



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 cm² and a little circular conduction bridge placed directly on a fingertip. We expected these dimensions and characteristics to be

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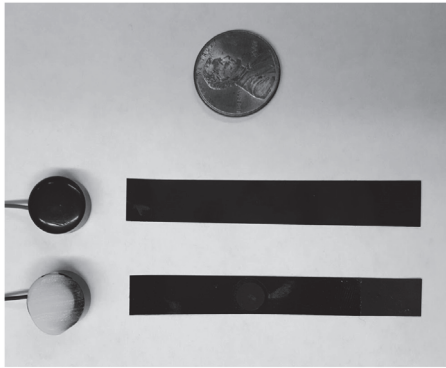


Fig. 1. Ag/AgCl hydrogel electrodes (left) and CSA electrodes (right) for EDA measurements.

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 $1\text{-}1/2'' \times 3/8''$ 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' reactivity (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

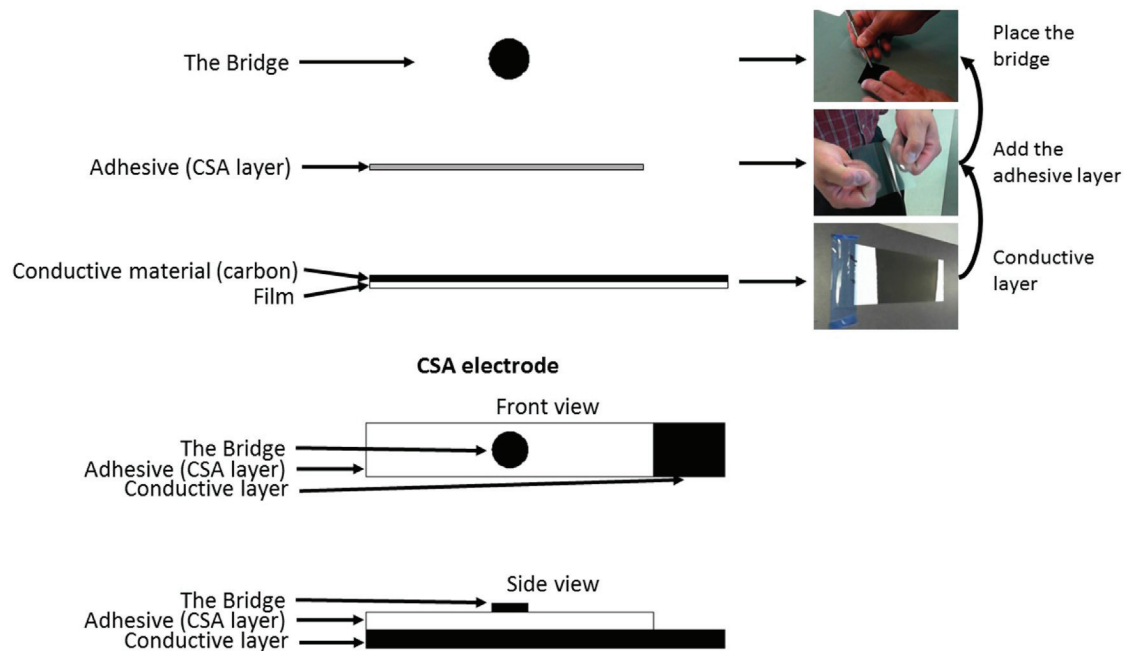


Fig. 2. Illustration of the fabrication process of CSA electrodes.

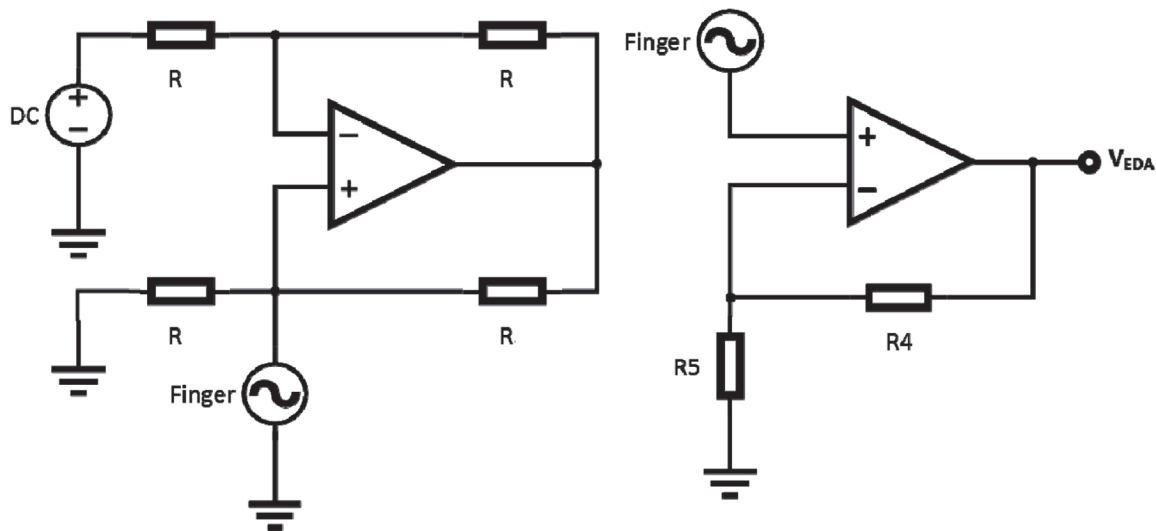


Fig. 3. Schematic of circuit used for measuring EDA using DC current source.

EDA devices fabricated for this study. It is powered by a source of 3.3 V. The current source applied a constant current to the subjects' fingers through the electrodes. The signal variations on the resulting voltage were acquired through a differential op-amp. Lastly, a filter was used to obtain the EDA signal. Similarly, two identical commercial AC-source fully isolated galvanic skin response amplifiers with low voltage (22 mVrms, 75 Hz AC, FE116, ADInstruments) were employed to collect EDA signals. All EDA signals were digitized through the PowerLab ADC (ADInstruments), sampled at 400 Hz.

In order to collect signals simultaneously from two different media, 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 types of devices (for instance, CSA electrodes were placed on middle and index fingers on half of the subjects).

Electrodermal activity is usually measured in conductance units, microsiemens [μS]. In our study, the AC-source devices provided values in μS . However, for the DC-source circuits used in this experiment, the raw voltage signal modulated by changes in subjects' skin conductance was acquired [mV]. Therefore, instead of a conductance increasing when the subject became stressed, we obtained a voltage that decreased at the same rate. This is why for the DC measurements the onset is determined by a drop in magnitude (as shown in the left panel of Fig. 5).

2.6. Signal processing

Once all data were collected, data were separated into the corresponding electrode and task. 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 transients, called skin conductance responses (SCRs), are elicited through startle tests like the one we implemented in the present study to induce physical stress (electric shocks). The SCR rise time (onset-to-peak time) and amplitude for both signals were measured, for further analysis and comparison.

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. 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 stimulus.

Emotional and cognitive stress are elicited to evaluate slow shifts of the EDA signals. Signals for these tests were high-pass filtered to remove any low frequency trend or baseline 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. Also, the recently-reported indices of sympathetic control based on frequency-domain and time-frequency domain analysis of EDA (EDASympn and TVSymp) were computed [18,19]. These indices utilize the spectral power within the band of 0.045–0.25 Hz. Frequency and time-frequency domain indices exhibited lower variability compared to time-domain measures of EDA, and acceptable consistency and sensitivity to cognitive stress.

2.7. Statistics

Acquired EDA signals using CSA and Ag/AgCl electrodes were compared independently for startle (shocks) and tonic (disturbing video and Stroop task) tests. 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

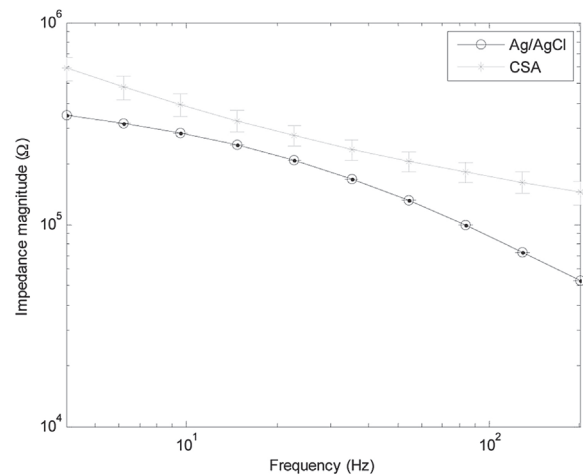


Fig. 4. Electrode-skin contact impedance measurements for CSA and Ag/AgCl EDA electrodes.

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 by computing the Pearson's Correlation Coefficient in time and frequency domain. Pearson's correlation coefficient mean and standard deviation throughout the subjects for each test were calculated. Difference in values of EDASympn and TVSymp obtained for baseline and test were compared between CSA and Ag/AgCl electrodes by means of *t*-test. Also, the differences between baseline and test values of EDASympn and TVSymp obtained using each type of electrode were tested to see if they have the same power to distinguish between the two stages. The same analysis was performed for signals obtained with the DC and AC source devices.

3. Results

Results for electrode-skin contact measurements are presented in Fig. 4. Ag/AgCl electrodes exhibited lower impedance compared to CSA electrodes for the range of frequencies of interest (4 Hz to 200 Hz). For an example of what an individual SCR looks like right

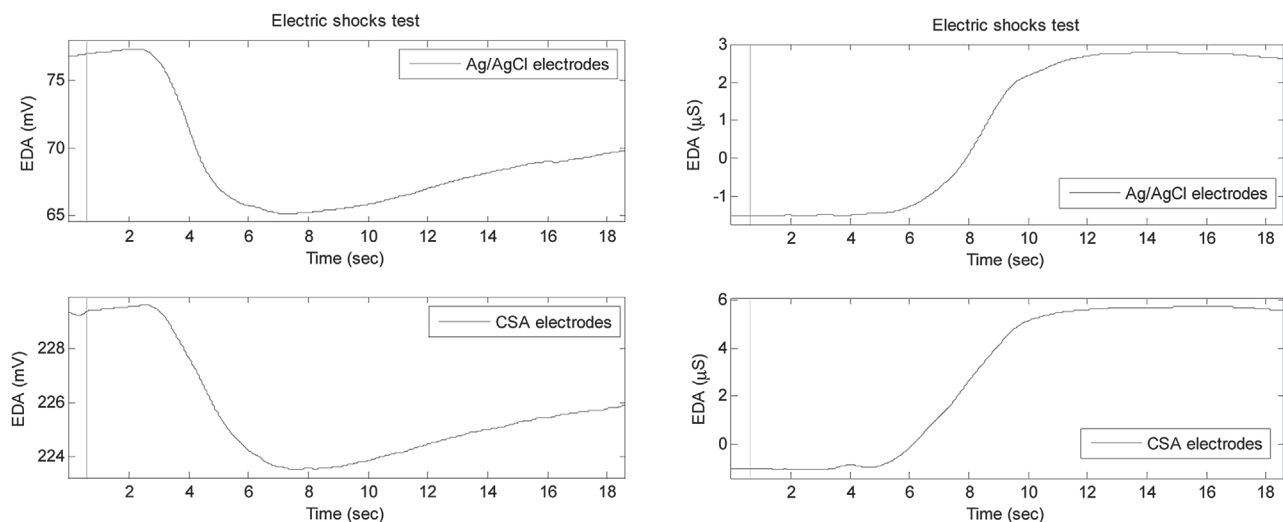


Fig. 5. Example of SCR for Ag/AgCl (top) and CSA (bottom) electrodes. Left: DC-source (mV); right: AC-source (μ S).

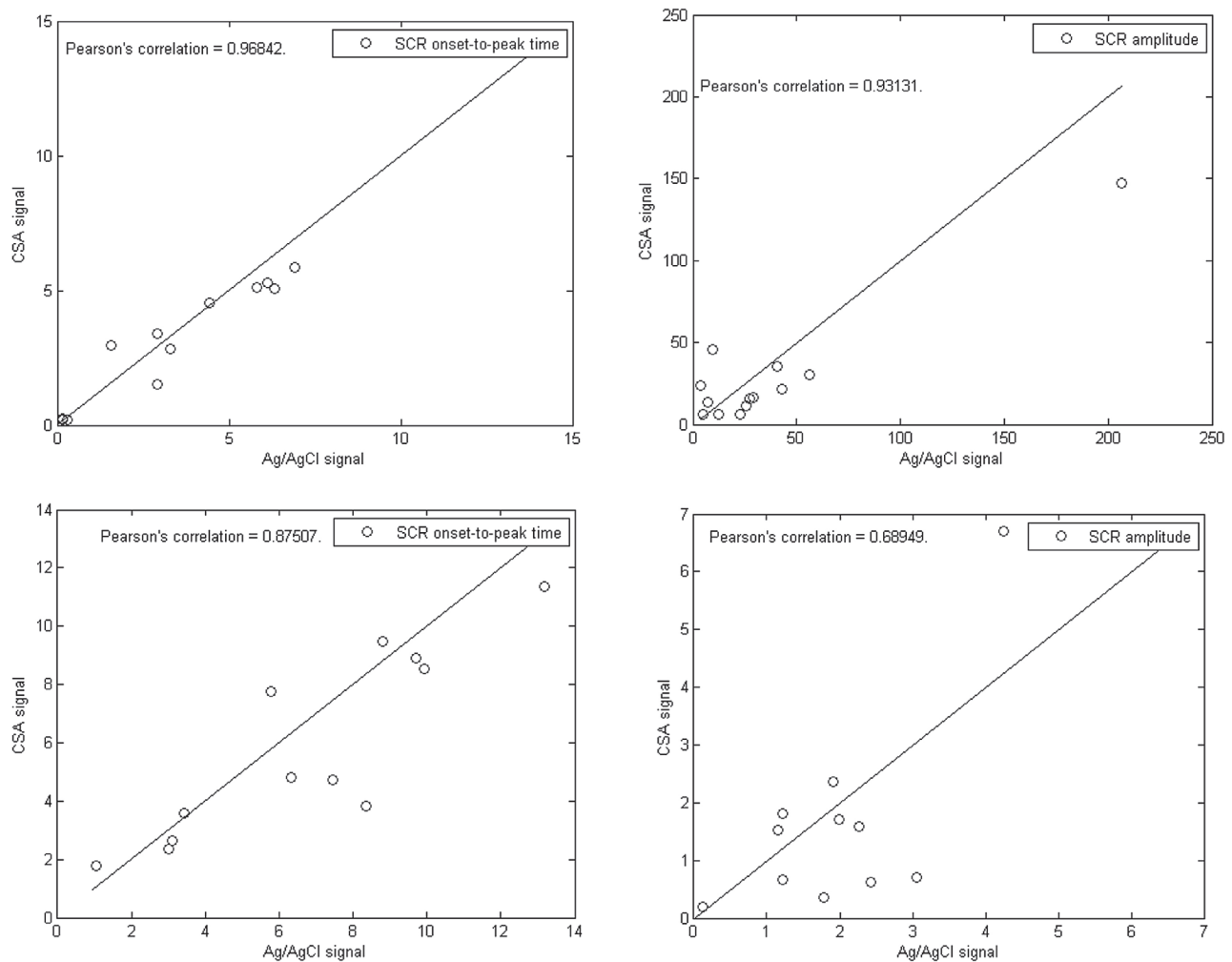


Fig. 6. Left: correlation analysis of onset-to-peak time; right: amplitude. Top: DC-source device; bottom: AC-source device. The black line represents the unitary slope straight line.

after electrical stimulation, for the two types of electrodes using the two DC- and AC-source devices, see Fig. 5. The vertical line is the time when the shock was applied. Notice in Fig. 5 that there is a delay of about three to five seconds from the actual shock time to the SCR onset. This delay time is in agreement with what has been reported in the literature [1,8]. For the DC-source devices, given that we acquired the potential produced by a constant current to the skin, an increase in skin impedance is transduced to subsequent reduction in the voltage. Therefore, each time a shock occurs the voltage signal drops significantly. For the AC-source devices, the readings are in μS , so the shock produces an increase in subjects' skin conductivity. Every shock can be recognized fairly easily. The trends are very similar and each shock is well captured by both types of electrodes.

Fig. 6 displays the results for rise time (left) and amplitude (right) correlation analysis, for DC- (top) and AC-source (bottom) devices. The two most commonly observed waveforms of the SCRs, the uniphasic and biphasic [8], were considered in the analysis. $N = 13$ and $N = 12$ SCRs were selected from the DC-source and AC-source data respectively, out of a total of 16 (2 shocks times 8 subjects). Unused shocks either saturated the SCR of one of the electrodes (in all three cases it was the Ag/AgCl) or elicited an SCR that was not distinguishable or was overlapped with other waves (4 times).

Using the DC-source device, an overall correlation of 0.97 for the onset-to-peak time measure was found between the measure-

ments performed using CSA and Ag/AgCl EDA signals. This indicates that both media exhibited a similar time for going from the onset to the peak on the elicited SCRs. Moreover, SCR amplitudes were also highly correlated between CSA and Ag/AgCl electrodes (0.93). With the AC-source devices, the obtained correlation values were lower, 0.87 for the onset-to-peak time and 0.69 for the amplitude.

Table 1 includes the results for DC- and AC-source EDA devices. In general, CSA electrodes seemed to obtain slightly lower SCR amplitudes, due to higher impedance than Ag/AgCl electrodes. Nevertheless, CSA electrodes appeared to capture the transit from onset to peak in a faster manner (somewhat lower onset-to-peak time). However, none of these differences are significant. For both materials the mean of the onset-differences is not statistically different from zero.

The Stroop test elicited noticeable reactions on the subjects' EDA, with both types of electrodes and devices. Fig. 7 shows representative EDA for a subject undergoing the Stroop task. Responses to disturbing video were more variable, ranging from negligible reaction (common within male subjects), to highly noticeable reaction (noticeable in some female subjects). CSA and Ag/AgCl electrodes demonstrated this same trend, throughout the experiment. The frequency-domain index, EDASympn, was not significantly different between the two types of electrodes, for both emotional and cognitive stress. The index was able to distinguish the differences between baseline and test when subjects underwent cognitive stress, and as expected, was not sensitive to the

Table 1
Results for comparing CSA electrodes to Ag/AgCl electrodes using DC and AC-source devices.

		DC-source devices		AC-source devices	
Electric Shocks (physical stress)					
		Ag/AgCl	CSA	Ag/AgCl	CSA
Onset-to-peak time (sec)		4.12 ± 3.52	3.94 ± 3.66	6.67 ± 3.56	5.82 ± 3.22
Amplitude (mV for DC, μ S for AC)		37.62 ± 53.29	29.3 ± 37.4	1.94 ± 1.09	1.66 ± 1.81
Onset-difference (sec)		0.0026 ± 0.13		0.31 ± 0.72	
Disturbing video					
		Baseline	Emotional Stress	Baseline	Emotional Stress
Time-domain correlation		0.96 ± 0.06	0.84 ± 0.23	0.6 ± 0.35	0.59 ± 0.37
Frequency-domain correlation		0.94 ± 0.08	0.96 ± 0.05	0.64 ± 0.33	0.84 ± 0.25
EDASympn	Ag/AgCl	0.12 ± 0.074	0.15 ± 0.085	0.14 ± 0.09	0.15 ± 0.082
	CSA	0.26 ± 0.22	0.19 ± 0.16	0.39 ± 0.33	0.33 ± 0.29
TVSymp	Ag/AgCl	0.3 ± 0.18	0.62 ± 0.45 [#]	0.29 ± 0.47	0.47 ± 0.44
	CSA	0.12 ± 0.027 [*]	0.19 ± 0.087 ^{*,#}	0.17 ± 0.05	0.37 ± 0.4
Stroop test					
		Baseline	Cognitive Stress	Baseline	Cognitive Stress
Time-domain correlation		0.92 ± 0.14	0.87 ± 0.14	0.63 ± 0.37	0.54 ± 0.45
Frequency-domain correlation		0.96 ± 0.04	0.91 ± 0.14	0.73 ± 0.34	0.92 ± 0.07
EDASympn	Ag/AgCl	0.1 ± 0.096	0.31 ± 0.21 [#]	0.11 ± 0.068	0.37 ± 0.23 [#]
	CSA	0.16 ± 0.088	0.32 ± 0.14 [#]	0.16 ± 0.14	0.38 ± 0.25 [#]
TVSymp	Ag/AgCl	0.37 ± 0.22	0.96 ± 0.44 [#]	0.23 ± 0.17	1.1 ± 0.78 [#]
	CSA	0.13 ± 0.06 [*]	0.23 ± 0.081 ^{*,#}	0.18 ± 0.12	0.48 ± 0.35 [#]

Values are mean ± standard deviation. EDASympn: normalized spectral index of sympathetic control; TVSymp: time-varying index of sympathetic control.

^{*} Represents significant differences between Ag/AgCl and CSA.

[#] Represents significant differences between baseline and test, for the given type of electrodes.

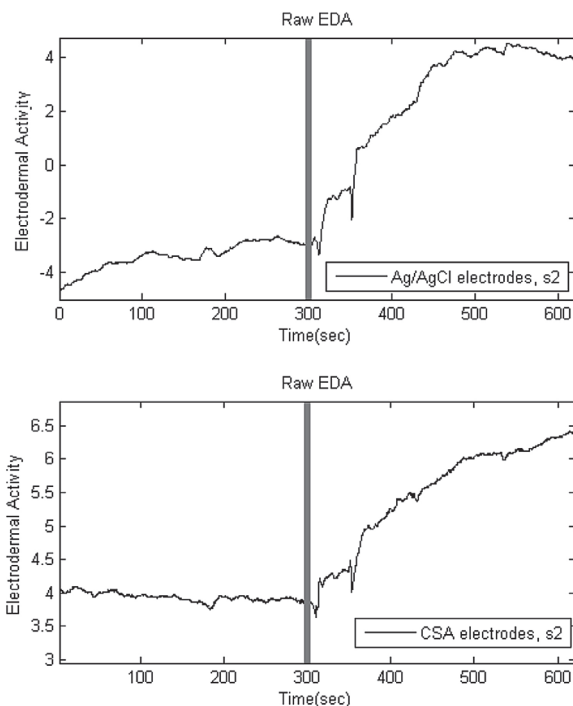


Fig. 7. EDA measurements (μ S) during baseline (before the line) and cognitive stress test (Stroop task), for Ag/AgCl and CSA electrodes, for a given subject. AC-source device was used for this specific subject.

elicited emotional stress. Nevertheless, high correlation, with low standard deviation, was found for baseline and test stages of emotional and cognitive stress tests (Table 1).

The time-varying spectral index, TVSymp, exhibited significant differences from baseline to cognitive stress, using any type of EDA electrode and device. Beyond that, it was able to detect differences from baseline to emotional stress with both kinds of electrodes, using the DC-source devices. When AC-source devices were used, the index was also insensitive to emotional stress, similar to EDASympn. Interestingly, there are noticeable differences in

the TVSymp index computed using signals from Ag/AgCl and CSA electrodes, when the DC-source devices were employed.

4. Discussion

The CSA electrode has demonstrated its ability to detect EDA dynamics similarly to Ag/AgCl hydrogel electrodes, using DC- and AC-source devices, in various stressful scenarios. This is in agreement with previous studies that showed how the CSA electrodes are suitable to detect bio potentials [10,20]. Figs. 5–7 all illustrate the direct correspondences between the measurements for both media. The results are similar for both media. The effect of the stimulus on the subject, for both the CSA and Ag/AgCl electrodes, can be clearly seen in the figures. Figures show differences in the amplitude of the responses and in the magnitude of the baseline wander of the signals, but the differences are circumstantial, because the measures are simultaneous, with the electrodes placed in different fingers. The comparison showed no significant differences and a high correlation of the results between the two media. It seems that a CSA electrode should be a valid replacement when it comes to recording EDA. This could save a substantial amount of money for hospitals due to the infinite shelf life the CSA electrode has to offer [10]. Our electrodes do not dry out, and thus do not have a shelf life limitation, as they do not employ hydrogel. This is another form of cost saving, both from reduced scrap and from reduced inventory management costs. Primarily, as we do not use Ag/AgCl, our electrodes can potentially be fabricated less expensively.

Electrode-skin impedance was higher for CSA electrodes, compared to Ag/AgCl hydrogels. The difference is more noticeable in the low frequency range, but is consistent throughout the frequency band of interest (4–200 Hz). Even though at very low frequencies CSA electrodes exhibited about two times the impedance of Ag/AgCl electrodes (600 compared to 350 Ω), those differences are reduced to less than 100 Ω on average as the frequency increases. We noticed that such difference in electrode-skin impedance did not affect the measures significantly.

Furthermore, the Ag/AgCl electrodes made it impossible to collect EDA signals on many occasions. The signal was very noisy and in some cases, there was no signal at all. This was due to polarization of the electrodes, impeding the use of the electrodes for a period of time. However, CSA electrodes worked properly when the

Ag/AgCl electrodes failed to work. Even though the use of sintered Ag/AgCl electrodes is the standard in order to minimize polarization of the electrode [1,21,22], we have found it to polarize and fail many times during the development of this study. Moderate correlation (>0.5) values found between the two signals (Table 1), can be also explained in the eventual failure of Ag/AgCl electrodes to properly collect EDA signals.

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. The onset differences were calculated by simply subtracting the values of Ag/AgCl SCR onsets from CSAs' SCR onset times, providing a difference value. If this value was negative then the hydrogel electrode responded first, and vice versa. Once all the values were recorded the mean value was taken, providing a value of 0.0026 ± 0.13 for DC-source devices and 0.31 ± 0.72 for AC-source devices. The mean of these onset differences are not significantly different from zero.

The disturbing video induced negligible changes in participants' stress levels, on average. The main characteristic that subjects reported from the emotional stress test was the subjectivity of the stress induced by the images, which highly varied depending on the novelty of the information, gender, cultural background, and other factors. For our purpose, we found high correlation between Ag/AgCl and CSA recordings. As expected, we found no differences in EDASympn from baseline to test during this test, for any type of electrodes, using either kind of device. Only TVSymp, a highly sensitive index of sympathetic arousal [19], exhibited significant differences from baseline as a result of the exposure to the disturbing video, exclusively when the DC-source devices were used. For its part, Stroop test results were in agreement with previous studies [18,19]. The computed EDASympn and TVSymp indices were able to distinguish differences between baseline and test using both CSA and Ag/AgCl electrodes, for DC and AC source devices.

Between the two media, there were significant differences only in the computed TVSymp index for the DC-source devices, both for emotional and for cognitive stress. This significant difference resulted from lower standard deviation values and greater sensitivity of the CSA electrodes with stimuli when compared to Ag/AgCl electrodes.

5. Conclusion

Overall, CSA electrodes had similar readings to the Ag/AgCl electrodes. The correlation between the signals obtained using the two types of electrodes was moderate to very high and there were only significant differences in the highly sensitive time-varying index of sympathetic control. The electrodes worked using DC- and AC-source EDA devices, for all three different types of stress: emotional, physical, and cognitive. Signals were slightly more correlated in the frequency domain, compared to the time domain. 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. In conclusion, CSA electrodes for collecting EDA signals are suitable surrogates of Ag/AgCl electrodes.

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