In-ear EEG from viscoelastic generic earpieces: Robust and unobtrusive 24/7 monitoring

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***Abstract*—We introduce a novel in-ear sensor which satisfies key design requirements for wearable electroencephalography (EEG) – it is discreet, unobtrusive and capable of capturing high-quality brain activity from the ear canal. Unlike initial designs which utilised custom earpieces and require a costly and time-consuming manufacturing process, we here extend the generic earmould concept to make ear-EEG suitable for immediate and widespread use. We propose a departure from silicone earmoulds, and instead outline a sensor based on a viscoelastic substrate and conductive cloth electrodes, both of which are shown to possess a number of desirable mechanical and electrical properties. Owing to its viscoelastic nature, the earpiece exhibits good conformance to the shape of the ear canal, thus providing stable electrode-skin interface, while cloth electrodes require only saline solution to establish low impedance contact. The analysis highlights the distinguishing advantages compared to the current state-of-the-art in ear-EEG. We demonstrate that such a device can be readily used for the measurement of various EEG responses.**

***Keywords*—electrophysiology, electroencephalography, biosensors, biomedical engineering, materials**

I. INTRODUCTION

WEARABLE health is envisaged to become the transformative force in global healthcare, which promises affordable, accessible and personalised diagnosis and treatment [1]. For this to become a reality, key advancements at the level of sensor technology are a pre-requisite. An ideal wearable sensor must be cheap, robust, unobtrusive, user-friendly and discreet for people to accept and wear it continuously. Inroads have been made in this direction by making the sensors either invisible or part of the accepted apparel and accessories. While it is relatively well-understood how to incorporate the various body-sensors into e.g. the clothing and watches, the requirement for discreet and unobtrusive sensing has proven to be particularly challenging in the area of electroencephalography (EEG) monitoring, where virtually all the devices are placed along the scalp. This is not only obtrusive, but also makes the recording process cumbersome and stigmatising.

EEG refers to the process of recording electrical brain activity. It is widely used in the fields of neuroscience, e.g. for monitoring brain activity during episodes of breathing cessation in patients suffering from sleep apnoea, and brain-computer interface (BCI), where brain waves are used to control, among other things, a cursor on the screen. Modern, state of the art sensors and systems are still very bulky, which is acceptable for inpatients, but prohibitive for outpatient ambulatory monitoring. Systems do exist (Emotiv, Mindo, etc.), which partially address the issues of portability and visual appeal, however, their indiscreet placement on the scalp prevents wide acceptance. To this end, we have recently introduced a novel EEG recording concept termed ear-EEG, which allows for electroencephalography signals to be acquired from inside the ear canal, thus paving the way towards non-stigmatising brain activity monitors [2].

The initial concept and prototypes were based on the personalised earpieces [3] widely used in the hearing aids industry. Their manufacturing process comprises a laborious and costly procedure of obtaining wax impressions of the subject's outer ear and ear canal, 3D scanning of the impressions, creating models and finally manufacturing earpieces with high resolution 3D printers. Although this yields tight-fitting earpieces – critical for good quality signals – it was found that this approach is not suitable for wide adoption due to cost, occasional difficulties of fitting, and the requirement for gelled electrodes to enable a low-impedance electrode-skin contact.

To address the issues of cost and ease-of-use, we have recently introduced generic earpieces made out of silicone, with conductive silicone electrodes, which fit most adult ears and can be used off-the-shelf. We also reported on the ability of such electrodes to provide good quality signals in a standard EEG paradigm of acoustic steady state response (ASSR) [4]. These silicone earpieces were able to record the ASSR even in the challenging scenario when all the electrodes – sensing, reference and ground – were placed on a single earpiece inside the ear canal. Although a significant improvement over the initial, custom-made, rigid prototype, the silicone earpieces still inherit some of the drawbacks of hard-shell earpieces: they require conductive gel for good electrode-skin contact and their non-guaranteed conformance to the shape of the ear canal leads to motion artefacts. Moreover, the conductive silicone electrodes exhibited signs of degradation over a period of several months which manifested itself in a significantly increased impedance of the electrodes.

In addition to our work, in the area of ultra-wearable EEG monitoring with generic earpieces, Hoon Lee *et. al.* [5] recently reported in-ear headphones, in which buds where made conductive by loading silicone substrate with carbon

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Manuscript received Month ??, 2015; revised Month ??, 2015.

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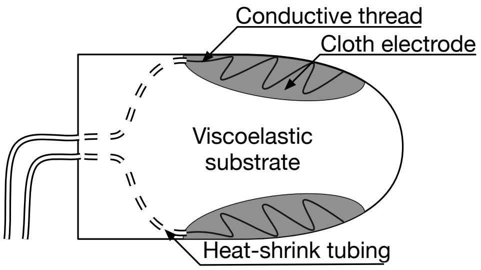
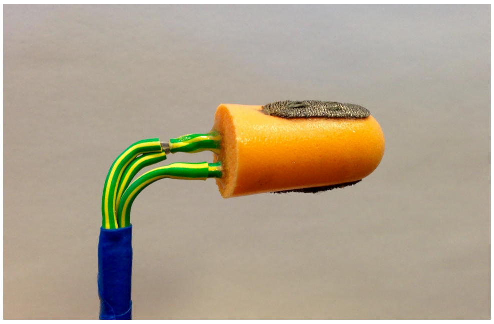
nanotubes. The EEG was acquired by measuring the potential difference between the two ears. The overall results were promising, but there are also several drawbacks to this approach. First, the potential difference is measured between two ears, thus requiring cumbersome cabling from both ears to the acquisition unit. Second, such a setup limits spatial resolution necessary to attribute measured activity to a particular brain hemisphere. Third, silicone buds provide suboptimal conformance to the shape of the ear canal, thus restricting the insertion depth and firmness of fit, leading to increased susceptibility to motion artefacts. Fourth, based on our experiments, the signal measured between two ears frequently contains strong cardiac component (ECG) [6], thus restricting the ability of such setup to acquire low frequency EEG. Finally, all of the earpieces described so far are too rigid to be used in young children, particularly newborns, because inserting the devices can damage the not yet fully formed bone around the ear canal.

To resolve these issues, we here introduce a novel earpiece which is comfortable to wear over extended periods of time, is safe to use even in newborns, and provides good quality EEG signals even in subjects, whose ear canals exhibit strong pulsation artefacts – critical cases, where the EEG recorded with custom-made plastic and previous generation silicone earpieces is compromised.



(a) Earpiece construction diagram.



(b) Photo of the earpiece.

Fig. 1. Proposed in-ear EEG sensor with a viscoelastic substrate.

II. EARPIECE SENSOR

The two key components comprising the new device are a memory foam substrate and conductive cloth electrodes. The viscoelasticity of the substrate is a critical characteristic which ensures that the earpiece can be effortlessly and safely placed in the ear canal. Following insertion, the device expands and redistributes pressure evenly along the entirety of its contact surface, thus providing a stable interface with the skin, robust to mechanical disturbances. The viscoelasticity of the substrate also ensures that energy from abrupt motion (e.g. pulsation) is absorbed, thus minimally disturbing the electrode-skin contact. This approach is an alternative solution to the motion-induced artefacts in ear-EEG compared to that we introduced in [7]. Cloth electrodes are extremely flexible, conductive, soft, comfortable to wear and conform to changes in the substrate's shape when the earpiece is compressed prior to insertion. Only a small amount of saline solution is required to provide good electrical contact between the cloth and the skin.

A. *Construction*

All of the previous materials used for in-ear EEG sensors (silicone and plastic) have proven to be too stiff and rigid. Unsuitable for delicate ears of the newborns, these provide unevenly distributed pressure along the outer surface of the device, when put inside the ear canal, providing loose and intermittent electrode-skin contact, susceptible to motion artefacts. To alleviate this problem, the earpiece material must be soft, easy to fit, robust and suitable to self-administer. Such a material is already widely available, e.g. in sound-blocking earplugs, and is currently gaining popularity with in-ear headphones in the form of comfortable, sound-isolating buds. Such materials are widely referred to as memory foams.

Memory foam is viscoelastic, characterised by the time-dependent nature in the stress-strain relationship. It is capable of undergoing significant relaxation under constant strain, akin to viscous materials that flow when strained. On the other hand, it does not permanently deform when squeezed, stretched or twisted (in the limited range of strains) and given enough time it returns to its original shape – characteristic of the elastic (rubbery) response.

Not all polymers are viscoelastic to any significant practical extent, but viscoelasticity can be engineered into a material by adjusting its chemistry and microstructure[1] [8]. For example polyurethane can be mixed with additional chemicals, controlling its density and viscosity, and subsequently foamed to produce memory foam widely used in mattresses and pillows, well known for their pressure-relieving properties [9].

It is self-evident that memory foam has many of the key characteristics required for a substrate of the in-ear EEG sensor. It can undergo significant compression without loosing the original shape – required for comfortable and easy insertion. The pressure on the outside surface of the foam earplug is uniformly redistributed, creating excellent contact with the skin at any point on the earpiece providing robust electrode-skin interface and comfort during long term wearing. Foam can

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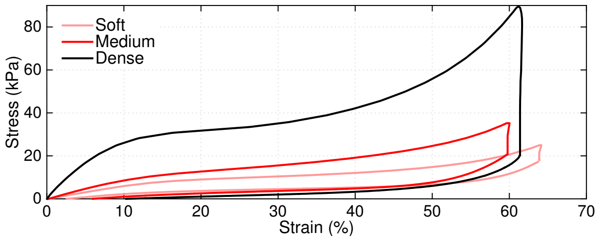
[1] Transparent polymer films in the car windshields are used in the viscoelastic regime, giving them significant energy dissipation capabilities during impact.

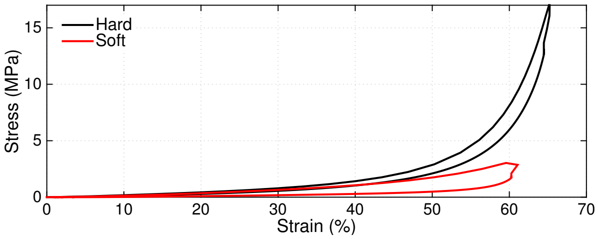
be engineered to exhibit various degrees of firmness, thus enabling earplugs suitable even for newborns. Finally, the material is cheap and can be moulded into many different shapes if needed.

To accommodate the high levels of compression that foam earplugs undergo prior to insertion, the electrodes must be made out of similarly flexible and sturdy material. We have tested a number of different options, namely: polyurethane-based silver-loaded flexible adhesive, conductive copper paint, silver-loaded silicone rubber and stretchable conductive fabric. We have established that the adhesive and the paint do not possess the required sturdiness when dry, and crack even under minor compression levels of the underlying substrate. Silicone rubber was found to be extremely hard to attach to the substrate as well as to the wires, it also exhibited high impedance after several straining cycles. Stretchable fabric performed best, it easily accommodated all of the required deformations, provided low impedance even after several months of use, and was straightforward to attach to the substrate and wires.

The chosen conductive cloth is made out of silver-coated nylon interwoven with elastic fibres. It can stretch in both directions and has very low impedance of only 0.5 Ohm/sq. To create electrodes, strips of fabric 4 mm wide and 1 cm long were cut, into which stainless steel thread was sewn, thus allowing standard wires to be soldered directly to the thread. Since the thread is made out of stainless steel and the cloth is silver-plated the whole electrode is resistant to corrosion. The fabric strips were then placed on two sides of the memory foam earplug opposite one another and were attached to the substrate using 3M adhesive transfer tape. Stainless still thread attached to the electrode was insulated with heat shrink tubing and passed through the bulk of the earplug exiting through the flat face of the earpiece. This arrangement created an in-ear EEG sensor with two electrodes diametrically opposed to each other as shown in Fig. 1.



(a) Stress-strain response of viscoelastic foam substrates.



(b) Stress-strain response of silicone substrates.

Fig. 2. Stress-strain responses of various earpiece materials.

B. Mechanical characteristics

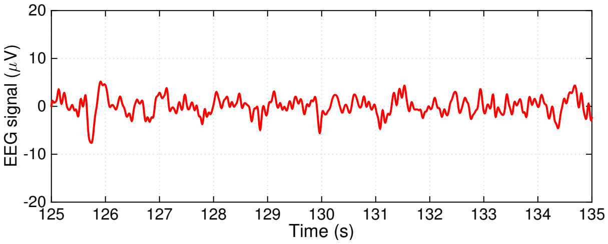
To evaluate the mechanical performance of the proposed earpiece and establish the key difference in its behaviour against the earlier prototypes, we have subjected the substrate to a strain test to produce stress-strain curves for a number of different variants of memory foam and silicone. Prior to the evaluation, earpieces were cut to approximately 16 mm tall cylinders with the opposing faces as flat as possible. The measurements we performed on a dynamic mechanical analyser where the cylinders were subjected to compressive strain. The first testing phase comprised rapid compression which squeezed the earpieces by 10 mm in 2.4 s. Then the strain was held constant for 1 min and finally slowly released at 2 mm/min rate. Corresponding stress-strain curves for different materials are shown on Fig. 2.

The plots in Fig. 2 reveal a significant relaxation exhibited by each of the viscoelastic earpieces following rapid compression – a key desired aspect for long-term wearability. This characteristic is critically important for both the comfort of the user as well as the contact quality between the electrode and skin. Additionally, all of the foam earpieces are significantly softer than their silicone counterparts for a given compression rate, e.g. they exhibit mere 5 kPa outward pressure at 40% compression compared to 300 kPa of silicone. To achieve secure placement within the ear no significant outward pressure is needed, this is achieved through excellent conformance of the viscoelastic material to the shape of the canal.

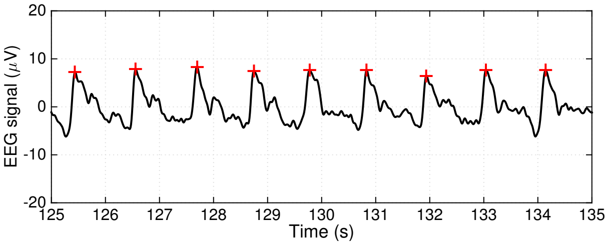
In general, there are two broad types of electrodes: nonpolarisable and polarisable [10]. The best known practical example which closely resembles the characteristics of the former type is the silver/silver chloride electrode. It has a thin layer of a slightly-soluble ionic compound which is usually brought in contact with an electrolyte containing anions of chloride, such that there is almost no overpotentials and the current passes freely across the electrode-electrolyte interface. The latter type – polarisable electrodes – are frequently made with noble metals and no charge crosses the electrode-electrolyte barrier, hence they are also known as capacitive electrodes.

Nonpolarisable electrodes are relatively robust to mechanical motion artefacts, particularly in the events when the electrode-skin distance changes without breaking the contact with electrolyte [11]. On the other hand, the capacitive electrodes, such as the conductive cloth in the proposed sensor, are very sensitive to such movements which change distance between the ‘capacitor plates’, creating electrical noise in the signals acquired. As mentioned earlier, viscoelastic materials possess good energy absorption capabilities, which allows our earpiece to mitigate the effects of motion artefacts, particularly those induced by pulsatile movements of the ear canal wall.

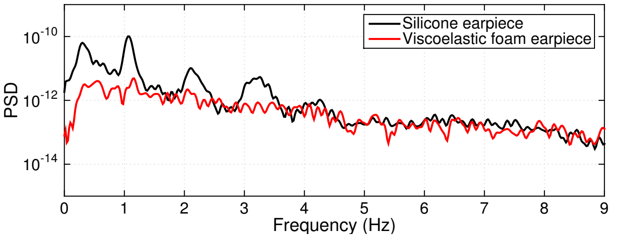
To verify this property we have tested the viscoelastic earpieces in people whose ear canals exhibited strong pulsation, against our earlier designs – the rigid plastic and silicone earpieces. One representative case is shown on Fig. 3, which compares the EEG signals obtained from the same person, from the same ear canal, when using the silicone-based earpiece and the viscoelastic foam-based one. Observe that the EEG from the proposed sensor does not have any



(a) In-ear EEG segment from memory foam earpiece.



(b) In-ear EEG segment from silicone earpiece.



(c) PSD of the EEG signals from silicone and memory foam earpieces.

Fig. 3. Comparison of signal quality between viscoelastic foam and silicone earpieces.

pulsation artefacts, while that from the silicone-based one is badly affected. Spectral analysis of these signals reveals that the silicone earpiece is not suitable for recording low frequency brain waves (<5 Hz) due to significant corruption of those frequencies from artefacts induced by pulsation, as indicated by '+' in Fig. 3(b)

C. Electrical characteristics

The two key aspects of the electrical characteristic of the proposed sensor are: (i) the ability to achieve low impedance electrode-skin contact without abrasion or other means uncomfortable to the user and (ii) the stability of such contact over time. Both of the requirements can be satisfied with the appropriate choice of electrodes – conductive cloth has all the mechanical characteristics to be used in conjunction with viscoelastic foam substrates and it also performs well in the context of EEG acquisition [12].

We have verified that the desired low impedance is achievable with just a saline solution and normal cleaning of the ear canal to remove any excess ear wax. Long term stability of such contact has been investigated through the following experiment: the user has been asked to wear the earpiece for a period of 5 hours and to record electrode impedances at approximately half-hour intervals using AVATAR – a portable biosignal acquisition unit by Electrical Geodesics. Prior to insertion, the ear was cleaned with cotton buds and water, no abrasion was performed and saline solution was applied to both electrodes in relatively small quantities. The outcome of the experiments is demonstrated in Fig. 4, which shows that the impedance of the in-ear electrodes remains essentially constant over the full duration of the experiment.

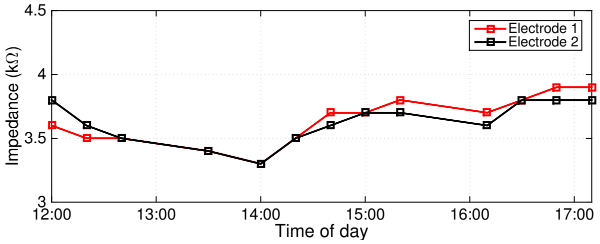


Fig. 4. Impedance variation of in-ear electrodes over time.

III. EEG ACQUISITION

After the mechanical and electrical characteristics of the proposed sensor have been tested and verified, we next consider its use in the context of EEG acquisition. In our previous work, we demonstrated the feasibility of recording EEG from within the ear canal using personalised earpieces [2], [13]. Here we validate the generic earpieces in a similar fashion via well-established auditory and visual evoked responses: the auditory steady-state response (ASSR) and the steady-state visually evoked potential (SSVEP), additionally we present transient evoked potentials.

The ASSR [14] is one of the primary EEG responses used to assess hearing threshold level [15]. When presented with either a broadband or a narrow-band auditory signal which is amplitude-modulated, typically with frequencies in the range 40-80 Hz, the human brain 'demodulates' the signal and produces a response at the modulation frequency. The response is typically most pronounced in the temporal lobe of the brain, which is located in close proximity of the ear canal, thus making the ASSR appropriate for testing the in-ear approach.

The SSVEP originates in the visual cortex [16], [17] in response to visual stimuli, typically a light source flashing at a fixed rate within the range 1 Hz to 100 Hz [17]. The electrical activity that constitutes the brain electrical response contains exactly the same or multiples of the stimulation frequency. This paradigm is widely used in e.g. brain computer interface due to its excellent signal-to-noise ratio. We also examined the transient response to a visual stimulus – the visual evoked potential (VEP) – by time-averaging epochs following stimulus presentation. Over the past half century transient evoked potentials have been used to study a wide variety of physiological aspects of brain function such as attention [18], and are frequently used in BCI applications [19].

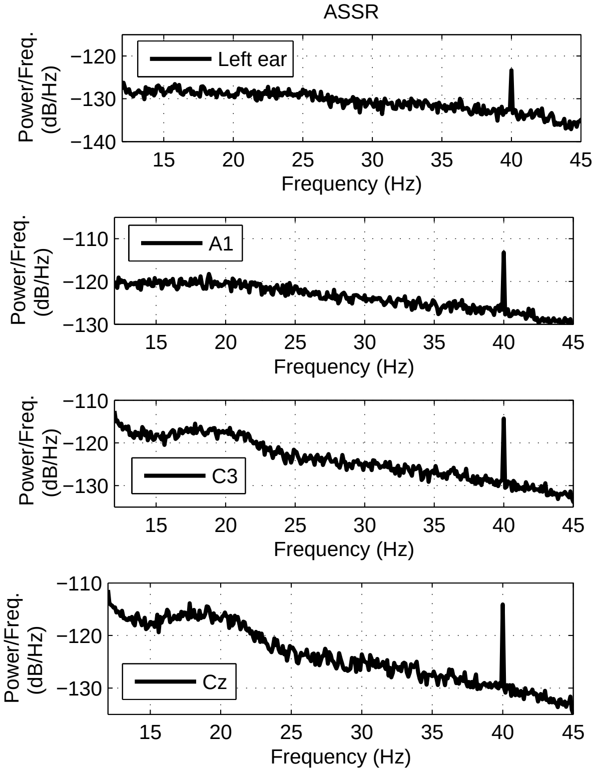


Fig. 5. PSD analysis of responses from an ear-electrode and mastoid (A1) and central regions (C3,Cz) scalp-electrodes, for an ASSR stimulus – a 40 Hz amplitude-modulated auditory tone. Observe responses from all electrode sites at 40 Hz.

A. Experimental setup

In all experiments, EEG was simultaneously obtained from both the proposed in-ear generic earpiece as well as standard on-scalp electrodes. The g.USBamp, a high quality 24-bit biosignal amplifier from g.tec, was used to perform all data acquisition; the unit facilitates simultaneous acquisition from independent recording setups, through its recording configurations with different ground and reference electrode placements, and thus enables a rigorous comparison between in-ear and on-scalp recordings. On-scalp EEG was obtained from electrode positions based on the international 10-20 system: the left mastoid (A1), the left-central (C3) and the central regions (Cz). All scalp electrodes were referenced to the right earlobe and the ground electrode was placed on the forehead. In-ear EEG was obtained from the left ear from two electrodes placed at diametrically opposed locations along the ear canal wall (see Fig. 1(b)), referenced to a gold-cap electrode placed behind the left helix, with the ground gold-cap electrode placed on the left earlobe. The data was acquired with a sampling rate of 1.2 kS/s. All recordings were performed on a healthy male subject aged 32.

The ASSR experiment was performed using over-the-ear headphones presenting an auditory stimulus comprising a 1 kHz sinusoid, amplitude-modulated with a 40 Hz sinusoidal signal. The audio was generated in MATLAB and was presented at a sufficiently loud volume to accommodate the lack of acoustic vents in the earpieces.

The VEP and SSVEP experiments were performed with a red LED of 13 000 mcd brightness. For the VEP experiments the LED was switched fully ON for 200 ms followed by a fully OFF state for 1800 msm while for SSVEP the LED's light intensity was varied sinusoidally from fully OFF to fully ON regimes at a rate of 15 Hz using pulse width modulation (PWM). An Arduino Uno board generated the PWM waveform with the aid of built-in counters, and the whole setup was placed inside an opaque black box with only the frontal region of the LED exposed, providing a viewing angle of 18°. The subject was seated approximately 70 cm away from the stimulus which was positioned at head height. In all of the experiments, the subject was instructed to observe the stimulus while avoiding any head movements or eye activity. The duration of the experiments was 250 s.

B. Experimental results

Fig. 5 shows the power spectral density (PSD) estimates for the ear- and scalp- recordings for the ASSR experiment. Prior to PSD analysis, the data was bandpass filtered using a 4th order Butterworth filter with cutoff frequencies at 1 and 45 Hz. The PSD analysis was performed using Welch's averaged periodogram method, the window length was 10 s and the degree of overlap was 50%. A clear peak at the 40 Hz modulation frequency is visible from all electrode locations. We define the signal-to-noise ratio (SNR) of the ASSR as the height of the response peak above the background EEG [13]. As shown previously using the personalised earpieces [2], [13], the results indicate that the SNR in ASSR obtained from the in-ear approach is on a par with that obtained from the on-scalp electrodes placed at the mastoid and temporal regions – at approximately 10 dB.

The result of the VEP experiment is demonstrated on Fig. 6. The raw signal was first bandpass filtered using a 4th order Butterworth filter with cutoff frequencies at 1 and 13 Hz. Subsequently the dataset was split into 110 two-second epochs, whose start and stop times were determined by the stimulus waveform. The samples where then averaged across all of epochs to produce the VEP signal. A clear pick is evident, approximately 180 ms after the stimulus start time.

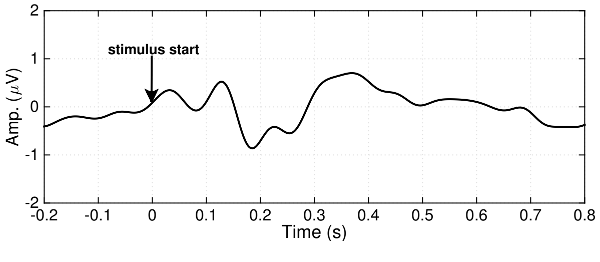


Fig. 6. VEP response to visual stimulus obtained with the proposed generic earpiece

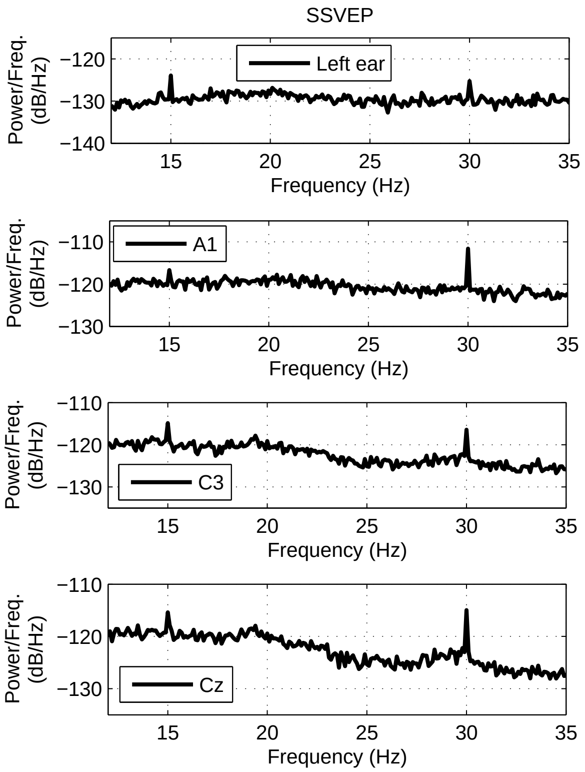


Fig. 7. PSD analysis of responses from an ear-electrode and mastoid (A1) and central regions (C3,Cz) scalp-electrodes, for an ASSR stimulus – an LED flashing at 15 Hz. Observe responses from all electrode sites at 15 Hz and at the first harmonic – 30 Hz.

Fig. 7 shows the PSD estimates for the ear- and scalp-recordings for the SSVEP experiment. Prior to PSD analysis, the data was bandpass filtered using a 4th order Butterworth filter with cutoff frequencies at 5 and 45 Hz. The PSD analysis was performed using the same setup as for the ASSR experiment. Clear peaks at the stimulus frequency – 15 Hz, and at the first harmonic – 30 Hz, are visible from all electrode locations. Given the distribution of the response across multiple harmonics, it was not straightforward to assess the SSVEP SNR. However the response obtained using the in-ear electrode is clearly weaker compared with those obtained from the central regions. This is as expected given the distance of the ear canal from the response source – occipital region.

IV. CONCLUSION

A novel in-ear sensor has been developed for high-quality long-term EEG monitoring. It is constructed with two key components – a viscoelastic substrate and conductive cloth electrodes. Both of these posses a number of desirable properties critical for unobtrusive and discreet in-ear sensing.

The substrate comprises a medium-density memory foam which enables the earpiece to conform even to the most intricately-shaped ear canals and to redistribute outward pressure along the entirety of its surface post insertion. These qualities lead to increased comfort for the wearer, provide secure placement of the device inside the ear canal with minimal pressure to the canal walls and thus allow the possibility to acquire ear-EEG in general population.

The electrodes of the proposed earpiece are constructed from conductive fabric and can accommodate all of the required deformations of the underlying viscoelastic substrate without losing any of the desirable electrical properties. Such electrodes have been shown to require only saline solution to achieve low impedance electrode-skin contact which enables stable electrical recordings, even over prolonged periods of time.

We have shown that the proposed device is virtually immune to motion artefacts generated by the pulsatile ear canal wall movements and allows acquisition of EEG signals all the way down to very low frequencies – crucial for monitoring brain activity during e.g. sleep. It has also been demonstrated that the proposed generic device can be readily used to acquire all of the standard EEG responses, namely steady-state and transient responses to visual and auditory stimuli, thus paving the way for truly wearable EEG acquisition.

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