# A New Soft Material Based In-the-Ear EEG Recording Technique

Hao Dong[1], Paul M. Matthews[2] and Yike Guo[3]*

***Abstract*— Long-term electroencephalogram (EEG) is important for seizure detection, sleep monitoring and etc. In-the-ear EEG device makes such recording robust to noise and privacy protected (invisible to other people). However, the state-of-art techniques suffer from various drawbacks such as customization for specific users, manufacturing difficulties and short life cycle. To address these issues, we proposed silvered glass silicone based in-the-ear electrode which can be manufactured using conventional compression moulding. The material and in-the-ear EEG are evaluated separately, showing that the proposed method is durable, low-cost and easy-to-make.**

## I. INTRODUCTION

Scalp EEG, both wet and dry electrode [4], have been used for seizure detection, sleep monitoring and etc., [1], [2], [3]. However, long-term monitoring is difficult with for many practical applications since it requires privacy (i.e., worn ”invisibly”) and wearing comfort. In-the-ear EEG techniques make the long-term monitoring possible [5], [7]. Unlike scalp EEG, which attaches many electrodes to a user's scalp, in-the-ear EEG devices bring a comfortable user experience. Moreover, the EEG signal is robust to noise incurred by users' movements and other noise sources [5]. In this paper, we will show the advantage of our soft material based technique for addressing these issues.

First of all, we review three representative in-the-ear electrode techniques. The first in-the-ear EEG device was invented in 2012 [5]. Aiming to prove the feasibility of recording EEG in the ear, the ear-canal-fit electrode was realized by embedding Ag/AgCl electrodes on a customized orthoplastic earpiece. The nonconducting orthoplastic earpiece is used to support Ag/AgCl electrode. The evaluations include alpha attenuation response (AAR), auditory steady-state response (ASSR) [6] and visual event-related potential (VERP), verified the practical realizability of recording in-the-ear EEG.

However, due to the variation of shape/size of the human ear canal, it would be extremely challenging to customize the ear electrodes owning to the unbend property of material. Meanwhile, the comfort issue has not been resolved.

Recent studies advanced fabrication of carbon nanotube polydimethylsiloxane (CNT/PDMS) based ear electrodes. CNT/PDMS belongs to conductive soft material that enables earpiece fit ears easily [7], and no requirement for any supporting structure. Therefore, the soft electrode material based technique simplifies the electrode structure. However, CNT/PDMS material is difficult to produce due to high production cost and long manufacturing process, limiting scalability for mass production [8], [9].

Neither soft nor hard materials are utilized for each method mentioned above. Recent study [10], shows another method, using memory foam as soft supporting material and conductive cloth electrodes as electrode material respectively.

The memory foam can be adjusted to fit the shape of ear canal then provide uniform pressure against the skin. Moreover, the chosen cloth electrode is made of silver-coated nylon interwoven with elastic fibres, providing comfort for long-term recording. However, the durabilities of both memory foam and silver-coated nylon are poor. What is more, the abrasion of cloth electrode will lead to low-frequency noise. Overall, this design illustrated how easier the combination of different materials to fabricate an electrode compared with producing them from soft electrode material only.

A more fundamental limitation of in-the-ear EEG is its spatial resolution which results that the EEG in the ear is mainly transmitted from the temporal lobe. Although, there is more information on auditory but less on other features, the information from frontal, occipital, parietal and central lobe can also be reflected and extracted from the EEG in the ear due to the high correlation of EEG signal with one location and its surroundings.

## II. MATERIAL

TABLE I
FEATURES OF DIFFERENT MATERIALS

| Material | Performance features |
|---|---|
| Tin | Low precision on low-frequency range |
| Gold or silver plating | Abrasion causes low-frequency noise |
| Ag/AgCl plating on non-silver material | Abrasion causes low-frequency noise, single use only |
| Silver | Durable and low noise |
| Ag/AgCl plating on silver | Fast signal stabilization, low noise, suitable for measuring evoked potential and event-related potential |
| Sintered Ag/AgCl | Fast signal stabilization, low noise, suitable for measuring evoked potential and event-related potential |

The level of low-frequency noise which is introduced during recording varies between different materials [11]. Typically, the electrodes are classified into different categories according to the materials used. Table I lists all the

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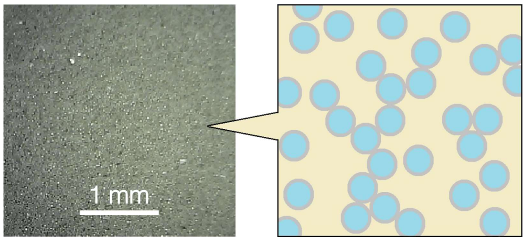


Fig. 1. Inner structure of silvered glass silicone (SGS)

possible materials with their performance. As illustrated in Table I, both sintered silver-silver chloride (Ag/AgCl) and Ag/AgCl plating on silver have relatively low noise which is the best performance feature for EEG recording. Compared with Ag/AgCl, silver has slightly higher noise but lower cost. Therefore, in our study, silver was chosen as the conductive medium for the sake of cost and mass production.

The proposed canal-type ear electrode (CEE) were fabricated in two steps. In the first step, the raw material was silvered glass beads filled silicone rubber. These were fabricated as silver, glass silver and silver conductive grains distribution in silicone rubber, through the pressure of conductive particle contact to achieve good conductivity. As illustrated in Fig. 1, the silvered glass silicone (SGS) is built from silvered glass beads filled with silicone rubber.

After producing the raw material, we can move forward to the moulding process. The advantage of our material is that conventional compression moulding can be used to achieve a given shape. The moulding process requires $200°C$, 150 seconds and 180 tons of pressure. A multi-parts steel mould can be used repeatedly for many times, and able to product over 50 pieces in one machining cycle. The finishing colour is yellow, but it can be dyed to different colour in the manufacturing process such as dark khaki, black. Fig. 7 shows our in-the-ear electrode made of SGS, each SGS-CEE cost around 0.2 USD during mass production.

The advantage of SGS-CEE is that it is easy to make. Comparing with CNT/PDMS [8], this method largely reduces the fabricate process from several hours to less than 150 seconds, making it low cost, high speed and capable for large scale manufacturing.

## III. Structure

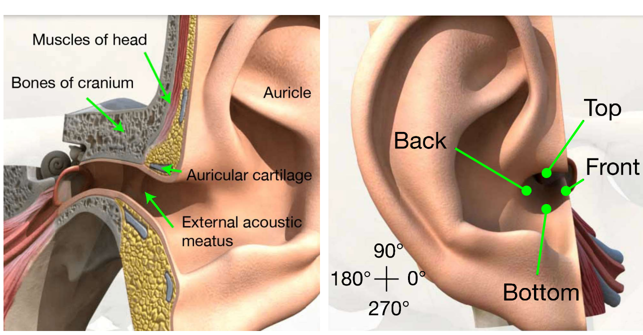


Fig. 2. Ear structure [13]

The ear canal is surround by auricular cartilage, muscles of head, bones of cranium and fat. So the EEG from different position of ear canal are different in some degree, and uniform pressure against skin is essential.

Inside the ear canal, both the bones of cranium and auricular cartilage are able to support the electrode, but due to the bones of cranium is hard, it will cause some pain if the electrode contact with it for a long time. In contrast, auricular cartilage is perfect for supporting the electrode, it can be attributed to its flexibility and shallow depth.

Fig. 3. SGS ear canal electrode

The SGS electrode is designed to different sizes to suit people of different ear sizes and provide uniform pressure against the skin. What is more, an additional non-conductive silicon part is added to provide support from the auricle and increase the stability of electrode inside the ear canal as shown in Fig. 3. Therefore, noise caused by movements is eliminated.

## IV. Evaluation

To evaluate the proposed in-the-ear electrode, we tested the material and in-the-ear EEG separately. The most common test methods are observing eyes blink, gritting teeth, Alpha attenuation response (AAR, also know as alpha rhythm detection) and Auditory steady-state response (ASSR). In the evaluation, in order to get the result close to wireless and wearable application, an analog and digital circuit was designed to record the EEG in dry way, the hardware informations were described on Table II (Note: CMRR - common-mode rejection ratio, ADC - analog to digital converter, LSB - least significant bit). After converting the analog signal to digital data, the circuit transmitted the data via blue-tooth low energy technology (BLE) to an iPhone 6.

TABLE II
Technical information of all-in-one in-ear EEG system

| **Parameters** | **Value** |
|---|---|
| CMRR | 120 dB |
| Input impedance | $10^{12}\Omega$ |
| Sampling rate | 512 Hz |
| ADC resolution | 12 Bits |
| Frequency response | 0.2-49 Hz |
| Voltage resolution | 0.18 $\mu$V/LSB |

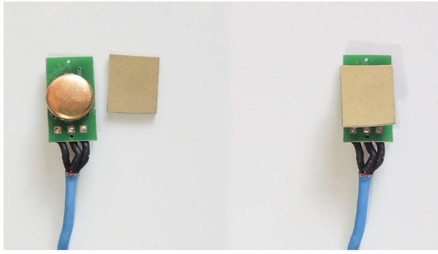

Fig. 4. Flat SGS dry electrode for recording at Fpz

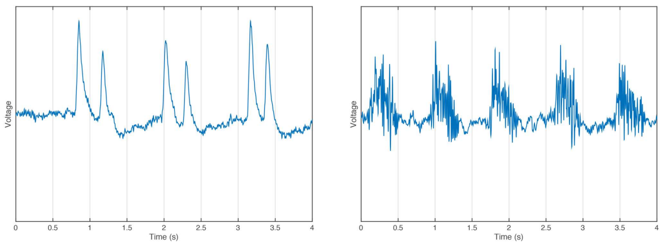


Fig. 5. EEGs detected for eye blinks and gritting teeth at Fpz using SGS sheet. Left: blinks 6 times; Right: gritting teeth 5 times; Voltage scale: $\pm 371uV$

For the evaluation of material, we recorded the EEG on the scalp using a 12x10x1.2mm SGS sheet placed between Fpz and active dry electrode (as shown in Fig. 4 ), and set the reference and driven-right leg (DRL) at the subject's left earlobe. From Fig. 5, the eye blinks and muscle artifacts can be clearly visualized on the measured EEG signal, where each eye blinks produces one peak, and each jaw muscle contraction will produce a continuous vibration.

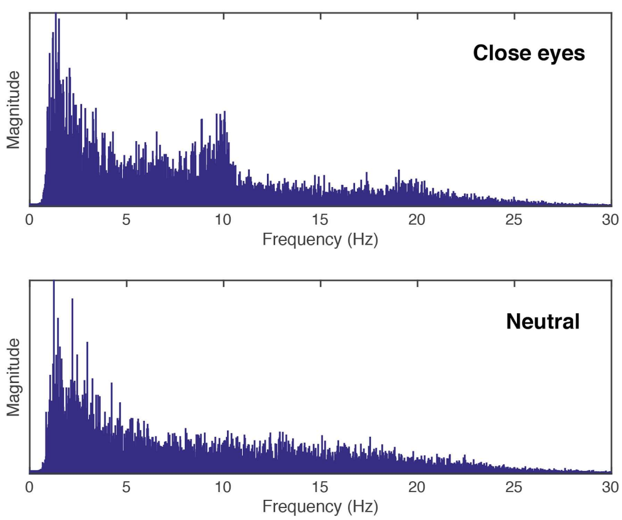


Fig. 6. Alpha attenuation response at Fpz. Upper graph shows eyes close case and lower graph shows eyes open case

For the evaluation, the neutral state is defined as that the subject is seating still on a backrest-chair and looking ahead under normal lighting condition. Close eyes state represents the condition which is the same with neutral state, but eyes closing. The alpha rhythm (8-12Hz) should has significant increase during close eyes period compare with neutral state.

In the AAR test, the alpha activity was successfully recorded from Fpz channel. Fig. 6 shows the frequency spectrums of EEG signals during neutral state and close eyes state. It can be clearly seen that the alpha rhythm (8-12Hz) has a significant increase during eyes closing compared to eyes opening. This test proves that the SGS is suitable for dry EEG electrode.

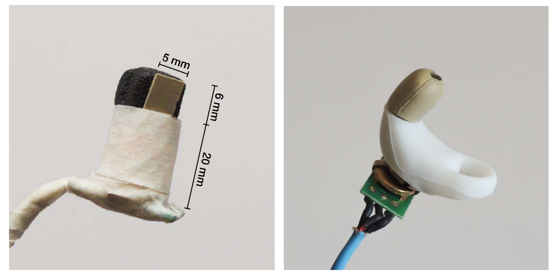


Fig. 7. SGS sheet dry electrode for testing EEG at different position in ear canal (left); Canal-type SGS dry electrode with electric circuit (right)

Furthermore, to evaluate the in-the-ear EEG, the EEG signal was measured from different positions of the ear canal. We measured the signals from 4 directions (shown in Fig. 2): top, bottom, front and back, using the electrode shown in the left side of Fig. 7. Our results suggested that the EEG recorded from front position contains artifacts caused by superficial blood vessels introducing artifacts synchronized with the heartbeat. The cardiovascular information can be extracted easily, but the EEG signal is distorted. Moreover, the distance between the bottom position indicated in Fig. 2 and temporal lobe is larger than the other positions', so the EEG from the bottom position collected lesser EEG information than others'. Among these positions, the top position was found to be the best position to detect alpha activity, likely due to a short distance to temporal lobe compare with others.

Fig. 8 shows the frequency and time-frequency analysis of EEG signal measured from the top position, where the red spot on the time-frequency spectrogram represents high amplitude. It is clear that the frequency between 8 to 12 Hz has significant and uninterrupted increases were found with eye closure. The left-hand side of Fig. 8 shows the amplitude of the alpha rhythm. Moreover, compared with EEG from frontal lobe, the eyes blink and gritting teeth artifacts from in-the-ear EEG are significantly lower.

Furthermore, to check the adaptable of using the SGS for long-term wearing, a skin compatibility test was made. To complete the test, a 15x15x1.2 mm material sheet was continuously attached to subjects' skin. The test on three participants showed no side effects of wearing it for a long time, which confirmed the skin compatibility of the SGS. Besides, the SGS sheets are used to measure EEG after skin compatibility test, the EEG quality is unchanged after skin contact for a week. This suggests that the skin does not cause material metamorphism.

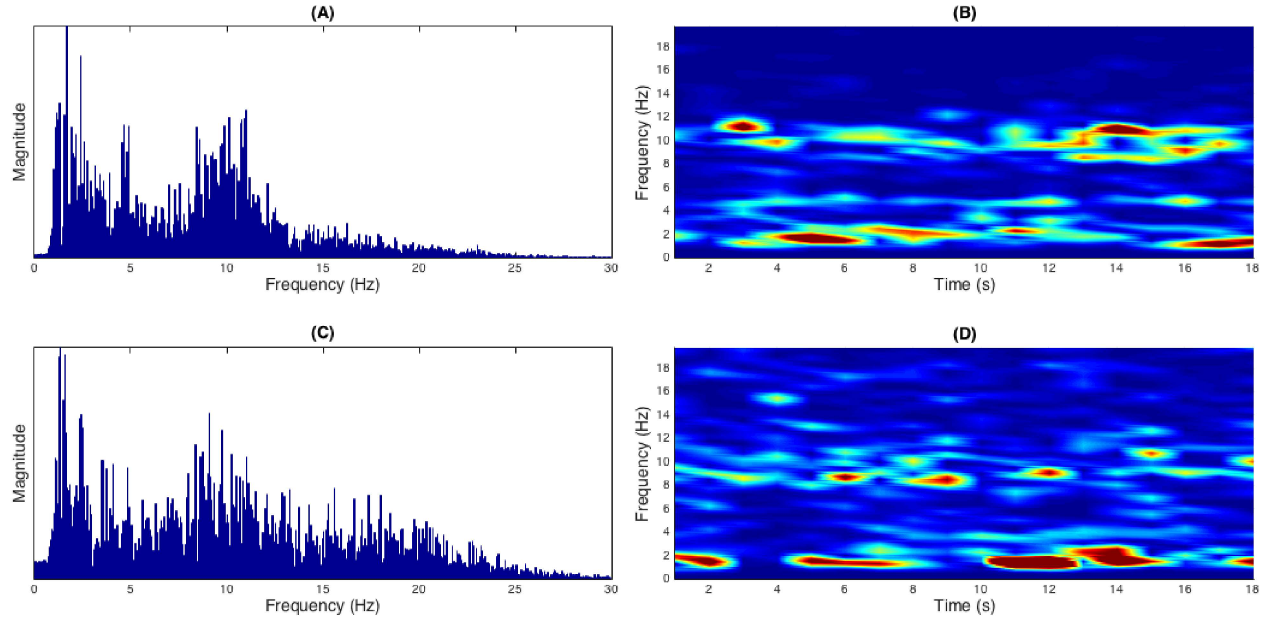


Fig. 8. Frequency spectrum (left) and time-frequency spectrogram (right) of AAR test using SGS sheet ear canal electrode to contact with the top position of ear canal. (A) and (B) for Subject I, the top position of right ear canal, reference and DRL both placed on left earlobe; (C) and (D) for Subject II, the top position of right ear canal, reference and DRL both placed on left earlobe

## V. CONCLUSIONS

Overall, the existing in-the-ear EEG electrode can be separated into three approaches: the first approach is using hard materials (Ag/AgCl + orthoplastic) only; the second approach uses soft supporting material (silver-coated nylon + memory foam); the last approach uses soft electrode material (CNT/PDMS) only .

Obviously, the hard electrode materials have been well studied. It is easy to find hard electrode materials to make an electrode according to any level of performance. In contrast, soft electrode materials have been slow to grow because the limited options of the base material (like PDMS) and the functional material (like CNT). The manufacturing issues also need to be solved to enable large production volumes.

One practical solution is the combination of both hard and soft electrode material with soft supporting materials, e.g., with silicone as supporting material and solid silver as the electrode material. Although the electrode made of those two materials can be used for many times, there are challenges in the connection between these two materials, and establishing uniform pressure against the skin. In the long run, from both material property respective and economic scale, the silvered glass silicone electrode is considered to be the most suitable material for manufacturing soft electrode without any supporting structure.

## ACKNOWLEDGMENT

The authors would like to thank Miss Xinman Ye, Dr Wei Pan, Miss Pan Wang and Mr Kehan Yu for helpful comments and suggestions on this paper.

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