Novel Dry Electrodes for Recording Electrodermal Activity

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Abstract— **Novel carbon/salt adhesive (CSA) electrodes have been found suitable for collecting electrodermal activity (EDA) signals. Ag/AgCl electrodes are considered the standard for collecting EDA signals, because it highly avoids electrodes' polarization. Ag is an expensive commodity. Furthermore, a hydrogel layer is needed for the Ag/AgCl electrodes to collect EDA signals. Adding hydrogel to the electrodes is a cumbersome process. Aforementioned circumstances highlight the need for a more accessible media to collect these signals, allowing EDA use to spread. Dry electrodes made with a mixture of carbon, salt and adhesive has shown to be suitable for collecting bioelectric signals. We have implemented a constant DC-source EDA circuit, with the intention of testing how these electrodes perform for collecting EDA signals. Recruited subjects (N=4) underwent a test including electric shocks, watching a disturbing video and performing the Stroop task. Time and frequency domain correlation were computed. For the obtained skin conductance responses (SCRs), amplitude, onset-to-peak time, and onset difference between the CSA and Ag/AgCl electrodes' acquired SCRs were computed. We found no significant differences on SCRs amplitude and onset-to-peak time between CSA and Ag/AgCl. Furthermore, the difference in onset time for simultaneous SCRs obtained using both media was not different to zero. We conclude that CSA electrodes are a suitable surrogate of Ag/AgCl electrodes for collecting EDA signals on healthy subjects using the implemented DC circuit.**

I. Introduction

Our aim was to evaluate Carbon/Salt/Adhesive (CSA) electrodes for measuring electrodermal activity (EDA). CSA electrodes' signals were compared to those obtained simultaneously using Silver/Silver Chloride (Ag/AgCl) hydrogel electrode, the gold standard for electrodermal recording [1]. Ag/AgCl EDA electrodes require the application of a paste-like hydrogel over a silver disc. The hydrogel layer significantly improves the signal quality by effectively lowering the impedance that exists at the electrode-skin interface, but the hydrogel layer degrades with time as it dehydrates, producing a higher impedance. This leads to signal quality impairment and an increased sensitivity to motion artifacts and noise [2]. Also, silver is an expensive commodity, making Ag/AgCl electrodes expensive.

EDA measures have been traditionally used to assess psychophysiological stress [1], [3], and recently has been used to assess sympathetic nervous system arousal under stressors of many kinds [4]–[8]. Given the current need to fully elucidate and delineate sympathetic nervous system dynamics using noninvasive means, new instrumentation for and signal processing of EDA have gained some popularity in recent years [1], [9], [10]. This recent impetus is because EDA is a measure of the changes in electrical conductance of the skin, with strong correlation to sweat production. EDA reflects only activity within the sympathetic branch of the autonomic nervous system because there is no parasympathetic innervation of eccrine sweat glands. As sweat production increases, the conductance of the skin increases due to high conductivity of the sodium chloride in the sweat. EDA results from the changes that such variable skin conductance produces to an applied constant source [11].

Growing relevance of EDA makes it desirable to develop affordable resources to acquire such data. EDA has many potential applications in society and industry. EDA could be used for monitoring the stress in which the divers are experiencing when working in stressful conditions. 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, between others. EDA could be used in the automobile industry to alert drivers when they are too tired to be driving because their bodies are showing levels of stress that verify the driver is falling asleep.

II. 4. Materials and Methods

CSA and Ag/AgCl electrodes used to collect EDA signals during this study are shown on Fig. 1. 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 unlike ECG Ag/AgCl that have an adhesive surrounding the hydrogel. FLEXcon developed CSA electrodes to address the issue of dehydration with the current industry gold standard electrodes for collecting bioelectric signals [12]. They were designed by combining a visco-elastic polymeric adhesive [13] with carbon black powder and a quaternary salt. This mixture is potentially much more economical than Ag/AgCl.

Fabrication process for CSA electrodes has been reported before [12]. After the CSA electrodes are fabricated, they are activated by sending a high voltage and current through the electrode, which results in significant reduction of impedance [14]. 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

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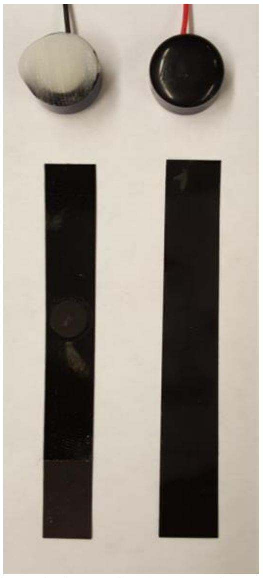

Figure 1. Ag/Ag hydrogel electrodes (top) and CSA electrodes (bottom) for EDA measurements.

conductive pathways. This can be described as many resistors in parallel.

A. Protocol

To compare CSA electrodes to the gold standard Ag/AgCl electrodes on acquiring EDA signals, a test involving electric shocks, watching a disturbing video and performing the Stroop task was employed. The electric shocks were implemented to perform a startle-like physical stress test; watching a disturbing video was meant to induce emotional stress; the Stroop task is a well stablished method to induce cognitive stress. The latter two induce stress in a tonic manner. The experiment took in overall 40 minutes. Subjects experienced each type of stress after a resting period to procure hemodynamic stabilization, and 5 minutes of baseline measurement.

Electrical stimulation phase required the use of a commercially available dog collar [15]. 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 left at this level throughout the entire period of electrical stimulation. This level of current was chosen because it was just above the threshold of feeling of 1 mA [16]. After the baseline recordings, there was 5 minutes of test where the subjects were stimulated twice, at unannounced moments (minutes 1 and 4). At the end of the five minutes the dog collar was taken off the subject in order to reduce subjects' stress.

Emotional stress was induced by presenting a disturbing video (adapted from [17]) to the subjects. After 5 minutes of baseline recordings, subjects were presented a video including images and sounds intended to elicit emotional stress on the subjects. Finally, the Stroop test was applied in the same manner as in [18]. Stroop test induces cognitive stress on subjects. Five minutes of baseline measurements were also recorded for the subject before the Stroop task took place. The whole protocol was approved by the Institutional Review Board of The University of Connecticut.

B. Subjects

For this experiment a total of N = 4 subjects were recruited. CSA and Ag-AgCl electrodes were used simultaneously on every subject to collect EDA signals. Subjects who used drugs frequently, sweat often and easily, or had a pre-existing conditions that puts them in harm during the experiment were excluded of the experiment. Subjects were not allowed to drink, smoke or use any other type of drug (excluding daily prescriptions) for a 48 hour period before testing.

C. EDA Device

Two identical EDA devices were implemented to perform a fair comparison between the two media. Fig. 2 shows the diagram of the circuit for the constant DC current source EDA devices fabricated for this study. It is powered by a source of 3.3 volts. The current source applies a constant current to the subject's fingers through the electrodes. The signal variations on resulting voltage is acquired through a differential op-amp. Lastly, a filter is used to get the EDA

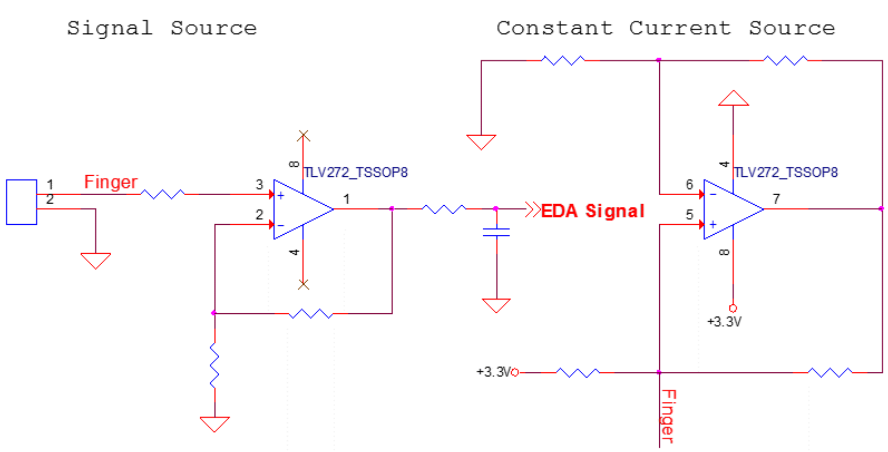

Figure 2. Schematic of circuit used for measuring EDA using DC current source.

signal. The range of conductance that can be measured with the circuit is 0.3 to approximately 20 µS. In order to collect signals simultaneously, two pairs of fingers were employed: (1) middle and index, and (2) ring and little. To procure a fair comparison, fingers were interchanged from subject to subject, for both type of devices (for instance, CSA electrodes were placed on middle and index on half of the subjects).

Given that we are using a constant current circuit in this experiment, the resulting raw voltage signal modulated by changes in subjects' skin conductance was acquired. Therefore, voltage decreases as skin conductance increases as a result of subjects' stress. That is why in our EDA measurements the onset is determined by a drop in the signal (as shown in Fig. 3).

D. Signal processing

All EDA signals were down-sampled to a frequency of 2 Hz, which is enough to maintain all the frequency components of the signal (< 0.5 Hz). EDA incorporates both rapid transient events and slow shifts. Rapid transient, called skin conductance responses (SCRs), are visible after startle like stimulus, like the one we implemented in the present study using electric shocks.

The first set of comparisons are implemented on SCRs' features. The SCRs rise time (onset-to-peak time) and amplitude of SCRs from CSA and Ag/AgCl electrodes' signals were obtained for comparison (see Fig. 3). Amplitude is defined as the absolute value of the difference in level between the onset and the peak of the SCR. Rise time is the difference in time between the same two points. Furthermore, the onset-difference between simultaneous SCRs was obtained. Onset-difference is defined as the time of SCR's onset obtained using Ag/AgCl electrodes minus the time of the onset of the corresponding (ideally simultaneous) SCR obtained through the CSA electrodes, as a reaction to the same electric shock.

Emotional and cognitive stress were used to evaluate the tonic shifts on the EDA signals. Signals for these tests were high-pass filtered to remove any very low frequency trend or wander (Butterworth, cutoff frequency=0.01 Hz). In order to obtain a frequency domain representation of the EDA signals, the power spectra were calculated using Welch's periodogram method with 50% data overlap. A Blackman window (128) was applied to each segment, the Fast Fourier Transform was calculated for each windowed segment, and the power spectra of the segments were averaged.

E. Statistics

First, the resulting SCRs from the electric shocks were compared in terms of their amplitude, onset-to-peak time and onset-differences between simultaneous recordings obtained using CSA and Ag/AgCl electrodes. T-test analysis was used to determine the significance of the differences in SCRs' amplitude and onset-to-peak time values obtained with the two media, and to evaluate the null hypothesis that the mean of the onset-differences is equal to zero.

EDA signals during emotional and cognitive stress, from CSA and Ag/AgCl electrodes, were compared on each subject using the Pearson's Correlation Coefficient in time

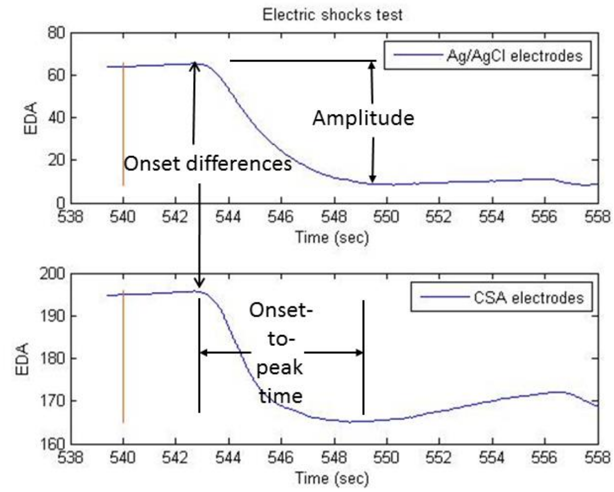

Figure 3. Example of SCR for Ag/AgCl (top) and CSA (bottom) electrodes. EDA in mV.

and frequency domain. Pearson's correlation coefficient mean and standard deviation throughout the subjects for each test were calculated.

III. RESULTS

The two most commonly observed waveforms of the SCRs, the uniphasic and biphasic [11], were considered in the analysis. Seven SCRs were selected from a total of 8 (2 shocks times 4 subjects). Unused shocks either made one of the electrodes' SCR to saturate or elicited a SCR that was not distinguishable or was overlapped with other waves. It is worth saying that many times Ag/AgCl electrodes tend to polarize, making it impossible for any EDA measures temporarily.

TABLE I. RESULTS FOR COMPARING CSA ELECTRODES TO AG/AGCL ELECTRODES

SCRs obtained after electric shocks		
	Ag/AgCl	***CSA***
Onset-to-peak time (sec)	4.3 ± 2.9	3.7 ± 2.4
Amplitude (mV)	25.1 ± 18.7	24.2 ± 14
Onset-difference (sec)	0.02 ± 0.17	
Electrodermal activity under emotional stress		
	Baseline	***Emotional***
Time-domain correlation	0.97 ± 0.03	0.8 ± 0.3
Frequency-domain correlation	0.91 ± 0.1	0.96 ± 0.07
Electrodermal activity under cognitive stress		
	Baseline	***Cognitive***
Time-domain correlation	0.99 ± 0.01	0.92 ± 0.05
Frequency-domain correlation	0.96 ± 0.03	0.96 ± 0.04

Values are mean ± standard deviation.
No significant differences were found between Ag/AgCl and CSA for any parameter.

Table I include the results for comparison of Ag/AgCl and CSA electrodes, using the selected measures. In general, CSA electrodes seemed to obtain slightly lower SCRs amplitude, which also means that smaller fluctuations on skin impedance were captured with them. Nevertheless, CSA electrodes captured the transit from onset to peak in a faster manner (somewhat lower onset-to-peak time). However, none of these differences are significant. The mean of the onset-differences is not either statistically different to zero.

Stroop test elicited noticeably reactions on the subjects' EDA, with both type of electrodes. Responses to disturbing video were more variable, ranging from negligible reaction (common within male subjects), to highly representative reaction (noticeable in some female subjects). CSA and Ag/AgCl electrodes demonstrated the same behavior, throughout the experiment. Nevertheless, correlation was found high in average with low standard deviation for baseline and test stages of emotional and cognitive stress tests (Table I).

IV. Discussion

The CSA electrode showed to be able to detect EDA signals in a similar manner to Ag/AgCl hydrogel electrodes, using a constant DC-current EDA device, for healthy subjects receiving electric shocks, watching disturbing scenes or performing a cognitive task. This is in agreement with previous studies that showed how the CSA electrodes are suitable to detect bio potentials [12].

Fig. 3 is an example of how the signals were similar in time domain. The effect of the stimulus on the subject, for both the CSA and Ag/AgCl electrode, can be seen by just plotting the signals. Differences in the amplitude of the responses and in the level value of the signals are circumstantial, because the measures were collected simultaneously in different fingers. The comparison showed no significant differences and a high correlation of the results in the overall. It seems like dry CSA electrode should be a valid surrogate of Ag/AgCl hydrogel electrodes when it comes to recording EDA. This would be able to save a substantial amount of money due to the infinite shelf-life the CSA electrode has to offer [12]. The CSA electrodes are also more economical since carbon is cheaper than silver.

Three different types of stress were induced to verify that the electrodes worked for each type of stress someone may undergo. For the electric-shocks test no significant differences were found for onset-to-peak time, amplitude, or onset-time, for any type of EDA devices. For disturbing video and Stroop task, mean correlation was always above 0.9 on baseline measurements, and slightly reduced (above 0.8) under emotional and cognitive stress.

V. Conclusion

In the overall, CSA electrode showed to achieve similar EDA readings as the Ag/AgCl electrodes. The correlation between the signals obtained using the two types of electrodes was moderate to very high and there were no significant differences to be noted. The electrodes worked for all three different types of stress: emotional, physical, and cognitive. The amplitude and onset-to-peak time testing also verified that the two electrodes were comparable to collect SCRs and there were no significant differences in their characteristics. As conclusion, CSA electrodes are a suitable surrogate of Ag/AgCl electrodes for collecting EDA signals.

References

[1] W. Boucsein, D. C. Fowles, S. Grimnes, G. Ben-Shakhar, W. T. roth, M. E. Dawson, D. L. Filion, and Society for Psychophysiological Research Ad Hoc Committee on Electrodermal Measures, "Publication recommendations for electrodermal measurements," *Psychophysiology*, vol. 49, no. 8, pp. 1017–1034, Aug. 2012.

[2] A. Searle and L. Kirkup, "A direct comparison of wet, dry and insulating bioelectric recording electrodes," *Physiol. Meas.*, vol. 21, no. 2, pp. 271–283, May 2000.

[3] J. T. Cacioppo, L. G. Tassinary, G. Berntson, and & 0 more, *Handbook of Psychophysiology*, 3 edition. Cambridge England ; New York: Cambridge University Press, 2007.

[4] T. P. Zahn and J. L. Rapoport, "Autonomic nervous system effects of acute doses of caffeine in caffeine users and abstainers," *Int. J. Psychophysiol. Off. J. Int. Organ. Psychophysiol.*, vol. 5, no. 1, pp. 33–41, May 1987.

[5] T. P. Zahn, J. L. Rapoport, and C. L. Thompson, "Autonomic effects of dextroamphetamine in normal men: implications for hyperactivity and schizophrenia," *Psychiatry Res.*, vol. 4, no. 1, pp. 39–47, Feb. 1981.

[6] G. Bohlin, "Delayed habituation of the electrodermal orienting response as a function of increased level of arousal," *Psychophysiology*, vol. 13, no. 4, pp. 345–351, Jul. 1976.

[7] E. S. Mezzacappa, R. M. Kelsey, and E. S. Katkin, "Breast feeding, bottle feeding, and maternal autonomic responses to stress," *J. Psychosom. Res.*, vol. 58, no. 4, pp. 351–365, Apr. 2005.

[8] G. H. Prystav, "Electrodermal, Cardiac, and Respiratory Activity to Repeated Cold Pressor Stimulation in Drug Addicts," *J. Gen. Psychol.*, vol. 94, no. 2, pp. 259–270, Apr. 1976.

[9] R. Freeman and M. W. Chapleau, "Testing the autonomic nervous system," *Handb. Clin. Neurol.*, vol. 115, pp. 115–136, 2013.

[10] A. P. Colbert, K. Spaulding, A. Larsen, A. C. Ahn, and J. A. Cutro, "Electrodermal activity at acupoints: literature review and recommendations for reporting clinical trials," *J. Acupunct. Meridian Stud.*, vol. 4, no. 1, pp. 5–13, Mar. 2011.

[11] N. S. Greenfield and R. A. Sternbach, *Handbook of psychophysiology*, vol. xii. Oxford, England: Holt, Rinehart & Winston, 1972.

[12] H. F. Posada-Quintero, B. A. Reyes, K. Burnham, J. Pennace, and K. H. Chon, "Low Impedance Carbon Adhesive Electrodes with Long Shelf Life," *Ann. Biomed. Eng.*, vol. 43, no. 10, pp. 2374–2382, Oct. 2015.

[13] C. Gutsche, "Pressure-sensitive adhesives and applications. István Benedek, second edition, 2004 Marcel Dekker, Inc., New York, ISBN~0-8247-5059-4, 747 pages, price $ 185," *Colloid Polym. Sci.*, vol. 283, no. 4, pp. 465–465, Jan. 2005.

[14] K. L. Lerner and B. W. Lerner, *The Gale Encyclopedia of Science*. Cengage Gale, 2008.

[15] R. Luijcks, H. J. Hermens, L. Bodar, C. J. Vossen, J. van. Os, and R. Lousberg, "Experimentally Induced Stress Validated by EMG Activity," *PLoS ONE*, vol. 9, no. 4, p. e95215, Apr. 2014.

[16] C. R. Nave and B. C. Nave, *Physics for the health sciences*. WB Saunders Company, 1985.

[17] B. S. Zheng, M. Murugappan, and S. Yaacob, "Human emotional stress assessment through Heart Rate Detection in a customized protocol experiment," in *2012 IEEE Symposium on Industrial Electronics and Applications (ISIEA)*, 2012, pp. 293–298.

[18] P. Karthikeyan, M. Murugappan, and S. Yaacob, "Analysis of Stroop Color Word Test-Based Human Stress Detection using Electrocardiography and Heart Rate Variability Signals," *Arab. J. Sci. Eng.*, vol. 39, no. 3, pp. 1835–1847, Sep. 2013.