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A New Generic Single-Channel Ear-EEG Recording Platform †

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Abstract: It has been demonstrated that electroencephalography (EEG) signals can be acquired from electrodes placed on an earpiece inserted into the ear, and the interest in dry ear-EEG has increased in recent years. However, the challenge is to find an excellent durable electrode material, with which the stable quality signals can be collected after repeated insertions. To achieve a sustained ear-EEG recording platform, a new generic earpiece designed with PDMS and the AgCl powder sintered electrode is proposed in this paper. The platform's characteristics are evaluated with an alpha band modulation and auditory steady-state response (ASSR), with the inclusion of different ear sizes of subjects. Recordings from the prototyped generic ear-EEG platform are compared to conventional scalp EEG recordings. The ear-EEG electrode exhibits good wear resistance. After repeated insertion and removal of the electrode, the quality of the signal acquired by the electrode was stable, and statistically significant ($p < 0.05$) responses were measured for ASSR paradigms.

Keywords: electroencephalography (EEG); ear-EEG; dry-contact electrode; wearable EEG; powder sintered electrode

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1. Introduction

Electroencephalography (EEG) is a well-established technique that provides valuable insights into brain activity, with applications both in clinical practice and basic and applied neuroscience [1,2]. Despite the widespread adoption, the number of critical EEG applications is limited in terms of the mobility requirements for the EEG equipment. Examples include brain–computer interfaces (BCIs) [3], long-term monitoring of neurological patients [4] and sleep monitoring [5]. To this end, a promising solution, the ear-EEG, which promises a robust, unobtrusive and non-invasive means for brain activity monitoring was proposed [6–8].

A novel idea to record EEG signals with electrodes placed in the ear canal was proposed by Looney, D. in 2011 [6]. Furthermore, by directly comparing simultaneously acquired scalp EEG and ear-EEG signals, several independent laboratories have shown that ear-EEG can capture brain signals that are closely related to those recorded with scalp EEG [7–9]. In contrast to the classical EEG cap, the ear-EEG sensors can be worn comfortably and unobtrusively [7]. The initial concept and prototypes of the ear-EEG sensor were based on the personalized substrates 3D-printed with rigid acrylic plastic, which has been widely used in the hearing aids industry. The personalized 3D printing yields tight-fitting substrates, which is critical for good quality signals. However, the rigid plastic provides unevenly distributed pressure along the outer surface of the device. When put inside the ear canal, there is loose and intermittent electrode–skin contact, which is susceptible to motion artifacts. Some soft rubber based on 3D printing is increasingly used [10,11]. However, time-consuming and high-cost problems still exist that are associated with a personalized design. To address the above issues, generic substrates were developed. For instance, Goverdovsky, V. introduced representative material, such as memory foam, to ensure conformance with the ear canal surface for a reduction in motion artifacts [12,13]. The pressure on the outside surface of the foam earplug is uniformly redistributed, thus creating excellent contact with the skin at any point on the substrate, and providing a robust electrode–skin interface and long-term wearing ability. However, the development of memory foam is restricted by its easy falling and inconvenient electrode installation, so a generic substrate is urgently needed, which conforms to the ear canal structure.

Except for the sensor substrate design, the dry-contact electrode is another important aspect of the ear-EEG sensor. Dry-contact electrodes were developed to increase the comfort and user-friendliness of the ear-EEG. There are two broad types of electrodes: polarizable and nonpolarizable [14]. The former type, such as platinum and titanium, easily introduce low-frequency noise during recording. In contrast, the nonpolarizable electrode has stable electrochemical properties. The well-known electrode is Ag/AgCl, and we must consider the wear situation when wearing the electrode. The above considerations motivated us to design a novel generic dry-contact ear-EEG recording platform, whereby a silver chloride powder sintered electrode is embedded in an earpiece substrate made of polydimethylsiloxane (PDMS). The electrode locations and earpiece design are informed by physiological recordings and anatomical measurements using a 3D scan and reconstruction. It fits most adult ears and increases the comfort and user-friendliness for long-term recording. The performance of our developed electrode is validated through a study of standard EEG paradigms.

2. Materials and Methods

The ear-EEG sensor's two key components are an earpiece substrate and an electrode. It is critical that the substrate could be effortlessly and appropriately placed in the ear canal. Although personalized earpieces [10] are comfortable, general-purpose earpieces eliminate the time-consuming process of personalized customization. Since it is reported that the ear dimensions are more in line with normal distributions across large human populations [15], we selected the appropriate generic earpiece parameters by ear impressions and 3D scanning with a micro CT. As a result, the designed dry electrode can eliminate the trouble of injecting conductive gel and be fitted for a long-term stable signal acquisition.

To make the sensor fit more comfortably inside the user's ear, the earpiece was manufactured using advanced 3D printing techniques. The fabrication process includes an impression, scanning, computer-aided design modeling, 3D printing, wiring process, pouring and curing.

3. Experiment

To further evaluate the performance of the electrode, it is necessary to compare the characteristics between the ear-EEG and the standard scalp EEG. As a result, we designed experiments to acquire them synchronously. For the ear-EEG, the measuring electrode and the reference electrode were situated within the different ears, and the reference position was the left earlobe. The on-scalp EEG was recorded using the scalp electrodes (10–20 electrode system [16]), relative to the right mastoid (reference) and the forehead as ground (common-mode feedback).

This study comprised recordings of spontaneous EEG, which focused on alpha-band activity modulated by visual attention. In this test, the subjects were asked to stay relaxed in a comfortable position, open their eyes for the 30 s, and then close them for 30 s. They were instructed to stare at the red cross on the screen, and then an auditory cue indicated a change in condition every 30 s. The auditory steady-state response (ASSR) stimulus in this paper was used for two kinds of audio (click and SAM). The first click sound is composed of the same rectangular impulse response, and the amplitude of the discrete rectangular impulse is −1 to 1. The following formula generates the sinusoidal amplitude modulation (SAM) sound:

$$S(t) = \sin(2\pi f_c t)(1 + \sin(2\pi f_m t))/2 \quad (1)$$

where f_c and f_m are the carrier frequency and modulation frequency, respectively. We set f_c to be 1000 Hz. For f_m, we used three kinds of frequencies (38 Hz, 40 Hz, and 42 Hz) to explore whether the ear-EEG electrode can accurately distinguish the steady-state response. For ASSR, each stimulus was broadcasted per second and repeated 120 times. A trigger was used to mark the continuous ear-EEG at each stimulus to divide the continuous ear-EEG into epochs. The data were filtered from 35 to 45 Hz and segmented in 1 s segments. The evoked signal was extracted by the time-domain averaging (TDA) of the segments, and the SNR was calculated as the ratio between the power of the first harmonic ASSR (at 40 Hz) and the mean power from 35 to 45 Hz excluding 40 Hz.

4. Results

We analyzed the correlation of the signals for subject A in the alpha-band modulation experiment between the ear-EEG and on-scalp electrodes in eyes-open and -closed conditions. There was a high correlation between the ear-EEG electrodes and the neighboring on-scalp electrodes, T8, F8, and P8. The degree of correlation decreases when the distance increases. The ear-EEG waveform is very similar to the on-scalp EEG waveform, thus demonstrating the feasibility of obtaining EEG signals from ear-EEG recordings. We also determined the spectral coherence values obtained between the on-scalp and ear-EEG electrodes. Similar to the correlation results, the degree of coherence between the ear-EEG electrodes and the neighboring on-scalp electrodes (T8) was high, decreasing for more distant on-scalp electrodes. Furthermore, the coherence between the ear-EEG and scalp-EEG signals at channel T8 in the temporal region of the brain was higher than the others. Moreover, during 5–20 Hz, the coherence of the eyes-closed condition was higher than that of eyes-open, which resulted from an increased alpha activity after the eyes were closed.

Alpha waves are one type of brain wave detected by electrophysiological and closely-related methods, such as electroencephalography (EEG), and can be predominantly recorded from the occipital lobes during wakeful relaxation with closed eyes, the earliest brain rhythm recorded in humans [17]. The subjects opened their eyes for 20 s and then closed their eyes, with alpha waves being detected when their eyes closed at 8–12 Hz. A similar power can be observed for both the ear-EEG and scalp EEG. Compared to previous studies of alpha-band modulations performed with wet ear electrodes, the modulation for the ear-EEG was lower in the present study [18]. This modulation was weaker because the amplitude of the waves was most prominent over the occipital lobe and parietal cortex, and less pronounced when approaching the frontal cortex. These properties show that, with the alpha-band modulation, we can perform measurements using the developed dry-contact ear-EEG platform.

For steady-state responses, it is natural to consider the power spectrum. We extracted the ASSR by averaging all the segments and computed the ASSR power. All of the ASSRs were statistically significant (F test). We can distinguish different frequencies by both the click and SAM sound. For different audios with the same modulation frequencies, click has a more robust steady-state response. The amplitude recordings were 10–15 dB higher than SAM, and the harmonic responses are still easily observable. We can observe that the overall signal level is 3–5 dB lower than the scalp-EEG for the same sound. However, the lower signal amplitudes of SAM did not compromise the signal quality, and the SNR was similar to that of click. Finally, as expected, ear-EEG and scalp EEG have similar amplitudes and SNRs.

5. Conclusions

The proposed ear-EEG electrode recorded EEG signals in response to various external stimuli. The earplug-shaped electrode offers an inconspicuous recording that maintains the user’s privacy. The shape and softness of the electrode enable it to be worn without any gel or additional devices, and to be worn repeatedly or for long periods of time while maintaining excellent contact. The electrode can also provide sound stimulation and applies to auditory BCI. This electrode addresses several limits of conventional electrodes and promises a novel paradigm of inconspicuous EEG recording, not only for partial clinical use, but for BCI and sleep monitoring.

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