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Exploring Electrodermal Activity in Water-Immersed Subjects

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***Abstract*— In conditions of pressure and temperature associated with immersion in water, humans are more susceptible to severe stress, challenging the human physiological control systems. Reliable tools for the assessment of the stress underwater are needed. Electrodermal activity (EDA) is considered a promising alternative for the assessment of the level of stress in humans. EDA is a measure of the changes in conductance at the skin surface related to sweat production. In normal humidity conditions, EDA changes in response to stress in three main ways: the skin conductance level (SCL) is increased, the occurrence of non-specific skin conductance responses (NS.SCRs) increases, and the normalized spectral power in the band from (EDASympn) 0.045 to 0.25 Hz is elevated. When skin is immersed in water, the humidity blocks the sweat glands, changing the dynamics of EDA. For this reason, we have tested the measures of EDA for subjects immersed in water, as response to cognitive stress. Four subjects were recruited for the experiment. Subjects remained four minutes underwater, prior to performing the Stroop task, a test utilized to induce cognitive stress. The SCL and NS.SCRs, didn't exhibit significant differences due to cognitive stress, compared to baseline measurements. EDASymp exhibited significant differences due to cognitive stress. We conclude that the only measure of EDA sensitive to cognitive stress under water is the EDASymp, and it can be potentially used to assess cognitive stress level in divers.**

I. Introduction

The electrodermal activity (EDA) is a physiological measure with strong correlation to sweat production, resulting from the changes in electrical conductance of the skin [1], [2], ultimately due to the changing levels of sweat in the ducts [3]. The dynamics of EDA exhibit two main constituents, the tonic and phasic components. In response to stress, EDA exhibits increase in the level of the tonic component, increase in the frequency of occurrence of spontaneous sine-like waves, and increase in spectral power in the band from 0.045 to 0.25 Hz. Although humidity is thought to impede most of the EDA dynamics by blocking sweat glands [4], [5], it is still unknown what dynamics of EDA are maintained in such environment. There are no studies looking at EDA as response to stress, in humid or water immersion conditions.

Because of the need to fully elucidate the sympathetic system dynamics, analysis of electrodermal activity (EDA) has gained much attention in recent years [6]–[8]. This is due to the fact that EDA reflects only activity within the sympathetic branch of the autonomic nervous system, because there is no parasympathetic innervation of eccrine sweat glands. EDA measures are a reflection of autonomic innervation of sweat glands, and its use is to assess if the sympathetic nervous system arousal has been increased or decreased [9]. Note that the traditional methods such as heart rate variability cannot be used to separate sympathetic and parasympathetic dynamics are they are known to interact nonlinearly [10] which is also seen in renal autoregulatory control mechanism [11], [12].

Traditional time-domain analysis of EDA has decomposed the signal into two time-domain measures: skin conductance level (SCL) and skin conductance responses (SCRs) [6]. SCL (usually expressed in microsiemens, μS) is a measure related to the slow tonic shifts of EDA. SCL is typically computed as a mean of several measurements taken during a specific non-stimulation rest period. The SCRs are the rapid phasic transient events contained in the EDA signals. The non-specific SCRs (NS.SCRs) are the number of SCRs in a period of time, and are a measure of tonic stress produced during a sustained stimuli. NS.SCRs are regularly expressed as the number of responses per minute [6]. In frequency-domain analyses of EDA, it has been found that the power in the 0.045 to 0.25 Hz band is the most sensitive to cognitive, physical and orthostatic stress [13], [14].

When the control systems break down due to prolonged hyperbaric exposures, humans are more susceptible to detrimental conditions characterized by autonomic imbalance [15]–[19]. Significant hyperbaric pressure and cold temperatures associated with increasing depth underwater are known to cause severe stress to the human physiological control systems [20]. Sudden situations usually arouse when divers are in duty, increasing the stress and affecting the performance of the diver. This situations need to be early detected. As noted, means for early detection of affected dynamic of the autonomic control in underwater conditions are needed.

As mentioned, EDA has shown to be a promising alternative for the assessment of the autonomic function, even at central levels as EDA is associated to central nervous mechanisms like cognitive stress [21]–[23]. The aim of this work is to explore the responsiveness of EDA in response to cognitive stress, for subjects immersed in water.

II. Materials and Methods

A. Protocol

Four healthy male volunteers were enrolled in this preliminary study. Participants were asked to avoid caffeine and alcohol for 24 hours preceding the test, and instructed to fast for at least 3 hours before testing. The experiments were carried out in a quiet room. The study protocol was approved by the Institutional Review Board of The University of Connecticut and all volunteers consented to be subjects for the experiment. EDA signal was recorded during the test. The galvanic skin response (GSR) amplifier FE116 (fully isolated AC excitation and automatic zeroing low voltage amplifier, 22 mVrms @75 Hz, ADINSTRUMENTS) was

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used to collect EDA. No on-line filtering was applied during the signal recording. EDA electrodes were placed on the index and middle fingers for all subjects. Skin was prepared with alcohol before placing the electrodes. Signals were digitized using a PowerLab system at 100 Hz, 12 bits resolution.

Fig. 1 illustrates the experimental setup. Subjects were immersed in water in an inflatable pool, breathing through a snorkel. EDA measurements were collected in subjects' left hand. Four minutes of relaxation were given to the subjects before test started, so they get used to the experimental conditions. The test was conducted with the subjects in supine position. EDA data was collected for 2 minutes of baseline (subjects relaxing under water), and 2 minutes for the subject to perform the Stroop task. During the Stroop task, subjects were shown congruent visualizations, in which the word was written in the color it expressed, and incongruent visualizations, in which the word and the color it was printed in were different (Fig. 1). Subjects were asked to mentally determine the color of a word which named a color, to induce cognitive stress [24]. In this experiment, the used colors were "blue," "yellow," "green," "red," "purple," and "black." The background also changed to be randomly congruently or incongruently colored with the word. A tablet-pc version of the original Stroop task was developed in our lab using customized software, and during the Stroop task the tablet was put in from of subjects' face using a stand. Before going underwater, subjects were allowed to practice the Stroop task saying the colors out loud, until the experimenter has corroborated that the subject has figured out how to perform the task.

B. *Signal processing*

The SCL, NS.SCRs and EDASymp indices were computed using the collected EDA data, for baseline and cognitive stress (Stroop task) stages. The EDA signal was decomposed into tonic and phasic components in the time domain, using the convex optimization approach [25]. The SCL [μS], was computed as the mean value of the tonic component of EDA taken during the two-minute stage [6]. The NS.SCRs index was computed as the number of SCRs per minute, during the two-minute stage.

For spectral analysis, EDA signals were down–sampled to 2 Hz. Before down-sampling, the data was filtered with an 8th-order Chebyshev Type I low-pass filter (0.8 Hz). Signals were high-pass filtered (0.01 Hz, Butterworth, 8th order) to remove any trend. The power spectra of EDA signals were calculated using Welch's periodogram method with 50% data overlap. A Blackman window (length of 128 points) was applied to each segment, the Fast Fourier Transform was calculated for each windowed segment, and the power spectra of the segments were averaged.

To analyze the power distribution of EDA for subjects immersed in water, the power density of the EDA spectra was analyzed in bands of 0.05 Hz, from 0 to 0.4 Hz. The paired t-test was applied to test for significant differences in the power in the bands between baseline and cognitive stress. Once the power distribution was analyzed, EDASympn [n.u.] was computed as the normalized power of EDA in the range 0.045 to 0.25Hz, as defined in a previous study [13].

The paired t-test was applied to test for significant differences in SCL, NS.SCRs and EDASymp indices between baseline and cognitive stress.

III. Results

As an illustrative example, Fig. 2 (top) shows the resulting EDA data for two minutes of baseline and Stroop task for a given subject. Note the tonic increment in the level of EDA. Interestingly, almost all subjects exhibited such behavior, not only during the Stroop test, but also during the baseline measurements when no stimulus was presented to the subject. Note that during Stroop test the presence of phasic components increased for this specific subject. The power spectra of the EDA signal for a given subject during baseline and Stroop test are included in Fig. 2 (bottom). Note how this subject exhibited marked differences between baseline and Stroop test. The spectral power of EDA beyond 0.25 Hz is minimal.

Recently, in a study involving subjects undergoing cognitive, physical and orthostatic stress in dry conditions, we found that most of the power of the EDA spectrum was largely confined to frequencies less than 0.45 Hz [13], [26], with more than 95 % of the spectral power of EDA is in the range 0 to 0.25 Hz [13]. In the present study, we have computed the percentage of energy of EDA within frequency

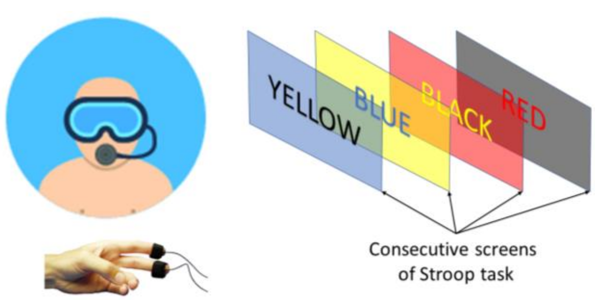

Figure 1. Experimental setup. The subjects are underwater, breathing through a snorkel. EDA data was collected in subjects' left hand. Sample of Stroop task screen, in which case the correct answers are Black, Blue, Yellow, and Red.

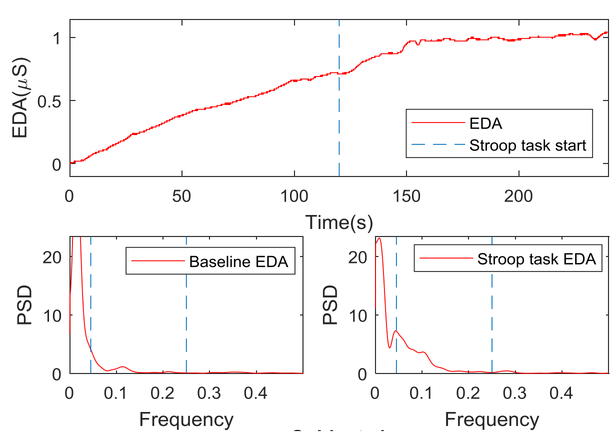

Figure 2. EDA data for a given subject undergoing Stroop test underwater. Top: Time domain (dotted line represents the start of Stroop task); Bottom: Frequency domain (dotted lines represent 0.05 Hz and 0.25 Hz, respectively). Bottom left: spectrum of baseline data; Bottom right: spectrum of Stroop task data.

TABLE I. PERCENTAGE OF POWER WITHIN THE FREQUENCY BANDS OF EDA FOR ALL SUBJECTS.

Range	Baseline	Cognitive stress
0 to 0.05 Hz	83.4 ± 8.91 %	58.6 ± 15 % *
0.05 to 0.1 Hz	8.59 ± 5.18 %	23.2 ± 6.99 % *
0.1 to 0.15 Hz	3.43 ± 1.78 %	9.75 ± 6.51 %
0.15 to 0.2 Hz	1.43 ± 0.958 %	3.36 ± 0.846 % *
0.2 to 0.25 Hz	0.811 ± 0.572 %	1.96 ± 0.769 %
0.25 to 0.3 Hz	0.503 ± 0.477 %	1.22 ± 0.556 %
0.3 to 0.35 Hz	0.507 ± 0.442 %	0.372 ± 0.279 %
0.35 to 0.4 Hz	0.336 ± 0.377 %	0.538 ± 0.525 %
>0.4 Hz	<1 %	<1%

*Statistically significantly higher with respect to baseline ($p<0.05$)

bands of 0.05 Hz, for all four immersed subjects (Table I). The first range, 0 to 0.05 Hz, comprises more than 83% in average during the baseline stage, and about 58% in average during the Stroop task. Power goes to the bands in the range 0.05 to 0.25 Hz during Stroop task. In such range, power is only about 14% on average during the baseline stage and increases to about 38% due to cognitive stress induced by Stroop task. Notice that about 95% of the total power is comprised in the range 0 to 0.25 Hz. The differences in the first (0 to 0.05 Hz), second (0.05 to 0.1 Hz), and third (0.15 to 0.2 Hz) bands are significantly different from baseline.

The results for SCL, NS.SCRs and EDASympn indices for all four subjects are provided in Table II. The SCL and NS.SCRs indices were not significantly increased during Stroop task, compared to baseline. EDASympn, the spectral-analysis index of EDA, was significantly increased by the Stroop test, compared to baseline stage. Although there is not significant difference in the amount of phasic reactions observed in the NS.SCRs, which accounts for the number of spontaneous occurrences of SCRs during the EDA, is significantly increased in the phasic components assessed quantitatively by the spectral indices.

IV. DISCUSSION

In this study we aimed to explore if the effects of cognitive stress in the sympathetic nervous system can be detected using EDA when subjects are immersed in water. The Stroop task was used to induce cognitive stress, and the time- and frequency-domain indices of EDA reported in the literature were computed for a group of four subjects. Our preliminary results show that time-domain indices did not achieve significantly different values during Stroop task, compared baseline measurements, which suggests that they have low sensitivity to cognitive stress under water. In contrast, frequency-domain index exhibited significant differences during the Stroop task, compared to baseline. We foresee that with more data we will find evidence supporting that phasic component of EDA, assessed by spectral analysis, is sensitive to cognitive stress in subjects immersed in water, and can be used to assess cognitive stress level in divers.

The EDA has been increasingly been used as an alternative for assessing sympathetic dynamics. EDA is product of sweat glands innervation, which are only handled by sympathetic nerves. The electrodermal response has been found to be inhibited by pharmacological central depressants in a manner analogous to its action to other sympathetic systems [27], [28]. This is controversial, as sympathetic-cholinergic system (of which sweat glands are part) was initially thought to respond only to peripheral stimulus (i.e. thermoregulatory sweating). For the immersed subjects, the thermoregulatory function was blocked, but we found that the EDA was also responsive to cognitive stress. This evidence indicated that a central adrenergic inhibitory mechanism is likely involved in the regulation of the electrodermal activity [28], [29].

TABLE II. MEASURES OF EDA UNDERWATER.

Indices of EDA	Baseline	Stroop test
SCL	0.505 ± 0.355	0.972 ± 0.631
NS.SCRs	12.9 ± 9.44	14.8 ± 5.19
EDASympn	0.166 ± 0.106	0.404 ± 0.084*

Values are expressed as mean ± standard deviation.
*Statistically significantly higher with respect to baseline ($p<0.05$)
SCL: skin conductance level; NS.SCRs: non-specific skin conductance responses, EDASympn: normalized power spectra in the 0.045 to 0.25 Hz band.

The EDA has shown to be sensitive to stress in several ways. There is usually a noticeable increase in the level conductance, quantified through the SCL index. Also, there is a remarkable increase in the occurrence of spontaneous SCRs, which are accounted in the NS.SCRs index. Finally, spectral analysis of EDA recently led to the observation that the band 0.045 to 0.25 Hz is sensitive to stress [13]. The sweating mechanisms are known to be limited in high-humidity environments, product of swelling of the epidermis after the skin is exposed to water. In this study, we found that highly-humid environment only partially affected the EDA dynamics. We think that immersion does not totally impede the generation of EDA as a manifestation of the central sympathetic arousal at the skin level. Similarly as how EDA has been used as a model system to study the affection of central structures in dry conditions [30], we surmise it can be also used to assess the level of stress faced by humans in immersed conditions

The tonic component of EDA, which is used to compute the SCL, was highly variable in this study, as it exhibited high variance compared to the mean (Table II). The breathing pattern adopted by subjects underwater partially explains the high variability of this changes in the tonic component of the EDA, which is the information utilized to compute SCL. Under water, even during relaxing periods subjects generally breathe with deeper breathes. Deep breath is known to elicit a general phasic sympathetic discharge, causing a increase in sweating. This increases electrical conductivity of the skin, producing a drift in the tonic component [6]. In practice, a deep breath is used to test subjects' EDA responsiveness [6]. The high humidity present in the environment, produced by the warm and constantly releasing steam water used in the study, can also help to explain for the tonic-component variability is, the skin could be constantly collecting water from the environment. Although we tried to perform measurements for more than 20 minutes, the tonic drift was never stabilized.

In contrast to the tonic component, the phasic component of EDA was still sensitive to cognitive stress. NS.SCRs and

EDASymp account for the phasic component of EDA (Table II). Although SCRs were not increased in frequency of occurrence, they are increasing in amplitude. That is the reason why NS.SCRs index is not sensitive to cognitive stress in this study, as for such index a threshold is fixed and SCRs reaching such threshold are considered. Using spectral analysis of EDA, we found significant reduction in the power in the very low frequency range (0 to 0.05 Hz), and significant increase in the 0.05 to 0.1 Hz and 0.15 to 0.2 Hz, compared to baseline. This was equal to the dry conditions, as the band 0.045 to 0.25 has been found to be highly sensitive to cognitive and other kinds of stress outside the water [13], [14]. As a result, in this study we found that EDASymp, which accounts for the amplitude of the phasic components associated to the SCRs, was significantly increased by cognitive stress, compared to baseline.

Underwater, EDA can be sensitive to the stress caused by immersion, which can be too high for some subjects, impeding other influences to be observable. In this study, the first two minutes were meant for subjects' relaxation; however, during the baseline measurement underwater, the mere immersion seemed to induce increasing stress to subjects. Subjects also reported that breathing through the mouth was stressful alone. Not only this way of breathing is not natural to humans, but the underwater environment itself is typically uncomfortable for humans.

V. Conclusion

In this preliminary exploration of EDA data for underwater subjects, we examined if the time- and frequency-domain indices can discriminate between the absence and presence of the cognitive stress. In summary, based on the significant differences between baseline and cognitive-stress conditions encountered, we conclude that EDA is markedly altered by cognitive stress underwater, despite the high humidity.

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