Brain-computer interface control with dry EEG electrodes

C. Guger[1], G. Krausz[1], G. Edlinger[1]

[1]g.tec medical engineering GmbH/Guger Technologies OG, Graz, Austria

guger@gtec.at

Abstract

Brain-computer interfaces (BCI) are mostly realized using the P300, motor imagery or steady-state visually evoked potentials (SSVEP) measured with the electroencephalogram (EEG) to control external devices. The EEG is measured non-invasively with electrodes mounted on the human scalp using conductive electrode gel for optimal impedance and data quality. But the usage of gel has also some disadvantages: long montage time, abrasion of the skin, need to clean the skin after the recording,... The gel based EEG acquisition limits also the frequent usage of BCI systems on a daily basis. Therefore a dry active electrode system was developed and compared to gel based active electrodes. Three subjects performed P300, motor imagery and SSVEP based BCI experiments. Evoked potentials, event-related desynchronization, power spectrum and accuracies were calculated for dry and gel based electrodes to compare them. The study showed that the new dry electrodes are able to pick up the corresponding frequency ranges of the EEG data for all three BCI approaches. The major advantages are the fast montage, no abrasion and no need of cleaning the skin. Nevertheless dry electrodes are more sensitive to noise and therefore a careful montage is necessary.

1 Introduction

For the realization of a brain-computer interface (BCI) system 4 different principles can be used: slow cortical potentials, oscillations in alpha and beta range, steady-state visually evoked potentials (SSVEP) and the P300 event-related potentials. Recently BCI technology has been utilized not only for supporting subjects with special needs but also to possibly enrich control option in robotics or gaming areas. However, some subjects report about discomfort when participating in EEG experiments or even rejected participation as hair washing after the experiments is necessary. In order to improve the subjects' acceptance of BCI technology many research groups are now working on the practical usability of dry electrodes to completely avoid the usage of electrode gel. Dry electrodes use either micro-needles to penetrate the first layer of the skin and to get in conduct with the conducting layers, use capacitive sensors or are penetrating the skin with mechanical springs that press the electrodes into the skin [1] [2] [3]. Early work focused on the usage of active and dry electrodes for the recording of electrocardiogram signals which is easier to do because of the larger signal to noise ratio and easier montage on the thorax.

Single trial classification of motor imagination using 6 dry electrodes was already shown by the Berlin BCI group [2] and resulted in about 30 % lower information transfer rate than with gel electrodes. Gargiulo constructed a dry electrode system with conductive rubber showing a high correlation between gel based and dry electrodes [4]. A stainless steel disk with 3 mm was used to prove the usefulness of it for spontaneous EEG and evoked potentials (EP) [3].

In this publication it is demonstrated that a recently developed dry electrode system can be used for motor imagery, SSVEP and P300 based BCI systems. Therefore the power spectrum, the time course of evoked potentials, event-related desynchronization/synchronization (ERD/ERS) values and BCI accuracy are compared for three different BCI setups.

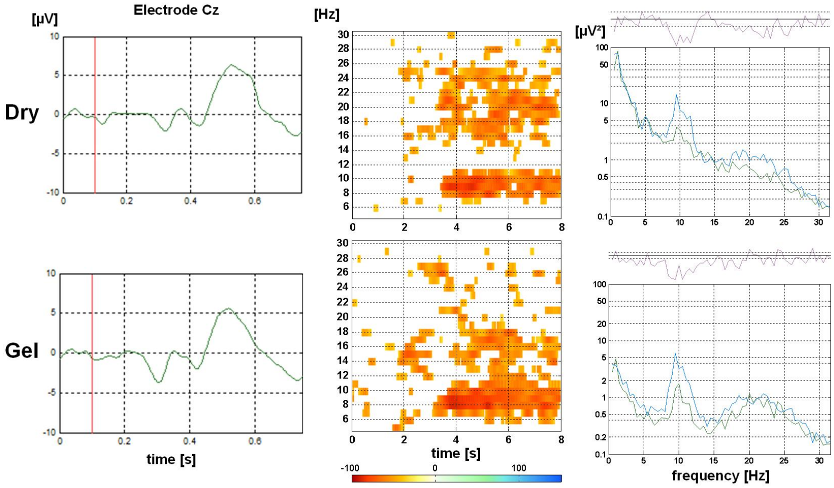

Figure 1: Left: P300 reponse for dry and gel electrodes in the copy spelling run of 1 subject. Each run had 5 characters and each character flashed 30 times (15 rowsm 15 columns). This gives in total about 5 minutes per run. The y-axis is scaled with +/-10 μV, the x-axis in seconds. Middle: ERDmaps of electrode positions C3 during right hand movement imagination for dry (top) and gel electrodes (bottom). Both show a strong ERD in the alpha range from second 3.5 until 8 over C3. The dry electrodes show a broader beta ERD. Only pixels with significant ERD/ERS values are displayed (bootstrap, $p<0.05$). Right: Reactive frequency components of the reference interval (0-2s, blue) and active interval (6-8s, green) of C3 of dry (top) and gel (bottom) electrodes. The graph above each power spectrum shows significant changes if the line crosses the dashed line (sign test, $p<0.05$).

2 Methods

Three subjects performed the P300, motor imagery and SSVEP experiments with the electrode montage Fz, Cz, P3, Pz, P4, PO7, Oz and PO8 for P300, FC3, CP3, FC4 and CP4 for motor imagery and PO3, PO, PO4, PO7, O1, Oz, O2 and PO8 for SSVEP. For P300 and SSVEP experiments subjects performed one run with dry electrodes (g.SAHARA) and one run with gel electrodes (g.BUTTERFLY). The EEG was amplified with a 24 Bit high resolution biosignal amplifier (g.USBamp). In the case of the motor imagery BCI the electrodes were mounted close together with 1.5 cm distance. Subjects were seated about 1 m in front of the computer monitor and were instructed about the experimental procedure.

P300 experiments were performed with intendiX. The intendiX speller shows 50 characters (A, B, ... Z; 0, 1, ... 9; and special characters) on the computer screen and highlights a whole column or row for 100 ms. Between the flashes there is a short time while only the grey matrix items are visible (60 ms). The BCI system must be calibrated in a first step on individual EEG data. Therefore the subject was asked to "select" (or attend to) the word WATER, one letter at a time. This training procedure took about 5 minutes. After training the BCI system using the calibration data, the subject was asked to write the word LUCAS, one character at a time, taking about 5 more minutes. The system uses a linear discriminant analysis for classification [5]. Figure 1 shows the evoked potential calculated from the EEG data from the copy spelling run for dry and gel electrodes. The P300 response is very similar in amplitude and latency.

For the motor imagery experiment gel based and dry electrodes were mounted beside each other to record EEG data (80 trials of left and right hand movement imagination) almost from the same region (1.5 cm apart). The motor imagery experiment started with the display of a fixation cross in the center of a screen. After 2 s, a warning stimulus was given in the form of a "beep". After 3 s, an arrow (cue stimulus) pointing to the left or right was shown for 1.25 s. The subject was instructed to imagine a right-hand movement or left-hand movement until the end of the trial,

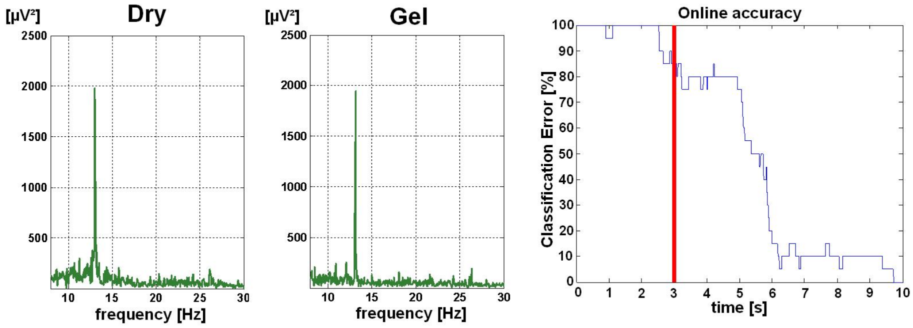

Figure 2: Power spectrum of EEG data of electrode Oz during 13 Hz LED stimulation. Right: Error rate of the SSVEP based BCI system with dry electrodes.

depending on the direction of the arrow. One trial lasted 8 s and the time between two trials was randomized in a range of 0.5-2.5 s to avoid adaptation.

The motor imagery BCI estimated the bandpower in two different frequency bands of the EEG data. The bandpower features were classified with a linear discriminant analysis resulting in a subject specific weight vector [6]. The reactive frequency bands in the alpha and beta range were identified from the power spectrum and a time-frequency evaluation of the ERD/ERS activity (ERDmaps) as shown in Figure 1. First the EEG data was visually inspected and about 5 % of the trials containing artifacts were removed. In both cases an ERD in the alpha and beta ranges can be found. EEG measured with dry electrode recordings show a broader activity in the beta frequency range. The power spectrum allows to identify the reactive frequency components in the EEG data. In the baseline period (without movement imagination) two alpha peaks can be found for this subject in both derivations (dry and gel). It is known from previous experiments from this subject that the higher alpha activity is more suppressed during the hand movement imagination and therefore this frequency band is used for the BCI control. The significant difference between baseline and imagination is proven by the sign test. EEG power spectra for the dry electrode show a higher difference in the beta region than for the gel based electrodes. However both measurements were done at nearby but still distinct locations. A clear difference comparing the two power spectra is the higher power found below 3 Hz for the dry electrode signal. However comparing power levels in alpha and beta ranges it can be stated that the ERDmaps and power spectra show very similar results for both types of electrodes.

One subject performed the SSVEP experiment with a training run to setup a subject specific weight vector and a testing run. This was done for dry and also for gel electrodes. The task of the subject was to attend for 7 seconds to one of 4 LEDS flickering with a certain frequency (10, 11, 12 13 Hz) and then to rest for 3 seconds. The task was repeated for the remaining three LEDS and the whole loop was repeated 4 times. The 4 LEDS were arranged in a 12 x 12 cm box and were controlled by a microcontroller resulting in a frequency error <0.025 Hz.

The SSVEP based BCI system is controlled with discrete frequency peaks showing if the subject is looking at a certain LED. Figure 2 displays the power spectrum of an important electrode positions Oz for dry and gel based electrodes when the subject is looking at the 13 Hz LED computed from the complete four 7 seconds segments. The peak at 13 Hz is very similar and also the 1^{st} harmonic components at 26 Hz can be seen. The real-time classification was done with a linear discriminant analysis of minimum energy parameters [7].

3 Results

The P300 subject reached 100 % accuracy with gel and dry electrodes when LUCAS was spelled with 5 minutes of training data only.

The motor imagery BCI accuracy was compared using a 10 times 10 fold cross validation technique that mixes the data randomly to have separate training and testing data. The error of run 1 with gel based and dry electrodes mounted beside each other is 18 % versus 15 %. Dry electrodes performed in this case slightly better and had an earlier best classification time point (7.5 s versus 8 s).

For the SSVEP BCI the accuracy for dry electrodes is shown in Figure 2, right. The red line indicates the time point when the subject started to look at one of the 4 LEDs. In the reference interval the accuracy is around 100 % and in the action interval the error drops down to finally 0 % at the end of the trial. A similar behavior was observed for the gel based electrodes.

4 Discussion

We could show that the used dry electrode sensor concept can be used for motor imagery, SSVEP and P300 based BCI systems. For dry electrodes no conductive gel is used and therefore a much higher skin-electrode impedance than for gel based electrodes can be expected. Electrodes with higher impedance can pick up more artifacts and are mostly sensitive for movements of the electrodes and cable swings which results in signal amplitudes much higher than for normal EEG. Electrodes with high impedance can also pick up electrostatic voltages in the surrounding and electro-magnetic noise. To solve these problems we reduced the impedance with multiple gold coated pins per electrode being in contact with the skin. Secondly we integrated an amplifier unit into the electrode itself to make it resistant against artifacts and to be able to record EEG with a high electrode impedance. Dry electrodes also show a higher polarization voltage than gel based electrodes and therefore the recording equipment must be able to accept DC voltages up to several mV. This was solved with an amplification unit with high input range in combination with a 24 Bit ADC.

It was shown that dry and gel electrodes reach similar accuracies and are able to pick up similar physiological responses for P300, SSVEP and motor imagery BCI experiments. Nevertheless group studies are required to show the usefulness in real life situations as needed for home applications.

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