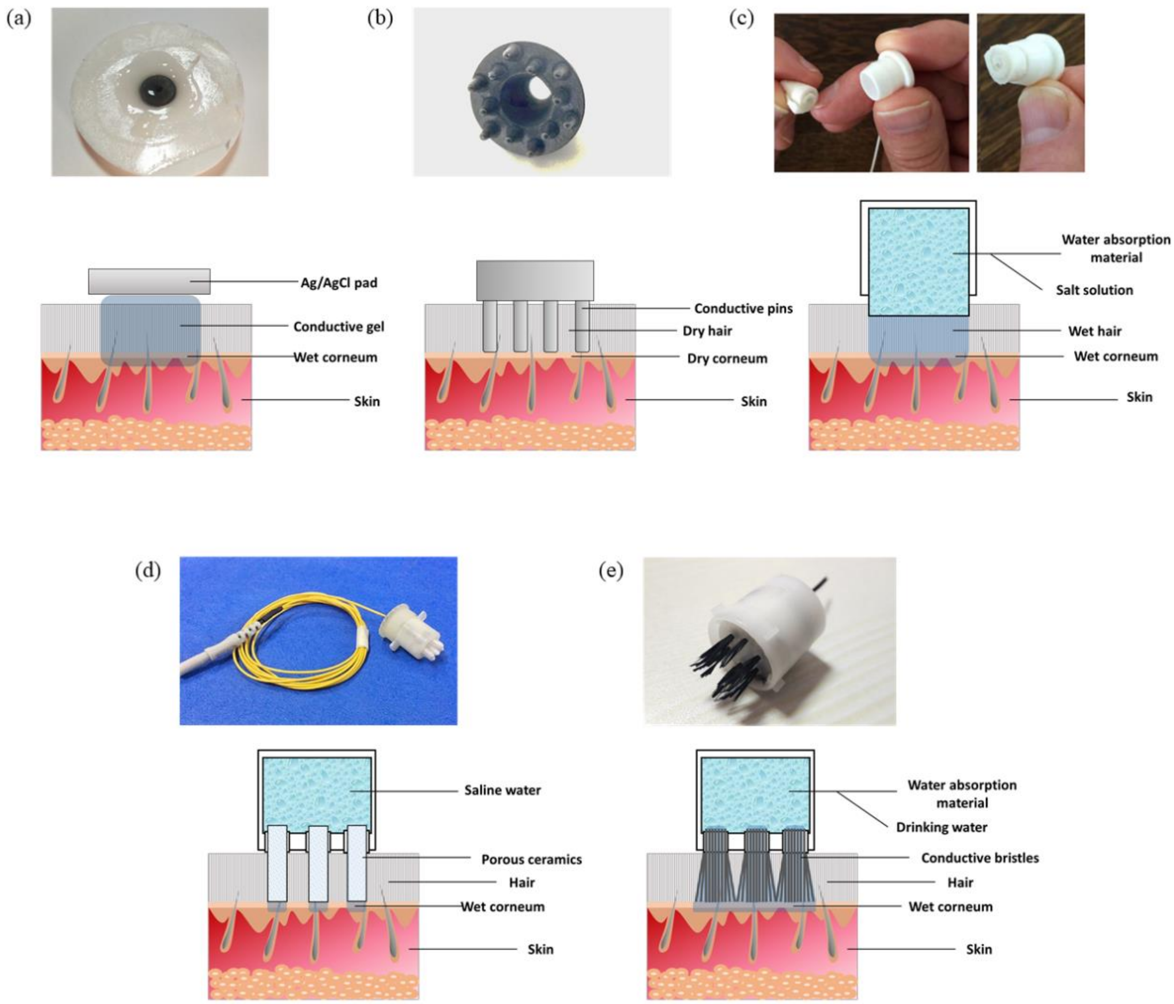

Fig. 1. Electrodes for EEG signal measurement. (a) Traditional Ag/AgCl wet electrode. (b) Pin-shaped dry electrode. (c) Water based electrode. (d) Porous ceramics semi-dry electrode. (e) Bristle-shaped semi-dry electrode.

shaped to penetrate hair or flat-shaped to be applied on forehead. Compared with the semi-dry electrode, the water-based electrodes are a big step in commercialization. The EGI, Mobita and Emotive BCI systems are using this kind of electrode [22, 23, 24]. Fig. 1c shows the electrode of Mobita. The water-based electrodes could store moisture through the fabric. When placed on scalp, the electrodes didn't contact to skin directly. The large amount of water in the fabric could wet hair and scalp. Wet hair became the electron transfer media. The contact impedance of water based electrode was similar to conventional Ag/AgCl wet electrode. Because water was mostly stored in fabric, the evaporation rate was usually very fast to increase the contact impedance rapidly over time. Adding water regularly was usually needed. Another drawback of water electrode is that it tends to leave plenty of water on hair and skin, easy to cause crosstalk of signals. In addition to the above problems, the previous semi-dry and water electrodes need saline or potassium chloride solution as electrolyte, thus increased the complexity. For regular users, it is difficult to prepare a solution with a precise concentration. Another problem induced by electrolyte evaporation after wearing for a long time, the salt is left on the skin, which may lead to an increasing concentration of electrolytes to causes skin irritation and salt residue. Because electrode materials themselves usually do not conduct electricity and the conductivity mainly realized by saline, the skin-electrode contact impedance of semi-dry and water-based electrodes could be several tens of kOhm.

In this study, we proposed a novel semi-dry electrode with bristle structure. Although there were some previous bristle like electrode designs [13, 29], but they were 'dry' electrodes. The previous bristle like dry electrode designs only solved the problem of let the electrode contact to scalp and overcome the obstacle of hair, but they could not reduce the high contact impedance of dry electrode. Comparing with other designs of bristles like electrode, the most important advantage of our design was that it was a bristle like 'semi-dry' electrode. In our design, bristles were not only a conductive medium of EEG signals from scalp to the lead wire, but also a transfer passage of water from the internal cavity in our electrode to the scalp. The water stored in the electrode could continuously wet the scalp under the electrode and drastically reduce the contact impedance for a long time. This feature made our design to be

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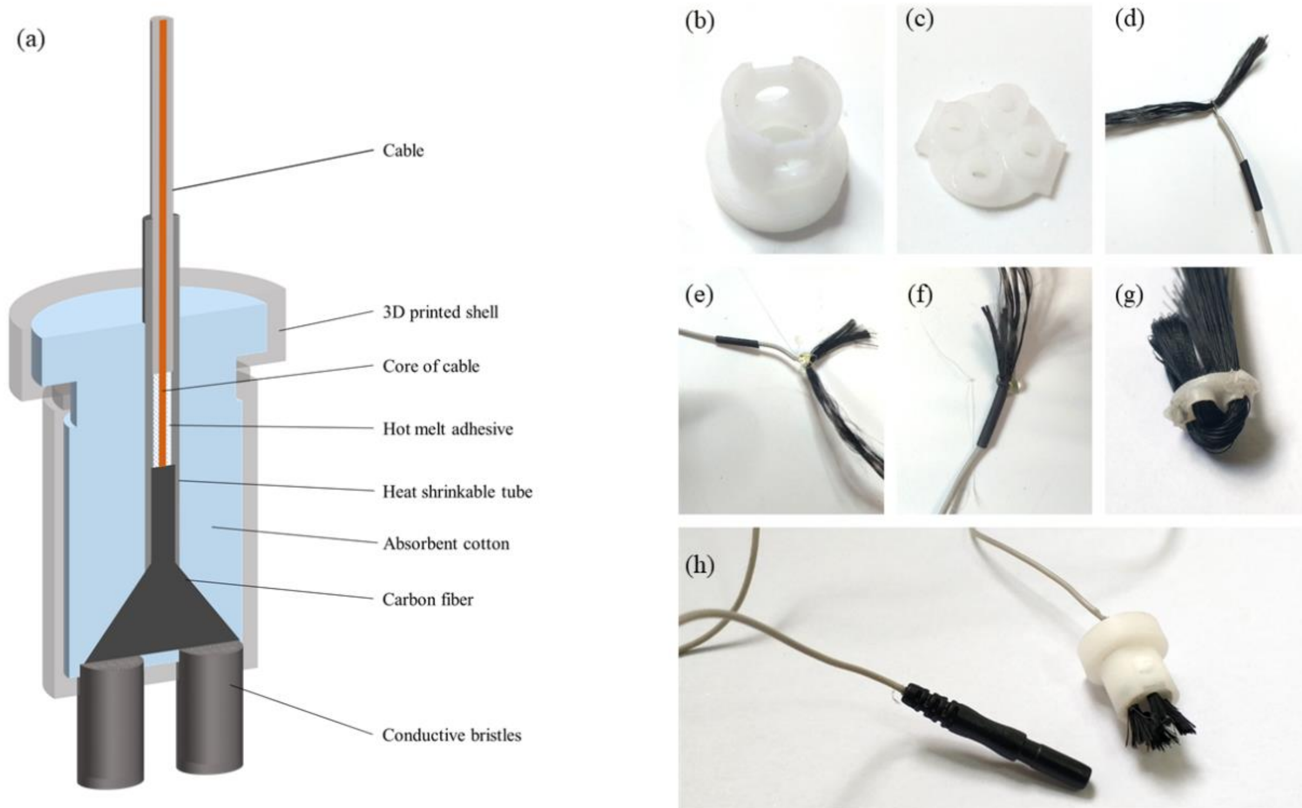

Fig. 2. Structure and fabrication process of bristle-shaped semi-dry electrode. (a) The cutaway view of bristle-shaped semi-dry electrode. (b) 3D printed cylinder. (c) 3D printed round lid. (d) Wire wounded around carbon fiber. (e) Hot-melt glue dropped on the contact point of carbon fiber and wire. (f) Use the heat-shrinkable tube to encase the contact point. (g) The conductive bristle structure. (h) The assembled electrode.

not only a 'bristle like electrode' and but also a 'semi-dry' electrode, and the skin-electrode contact impedance was much lower than previous bristle-shaped 'dry' electrodes when it maintained the features of long working hours and easy-to-use. And the bristle-shaped semi-dry electrode is developed from our previous bristle-shaped dry electrode[29] and porous Ti semi-dry electrode[30] designs. The bristle-shaped carbon fiber dry electrode could overcome the obstacle of hair, but the contact impedance was high. The porous Ti semi-dry electrode had low contact impedance, but it was rigid and was hard to be used in hairy areas. To overcome the drawbacks in our previous designs, we tried to develop a new electrode in this paper that has the advantages of both previous designs at the same time: the electrode should be able to overcome the hair by bristle structure and also can reduce contact impedance by moistening skin. In this design, we combined the bristle-shaped structure and the 'semi-dry' characteristic.

In the design, the 'semi-dry' characteristic was implemented by water absorption of the fiber, as shown in Fig. 1e. The bristle structure was fabricated from totally soft conductive fiber. When the electrode was pressed on scalp, the bristles can penetrate through hair and contact to skin directly. The conductive fiber bristles also can scatter on scalp to enlarge the contact area, which could lead to lower contact impedance and better comfort. The ends of conductive fibers were connected to absorbent cotton sucked with water, which could penetrate from conductive fiber bristles to skin fiber continuously and reduce the impedance of stratum corneum. Because the conductive nylon fiber has a strong conductivity and could contact to skin directly, just using drinking water the impedance between skin and electrode could be reduced to a level of several kOhm. Because the process of saline preparation was avoided, the application of our semi-dry electrode was more convenient than semi-dry electrodes using saline water. Because the water oozed very little, when the electrode was removed from skin, there's almost no liquid left. To evaluate the performances of the semi-dry electrode, the skin-electrode contact impedance was measured with the mean valve of 15kOhm, and the quality of EEG signals was analyzed as well. The experimental results showed dry electrode could detect EEG signals at hairy area and the influence on skin was quite small.

The experiment in this paper has been approved by the Scientific Research Ethics Committee of Bio-x Center, Shanghai Jiao Tong University. All the subjects knew the test procedure and were completely voluntary.

TABLE I
THE STANDARD PHYSICAL PERFORMANCE OF CARBON COATED NYLON FIBER

Diameter	0.13mm
Intensity	5.0 Gram/danier
Breaking elongation	34%
Average resistance	3x104Ω•cm
Water/hydrolysis	Strong resistance
Melting point	254℃

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II. Design of the EEG electrode

A. Features of the EEG Electrode

The electrode was composed of a cavity that stored water and several conductive bristles with ends implanted into it. The bristles were fabricated from hydrophilic material, such that water could spread from the roots to the top. Fig. 1e shows the schematic diagram of bristle-shaped semi-dry electrode. Unlike traditional pin-shaped dry electrode made from metal or conductive plastic, the conductive bristles were soft and flexible. When placed on the scalp, the bristles would bend on skin, and the flat base of the electrodes could be pressed directly to the scalp to realize large area contact, without the discomfort and instability caused by the point contact between pins and skin.

The hydrophilic conductive bristles were fabricated from carbon coated nylon, which material has been widely applied to antistatic clothing and wearable smart fabrics. The carbon coated nylon conductive fiber was Resistat®F902 A013 fabricated by Shakespeare. The diameter of the nylon is 0.13mm. It is a kind of nylon 6 single filaments impregnated with conductive carbon particles. The fiber has a circular section in which the carbon coating is about 1 micron thick. The standard physical performance is shown in table 1(The unit ‘danier’ is a unit to describe the density of textile fibers of a specified length. It refers to the mass grams of 9000m long fiber at a constant moisture regain, and it is a measure of fiber fineness. And the unit ‘Gram/Danier’ describes the intensity of fibers. It refers to the force required when the fiber breaks for per danier).

The cavity used for storing water was filled with absorbent cotton, which could absorb water and prevent water flow. The absorbent cotton was compacted with direct contact to carbon coated nylon bristles. When the electrode was applied to EEG recording, the water would penetrate from absorbent cotton to carbon coated nylon, and finally spread to the contact surface of skin- electrode. The water could enhance the conductivity of skin. Mover, the bristles could provide larger contact square than pin-structure dry electrode, as illustrated in Fig. 1e. When the electrode was pressed on scalp, the bristles can scatter to enlarge the contact area, which also lead to reduce of contact impedance. Due to the water penetrated the surface of the skin through capillary action, the amount was very small. When the semi-dry electrode was removed from skin, no free water would remain and no extra cleaning needed, thus the convenience was similar to dry electrodes while the contact impedance was similar to wet electrode.

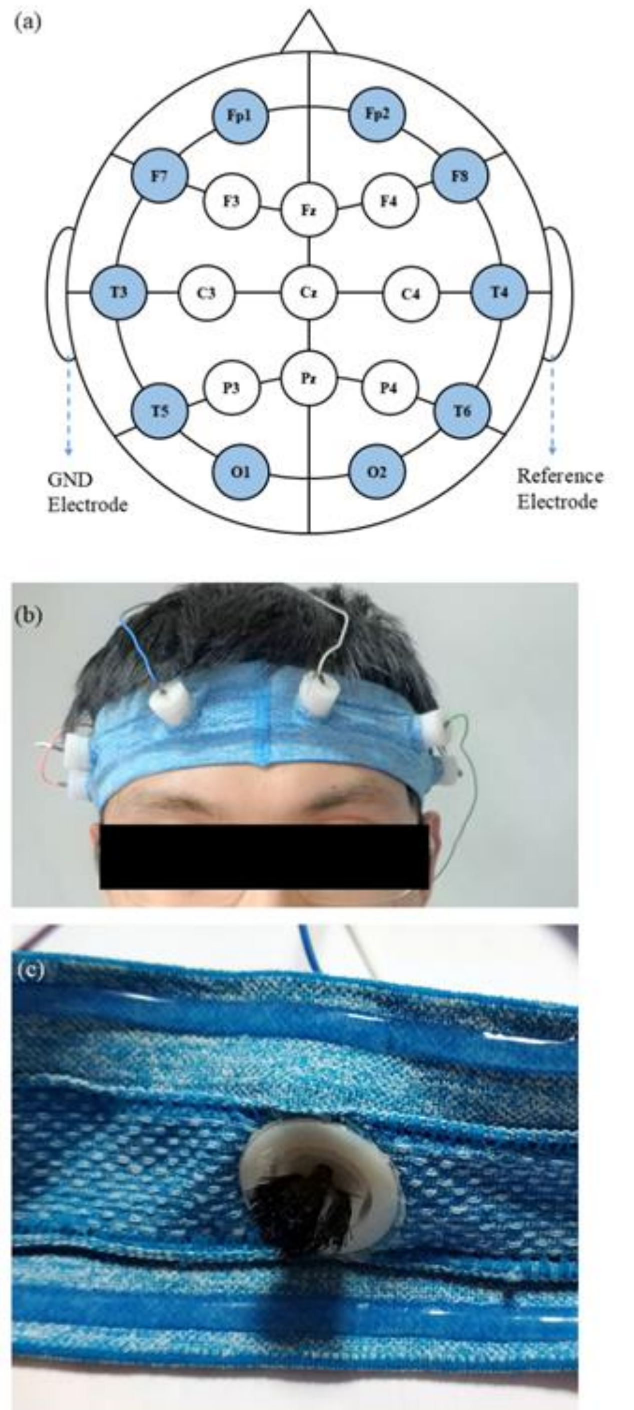

Fig. 3. Bristle-shaped semi-dry electrode headband. (a) Electrodes’ location. (b) Headband wearing. (c) Bristle-shaped semi-dry electrode fixed in the headband.

B. Electrode fabrication

Fig. 2a showed the internal structure of the semi-dry electrode. The body of the electrode was a 3D printed cylinder (Fig. 2b), as the cavity used for storing water. The absorbent cotton in the cavity was compressed to provide enough frictional force to prevent the slide of carbon coated nylon. The carbon coated nylon was fixed on a 3D printed round lid (Fig. 2c), which would be fixed on the cavity by hot melt adhesive. Four holes with a diameter of 2.3 mm were placed on the lid. 250 pieces of carbon coated nylon threaded the holes continuously. After threading, carbon coated nylon wire exposed to the outside of the lid was cut into 5 - 7mm long segments by an electric soldering iron and formatted the bristle structure (Fig. 2g). On the inner side of the lid, the ends of nylon bristles were melted together by the electric soldering iron.

The connection of carbon material and metal wire was always a challenge to carbon based electronic device. For a semi-dry electrode, the connect part had a risk of contact with

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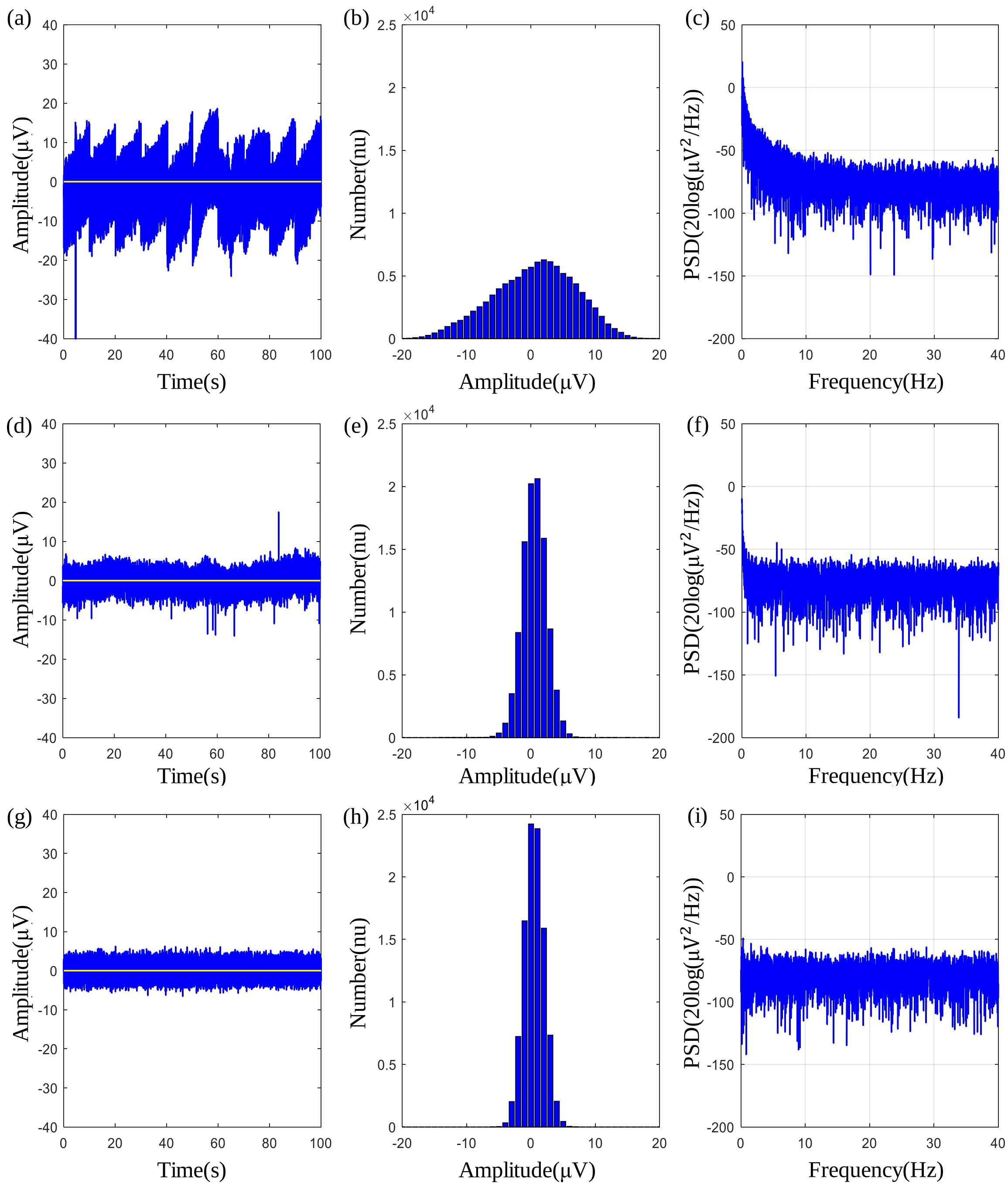

Fig. 4. Short circuit noise test. (a) Noise measured by Ag/AgCl wet electrodes. (b) Number of noises measured by Ag/AgCl wet electrodes with different amplitudes. (c) PSD of noises measured by Ag/AgCl wet electrodes. (d) Noise measured by semi-dry electrodes. (e) Number of noises measured by semi-dry electrodes with different amplitudes. (f) PSD of noises measured by semi-dry wet electrodes. (g) Noise measured without electrode. (h) Number of noises measured without electrode with different amplitudes. (i) PSD of noises measured without electrode.

water and the problem would be more serious than dry devices. When the water was immersed in the connect parts of carbon material and conductive wire, the metal in the conductive wire would be severely oxidized due to the principle of the original battery. If no action was taken, the metal in the wire contacted with the carbon fiber would even dissolve completely. In this study, we use hot-melt glue and heat-shrinkable tube to isolate water, the structure of the connection between conductive bristles and signal wire was shown in Fig. 2a. First, one heat-shrinkable tube was harnessed to the wire. And the wire was then wrapped around a bundle of carbon fiber, as shown in Fig. 2d. We then drop some hot-melt glue on the contact point of carbon fiber and metal wire, as shown in Fig. 2e. Before the hot-melt glue started to solidify, we pushed the heat-shrinkable tube to encase the contact point, shown in Fig. 2f. Then we used a hot air blower to heat the hot-melt glue and heat-shrinkable tube. Due to the shrinkage of the heat-shrinkable tube, the hot-melt adhesive would penetrate into the gap between the carbon fibers and form a sealed structure to prevent water. After cooling, the carbon fiber was then cut into 4mm long bristles and connected

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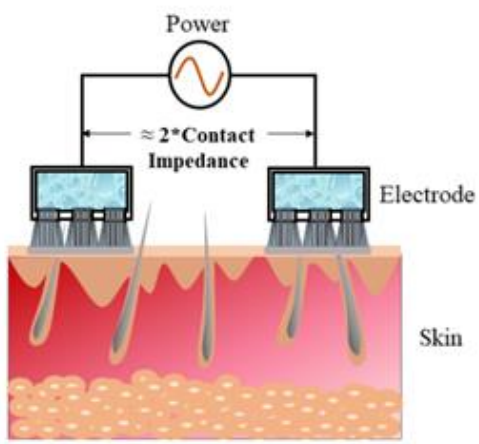

Fig. 5. The schematic diagram of contact impedance measurements.

to the end of carbon coated nylon bristles. The heat-shrinkable tube would get stuck in the 3D printed water chamber and prevent the signal wire from escaping. In this case, the connection between conductive bristles and signal wire was durable and stable. Fig. 2h shows the prototype of the assembled electrode.

After the fabrication, a modified sports headband with 3D printed electrode holder was used to fix the dry electrode on scalp. We referred to the electrode fixation method of g.tec brain cap. The size of the semi-dry electrode was compatible with the g.tec brain cap. Fig. 3b showed the headband wearing on head and Fig. 3c showed the electrode fixed in the headband. The electrode locations on the headband included Fp1, Fp2, F7, F8, T3, T4, T5, T6, O1 and O2, shown in Fig. 3a.

III. Test of the Electrode

The performance of semi-dry electrode was compared with Ag/AgCl wet electrode. The short circuit noise of wet and semi-dry bristle-shaped electrodes were both tested (Section III. A. Measurement of short circuit noise). And we also tested the electrochemical performance of both electrodes (including the measurement of contact impedance changes with signal frequencies and the equal circuit model, in Section III. B. Electrochemical performance and contact impedance test). A NeuroScan Nuamps EEG amplifier was connected to the semi-dry and Ag/AgCl electrodes for EEG signal measurements. The measured signals were recorded by Curry 7 software on a Surface Pro 4 tablet. To reduce the common mode noise, the Surface Pro4 tablet was powered by the internal battery. The sampling rate was set to1000Hz. The Ag/AgCl electrodes were 3M 2223CN patch electrodes with gelatin removed. We used the Ag/AgCl platform in the path electrodes and conductive gel to assemble into wet electrodes. The conductive gel in this study was fabricated by Quik-Gel^{TM}. Fig. 3a shows the location of electrodes. The tested electrodes were placed on head based on international10/20 system. During EEG signal measurements, the GND electrode was Ag/AgCl wet electrode and placed on left mastoid. We also placed a wet electrode behind right ear as ‘Reference’. The EEG signal measured by Reference electrode was subtracted from the signals measured by the tested

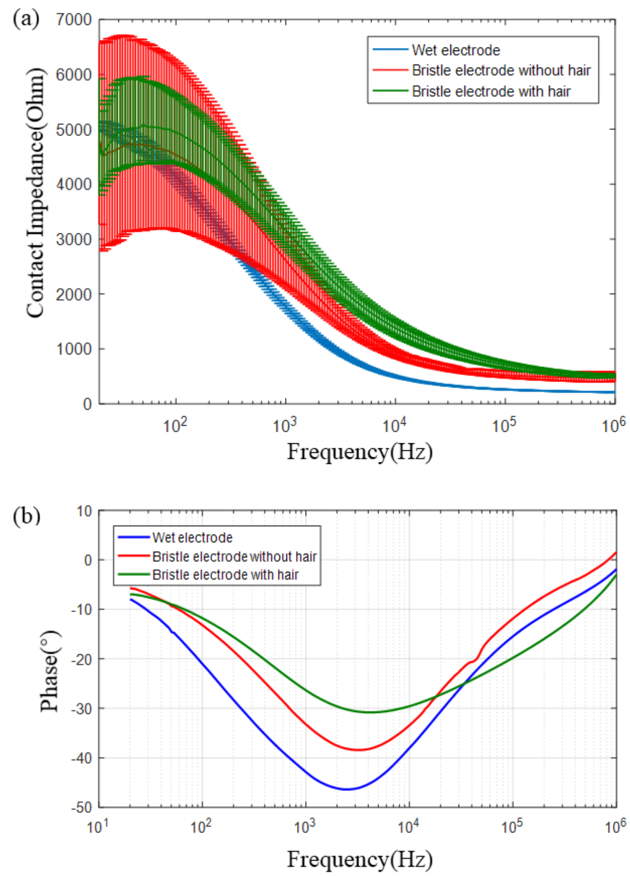

Fig. 6. Contact impedance and phase test. (a) Contact impedance at different frequencies. (b) Phase at different frequencies.

electrodes to reduce the common mode noise.

A. Measurement of short circuit noise

The short circuit noise of semi-dry electrode and Ag/AgCl wet electrode was measured by acquiring the signal of the electrodes that were attached to a polished silver plate (10cm * 10cm). We first tested the semi-dry electrode. There semi-dry electrodes were pasted on the silver plate. Then the semi-dry electrode connected to EEG recording channel was pasted beside it. Finally, a reference electrode was also pasted on the copper beside the recording electrode. After 100 seconds noise recording, all semi-dry electrodes were replaced by Ag/AgCl wet electrodes and also recorded 100 seconds of noise. The recorded noise was counted in the time and frequency domain. Fig. 4 shows the circuit noise of Ag/AgCl wet electrode and bristle-shaped semi-dry electrode. The result showed the bristle-shaped semi-dry electrode had better noise level compared with wet Ag/AgCl electrode. Fig. 4b and Fig. 4e shows the number of noises with different amplitudes. The PSD of noises in Fig. 4c and Fig. 4f shows the semi-dry electrode had less low frequency noise, which we speculated may benefit from the semi-dry electrode's lack of fluidity gel. The measurement of the noise of the amplifier was also performed on the same channels as wet and bristle semi-dry electrode tests. Three EEG lead wires with electrode interface removed were prepared. The wires were soldered together by tin. Figure 4g

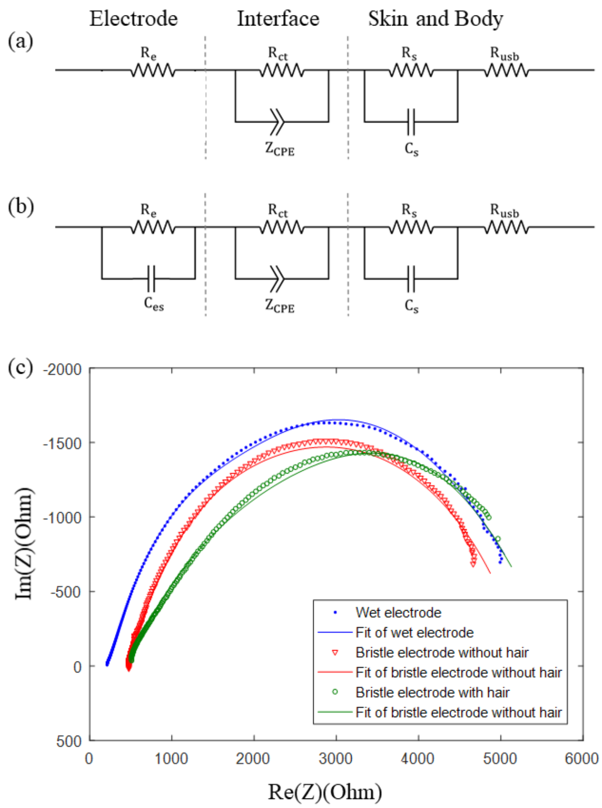

Fig. 7. Equivalent circuit test. (a) Equivalent circuit model of Ag/AgCl wet electrode. (b) Equivalent circuit model of semi-dry electrode. (c) Nyquist plot of wet and semi-dry electrodes.

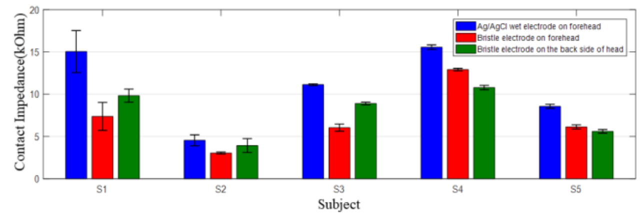

Fig. 8. Contact impedance on different locations and subjects.

shows the short circuit noise of the amplifier. Figure 4h shows the number of noises with different amplitudes without any electrodes, and Figure 4i shows the PSD of noises without any electrodes.

B. Electrochemical performance and contact impedance test

The electrochemical performance test includes the measurement of contact impedance changes with signal frequencies and the equal circuit model of the electrode.

The skin-electrode contact impedance under different frequencies was measured by a Keysight E4990A impedance analyzer. Fig. 5 shows the schematic diagram of contact impedance measurements. We placed two same electrodes on scalp (1cm gap). Since the impedances of conductive wire and skin organization under cuticle are low enough to be ignored, the electrode-skin contact impedance can be considered as half of the impedance between two electrodes. A fixed AC voltage signal was applied between two electrodes. The impedance could be measured by detecting the current flowing through the electrodes. The amplitude of the test signal for the impedance test was 5 mV, and the frequency of test signal ranged from 20Hz to1MHz. The real and imaginary parts of impedance were recorded. Fig. 6a shows the contact impedance. The result shows the bristle-shaped semi-dry electrode had similar contact impedance compared with Ag/AgCl. The standard deviations of semi-dry electrode were bigger than that of wet electrode, which may because the conductive gel has a stronger ability to adapt to the skin surface. The result also showed there was no significant change on the contact impedance of semi-dry electrode from no-hair area to hairy area. Fig. 6b shows the phase of Ag/AgCl wet electrode and bristle-shaped semi-dry electrode. The result shows phase of semi-dry electrode had smaller lag than wet electrode.

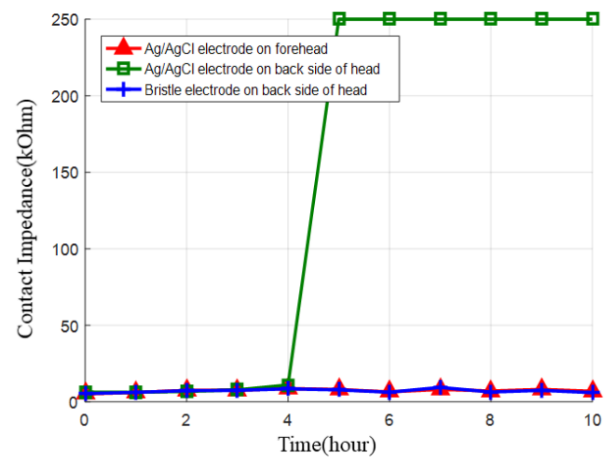

Fig. 9. Long term contact impedance test.

The equivalent circuit was calculated by Zview2. The equivalent circuit models for wet electrode and semi-dry

TABLE II
THE NUMERICAL FITTING RESULTS OF EQUIVALENT CIRCUIT COMPONENTS OF WET ELECTRODES

Item	C_{es}	R_e	Y_0	n	R_{ct}	C_s	R_s	R_{usb}
Unit	F	Ω	$\Omega^{-1}.cm^{-2}.s^{n}$	Nu	Ω	F	Ω	Ω
Ag/AgCl electrode	0	25.8	7.79E-7	0.743	4106	2.03E-6	1005	208.6
Bristle without hair	1.08E-7	65.9	7.90E-7	0.715	4343	2.01E-7	420.1	464.3
Bristle with hair	8.10E-19	844.4	1.41E-6	0.579	4395	4.85E-7	844.4	141.6

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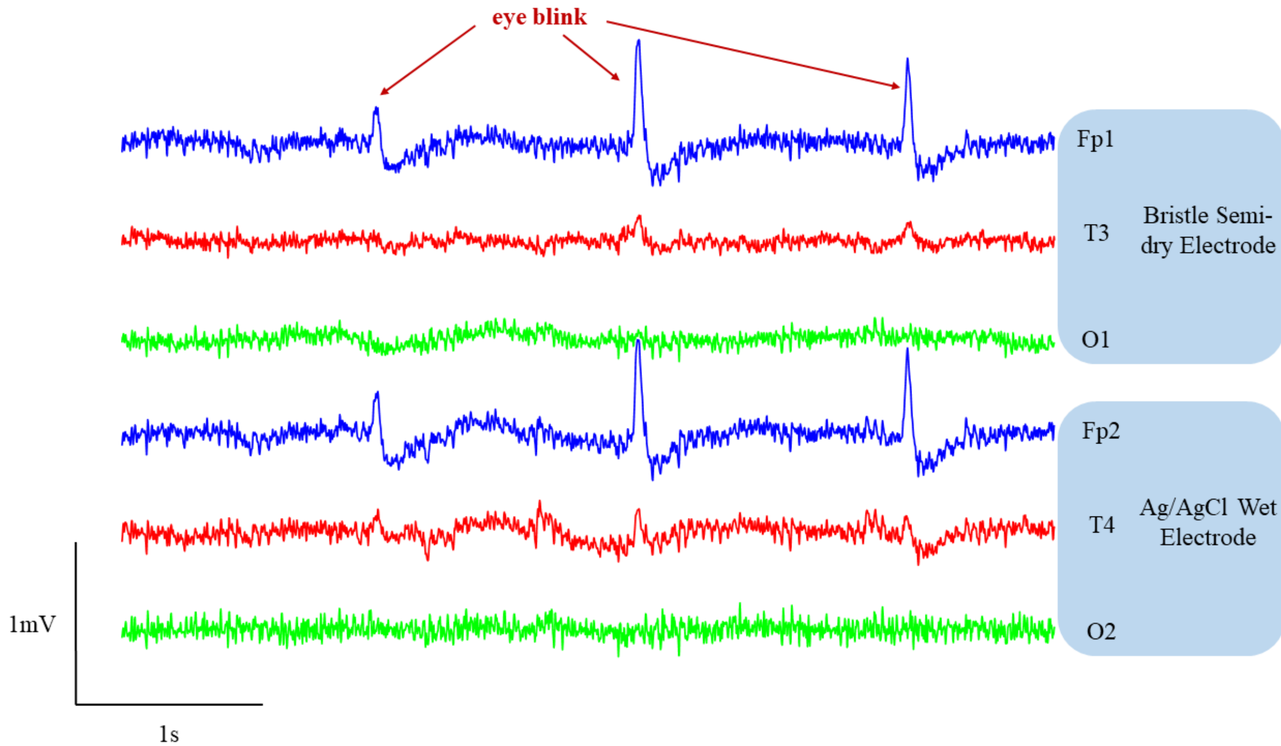

Fig. 10. EEG signals measured by bristle-shaped semi-dry and wet electrodes.

electrode were created in our previous studies [10]. Fig. 7a shows the equivalent circuit models for wet electrode. Fig. 7b shows the equivalent circuit models for bristle-shaped semi-dry electrode. The C_{es} represented the capacitance of semi-dry electrode due to lack of the conductive gel. R_e represented the resistance of the electrolyte and the leads. The R_{ct} represented the charge transfer resistance. The skin consisted of several layers which could be modeled by R_s and C_s in parallel. The R_{usb} represented the resistance of body except the skin. The Z_{CEP} represented the interface of electrode and electrolyte. The constant phase element (CPE) was expressed as follows:

$$Z_{CEP} = \frac{1}{Y_0(j\omega)^n}$$

where $j = \sqrt{-1}$, ω represented the angular frequency (rad s^{-1}) $= 2\pi f$, and f was the frequency in Hz. The parameter n changed from 0 to 1 corresponding to the CPE changed from a pure resistance to a pure capacitance. The parameter Y_0 represented the capacitance value when n = 1.

Fig. 7c shows the fit source data measured by E4990A impedance analyzer and the fitted results. The data of semi-dry electrode were measured on both hairy area and no-hair area to evaluate its ability of measuring EEG signals on hair. Table 2 shows the parameters of equivalent circuit.

The contact impedance in different locations was measured by the NeuroScan Nump. The GND electrode was Ag/AgCl wet electrode and placed on left mastoid. The frequency of test signal was set to be 10Hz as the default setting of NeuroScan Nump. Five subjects were tested in this study without any skin preparation, including 2 female (numbered S1, S2) and 3 males (numbered S3-S5) between the ages of 23-28. The test was carried out on location Fp2, F8, T4, T6 and O2. For each subject on each location, the skin-electrode contact impedance of semi-dry electrode in a dry state or wet state and wet Ag/AgCl electrode was measured.

Fig. 8 shows the average contact impedances of different subject and location. The result shows the contact impedance of

TABLE III
THE COMPARISON OF DIFFERENT ELECTRODES

Electrode type	Average contact impedance	Area of application	Rigidity/Flexibility
Electrode in this paper	15kOhm	Hair/No hair	flexible
Porous Ti Semi-dry electrode [30]	Not measured	No hair	rigid
Ceramic semi-dry electrode [21]	21-25kOhm	Hair/No hair	rigid
Ag bristle dry electrode [13]	80kOhm	Hair/No hair	flexible
Carbon fiber dry electrode [29]	300kOhm	Hair/No hair	flexible
Commercial dry electrode [31]	100-2000kOhm	Hair/No hair	rigid/flexible
Wet electrode [31]	5-10kOhm	Hair/No hair	rigid

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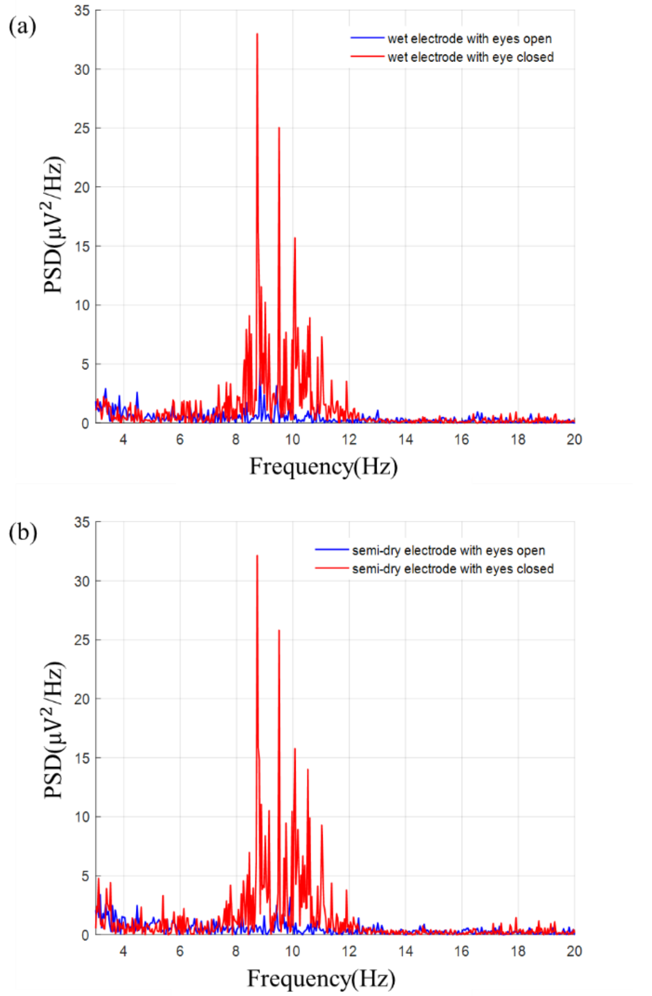

Fig. 11. Spontaneous potential measurement. (a) Spontaneous potential tested by Ag/AgCl wet electrodes. (b) Spontaneous potential tested by bristle-shaped semi-dry electrodes.

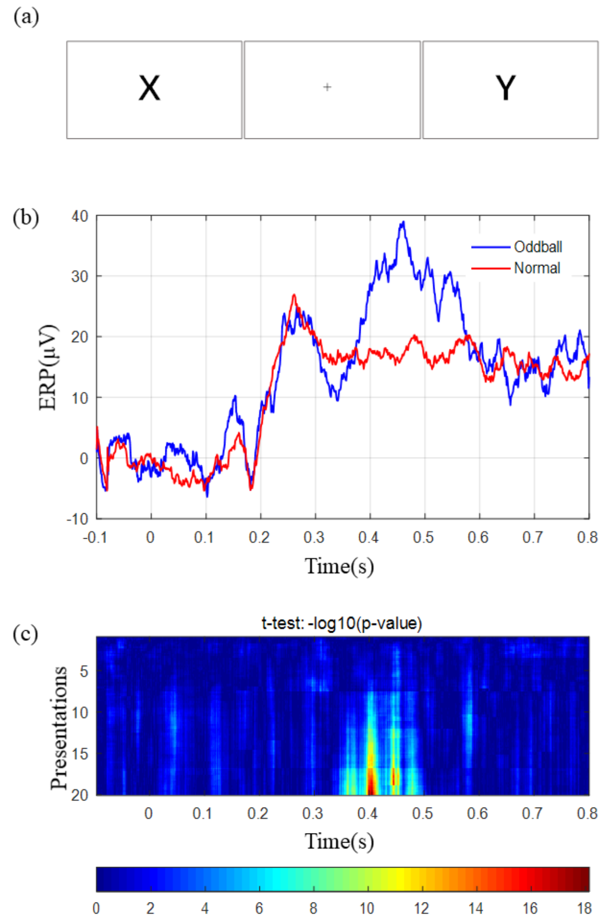

Fig. 12. P300 visual evoked potential measurement. (a) The stimulant material. (b) The P300 signals recorded by bristle-structure semi-dry electrode. (c) The statistical significance.

bristle-shaped semi-dry electrode was even slightly smaller than wet electrode in the test. And the impedance on hairy area was only slightly larger than it on exposed skin. We think this phenomenon may be because some of the subjects had some cosmetics or skin secretions on their skin, and the brush structure helped remove these substances and direct contact with the skin.

The semi-dry electrode was fixed on the back side of the head, where the hairs were about 3cm long. A wet electrode was fixed beside the semi-dry electrode. Another wet electrode was fixed on forehead, and its path was tightly attached to the exposed skin to prevent the evaporation of conductive gel. The test lasted for more than 10 hours. Every 1 hour, the contact impedance was measured by the NeuroScan NuAmps.

Fig. 9 shows the average contact impedance measured on forehead at 10 Hz. The wet electrode on hairy area could continuously work for about 4 hours. Then the contact impedance substantially increased. Because the range of NeuroScan NuAmps' impedance measurement is 0-250kOhm, so the data of 250kOhm could be considered as a disconnection between scalp and the wet electrode. The wet electrode on forehead and the semi-dry electrode both could work over 10 hours. After removed, we found that both wet and semi-dry electrodes were still moist. The wet electrode on forehead benefited from sealed conductive gel, which was almost impossible at hairy area, and the long endurance of semi-dry electrode was realized by continuous water supply.

The contact impedance during normal EEG recordings was also measured by the NeuroScan NuAmps amplifier. Before each time we used the semi-dry electrode to measure the EEG signals, we first measured the contact impedance by the NeuroScan NuAmps amplifier to ensure the electrode was properly placed. During our normal usages of the electrodes, the contact impedance was recorded with a mean value of 15kOhm. Table 3 shows the mean contact impedance compared with previous designs and traditional wet electrode, and the softness and application area of different electrodes are also compared.

C. *Measurement of EEG signals*

In this work, spontaneous potential, P300 visual evoked potential and steady-state visual evoked potential (SSVEP) were measured to evaluate the performance of conductive bristle semi-dry electrode on EEG signal recording [28]. Fig. 10 shows a section of 5 seconds long EEG signal recorded by 3 bristle-shaped semi-dry electrodes and 3 Ag/Ag/AgCl wet

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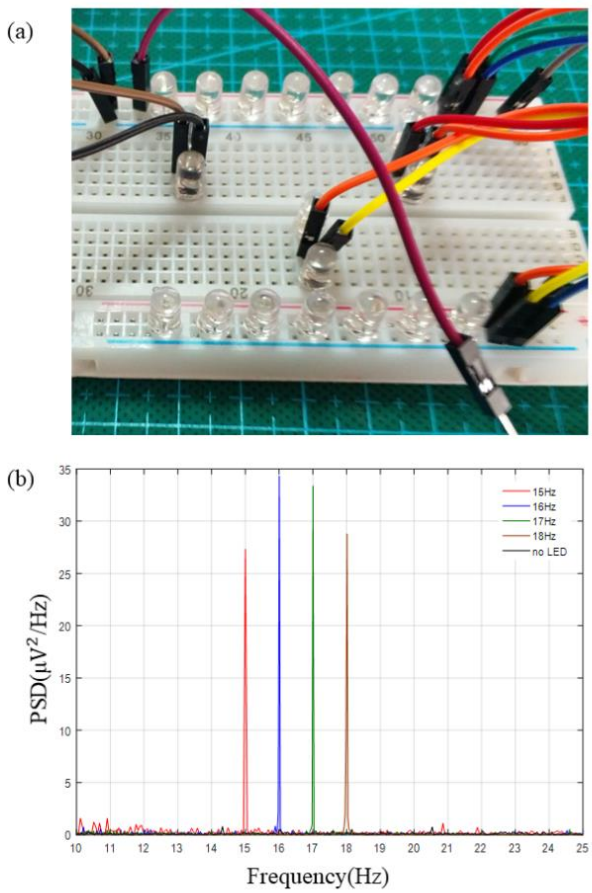

Fig. 13. Steady-state visual evoked potential measurement. (a) The LED array used for the steady-state visual evoked potential test. (b) The PSD of EEG signal with different LED stroboscopic frequencies.

electrodes. Eye blinks could be observed in Fp1 and Fp2.

1）Spontaneous potential measurement

In this test, the electrodes for test were placed on forehead. A semi-dry electrode and a wet Ag/AgCl electrode were tested. The wet electrode was fixed by its adhesiveness on the foam patch. The contact impedance of wet electrode was tested before EEG signal measurement to ensure it was less than 5kOhm. The semi-dry electrode was placed at Fp2 by the band. During the measurement, the subjects were asked to close or open eyes under instructions to motivate or constrain alpha rhythms. The baseline of recorded EEG signal was removed by Curry 7, and the 50Hz noise was also rejected by Butterworth filter in the Curry 7.

Fig. 11 shows the power spectral density (PSD) of EEG signals detected by wet electrode and semi-dry electrode. Fig. 11a shows the PSD of wet electrode. Fig. 11b shows the PSD of bristle semi-dry electrode. When eyes were opened, there was no trace of Alpha rhythms on both electrodes. When eyes were closed, a peak could be observed at the frequency of alpha rhythms signal bandwidth from 8 to 13 Hz [25] from both wet and semi-dry electrodes. The PSD of EEG signals measured by wet and semi-dry electrodes had similar change tendency with Ag/AgCl wet electrode. The bristle-shaped semi-dry electrode and Ag/AgCl wet electrode had the similar performance in Alpha rhythms measurement.

2）P300 visual evoked potential measurement

The semi-dry electrode was placed at location O1. The stimuli was edited by Eprime 2.0. A 60 Inch Sony liquid crystal television was used to play the stimuli video. Fig. 12a shows the stimulant material. During the test, the task program randomly display ‘X’ or ‘Y’ on the center of screen as the stimuli. For each stimuli, the letter ‘X’ or ‘Y’ lasts for one second. The intervals between stimuli were randomly altered from 1s to 1.5s to prevent habituation. On the stimulus gap, a ‘+’ symbol was displayed on the center of screen to attract the attention of the participants. The stimuli were repeated 100 times over about 4min. During the test, the letter ‘X’ appeared 80 times for the normal stimuli, and the letter ‘Y’ appeared 20 times for the oddball stimuli.

The analysis of the P300 signals followed the following steps: band-pass filtering 1-30 Hz (chebyshev filter of order 3), followed by condition-wise averaging of stimulus-aligned segments. The statistical significance of the difference between the two conditions was computed with two-sample t-tests for every sampled time point from -40 to 800ms and cumulative for each new presentation of the oddball stimulus. The null hypothesis is that the two subpopulations of values.

Fig.12b shows the P300 signals recorded by bristle-structure semi-dry electrode and wet Ag/AgCl electrode. Two-sample t-tests for every sampled time point from -100 to 800ms were calculated to evaluate the statistical significance of the difference between normal and oddball stimuli. Significant differences could be observed at 300ms. Fig.12c shows the statistical significance of semi-dry electrode for every sampled time point from -100 to 800ms. After the stimulations occurred, the significant differences could be observed between the lag of 300ms and 500ms.

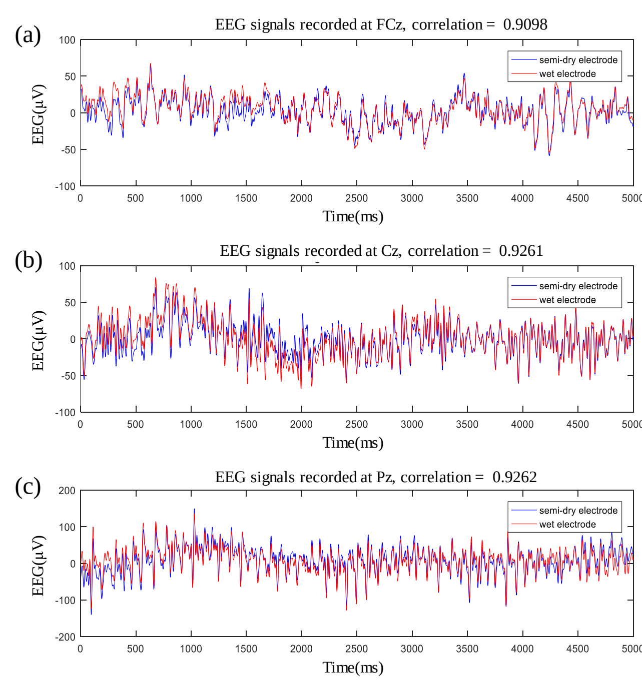

Fig. 14. EEG signals recorded in very hairy areas. (a) EEG signals recorded at FCz. (b) EEG signals recorded at Cz. (c) EEG signals recorded at Pz.

3）Steady-state visual evoked potential（SSVEP） test

Fig. 13a shows the LED array used for the steady-state visual evoked potential test, which was turned on and off alternately at different frequencies to stimulate specific EEG signals [26]. The stroboscopic flash frequency was set to 15Hz, 16Hz, 17Hz and 18Hz, controlled by a programmable voltage sources. The voltage applied on LED was set to 5V. During the test, the subject was asked to gaze at the flashing LED for about 20 seconds. The semi-dry electrode was placed at location O1, closed to the visual center of brain. After recording, the PSD of EEG signals with different LED flash period were calculated to observe SSVEP phenomenon. Fig. 13b shows the PSD of EEG signal with different LED stroboscopic frequencies, peaks at 15Hz, 16Hz, 17Hz and 18Hz could be observed in the PSD of recorded EEG signals, exactly corresponded to the frequency of LED stroboscopic flash.

4）EEG signal test on very hairy areas

The EEG signals on Cz, Pz and FCz were recorded by both bristle shaped semi-dry electrodes and traditional wet electrodes to evaluate the performance on very hairy area. The semi-dry electrodes were fixed by a band and the wet electrodes were fixed by the glue of themselves. The distance between two different electrodes was about 1cm to avoid the crosstalk caused by conductive gel. The wet electrodes were still 3M2223CN gel electrode. The hydrogels of the wet electrodes were removed and replaced by Ten20® conductive gel to reduce the impedance and pass through the hair. The distance between wet and semi-dry electrode was about 1cm. The signals at FCz were measured first, then the signals at Cz were measured. Finally, we measured the EEG signals at Pz. The signals recorded by semi-dry electrodes were compared with the wet electrodes. The correlation between two electrodes was calculated and were all above 0.9 (0.9089 at FCz, 0.9261 at Cz and 0.9262 at Pz). Figure 14 shows the result. The signals recorded by wet and semi-dry electrodes on very hairy areas are very similar.

IV. CONCLUSIONS

In this study, a novel passive semi-dry bristle-shaped electrode for EEG recording in hairy area was proposed. The special connection method between metal lead wire and carbon conductive materials was designed to avoid metal wire oxidation due to the primary battery principle and make the electrode durable. Conductive bristles fabricated by carbon coated nylon were placed on the electrode. The bristle-shaped electrode was totally soft and could continuously spread moisture to the scalp through hair for over 10 hours. The skin-electrode contact impedance was several kOhm, similar to conductive gel wet electrode. The result of noise test showed the bristle-shaped electrode may have even less low frequency noise compared with wet electrode. The ability of recording EEG signals was tested by recording spontaneous potential, P300 and SSVEP signals.

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