Framework for Evaluating EEG Signal Quality of Dry Electrode Recordings

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***Abstract*— Dry electrodes provide the possibility of moving EEG usage from the research and clinical environment to real life applications. Having a framework for evaluating the performance of dry electrodes would facilitate this process and help EEG system developers to test their designs. This paper describes an evaluation method for dry electrode EEG recordings. The framework includes a setup for synchronous recordings with a parallel dry and gel electrode montage procedure. Several protocols are implemented to evaluate both the time and frequency content of the signal and to compute the setup and settling time. Signal quality was evaluated using signal correlations, SNR and P300 component characteristics. The preliminary data analysis and results show that a comparison between gel and dry electrodes is possible but improvements need to be made to the current evaluation framework.**

I. Introduction

The majority of the applications developed with the help of electroencephalographic (EEG) signals, is used in a controlled research or clinical environment. This restricted usage is partly due to the sensors needed for acquisition. The accepted method of obtaining a good quality EEG signal is through conductive gel electrodes. These are cumbersome to apply, uncomfortable and difficult to use.

Currently, the scientific community is focusing on developing new dry electrode technologies that can measure EEG signals in a more easy and comfortable way [2]. The new systems and circuits developed need to reach the performance of the available gel electrode recording systems. The lack of conductive gel means a higher skin-electrode contact impedance that directly impacts the quality of the EEG signal. Also, dry electrode recordings prove to be more susceptible to motion artifacts, low frequency noise and external interference due to less adherence to the skin. Existing dry sensor technology has not yet been adopted by the healthcare and research communities as the quality of the obtained signal has not been proven to reach that obtained with conventional gel electrodes. Hence, there is a need to define a method that can indicate when the acquired EEG signal has a high enough quality. Several research groups have tried to validate the signal quality obtained through dry electrodes, but so far there is no unified view on a method that should be used for evaluation [1] [2] [3] [4].

This paper describes a general purpose EEG signal quality evaluation framework. Since good quality signals are known to be obtained with gel electrodes, a comparison of gel and dry recordings was used to quantify the quality of the latter. Information is encoded in the EEG signal in both the time and frequency domain and the protocols proposed were chosen to elicit specific responses that permit an analysis in both domains. The second section of the paper will describe these protocols in detail while the third section will present the data analysis performed and the results obtained. Finally, the limitations of the framework are discussed in the last section.

II. Methods

A. Experimental Setup

The experimental setup consisted of a parallel measurement system made up of four BioPac EL120 Ag/AgCl dry pin electrodes and six standard gel filled Ag/AgCl cup electrodes connected to separate blocks of the biosignal amplifier g.USBamp [5]. The EEG measurements were recorded on a Windows operated PC with the open source platform openVibe [6], which also provided visual stimulations on a dedicated LCD display and real-time visualization of the recordings on a separate screen.

Two groups of one dry contact and two gel electrodes were placed at the positions Cz and Pz (Fig. 1) of the 10-20 International System, in a similar way to that described in [4]. The electrode numbering scheme used in the next sections is described in Fig.1. Comparisons are made between one dry electrode and one gel electrode. The content of the EEG signal is highly dependent on the scalp recording position and perfect spatial synchronization cannot be obtained with these sensor types. To estimate the impact of the variability caused by the different recording positions of the two electrodes, an additional comparison between two adjacent gel electrodes is also made. A rigid headset was used to correctly position the dry electrodes and also provide good landmarks for attaching the gel electrodes. Position Cz was chosen as it is commonly used in EEG studies, while at the Pz position the steady-state visually evoked potentials (SSVEP) response is stronger.The distance between two adjacent sensors was approximately 1.5 cm. Separate references and grounds were chosen for each system to eliminate any additional variations due to impedance differences. The dry (RD, GD) and gel (RW, GW) reference

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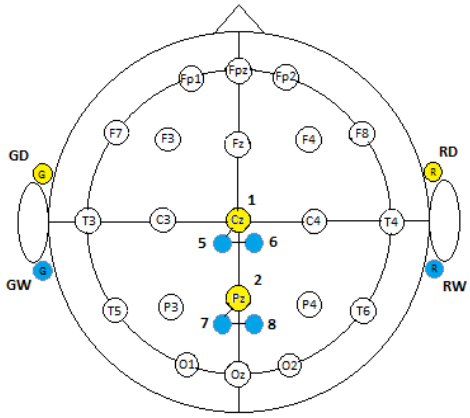

Fig. 1. Positions of the electrodes on the scalp. The yellow circles represent the dry electrodes (1, 2, GD, RD) while the blue ones the gel electrodes (5, 6, 7, 8, GW, RW). Numbers were allocated to each electrode according to their input slot in the amplifier.

and ground electrodes were placed close to each other behind the right and left ear, respectively.

The g.USBamp bio-signal amplifier was chosen as it allows simultaneous recordings of different physiological signals [5]. A single recording system was used to avoid additional signal differences introduced by different equipment characteristics. OpenVibe records the signals received from the amplifier at a sampling frequency of 512Hz while also providing the visual stimulations and allowing easy access to the stimulation timing information, synchronized to the recordings.

B. Paradigms

Eleven subjects (aged between 22 and 35 years, 3 female and 8 male) were recruited for the experiment and gave written consent for participation. All of them had normal or corrected to normal vision. Their hairstyle was categorized by the experimenter on a scale from 0 to 3 according to the hair length, thickness and density, 3 denoting - short, thin, rare hair or no hair and 0 denoting- long, thick, dense hair.

The entire protocol lasted for about 30-45 minutes. Participants were comfortably seated in an isolated room at a distance of 50 cm from the screen. First, the dry electrode headset was fixed and then the gel electrodes were placed relative to the dry electrode positions. The quality of the recordings was checked visually by the experimenter before starting and in between the different experimental tasks. The protocols used can be divided into three main categories: continuous recordings, steady-state visually evoked potentials (SSVEPs) and P300 event related potentials (ERPs) .

1) Continuous recording paradigm: Continuous EEG recordings contained two stages. In the first one, the participant watched a neutral video for about 10 minutes (eyes open). At the beginning of the paradigm, the experimenter lifted the dry electrode headset and placed it back on the scalp to simulate the setup and settling time of the dry electrodes. In the second stage, the subject closed his/her eyes for approximately one minute (eyes closed).

2) SSVEP paradigm: SSVEPs are elicited while observing visual stimuli at a certain frequency and represent specific cortical responses that appear at the stimulation frequency and multiples of this frequency. SSVEP responses for the evaluation framework were elicited at frequencies outside the alpha range (8-13Hz) to eliminate superposition of the phenomena. To avoid inadequate frequency rendering due to the PC timing and the 60Hz refresh rate of the LCD display, a stimulation frequency of 6Hz was chosen [6], [8]. Subjects were asked to focus on a white square on a black background, flickering at the stimulation frequency for about one minute, in two conditions: once while seated (SSVEP seated) and once while walking in place (SSVEP walking).

3) P300 ERP paradigm: ERPs containing P300 components are elicited while identifying a target stimulus among non-target stimuli. The P300 component is a positive deflection that appears on the EEG approximately 300ms after target stimulus onset. The visual stimulation in this case was a P300 Speller interface available as part of an openVibe BCI demo [6]. The stimulation consisted of a 6x6 grid of letters whose rows and columns were flashed randomly. Three target letters (‘C’,’A’,‘T’) were used and for each letter the grid is flashed twelve times, resulting in 17% of target stimuli and 83% of nontarget stimuli. The inter-stimulus interval was set to 500ms. Subjects were asked to count the number of times each target letter was flashed.

III. Data Analysis and Results

The processing of the EEG data was performed in Matlab. Data pre-processing included band pass filtering and artifact removal. Filtering is required to remove low frequency components caused by impedance drifts and high frequency components induced by interference from the 50Hz supply line and other external sources. A Chebyshev Type II filter was chosen due to its flat pass band and steep transition bandwidth. To eliminate phase distortion, the filter was applied forward and backwards on the data [9]. Different cut off frequencies were applied on different types of recordings, according to the processing performed (see below). Artifact removal was performed through a manual selection of segments containing artifacts based on the signal amplitude and standard deviation of each recording.

A. Signal correlations

Pearson’s product moment correlation coefficients were computed on the data obtained from the eyes open and eyes closed paradigms between pairs of dry-gel and gel-gel electrodes at Cz and Pz positions. For the eyes open data, only the last five minutes of recordings were considered, when it was assumed the signal has settled. For the eyes closed data, the full recordings were used. The data was filtered between 2-30 Hz. To avoid introducing time differences through artifact removal, the same segments were eliminated from the recordings of the Cz and Pz sites. The mean values obtained are reported in Table I. All recordings from two subjects and the Pz recordings of another three were eliminated after visual inspection of the EEG signals showed noisy data.

Coefficients obtained for gel-gel comparisons were higher than 0.90 indicating a strong similarity, whereas the dry-gel coefficients varied according to recording position and paradigms used. The values found are lower than those encountered in literature for similar configurations, but follow the same decreasing trend from Cz to Pz electrodes and from the eyes closed paradigm to the eyes open one [3], [4]. Differences arise from the fact that previous studies used active electrodes, larger bandwidths and shorter distances between electrodes.

B. Signal-to-Noise Ratio

The data used for the frequency domain analysis was obtained with the eyes closed and SSVEP paradigms. The strength of the SSVEP response is proportional to the level of noise present in the recording and thus can be used to establish the level of contamination of the acquired signal [7].

An SNR was defined to quantify the strength of the specific cortical response with respect to the background EEG. The signal power is represented by the mean power spectral density (PSD) of the signal in the band of interest whereas the noise power as the mean of the PSD of the signal outside the band of interest:

$$SNR = \frac{mean(PSD_{band\ of\ interest})}{mean(PSD_{signal\ band-band\ of\ interest})} \quad (1)$$

For the eyes closed data, the band of interest is equal to the alpha band, 8-13Hz, whereas for the SSVEP data the band of interest is around the stimulation frequency and its harmonics: 5-7, 11-13, 17-19, 23-25Hz . The signal band was taken between 4-30Hz to exclude the influence of any low frequency residual components not removed through filtering. The same filtering and artifact removal methods were used as in the case of the correlation computations, except in the case of the SSVEP walking paradigm which is based on artifact inducing motions and thus no artifact removal is performed. The spectrum was computed using Welch's method on a window of 2 seconds and 75% window overlap. Results of the mean SNR values per electrode are summarized in Table II, while an example of the recordings' spectra is shown in Fig.2. Due to noise present in the entire spectrum, the entire recordings from 2 subjects and the Pz recordings of another 3 were eliminated from the SSVEP seated paradigm. For the SSVEP walking paradigm, the recordings with a noise floor higher than $50\mu V^2$ were excluded .

For all three paradigms, larger mean SNR values were obtained for gel electrode recordings when compared to the dry ones. The SNR values for the SSVEP response are much lower than in the case of the eyes closed paradigm as the alpha waves present a stronger PSD peak due to beta activity suppression. As the electrodes are placed closer to the visual cortex, a better SSVEP response strength can be seen in the gel electrodes around Pz, however an opposite trend is seen in the dry electrodes. This can be an indication of a worse contact at this site. The SNR values for the SSVEP walking paradigm in gel electrodes are the lowest due to the artifact induced noise. All dry electrode recordings were eliminated since no response was observed due to excessive noise.

TABLE I

CORRELATION COEFFICIENTS FOR THE DRY-GEL AND GEL-GEL ELECTRODE PAIRS

	Cz		Pz	
Paradigm	*1-5*	*5-6*	*2-7*	*7-8*
Eyes closed	0.60	0.95	0.49	0.93
Eyes open	0.51	0.95	0.40	0.96

TABLE II

MEAN SNR VALUES IN DB PER ELECTRODE

	Cz			Pz		
Paradigm	*1*	*5*	*6*	*2*	*7*	*8*
Eyes closed	6.49	8.29	8.05	4.60	9.60	9.92
SSVEP seated	0.81	2.12	2.32	0.37	2.75	2.85
SSVEP walking	-	1.38	1.42	-	1.38	1.66

C. P300 Component Analysis

The amplitude difference between the target P300 component and the non-target baseline EEG can be used as a parameter for comparison. Since ERPs have a very low amplitude and low frequency components, the analysis is extremely sensitive to distortions introduced by filtering and thus the Chebyshev filter was applied between 0.5-15Hz [2], [9]. After filtering, the recordings are divided into 500ms trials starting from the stimulus onset. Target and non-target trials are averaged, excluding the ones containing artifacts. Two of the subjects were eliminated from the analysis as they presented no ERPs in any of the recordings.

P300 components can be seen in all target averages of valid gel electrode recordings. In the case of dry electrode recordings, P300 components can be seen for Electrode 1 in 8 subjects and for Electrode 2 in 5 subjects. The mean values of the differences of the available peaks are reported in Table III, while an example of a P300 response is shown in Fig. 3. Similar amplitude difference values were obtained for gel recordings and lower values are reported for the dry ones. These results also reflect a worse contact in the Pz position, where lower amplitude values were obtained.

D. Setup and Settling Time

The settling time is defined as the time between the moment the electrode makes contact with the scalp and the moment a

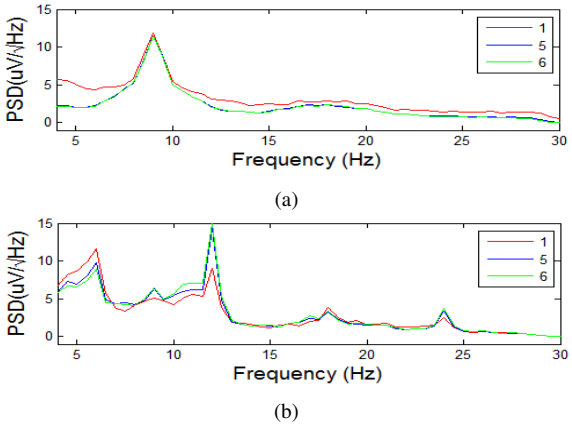

Fig. 2. a. Spectrum of eyes closed data of Subject 3 at Cz b. Spectrum of SSVEP seated data of Subject 8 at Cz

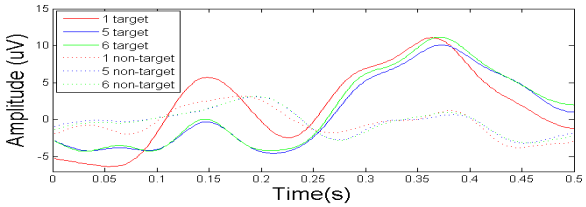

Fig. 3. Averages of target and non-target trials of Subject 4 at Cz

stable EEG signal is obtained. Since it is difficult to establish the exact moment of contact, the setup and settling time is computed from the eyes open recordings when the mounting procedure was simulated. A threshold value is determined for each individual channel as the standard deviation of the last 50 seconds of the recordings (when it is assumed the signal is stable) multiplied by an empirically determined constant. This multiplication constant has to be high enough not to eliminate valid EEG data. When the standard deviation of one second epoch of the signal is higher than the threshold, the signal is considered unstable. The mean time obtained over all participants for the settling and setup of the Cz dry electrode was 9.9 seconds, while for the Pz dry electrode it was 12.2 seconds.

IV. Discussion

The results presented show that it is possible to evaluate dry electrode systems through a comparison to standard gel electrode systems using the parameters proposed. Lower values were obtained in the case of dry-gel correlations when compared to gel-gel correlations and the same trend was observed in the case of SNR computations and P300 component extraction. Generally, the dry electrode from the Cz position obtained a better performance than the one in the Pz position. These results suggest that better electrode and headset designs should be used for a better signal.

EEG quality is strongly dependent on the properties of the recording electrode. Due to the short pins of the dry electrodes, proper skin-electrode contact could not be obtained for all participants as they had longer and thicker hair. Fig. 4. illustrates this relationship: hair scoring is plotted versus correlations between dry-gel electrodes and versus a ratio between the SNRs of the same electrode. This allows better inter-subject comparisons, eliminating the effect of subject response variability. Ratios closer to or greater than one are desired since they show a good SNR for the dry electrode. For this electrode type, subjects with a lower hair scoring proved to have worse results. This behavior can be observed for instance, in Subjects 6 and 10 who were both eliminated from the analysis as the data proved to be too noisy. The variability in the ratios can be explained by the experimenter not being able to achieve equal force application on dry electrodes among participants and due to headset design limitations and subject head shape differences.

Another limitation is introduced through the non-ideal synchronization between stimulations and recordings. The timing synchronization was checked with a sensor detecting light

TABLE III

Mean P300 Difference values per electrode

	Cz			Pz		
	1	*5*	*6*	*2*	*7*	*8*
Difference (μV)	4.73	5.38	5.67	2.58	4.56	4.80

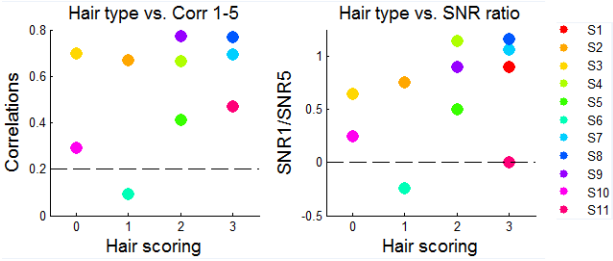

Fig. 4. Parallel between subject hair type and results for the eyes closed paradigm of electrodes 1 and 5

intensity changes. In the case of the ERPs, differences of up to 10ms were measured between the timing provided by openVibe and the time detected by the sensor. Timing errors imply that the signal cannot be accurately split into trials and thus they might impact the P300 analysis. This indicates the need for a more accurate stimulation rendering method.

Besides finding solutions for the timing synchronization and the dry electrode mounting problems, future work should focus on improving the signal quality estimation methods by adding parameters for evaluation. For instance, skin-electrode contact impedance measurements could be used to estimate when proper contact is obtained.

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