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CNT/PDMS-based canal-typed ear electrodes for inconspicuous EEG recording

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Abstract

Objective. Current electroencephalogram (EEG) monitoring systems typically require cumbersome electrodes that must be pasted on a scalp, making a private recording of an EEG in a public place difficult. We have developed a small, user friendly, biocompatible electrode with a good appearance for inconspicuous EEG monitoring. *Approach.* We fabricated carbon nanotube polydimethylsiloxane (CNT/PDMS)-based canal-type ear electrodes (CEE) for EEG recording. These electrodes have an additional function, triggering sound stimulation like earphones and recording EEG simultaneously for auditory brain–computer interface (BCI). The electrode performance was evaluated by a standard EEG measurement paradigm, including the detection of alpha rhythms and measurements of N100 auditory evoked potential (AEP), steady-state visual evoked potential (SSVEP) and auditory steady-state response (ASSR). Furthermore, the bio- and skin-compatibility of CNT/PDMS were tested. *Main results.* All feasibility studies were successfully recorded with the fabricated electrodes, and the biocompatibility of CNT/PDMS was also proved. *Significance.* These electrodes could be used to monitor EEG clinically, in ubiquitous health care and in brain–computer interfaces.

Keywords: electroencephalogram (EEG), CNT/PDMS, ear electrode, inconspicuous recording, BCI, U-healthcare

(Some figures may appear in colour only in the online journal)

1. Introduction

An electroencephalogram (EEG) is a noninvasive recording of the brain's electrical activities that is useful in the diagnosis of neurological diseases, including epilepsy, encephalopathy, tumors, brain death, coma, stroke and other brain disorders [1–3]. Technological advances have enabled EEG-based brain–computer interfaces (BCIs) to help people with severe motor impairments such as amyotrophic lateral sclerosis (ALS, or Lou Gehrig's disease) [4–8], and have allowed ubiquitous (u)-health systems to monitor brain activity continuously. However, electroencephalography has limitations that have prevented its widespread use. Conventional electrodes and EEG recording systems are generally uncomfortable and cumbersome. In general, standard EEG electrodes are attached to the scalp with conductive paste, with hair being an obstacle to noiseless measurements. The desire of patients to maintain a good appearance, to avoid publicizing

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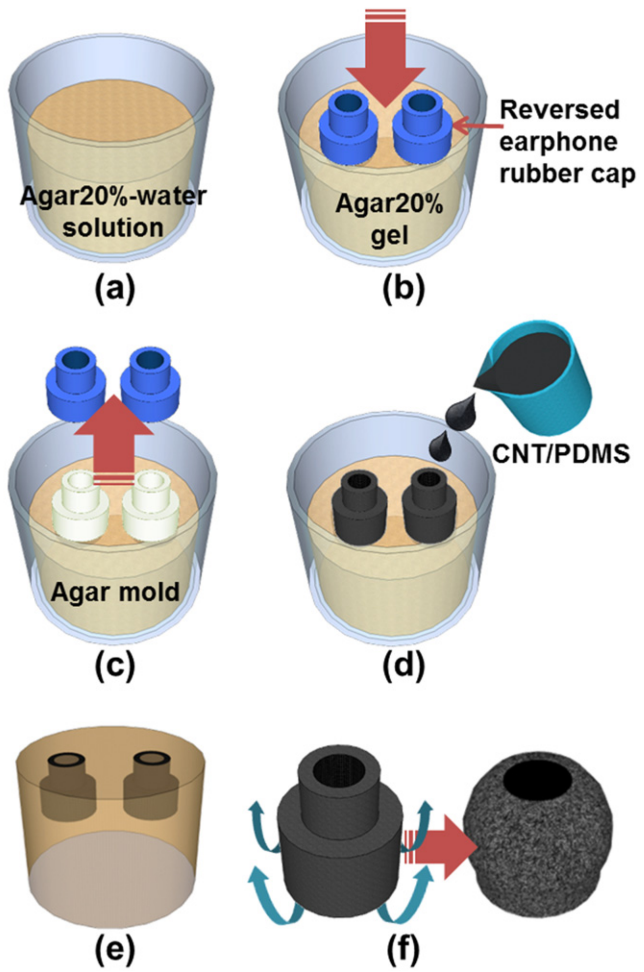

Figure 1. Schematic illustrations of the fabrication process of the CNT/PDMS-based CEE cap. (a) The preparation of a 20% solution of agar in water. (b) The placement of earphone rubber caps into the agar gel. (c) The removal of the earphone rubber caps after the agar gel had fully solidified. (d) The pouring of the CNT/PDMS into the agar mold. (e) The removal of the agar mold after the CNT/PDMS had cured. (f) By inverting the CNT/PDMS electrode, we can get the completed CNT/PDMS-based CEE cap.

their illnesses, and to appear normal during recording has meant that such scalp-type electrodes are difficult to use for BCI and u-health. Therefore, electrodes that enable inconspicuous EEG recording would increase the privacy and social activity of patients, enhancing the need to develop such electrodes [1]. A gel-free system is another critical requirement for long-term EEG recording, since the currently used paste may cause the redness and irritation of human skin, and may make patients uncomfortable by sticking to hair and being hard to remove. The gel also dries over time, dramatically reducing signal quality [9–11].

Recently, Mandic *et al* proposed in-the-ear EEG recording as a novel inconspicuous EEG recording method [12, 13]. These electrodes have several advantages, including being easier to position and wear, not requiring paste and being more tractable. Moreover, recording with these electrodes is more comfortable for patients and is relatively resistant to electromagnetic interference. In addition, the signal-to-noise ratio (SNR) of the in-the-ear recording has been reported to be comparable to that of on-scalp recording [14]. In-the-ear EEG recordings from auditory stimulation would likely result in a high signal quality due to the short distance between the ear and the auditory cortex of the brain stem [11]. Despite these advantages, the materials of this in-the-ear electrode are hard, which may be uncomfortable for long-term wear and may prevent stable conformal contact to the surface of ear. In addition, the direct contact of metal to skin may cause skin trouble when used over the long term. To address these limits, soft and skin-compatible electrodes that can be stably positioned in the canal of the ear, maintaining conformal contacts to the skin, are required.

In this paper, we have developed a canal-type ear electrode (CEE) using a composite of a carbon nanotube and polydimethylsiloxane (CNT/PDMS). The shape of the CEE is the same as that of a commercial canal-type earphone. A soft and skin-compatible CNT/PDMS-based conductive CEE cap, which looks like the rubber cap of an earphone, has the role of the metal in conventional electrodes. Due to their familiar design, users did not feel uncomfortable during EEG recordings in public places or in daily life, since individuals wearing these electrodes would appear to be listening to music. PDMS is a popular material for biomedical applications due to its flexibility, biocompatibility, high gas and water permeability, and adaptability to various fabrication methods [15–17]. CNTs are also widely used in biomedical research because of their outstanding electrical, mechanical and thermal performance [18]. We fabricated electrically conductive CNT/PDMS by dispersing CNT into a viscous PDMS solution [19]. The resulting CNT/PDMS composite is sufficiently flexible to provide close contact between the inner skin of the ear canal and the electrode, maintaining good contact impedance without the use of a conducting gel. We tested its biocompatibility, and its electrical and mechanical properties were evaluated by measuring the contact impedance and Young's modulus. Using the proposed electrode, several standard evoked potentials from brains were recorded, including the alpha rhythm, N100 auditory evoked potential (AEP), steady-state visually evoked potential (SSVEP), and auditory steady-state response (ASSR). The subjects were also administered questionnaires assessing comfort and ease of use.

2. Materials and method

2.1. Fabrication method

2.1.1. Production of CNT/PDMS. To fabricate the CNT/PDMS composite, multiwall CNTs (Ctube100, length 1–25 μm, purity 93%; CNT Co., Korea) were dispersed into PDMS (Sylgard 184, Dow Corning, Midland, MI), as described previously [20]. Due to the large surface areas of the CNTs, they generate strong van der Waals interaction forces, resulting in their aggregation. Since a good electrical conductance is required, the dispersion of the CNTs in viscous PDMS pre-polymer is important. The CNTs were

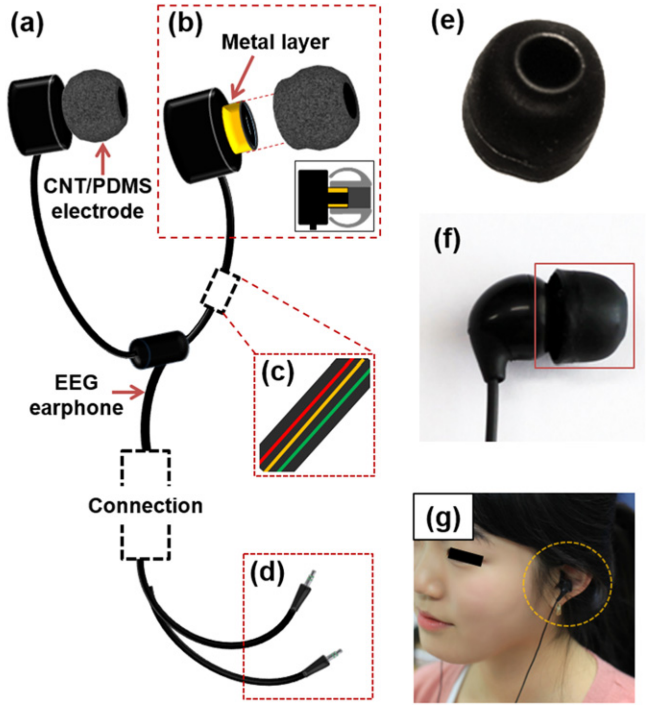

Figure 2. (a) A schematic illustration of a CNT/PDMS-based CEE connected to a CNT/PDMS-based cap and an EEG earphone. (b) The direct connection of the fabricated CNT/PDMS-based CEE cap to the metal layer, which was connected to the signal transmission line. (c) A diagram showing that the CNT/PDMS-based CEE line consisted of three lines: two for producing sound and one for transmitting the EEG signal. (d) A diagram showing that the terminal of the CNT/PDMS-based CEE was composed of two earphone plugs: one for sound and one to transmit the EEG signal. (e) A fabricated view of the CNT/PDMS-based CEE cap. (f) The completed CNT/PDMS-based CEE connected to the CEE cap and the EEG earphone. (g) An image showing that the CNT/PDMS-based CEE in the ear looks like a standard earphone.

subjected to two dispersion steps without chemical treatment. CNTs were initially dispersed to 4.5 wt% using a milling machine (EXAKT 50, EXAKT Technologies Inc., Oklahoma City, OK). This dispersion was subsequently diluted under shear flow (250 rpm, the diameter of the cylindrical stirrer = 5.5 cm and the gap between the beaker and the cylindrical stirrer = 1 mm) for 15 h at room temperature. Using this protocol, CNTs were expected to be uniformly dispersed in PDMS because the hydrodynamic force was stronger than the interaction force between the CNTs [19–21].

2.1.2. Fabrication of CNT/PDMS-based CEE. CNT/PDMS-based CEEs were fabricated in three steps (figures 1 and 2). In the first step, a CEE cap mold was fabricated to make an electrode shaped like the rubber cap of a canal-type earphone. Agar powder was mixed in water to generate a solution of >20% density agar solution (figure 1(a)). This solution was heated until it transformed into a gel. Before cooling, the rubber cap of the canal-type earphone was inverted and dipped into the gel (figure 1(b)). After the gel was completely solidified, the rubber cap was removed, yielding a CEE cap mold (figure 1(c)). In the second step, a CNT/PDMS-based CEE cap was fabricated. The prepared 4.5 wt% CNT/PDMS solution was poured into the agar mold (figure 1(d)). After the CNT/PDMS was thermally cured at 80 °C for 3 h (figure 1(e)), the CNT/PDMS-based CEE cap was taken from the agar mold and inverted to its original shape (figure 1(f)). The EEG earphone, designed similar to a commercial canal-type earphone to connect to the CNT/PDMS CEE cap, was prepared simultaneously (figure 2(a)). A metal (copper) layer, used to transmit EEG signals to external amplifiers through the CNT/PDMS-based CEE cap, was attached to the connecting part of the EEG earphone (figure 2(b)). For the simultaneous recording of the EEG signal and the triggering of sound stimulation, each side of the EEG earphone had three inner lines: two used to produce sound and one for transmitting EEG signals (figure 2(c)). The end of the EEG earphone system was composed of two earphone plug terminals: one for the built-in speaker and the other for recording EEG signals (figure 2(d)). In the third step, the CNT/PDMS-based CEE cap, of the same size and shape as the rubber cap (figure 2(e)), was connected to the metal layer of the EEG earphone (figure 2(f)).

2.2. Electrical and mechanical performance

Because the CNT/PDMS electrodes are inserted into the ear canal without gel, the electrode–skin contact impedance is critical in determining the signal quality. The contact impedance was measured using a commercial impedance analyzer (Solartron1260, Solartron Analytical, UK) combined with a biomedical interface (Solartron1294, Solartron Analytical, UK). Measurements were obtained by three- and four-electrode contact impedance measurement methods [22], using 2 cm diameter sheets (with a similar contact area compared to the CEE cap) of CNT/PDMS and Ag/AgCl electrodes, each placed 1 cm apart from each other. As several electrodes could not be placed inside the ear at the same time, the electrodes were placed directly on the smooth part of the forearm. The contact impedance was calculated by subtracting the four-electrode impedances from the three-electrode impedances at each frequency between 1 to 1000 Hz. Since valid contact impedance required the electrode to fit well and maintain its original shape inside the ear canal, the Young's modulus of the CNT/PDMS was measured to determine the rigidity and durability of the electrode. A CNT/PDMS sheet (5 mm × 10 mm × 0.25 mm) was mounted onto a universal testing machine (Instron 5900) and stretched with a 20 N load cell number at a cross-head speed of 0.25 mm min^{-1}. Young's modulus was obtained from the stress–strain curve.

2.3. EEG measurements

Six healthy volunteers (two women and four men, mean age 24 ± 3 years), recruited at Korea University through advertisements, participated in the EEG recording experiments. None of these participants had any ear diseases. All subjects provided written informed consent and were allowed to stop an experiment if they felt uncomfortable. Each experiment was performed in a quiet, temperature-adjusted room (temperature 23 °C, humidity 50%). We scrubbed the skin inside the ear with a 60% alcohol–water solution to clean it. All participants wore both the CNT/PDMS-based CEE in the ear and conventional EEG electrodes with paste (Elefix, Nihon Kohden) on the scalp (C_z for AEP and ASSR, and O_z for alpha wave detection) simultaneously. All EEG signals were measured using a commercial amplifier (MP150, BIOPAC Systems, Inc., CA, US), band-pass filtered from 0.5 to 50 Hz, amplified 1000 times and sampled at a rate of 10 kHz. The recordings from the two electrodes were compared. Moreover, for the direct comparison of signal quality, conventional electrodes and CNT/PDMS electrodes were placed side by side on the scalp and the EEG signal was recorded. In addition, all participants were given a questionnaire regarding which electrode was more comfortable to wear. The study protocol was approved by the Institutional Review Board of Korea University, Seoul, South Korea (IRB No: KU-IRB-13-55-A-2).

2.3.1. Alpha wave detection.

Alpha waves can be detected at the specific EEG frequencies of 8–14 Hz when the subject is relaxed. To measure alpha rhythms, experiments were conducted in a tranquil environment with the subjects seated in a comfortable chair. Subjects were instructed to close their eyes for 20 s and open them for 20 s. For spectrogram analysis, subjects were instructed to open their eyes for 10 s, and then to close them for 10 s.

2.3.2. N100 Auditory evoked potential (N100 AEP).

N100 AEP is a dominant negative peak of an EEG after one shot of auditory stimulation. The auditory stimulation and EEG recording were conducted at the same time using the CNT/PDMS-based CEE. Auditory stimuli at 1 kHz for 500 ms at an adjusted amplitude of 90 dB were repeated 100 times for 3 mins, with the intervals between stimuli ranging randomly from 1 to 1.5 s in order to prevent adaptation to stimulation. To avoid noise from visual factors, subjects were instructed to close their eyes during the auditory stimuli. The recorded signals were band-pass filtered at 2–20 Hz using a third-order Butterworth filter, and all segments were averaged. Repeat results were pooled and averaged, and student's *t*-tests were computed at every sampled time point from 0 ms to 500 ms and cumulatively for each new presentation for statistical significance [23].

2.3.3. Steady state visually evoked potential (SSVEP).

SSVEP is the brain's natural response to visual stimuli at specific frequencies. Exposure of the eyes to visual stimulation at frequencies of 1 Hz to 90 Hz stimulates the retina, generating EEG signals at the same frequency [24–26]. The visual stimuli were six flashes of LEDs at 14 Hz with a 50% duty cycle. The distance between the LEDs and each subject was about 40 cm, and the subjects were instructed to concentrate on the visual stimuli during recording. Each stimulation lasted for 30 s, with a 10 s interval between stimuli to relieve eye fatigue. The EEGs were recorded in a dark, silent room to reduce disturbances by other stimuli.

2.3.4. Auditory steady-state response (ASSR).

Measurements of auditory steady-state response (ASSR) require specific auditory stimuli. The ASSR is typically evoked by amplitude modulated (AM) stimulations [27]. We utilized a modulation frequency of 40 Hz and a carrier frequency of 1.5 kHz for AM stimuli [28–31]. The auditory stimulation was modulated at a sampling rate of 100 kHz by MATLAB (The Mathworks, Natick, MA, USA, version 2010). In the experiments, subjects were instructed to concentrate on the 40 Hz modulated sound, which stimulated both ears through the CNT/PDMS-based CEE. One trial lasted about 1 min, and each trial was repeated 20 times, with a 20 s rest between trials. The acquired EEG data sets and PSD from each subject were accumulated and averaged. Because of the possibility of auditory BCI with CNT/PDMS-based CEE [32], the ASSR was recorded at two different stimulation frequencies. For 40 Hz ASSR, two modulation frequencies were chosen: 37 Hz and 43 Hz. In addition, 2.5 kHz and 1 kHz, which can be easily distinguished, were chosen as the carrier frequencies of two auditory stimuli. Two different auditory stimuli were triggered simultaneously in both ears through the CNT/PDMS-based CEE, with the right ear stimulated with a 2.5 kHz tone and a beat frequency of 37 Hz, and the left ear stimulated with a 1 kHz tone and a beat frequency of 43 Hz. Participants were instructed to concentrate on one of the auditory stimuli. An assistant touched the subject's shoulder (left or right) just before the experiment to indicate which sound to concentrate on. Each trial lasted about 1 min, with 20 trials in each direction and a 20 s interval between stimulations. The tests were performed in a quiet room, with the subject seated in a comfortable chair. During the experiment, the subjects were instructed to close their eyes to prevent noise from visual stimuli [33–35].

2.4. Biocompatibility

As the demand for EEG recording for BCI and u-healthcare increase, the CNT/PDMS-based electrode was designed for long-term wear. To assess the response of the skin to long-term contact with an electrode, two types of biocompatibility test were performed. The first was to test the cytotoxicity of the electrode materials by culturing skin fibroblast (CCD-986sk) cells on the CNT/PDMS. About 5×10^4 cells were seeded directly onto a CNT/PDMS sample and cultured for seven days in Dulbecco's modified Eagle medium (Gibco), supplemented with high glucose, 25 mM sodium, 10% fetal bovine serum and 25 mM 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid. The viability of the cells was analyzed using a live/dead assay kit (Invitrogen, CA). The skin fibroblast cells were stained and examined under an inverted fluorescence microscope (EVOS; AMG, USA). To test skin compatibility, observing the biocompatibility inside the ear is not easy in cases where itching, swelling, or redness occurred. Therefore a 2 cm × 2 cm × 0.5 mm CNT/PDMS sheet was attached to the upper arm of a volunteer to test skin compatibility, although any ear wax effects were absent, with air-permeable tape (Himom Band, JW Pharmaceutical

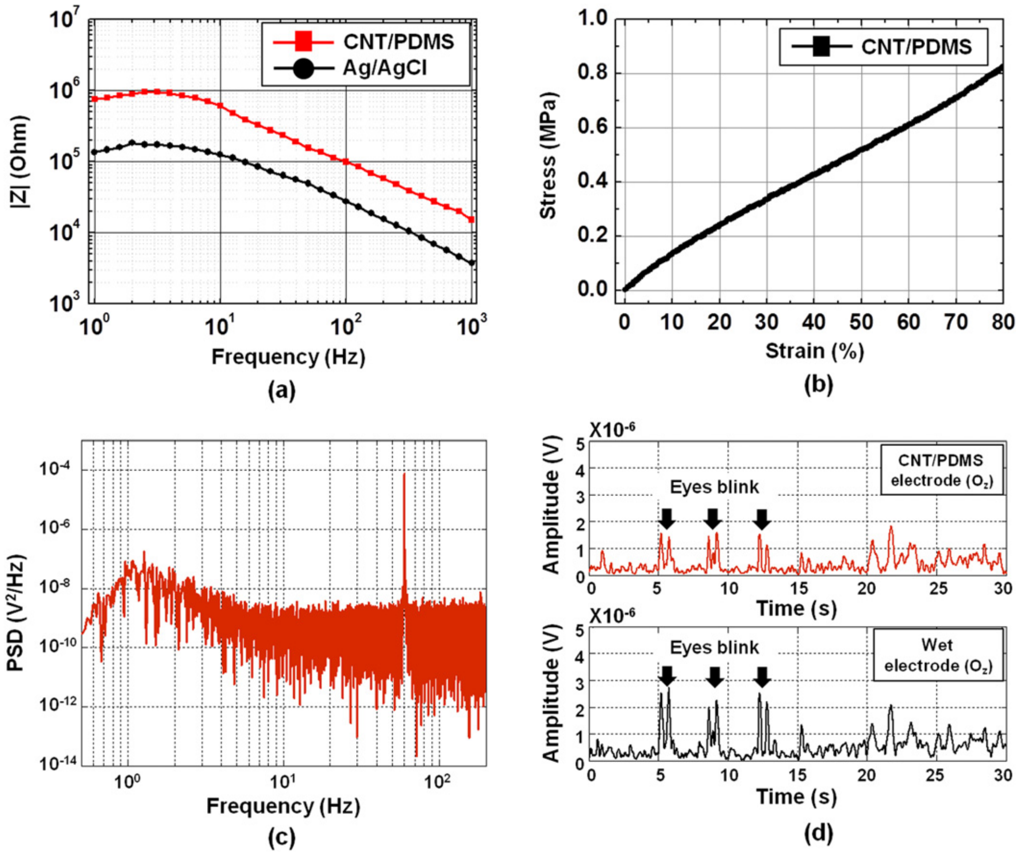

Figure 3. (a) The measurement of the electrode–skin contact impedance of the CNT/PDMS and Ag/AgCl electrodes at each frequency between 1 Hz and 1000 Hz. (b) The relationship between the tensile stress and strain of CNT/PDMS. (c) The PSD of system noises over frequency. (d) The signal quality comparing CNT/PDMS and conventional wet electrodes on the scalp.

Corporation, Seoul, Korea) and remained for seven days. Before the CEE was inserted into the ear, ear wax was removed so the influence of the ear wax would not be considered. The condition of the skin was monitored, including itching, swelling and redness [20].

3. Results

3.1. Electrical and mechanical performance test

Figure 2(f) shows a CNT/PDMS-based CEE, shaped as a general canal-type earphone. This electrode was 10 mm in diameter and 11 mm in height (figure 2(e)), allowing it to measure EEGs by being placed into the ear canal (figure 2(g)). Because this electrode is a dry-type electrode, its contact with the skin is important. We therefore compared the contact impedance of the CNT/PDMS and Ag/AgCl standard electrodes at frequencies between 1 Hz and 1000 Hz (figure 3(a)). The contact impedance of the CNT/PDMS electrode decreased as the frequency increased, with a maximum impedance of about 1 MΩ at frequencies of less than 5 Hz. The contact impedance of the Ag/AgCl electrode showed a similar pattern, except that this electrode had a maximum impedance of about 300 kΩ at frequencies less than 4 Hz. The mechanical properties of the CNT/PDMS were assessed by measuring the tensile stress–strain curves (figure 3(b)). The strain increased linearly with increasing stress, and the Young's modulus was almost constant at 1 MPa.

3.2. EEG measurement

The system noise measurement was recorded with a high peak of 60 Hz power noise (figure 3(c)). The maximum PSD of the noise before the power noise was observed at 1–2 Hz, and the high amplitude of noise in the low-frequency band (0–3 Hz) was filtered. An assessment of the signal quality by direct comparison between CNT/PDMS and conventional wet electrodes was conducted. The result of time domain simultaneous recording is shown in figure 3(d). Three artifacts from the blinking of eyes were observed in both two graphs similarly. Moreover, every EEG signal trace of CNT/PDMS electrodes that was recorded on the scalp mimicked the wet electrode's signal.

3.2.1. Alpha rhythm detection. Alpha rhythm waveforms were successfully recorded by both the CNT/PDMS CEE and conventional on-scalp electrodes (figure 4). Alpha waves were detected at the alpha band (8–14 Hz) when the subjects' eyes were closed. As seen in figure 4(a), the dominant peaks at 10–12 Hz were observed when the subjects had their eyes

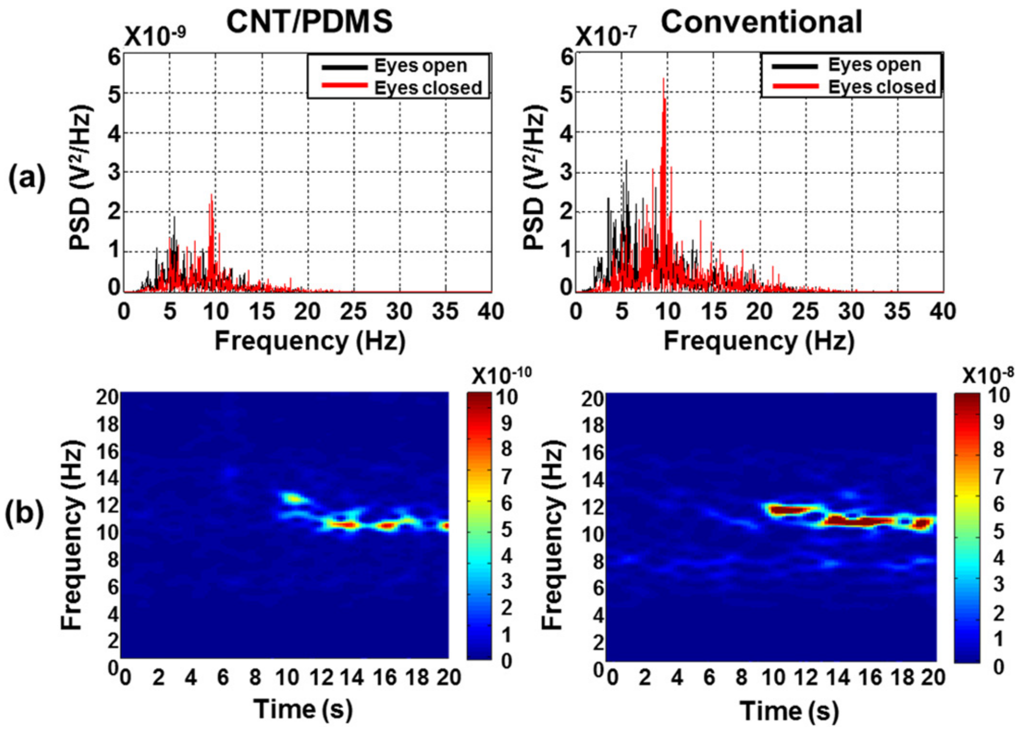

Figure 4. The detection of alpha rhythms with a CNT/PDMS-based CEE and conventional type EEG electrodes for eyes open and closed. The absolute value of the conventional type electrode was higher than that of the CNT/PDMS-based CEE, but the signal-to-noise ratios (SNRs) of the devices were similar. (a) A PSD of alpha rhythm appearance. (b) A spectrogram of the alpha rhythm. Subjects were instructed to close their eyes after 10 s for 20 s.

closed (red lines) and disappeared when the subjects had their eyes open (black lines). The recorded EEG spectrograms also showed evidence of alpha rhythm (figure 4(b)). The subjects opened their eyes for 10 s and then closed their eyes, with alpha waves clearly detected after 10 s at 9–13 Hz. The mean PSD of the alpha waves increased from $1.56 \pm 0.66\,\mathrm{nV^2\,Hz^{-1}}$ when the subjects' eyes were open to $6.91 \pm 2.2\,\mathrm{nV^2\,Hz^{-1}}$ when their eyes were closed (table 1). The amplitude of the signal recorded by conventional electrodes was higher than that of the CNT/PDMS electrodes in all subjects; however, it was dominantly observed in both electrodes.

3.2.2. N100 Auditory evoked potential. The AEP was measured to verify the validity of the CNT/PDMS CEE. Each subject was administered over 100 auditory stimuli (beeps), and each evoked response was recorded. The AEP measurements were averaged over each segment of beep stimuli. Plots of the mean AEP (black line) and its standard deviation (blue line) showed a negative peak at 100 ms (N100) after auditory stimulation (figure 5). The N100 peak is normally detected 80–120 ms after the onset of sensory stimulation. To verify these results statistically, we performed *t*-tests to determine a *p*-value for each subject of the negative peak between 80 ms and 120 ms (table 1). We found that the *p*-value for each subject was less than 0.01, indicating that the N100 AEP 80–120 ms after stimulation was statistically meaningful. The dominant negative peak near 100 ms and the *p*-value data clearly verify the validity of the CNT/PDMS-based CEE for EEG recording.

3.2.3. Steady-state visually evoked potential (SSVEP). SSVEP normally appears as a dominant peak at a specific frequency accompanied by sub-harmonics. Using the CNT/PDMS-based CEE, we observed a very sharp, dominant peak at 14 Hz, with sub-harmonic frequencies of 28 Hz and 42 Hz for all subjects (figure 6).

3.2.4. Auditory steady-state response (ASSR). The 40 Hz ASSR experiment yielded a very sharp and dominant peak at 40 Hz in all subjects (figure 7(a)). Although the peak of the on-scalp-type electrode was larger than that of the CNT/PDMS electrode, the higher SNR of this electrode value indicated that the CNT/PDMS-based electrode can record 40 Hz ASSR with a high signal quality. The selective attention ASSR experiment for auditory BCI showed the appearance of a signal at the frequencies of 37 Hz and 43 Hz simultaneously (figure 7(b)). Furthermore, the 37 Hz peak was larger than the 43 Hz peak when the subjects focused on the 37 Hz AM stimulus, and vice versa (table 1).

3.3. Bio- and skin-compatibility test

Using a live/dead assay kit, we found that >93% of skin fibroblast cells cultured on the CNT/PDMS surface for seven days were alive (figure 8(a)), indicating that CNT/PDMS is nontoxic to cells (the cell viability of a control dish exceeded 99%). The attachment of a CNT/PDMS sheet to the skin of the upper arm of a volunteer for one week showed no adverse effects, including erythema or urticarial (figure 8(b)). These

Table 1. The results of the feasibility test for each subject.

						Selective attention ASSR			
						37 Hz		43 Hz	
	Alpha rhythm (open) ($nV^2 Hz^{-1}$)	Alpha rhythm (close) ($nV^2 Hz^{-1}$)	AEP (t-test /*p*-value)	SSVEP ($nV^2 Hz^{-1}$)	40 Hz—ASSR ($pV^2 Hz^{-1}$)	37 Hz ($pV^2 Hz^{-1}$)	43 Hz ($pV^2 Hz^{-1}$)	37 Hz ($pV^2 Hz^{-1}$)	43 Hz ($pV^2 Hz^{-1}$)
Sub_1/Male	1.249	5.566	$<10^{-2}$	29.13	81.36	408.5	153.8	256.1	753.1
Sub_2/Male	0.772	3.893	$<10^{-3}$	10.43	35.03	243.8	78.08	82.9	221.6
Sub_3/Male	2.034	7.824	$<10^{-3}$	40.56	301.6	641.2	64.06	78.9	432.2
Sub_4/Female	2.739	10.95	$<10^{-3}$	59.79	416.6	1310	63.27	189.6	1205
Sub_5/Female	1.489	6.756	$<10^{-3}$	12.38	79.92	731.4	231.6	95.74	737.3
Sub_6/Male	1.073	6.47	$<10^{-2}$	18.64	64.01	885.2	117.1	93.54	622.7
Mean ± std	1.559 ± 0.66	6.91 ± 2.2	—	28.5 ± 17.4	163.1 ± 143.3	703 ± 345	118 ± 60.1	133 ± 66.8	662 ± 304

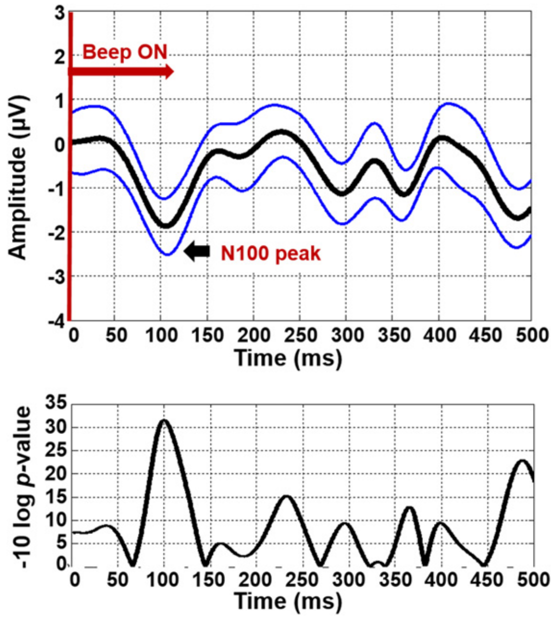

Figure 5. Average N100 AEP signals (black bold line) with standard deviations (blue line), showing a dominant negative peak near 100 ms. A statistically significant *p*-value at 100 ms showed the validity of the N100 AEP result.

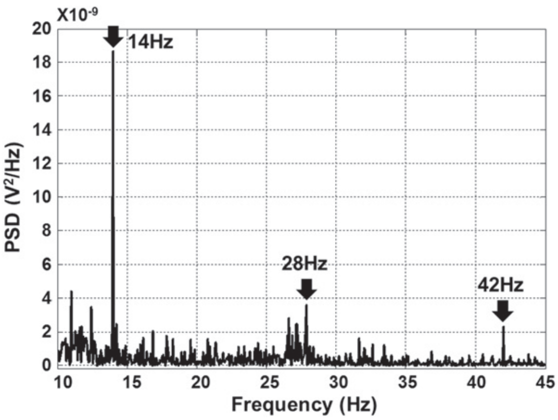

Figure 6. The power spectrum density of the EEG signal recorded by the CNT/PDMS–based CEE on the 14 Hz SSVEP test. In addition to the dominant 14 Hz peak, subharmonic peaks were also observed.

findings demonstrate that CNT/PDMS is bio- and skin-compatible for use as a long-term wearable electrode.

3.4. Comfort survey

Most subjects reported that the CNT/PDMS electrode was more comfortable than the on-scalp type conventional electrode (table 2). Moreover, most subjects commented that the proposed electrode was familiar because it felt like a standard earphone. They reported it to be convenient to use and comfortable to wear. In contrast, the on-scalp-type electrode was uncomfortable and unpleasant because of the conductive paste on the scalp. This survey clearly indicated that the newly developed electrode is more comfortable and convenient than the conventional electrode.

4. Discussion

We have described here the fabrication of a novel CNT/PDMS-based CEE to record an EEG from the ear. This electrode successfully overcame several of the drawbacks of conventional-type EEG electrodes, including setup difficulties, discomfort, cumbrousness, unsightly appearance and poor biocompatibility. The well-dispersed soft CNT/PDMS composite material enabled the close contact of the electrode to the ear, without any discomfort. Although wax and/or hair would increase the contact impedance, its contact impedance was only three-/four-times higher compared to the Ag/AgCl electrode when those were placed on the forearm. The morphology of the CNT/PDMS electrode is identical to that of a canal-type earphone, providing several advantages for the inconspicuous recording of an EEG. Therefore, people around the user are unable to determine that the user is wearing the electrode. As most patients are reluctant to reveal illnesses, they do not want to record EEGs in public places. Using the CNT/PDMS-based CEE, however, can allow the discreet recording of EEG signals. Users would not be self-conscious about the way they look when wearing this earphone-shaped electrode to record EEGs in public places. This earphone electrode is also more comfortable to wear than conventional electrodes, as shown by our survey of subjects who wore both. Furthermore, the concept of the earphone-shaped soft electrode enabled gel-free EEG recording. In general, conventional on-scalp-type electrodes require a conductive paste to attach them to the scalp. This paste is not only uncomfortable, but can induce redness and irritation of the skin. Even dry conventional electrodes require an additional attachment for EEG recording. In contrast, the proposed CNT/PDMS-based CEE can be worn by placing it inside the ear. In addition, the bio- and skin-compatibility tests showed that CNT/PDMS did not have any negative effects. The canal-type electrode cap provided excellent contact with the skin of the inner ear and placement in a fixed position. Despite its good contact with the skin, high impedance electrodes might respond sensitively to artifacts, including dangling wires. However, EEG signals normally used for BCI were distributed in relative high frequencies, while artifacts are generally distributed in the low frequency band ($0 \sim 5$ Hz). Furthermore, EMI effects would be neglected by using electrical shielded wire. The mechanical properties of CNT/PDMS enabled close contact to be maintained while moving, allowing users to wear this electrode throughout daily life without the assistance of an expert. In addition, its SNR was similar to that of conventional EEG electrodes. Finally, the sound stimulation provided by the CNT/PDMS-based CEE was similar to that of an earphone. Wearing a CNT/PDMS-based CEE may block ambient sound; it may feel a little stuffy for users in long-term recording. However, it does not affect the signal quality directly. Since neural engineering studies of auditory BCI systems for blind people are actively progressing, these electrodes can be widely used for auditory and other types of BCI [36].

The feasibility of use of the CNT/PDMS-based CEE was demonstrated by measuring several standard EEG paradigms,

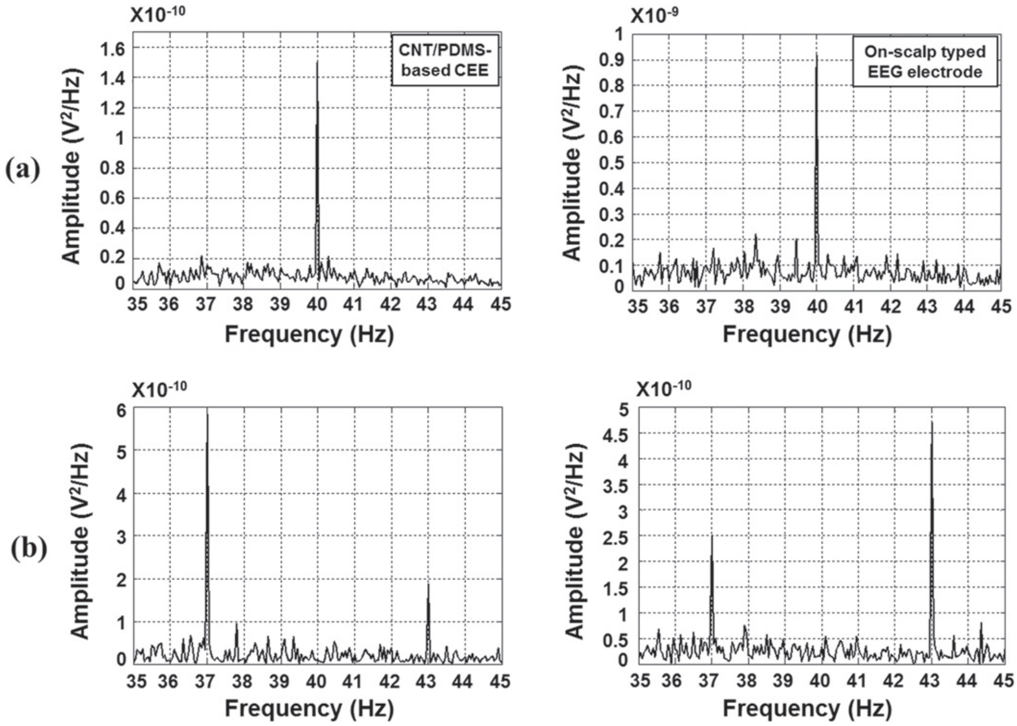

Figure 7. The power spectrum densities of EEG signals measured by the CNT/PDMS–based CEE and conventional electrodes on the ASSR test. (a) Responses to 40 Hz auditory stimuli by conventional electrodes (right) and CNT/PDMS-based (left) electrodes simultaneously. (b) Responses to selective attention ASSR tests by CNT/PDMS composite electrodes comparing 37 Hz (left) and 43 Hz stimuli (right).

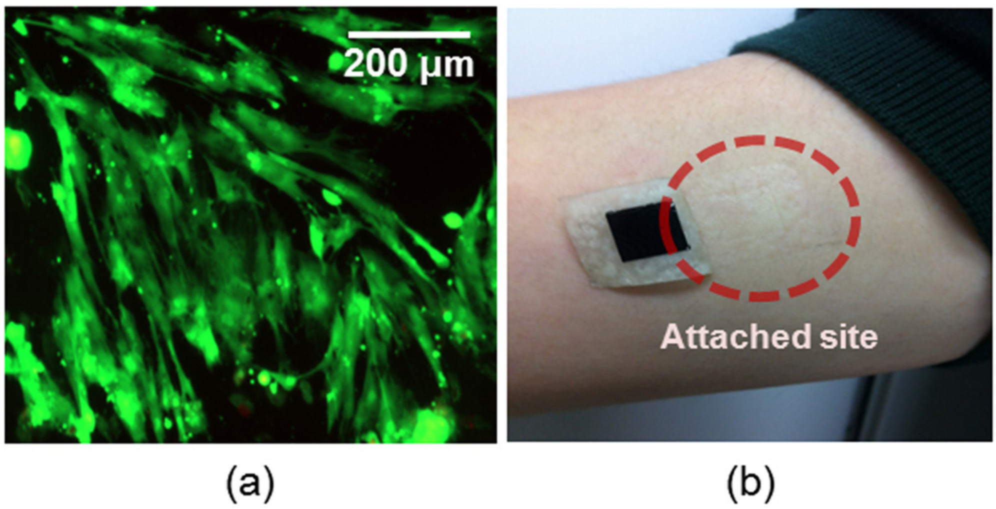

Figure 8. Bio-and skin-compatibility tests of CNT/PDMS. (a) A live/dead assay of cells cultured on CNT/PDMS. The cell viability on the CNT/PDMS exceeded 93% (the green color shows live cells, and the red color shows dead cells). (b) Attachment of the CNT/PDMS sheet to the skin of a subject's upper arm for one week showed no side effects following the removal of the sheet.

including the alpha rhythm, N100 AEP, SSVEP and ASSR. The alpha rhythm signals were detected on the PSD and spectrograms by comparing signals obtained when the eyes were closed and open. The conventional electrodes showed a higher amplitude than the newly developed electrode because of the electrode attachment location. Moreover, in the time domain, we couldn't find any meaningful data without filtering, as its amplitude was so small in the ear while it was dominantly shown when attached on O_Z (figure 3(d)). This implies that CNT/PDMS-based CEE limited alpha wave detection is not due to its intrinsic characteristics but rather to the electrode placement, as alpha activity does not appear near the ears [11]. Furthermore, the CNT/PDMS-based CEE successfully recorded N100 AEP and SSVEP. The evoked potential in response to beeps showed a highly statistically significant waveform at N100 (p-value $< 10^{-3}$), and the evoked potential in response to 14 Hz LED visual stimulation yielded a dominant peak ($28.5 \pm 17.4\,\mathrm{nV}^2$) in the 14 Hz frequency domain. On ASSR, both the new and conventional electrodes were successful in observing a 40 Hz peak, and the

Table 2. The result of a survey comparing the comfort of the CNT/PDMS composite CEEs with conventional electrodes.

	Feels more comfortable than conventional on-scalp-type electrodes?	Other comments	
		CNT/PDMS-based CEEs	Conventional on-scalp-type electrodes
Sub_1/ Male	Yes	More convenient and comfortable to wear than on-scalp-type electrodes; kept hair clean.	Felt uncomfortable because of long lines, and paste remaining on the hair was irritating.
Sub_2/ Male	Undecided (similar)	Because the subject had an abnormally small ear canal, the electrode didn't fully contact in the ear. But the earphone-type electrode was more convenient to wear than the on-scalp-type electrodes.	Recording was not that bad, but it was unpleasant because of the remaining paste.
Sub_3/ Male	Yes	Very easy to use; the system setting was also simple.	Setting the system was too time consuming and the subject did not like the paste.
Sub_4/ Female	Yes	It fitted in the ear canal perfectly, and was comfortable to wear.	The subject was displeased with using the paste.
Sub_5/ Female	Yes	The concept is nice and simple, and the electrode was comfortable and convenient to wear.	Finding the exact locations for electrodes was difficult and time consuming.
Sub_6/ Male	Yes	The paste-free concept is ingenious and wearing is also very simple.	The paste stuck in the subject's hair, making him feel uncomfortable during the recording period.

directional 37 Hz and 43 Hz selective ASSR tests by the developed electrode were also successful, with dominant peaks. In addition, as the EEG signal line was very close to the sound line, cross-talk would be an important issue. However, when the sound signal was amplitude-modulated, its frequency band became much higher (beside the carrier frequency) compared to the EEG band, so cross-talk could be ignored, although cross-talk was observed in the EEG signal. Taken together, these results demonstrate the validity of the CNT/PDMS-based CEE for EEG measurements. Although the developed electrode is limited to use in the clinical area because the CNT/PDMS-based CEE can only record a subset of a full cap EEG, it is capable of making a functional EEG recording. Moreover, the shape of the electrode makes it comfortable, of good appearance and paste free during recording, suggesting that the CNT/PDMS-based CEE may be extensively used for u-health, BCI and the recording of other bio-signals.

5. Conclusion

In summary, the CNT/PDMS-based CEE was able to record an EEG in response to various external stimuli. This earphone-shaped electrode offers 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 is applicable 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 u-healthcare.

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