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Electrode-Skin Impedance Characterization of In-Ear Electrophysiology Accounting for Cerumen and Electrodermal Response

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Abstract— **Conventional electroencephalography (EEG) requires placement of several electrode sensors on the scalp and, accompanied by lead wires and bulky instrumentation, makes for an uncomfortable experience. Recent efforts in miniaturization and system integration have enabled smaller systems, such as wearable, in-ear EEG devices that are gaining popularity for their unobtrusive form factor. Although in-ear EEG has been demonstrated in recent works, dynamics of the ear and ear canal that directly affect electrophysiological measurements have been largely ignored. Here, we present a quantitative analysis of electrode-skin impedance for dry-contact in-ear EEG that accounts for cerumen (earwax) and electrodermal (sweat gland) response. Custom fitted earmolds with 16 embedded electrodes were developed to map the skin conductance in the ear canal of 3 subjects. In the presence of cerumen, the measured average dry-contact impedance in the ear canal was 86% higher than canals removed of cerumen. Electrodermal activity was also found to play a role in electrode-skin impedance, showing up to 25% decrease in dry-contact impedance in response to tactile stimulation. The better understanding of the dynamics of in-ear conditions serves to improve consistency and accuracy of in-ear electrophysiology.**

I. Introduction

Electroencephalography (EEG) has long been the standard for measuring electrical signals generated in the brain. It is an indispensable tool used by neuroscientists and medical practitioners for detection of brain states, neurological disorders, motor control and coordination. The applications for EEG both inside the laboratory and in the consumer market continue to grow in our increasingly technology-connected society, but the utility and wider acceptance of this technique is often limited by the uncomfortable scalp electrodes and accompanying wires [1]. The basic setup of the EEG apparatus has not changed in decades, so it comes as no surprise that efforts have been made to improve the comfort and usability of the technique.

Recently, there has been work demonstrating in-ear electrophysiology that offers comparable performance to conventional EEG systems with much improved comfort, wearability, and discretion [1-4]. These devices often use standard wet electrodes or dry electrodes, which have been validated in use on the scalp or the skin. However, what these studies have neglected to consider is the dynamics of conductance at the electrode-skin interface caused by the unique properties of the ear canal that are not observed elsewhere in the body [5]. Specifically, the prevalence of cerumen (earwax) in the ear canal, humidity, and high density of apocrine glands create a complicated environment for electrodes and merits investigation [5-7].

The aim of this study was to quantitatively evaluate the skin conductivity in the ear canal and investigate the impact of cerumen on electrophysiological measurements recorded in this environment. A secondary goal was to investigate the effects of systemic galvanic skin response on conductivity in the ear and ear canal. The focus of the study is on dry-contact characterization of the electrodes for long-term use with minimal preparation avoiding the need for cumbersome in-ear gel application. For reference, additional gel-based wet-contact measurements are included.

II. Methods

A. Data and Subjects

Data gathered for these set of studies is part of a larger study evaluating ear-based wearables as alternatives for scalp-based electrophysiology and palm-based galvanic skin responses. Physiological responses during normal daily activities were measured from subjects in a non-invasive, unobtrusive manner. In this study, skin conductance (SC) measurements were performed over a large portion of the ear canal and concha. Galvanic skin response (GSR) was measured in parallel from conventional palm-based sensors for correlation assessment. In total, data was collected from 24 trials in each ear of 3 healthy subjects.

Subjects were instructed to refrain from cleaning their ears for a minimum of two weeks before experiments were conducted to maintain normal levels of cerumen. In subsequent control experiments, cerumen was removed from the ears of subjects using an over-the-counter earwax removal solution (Murine System) and following the products recommended use protocol.

B. Ear Molding

Ear impressions were made by a licensed audiologist at Dietsch hearing center (San Diego, CA) for each of the subjects involved in the study. The standard two-part impression material was injected into the ear canal, past the secondary bend, out through the auditory meatus, and onto the concha depression. Three-dimensional laser scanning techniques were used to create editable CAD representations of each subjects ear mold. This enabled the design and

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fabrication of custom fitted, in-ear electrode sensing devices best suited for comfort, conformability, and electrode-skin contact in each subject (Figure 1).

Specialized 21-gauge (Ag/AgCl) electrodes were fitted uniformly in predetermined regions of interest across the ear molds attached to fine gauge, insulated wire in the lumen of the device. A total of 17 electrodes were fitted with 8 to span the region of the ear canal, another 7 covering the concha cavum, 1 in the concha cymba, and 1 non-recording, driven-right-leg (DRL) electrode, also in the concha cymba. Each electrode sat above the surface of the ear mold over a countersink feature that acted as a well to contain electrolyte gel administered to the electrode-skin interface through embedded micro silicon tubes. Electrolyte gel was kept contained between the surface of each electrode and the skin spanning the opening of the countersink.

C. Equipment and Measurement

Real-time measurements of skin conductance activity at multiple sites on the body were managed simultaneously by a low-noise, multichannel biosignal amplifier and analog-to-digital converter (ADC) (Texas Instruments ADS1299) [8-11]. Four ADC chips were utilized on a custom designed printed circuit board (PCB) capable of 32-channel recording with on-board filtering, bias drive, and current sources (Figure 2). With 16 custom wet or dry configurable electrodes for the ear and 4 conventional adhesive gel electrodes placed on the palm and fingers, skin conductance was mapped in these areas.

Mapping of skin conductance in the ear canal was achieved by programmatically selecting pairs of electrodes and passing a fixed alternating current across using the ADCs programmable gain amplifier (PGA). A pull-up and pull-down current source was connected to the positive and negative electrodes, respectively, and the resulting voltage measured by the channel amplifier was recorded. The next permutation of the two-electrode configuration was selected and the process was repeated.

D. Electrode-Skin Contact Configuration

The custom ear electrodes designed for this study are capable of both dry and wet contact with the subject's skin. To assess the effects of contact type on electrode-skin impedance, three contact configurations were tested. For *Dry* contact, dry earpiece electrodes were fitted into the subject's ear. The *Dry-settled* configuration was the same, except impedance measurement was performed after a few minutes. The *Wet* contact configuration involved application of commercial electrode gel (Spectra Gel, Parker Laboratories, New Jersey) either directly to the electrodes or through embedded silicon tubes, depending on the earpiece.

E. Setup for Galvanic Skin Response Study

The palm and fingers of the human hand is an ideal place to measure the galvanic skin response because of the presence of a high concentration of eccrine sweat glands and the relative convenience of electrode placement. Standard

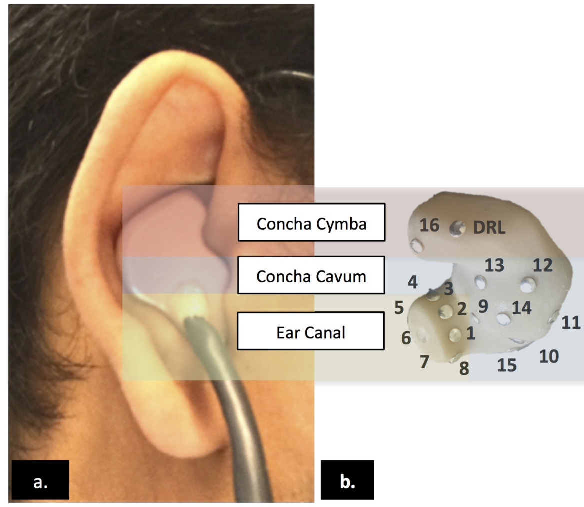


Fig. 1. Shown on the left is one of the custom earpieces built specifically for the subject pictured. The tight fitting electrode earpieces maintain consistent electrode-skin contact and require no additional external restraints. A shielded multicomponent cable connects the earpiece to the amplifier system, shown in Figure 2. On the right, conductance measurements of different regions of the ear in contact with the earpiece are mapped to corresponding regions on a 3D model. The model is positioned to represent an earpiece pulled out of the subject's ear (shown on the left), and rotated counter-clockwise 180 degrees. The conductance is represented by a colormap ranging from dark red, 500 nS to dark green, 1 uS. Highest conductance values are observed in the ear canal and lowest in the Concha Cymba.

clinical gel electrodes were placed between to palm and first knuckle on the inside face of the index and middle fingers. Skin conductance measurements from the hand served as a suitable comparison to the in-ear measurements for this study.

To achieve a baseline tonic skin conductance level, subjects fitted with hand and ear electrodes were positioned in a relaxed position, not actively engaged in any task or complex thoughts for 10 minutes. After the baseline, a quick pinprick stimulus was administered by the subject at time 0. Skin conductance was measured for up to 4 minutes after stimulus, capturing any phasic change in skin conductance response.

III. Results

Impedance values recorded across 16 channels in the ear (Figure 3) show marked variation under 3 electrode-skin contact conditions: *Dry*, *Dry-settled*, and *Wet*. Time zero dry contact impedance values in the ear canal (channels 1-8) and concha (channels 9-16) average 1 MΩ and 8 MΩ, respectively. After allowing the dry electrodes to settle in for 2 minutes, dry-contact impedance are reduced by 50% on average across channels. Wet electrode impedance were considerably lower than both dry configurations, as expected, 565 kΩ and 600 kΩ on average in the ear canal and concha, respectively.

Assessment of electrode-skin contact type in the ear based on impedance showed marked difference between the 3 configurations used. Dry contact electrodes in the ear canal (channels 1-8) had an average impedance of 1 MΩ and

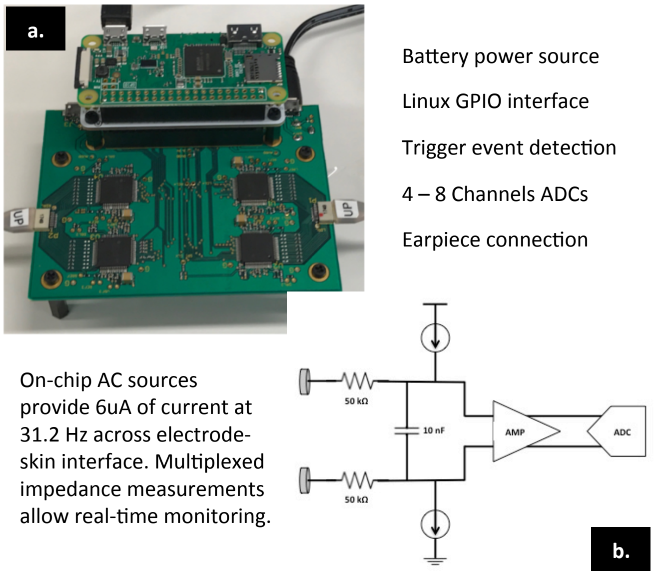


Fig. 2. Acquisition system and impedance circuit diagram.

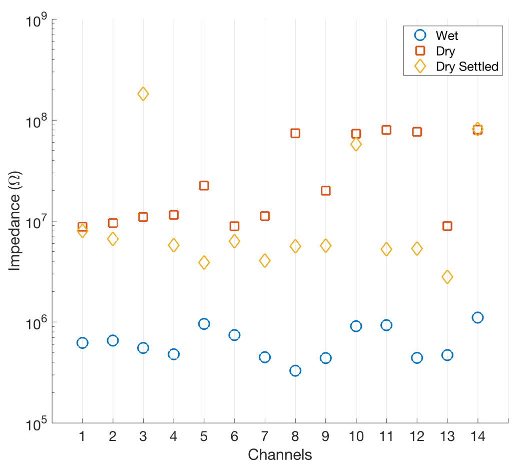


Fig. 3. Impedance values recorded across 16 channels in the ear show marked variation under 3 electrode-skin contact conditions: *Dry*, *Dry-settled*, and *Wet*. Time zero dry contact impedance values in the ear canal (channels 1-8) and concha (channels 9-16) average 1 MΩ and 8 MΩ, respectively. After allowing the dry electrodes to settle in for 2 minutes, dry-contact impedance values are reduced by 50% on average across channels. Wet electrode impedance were considerably lower than both dry configurations, as expected, 565 kΩ and 600 kΩ on average in the ear canal and concha, respectively.

in the concha (channels 9-16) of 8 MΩ. Repeating this measurement after 2 minutes, produces impedance values 50% lower on average across channels. A known behavior of dry contact electrodes, a few minutes of direct contact with the skin dramatically reduces initial contact impedance. In third configuration, wet contact electrodes, impedance values were significantly lower than both dry configurations, as expected, with ear canal reporting 565 kΩ and the concha 600 kΩ on average.

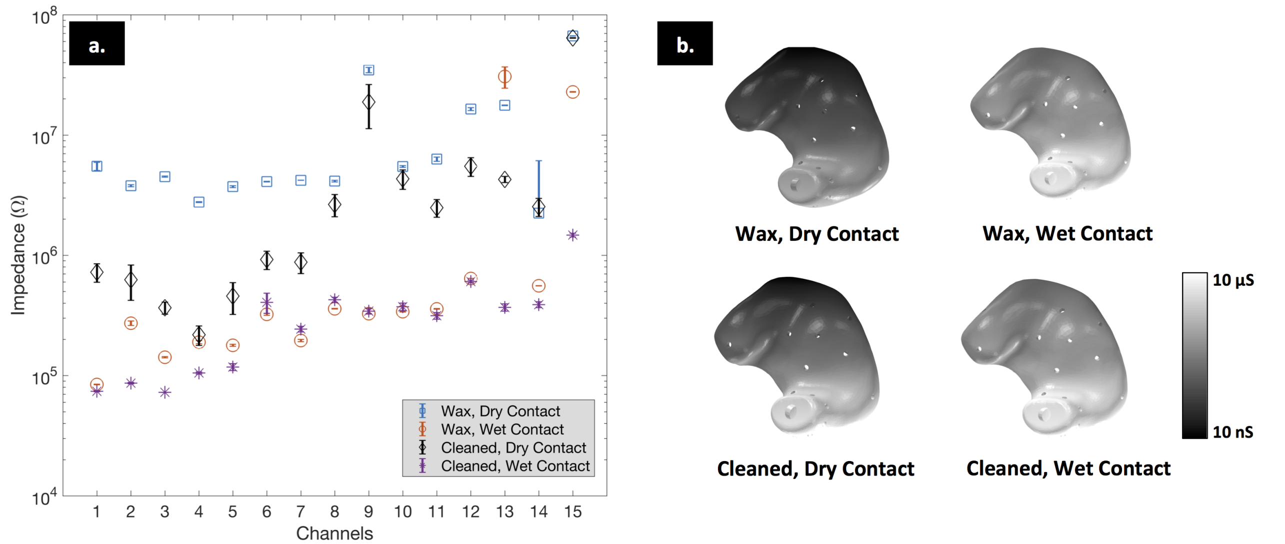
Alternating current measurements in the ear also showed a considerable difference in electrode impedance when measured in the presence of cerumen and after its removal (Figure 4). Dry contact electrodes in a subject's ear with normal cerumen reported impedance values of 4.12 MΩ on average across channels in the ear canal. After removal of cerumen from the subject's ears, impedance decreased by 86.% to 574 kΩ on average. With wet electrodes, removal of cerumen also shows the same trend in impedance reduction. Wet electrodes, with cerumen, measured 213kΩ and without, 112kΩ for a 47% decrease in impedance.

Finally, electrodermal activity in response to a stimulus was observed on the palm and in the ear canal of subjects (Figure 5). On the palm, 2 minutes before the stimulus, a steady impedance of 880 kΩ was recorded. One second after the stimulus, a 3.5% impedance decrease is observed, followed by a sharp 47.2% decrease at 2 seconds after stimulus. From the onset to this minimum takes 1 second, and from minimum to when the palm impedance recovers to its normal value takes 5 seconds, for a total electrodermal response lasting 6 seconds. In the ear canal, electrodermal activity was observed, with a response starting 2 seconds after stimulus and reaching impedance minimum at approximately 5.5 seconds after stimulus, sustained at minimum for a second or more on some channels. Impedance in the ear canal recovers to nearly normal approximately 9 seconds after stimulus, for a total electrodermal response last about 7 seconds. In the concha, the third region monitored during this study, no obvious electrodermal activity was observed.

Onset of electrodermal activity in the ear canal was delayed compared to the palm by at least 1 second. Response duration was also 40% longer in the ear canal compared to the palm and recovery to normal impedance levels was slower and less complete in ear. The concentration of apocrine sweat glands in the outer ear canal and both apocrine and eccrine sweat glands in the external auditory meatus and concha are the likely the reason for the observed electrodermal activity in the ear. The latency in response and sustained response in comparison to the palm could be explained by the relative distance between the ear and the finger pinprick. Also, the ear canal in these tests is partially occluded, potentially causing an increase in the time taking for sweat to evaportate and humidity to normalize, when compared to the unobstructed hand.

IV. Conclusion

Investigating the dynamics of the ear and ear canal for ear-based electrophysiology shed light on some of the underlying physiological factors that influence recording. Specifically, for subjects with higher concentrations of cerumen, in-ear electrodes will see considerably greater impedance than for subjects with no or removed cerumen. The concentration and location of cerumen can also vary over time because of the natural flow of the substance from the middle ear to the acoustic meatus, creating a measurement environment far less consistent than the scalp. The in-ear environment has been not been found to be prohibitive to EEG, rather special consideration must be made to account for its dynamics to ensure high signal fidelity and repeatability.



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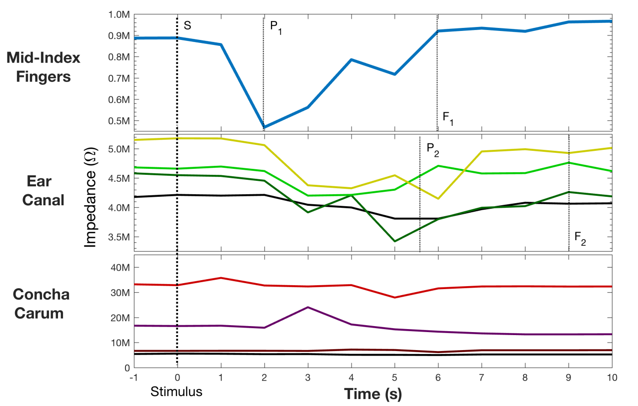

Fig. 5. Regional dependence of electrodermal response. Skin impedance was monitored on 3 regions of the body: (Top) Middle and Index fingers, (Middle) Ear canal, and (Bottom) Ear Concha. The subject is in a relaxed state with baseline skin impedance before a stimulus is introduced at time zero. The palm shows a decline in impedance 1 s after stimulus and a minimum at 2 s. The recover to baseline impedance takes approximately 4 s after stimulus. In the ear canal, a response begins 2 s after stimulus, reaching a minimum between 5 to 6 s, and recovering slowly to near baseline 9 s after stimulus.

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