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Dry carbon/salt adhesive electrodes for recording electrodermal activity

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ABSTRACT

In this work, dry carbon/salt adhesive (CSA) electrodes are found to be suitable for collecting electrodermal activity (EDA) signals. Silver/silver chloride (Ag/AgCl) electrodes have been considered as a reliable media to obtain EDA signals. However, mainly the cost and the need for a hydrogel layer make it difficult to disseminate the practice of using EDA signals in practical applications. A mixture of carbon salt and adhesive has shown to be suitable for collecting bioelectric signals (FLEXcon's Patent #8,673,184). With the objective of testing how these electrodes compare for collecting EDA signals, AC and DC source devices were employed. Sixteen subjects underwent electric shocks and tonic emotional and cognitive stress. No significant differences were found in amplitude, onset-to-peak time and onset time between CSA and Ag/AgCl electrodes. Frequency-domain index, EDASympn, was not found to be different between the two electrode types. The time-varying spectral index was different between Ag/AgCl and EDA electrodes for DC devices, not for the AC devices. Ag/AgCl electrodes often polarized impeding the collection of EDA signals, suggesting that CSA electrodes provide better fidelity EDA measures. We conclude that CSA electrodes are a suitable surrogate of Ag/AgCl electrodes for collecting EDA signals.

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1. Introduction

This paper describes the evaluation of carbon/salt adhesive (CSA) electrodes for measuring electrodermal activity (EDA). CSA electrodes' performance was compared to Silver/Silver Chloride (Ag/AgCl) hydrogel electrodes, the gold standard for electrodermal recording [1]. EDA measures have been traditionally used to assess psychophysiological stress [1,2], but recently have also been used to assess sympathetic nervous system arousal under stressors of many kinds [3–7]. The increasing relevance and popularity of EDA and the ease of data acquisition via wearable devices necessitates the development of better electrodes and instrumentation.

The EDA is a measure of the change in conductance of the skin [1]. EDA is measured as the modulation produced by such conductance changes on a power source [8]. EDA has many potential applications in society. For instance, in wearable devices, EDA signals could be used to develop alarms of high or increasing levels of cognitive (related to workload), physical (during workout) or emotional stress, among other things. EDA data acquisition with Ag/AgCl electrodes requires the application of a paste-like hydrogel over a silver disc. While the hydrogel layer significantly improves the signal quality by effectively lowering the impedance that exists at the electrode-skin interface, impedance increases when the hydrogel layer degrades with time because of dehydration. This leads to a loss of signal quality and an increased incidence of motion artifacts and noise [9]. Also, Ag/AgCl electrodes are expensive since silver is an expensive commodity. The Ag/AgCl electrodes we used for this study needed to be taped to the subject's fingers, because they don't have any self-attaching system similar to ECG Ag/AgCl that have an adhesive surrounding the hydrogel.

The most salient advantages of CSA electrodes are their consistently low impedance and no shelf life limitations without the use of a hydrogel layer [10]. These electrodes are cheap to make, and because of their ease of fabrication and flexibility they can be designed, tuned and configured depending on the application. For this study, we have made electrodes in such a way that they wrap around the fingers, with electrode-skin contact surface of around 2 cm^2 and a little circular conduction bridge placed directly on a fingertip. We expected these dimensions and characteristics to be

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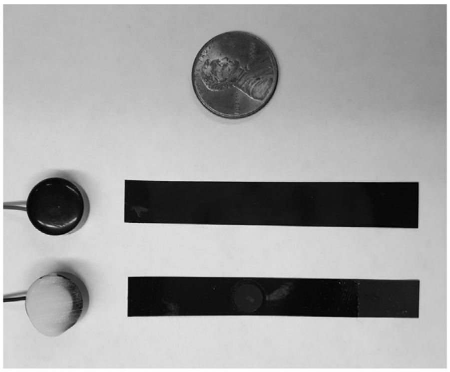

Fig. 1. Ag/AgCl hydrogel electrodes (left) and CSA electrodes (right) for EDA measurements.

suitable for EDA measurements, because of the finger's anatomy and the nature of the EDA signal.

Most EDA devices involve the application of an external constant current or voltage source via electrodes on the skin, either direct current (DC) or alternating current (AC). These are termed exosomatic methods. EDA devices measure the modulated current or voltage (depending on whether the constant source is voltage or current, respectively) to compute the skin conductance. Although AC-source devices have shown advantages over DC-source devices (mainly, avoiding electrode polarization [1]), both types are still widely used.

We aimed to compare CSA to Ag/AgCl electrodes for the task of acquiring EDA signals. First, the electrode-skin impedance was measured for CSA and Ag/AgCl electrodes. The electrodes were tested with representative types of stressors for which EDA is used, namely physical, emotional, and cognitive stress. The same protocol was followed using DC- and AC-source devices.

2. Materials and methods

Fig. 1 shows CSA and Ag/AgCl electrodes used to collect EDA signals during this study. FLEXcon developed CSA electrodes to address the issue of dehydration with the current industry gold standard electrodes for collecting bioelectric signals [10]. They were designed by combining a visco-elastic polymeric adhesive [11] with carbon black powder and a quaternary salt. This mixture is potentially much more economical than Ag/AgCl. The process of fabrication of CSA electrodes, and the implemented methods to compare them to Ag/AgCl electrodes are described below.

2.1. Fabrication of CSA electrodes for EDA

To create the testable CSA electrodes for EDA measurements, the conductive base layer, the adhesive, and the bridge were prepared beforehand. The fabrication process is depicted in Fig. 2. We cut the material to 1-1/2" × 3/8" so that an electrode can be wrapped around a finger, with the bridge in contact with the fingertip.

2.2. Electrode activation

After the CSA electrodes were fabricated, they were activated by electrophoresis [12]. This produces multiple isolated Z direction (out of plane) conductive pathways in the adhesive. The bridge, or conductivity-enhancing feature, is a low impedance electrically conductive material that produces generally lower electrode impedance by connecting in parallel the Z direction conductive pathways. The bridge is specifically designed to balance electrical, mechanical and electrode adhesion properties: its conductive loading level provides electrical conductivity, its polymeric content and thinness provide mechanical flexibility, and its small footprint minimizes reduction in adhesive bonding.

2.3. Protocol

The study protocol was approved by the Institutional Review Board of The University of Connecticut and all volunteers provided written informed consent to participate in the experiment. Electrode-skin contact impedance was measured for both media. For procuring a fair comparison, skin properties were kept as constant as possible by doing all measurements in a single day, on a single subject. The skin of the test subject was cleaned before each measurement by wiping with a 70% alcohol-impregnated cotton pad, which was allowed to evaporate before applying the electrodes. Two electrodes were mounted, one each on the index and middle fingers. These electrodes were connected to the Hiroki IM3570 impedance analyzer, and each measurement is the result of averaging 10 measurements. The signal voltage amplitude was set to 1 V and the frequency range from 4 to 200 Hz. N = 7 pairs of CSA electrodes were used for impedance measurements.

To evaluate CSA electrode performance on measuring EDA, three types of stress were monitored throughout this study: physical (electrical stimulation), emotional (disturbing video), and cognitive (Stroop test). Subjects experienced each type of stress after a resting period to procure hemodynamic stabilization.

First, the subject went through the electrical stimulation phase. This phase required the use of a commercially available dog collar [13]. The contact points of the receiver were placed on the inside of the subjects forearm. The power level on the transmitter was set to a level just enough to elicit a response on the subjects (amperage of less than 1.5 mA) without any risk, and remained at this level throughout the entire period of electrical stimulation (5-min baseline plus 5-min stimulation). This level of power was chosen because it was just above the threshold of feeling of 1 mA [14]. This also was chosen to adhere to the University of Connecticut's IRB recommendations and reduce any unnecessary discomfort to subjects. After the baseline recordings, there were 5 min of test during which the subjects were stimulated twice, at minutes 1 and 4. Subjects were not told when the shocks were going to be given. Each shock lasts about 100 ms. At the end of the five minutes the dog collar was taken off the subject.

The second part consisted of emotional stimulation by presenting to the subjects a disturbing video (adapted from [15]). After 5 min of baseline recordings, subjects were presented a video including images and sounds intended to elicit emotional stress on the subjects (the video was approved by the IRB at The University of Connecticut). Finally, during the third stage Stroop test was applied in the same manner as in [16]. Stroop tests induce cognitive stress on subjects. Five minutes of baseline measurements were also recorded for the subject before the Stroop task took place. The length of the overall experiment was just above 40 min.

2.4. Subjects

N = 16 subjects (5 female, 11 male, age 25 ± 7.7 years old) were selected. CSA and Ag-AgCl electrodes were used simultaneously on every subject to collect EDA signals. All subjects were screened to avoid risks to participants as well as undesirable influences to subjects' reactiveness (e.g. caffeine).

2.5. Devices

Data were collected using both DC- and AC-source EDA devices (N = 8 subjects for each). Two identical DC-source EDA devices were implemented to perform a fair comparison between the two media. Fig. 3 shows the schematic diagram of the circuit for the DC-source

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