Mathematical approach to recover EEG brain signals with artifacts by means of Gram-Schmidt transform

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ABSTRACT

A novel method for removing oculomotor artifacts on electroencephalographical signals is proposed and based on the orthogonal Gram-Schmidt transform using electrooculography data. The method has shown high efficiency removal of artifacts caused by spontaneous movements of the eyeballs (about 95-97% correct remote oculomotor artifacts). This method may be recommended for multi-channel electroencephalography data processing in an automatic on-line in a variety of psycho-physiological experiments.

Keywords: electroencephalogram, EEG math processing, EEG automatic analysis, Necker cube, the Gram-Schmidt transformation, electrooculography

1. INTRODUCTION

Electroencephalography is the indispensable method for studying the cognitive and electrophysiological processes in regions and structures of human and animal brain. EEG recording method (EEG) is simple, affordable, non-invasive and allows you to develop almost any arbitrarily complex design of the experiment, practically no time-limited framework. The obvious disadvantage of the EEG signal is the inevitable noisy and the presence of artifacts neurogenic and technical nature (electro-magnetic noise and hardware error).[1,2] The present work is devoted to solving the problem of selection and removing oculomotor artifacts in human multichannel EEG data. This type of artifacts has powerful amplitude and occupies a time-varying frequency range (from the minimum registration frequency spectral signal and to 8–15 Hz).[3,4] Oculomotor artifacts can be detected on the EEG in the vicinity of the eye, and at a significant distance, up to the occipital regions, so the problem of removing these artifacts is very important.

In medical studies, EEG fragments containing artifacts are removed manually due to high degree of moral and legal responsibility to the patient in the event of an erroneous interpretation of EEG data. At present there are many methods for removing artifacts oculomotor.[5–16] Among the most efficient approaches is necessary to mention on the basis of the method of the independent component[5,6,8,9] and its improved modification — regression analysis.[12–15] However, these approaches are rarely used in routine practice due to the high computational complexity, together with a high risk of error in determining the appearance of artifacts. For effective removal of artifacts in the EEG oculomotor need information about eye movements (electrooculogram, EOG) and the combination of the two procedures:

- linear subtraction EOG signal from the EEG data using empirically selected weighting coefficients depending of the degree of EEG channel distance from the place of EOG registration; diagnostic of EEG fragments with contain artifacts;
- removing EEG fragments containing artefacts (manually).

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The described combination is ineffective in experiments that require the analysis of low-frequency component of the EEG, which include cognitive studies.[17–20] Removal fragments of EEG signal and linear subtraction leads to a shortening of the time series of EEG (up to 10–20 % of the initial length), which reduces the informative value and spectral content distorts the signal.

In this paper, we propose a novel method for removing oculomotor artifacts on EEG signals based on the transformation of Gram-Schmidt using EOG signals. It has been shown that the removal of oculomotor artifacts is highly efficient and is relatively simple to implement, and this technique can be used to remove the oculomotor artifacts in the EEG records in an automatic mode, and the effectiveness of the method does not fall.

2. EXPERIMENTAL SETUP

The experimental studies were performed in accordance with the ethical standards[21] and approved by the local research ethics committee of Saratov State Technical University. Fifteenth healthy subjects from a group of unpaid volunteers, male and female, between the ages of 18 and 25 with normal or corrected-to-normal visual acuity participated in the experiments. All persons have provided informed consent before participating in the experiment.

Pre-standard testing was conducted to determine the leading and trailing in the eye each participant. Analysis oculogram form in seven subjects did not reveal distinctions between the signals registered near the master and slave eye. Later, for the convenience and unification of the experimental work was recorded vertical oculogram only by the right eye (Figure 1 a). During the experiment, we have been recording data of 19 channel EEG with the discretization 250 Hz using the electroencephalograph-recorder Encephalan-EEGR-19/26 (Russian Federation). This equipment has been certified for medical use in the Russian Federation, the CIS countries, in the EU and UK area. The monopolar registration method and classical ten-twenty electrode system were used (Fig. 1, b).

In order to reduce the impact of error factors and optimize the signal filtering process, each subject participated in a series of similar 3–5 experimental design. Each series consisted of two stages:

1. EEG and EOG data background registration in resting position with eyes closed in compliance with the instructions to make a minimum of eye movement (5 minutes);
2. registration of EEG and EOG signals during the horizontal and vertical movements of the eyes, as well as during blinking (5 minutes).

Taking into account pauses between the experimental stages, the total duration of the experiment was about 10–13 minutes.

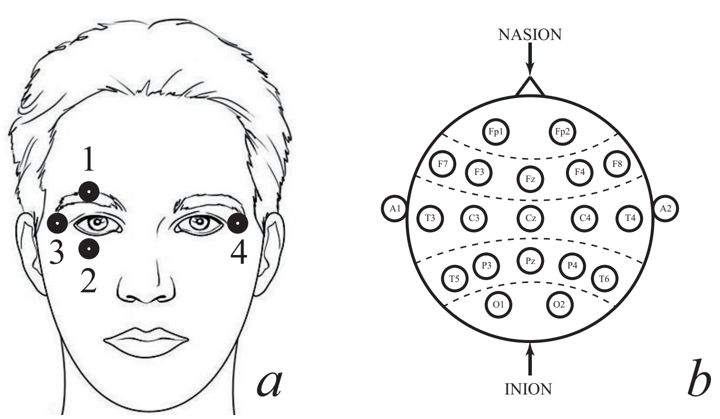

Figure 1. (a) The EOG electrode placement scheme. For EOG recording we use two pairs of electrodes: electrodes 1 and 2 — for registration of vertical EOG and the electrodes 3 and 4 — horizontal ones. (b) International EEG electrode placement scheme “10 – 20”.

It is well known that the form of the oculomotor EEG artifacts depends on the type of eye movement in the horizontal / vertical direction in the presence/absence of of the angular momentum, and in accordance with that oculomotor artifacts can be classified into several types.[3,4] Eye movements are accompanied by changes in the electrical potential because the eyeball has an electric dipole moment, formed by the potential difference between the retina and cornea of the eye.[3,4,12,13] Figure 1 a demonstates the electrodes (1)—(4) scheme registrated a potential difference generated by all possible movements of the eyeball.

3. MATHEMATICAL METHOD FOR EEG ARTIFACTS REMOVAL USING EOG SIGNALS

EEG signals recorded in the subjects with their eyes open, can be represented as a linear combination of signals of the brain electrical activity and interference caused by eye movements. In this case, removing the interference (extraocular artifacts) can be accomplished by a mathematical transformation of EEG and EOG signals using the method of Gram-Schmidt orthogonalization.[22] We now describe the proposed approach.

Let $g_i(t)$ is the EEG signal from the i channel, $h(t)$ and $s(t)$ are the EOG signals containing information on the vertical and horizontal movements of the eyes (or pairs of the sensors 1–2 and 3–4, Fig. 1 a). Further, these signals have represented the Gram-Schmidt orthogonalization procedure:

$$g_i'(t) = g_i(t) - h^0(t) \int_{t_1}^{t_1+T} h^0(t') g_i(t') dt', \tag{1}$$

$$\tilde{g}_i(t) = g_i'(t) - s^0(t) \int_{t_1}^{t_1+T} s^0(t') g_i'(t') dt', \tag{2}$$

where $\tilde{g}_i(t)$ – signal after oculomotor artifacts filtration, t – the time interval during the removal of artifacts; $t \in [t_1, t_1 + T]$, where t_1 – the time start and T – the interval duration. Signals $h^0(t)$ and $s^0(t)$ — a normalized "reference" EOG signals, corresponded to the vertical and horizontal eye movements:[12,14]

$$h^0(t) = \frac{h(t)}{||h(t)||}, ||h(t)|| = \sqrt{\int_{t_1}^{t_1+T} (h(t))^2 \, dt}, \tag{3}$$

$$s^0(t) = \frac{s(t)}{||s(t)||}, ||s(t)|| = \sqrt{\int_{t_1}^{t_1+T} (s(t))^2 \, dt} \tag{4}$$

Orthogonalization (Gram-Shmidt) procedure (1)–(4) has been performed with the signals from all 19 registered EEG channels. In the absence of oculomotor artifacts on separate channels of EEG orthogonalization procedure does not change the original form of the EEG signal. This feature follows of the form itself Gram-Schmidt transform, which will be demonstrated below. Note that the horizontal movement of the eyes, the most manifested in the EOG signal $s(t)$, has minimal effect on the EEG shape. Interference on the EEG signals have largely been caused by the vertical movements of the eyes, which are the most manifested on the EOG signal by a vertical pair sensors $h(t)$, so the information from a horizontal pair of sensors $s(t)$ has been excessive, and further calculations using data only $h(t)$.

To filter the oculomotor artifacts in the EEG data in real-time procedure (1)–(4) have been modified in the following way:

$$g_i'(t) = g_i(t) - h^0(t) \int_{t-T/2}^{t+T/2} h^0(t') g_i(t') dt', \tag{5}$$

$$\tilde{g}_i(t) = g_i'(t) - s^0(t) \int_{t-T/2}^{t+T/2} s^0(t') g_i'(t') dt', \tag{6}$$

$$h^0(t) = \frac{h(t)}{||h(t)||}, \quad ||h(t)|| = \sqrt{\int_{t-T/2}^{t+T/2} (h(t))^2 \, dt}, \tag{7}$$

$$s^0(t) = \frac{s(t)}{||s(t)||}, \quad ||s(t)|| = \sqrt{\int_{t-T/2}^{t+T/2} (s(t))^2 \, dt}, \tag{8}$$

where t is the time interval during the removal of artifacts; T is the interval duration and $t+T/2$ is the registered "current" point in time. In realizing this algorithm in real time EEG signal without artifacts after processing was a time delay $(t - T/2)$. For efficient removal of artifacts in real time the value of T is varyied from 1.5 to 5 seconds.

4. RESULTS

In the first stage of the experiment (background recording with closed eyes) on the EEG were no artifacts that require removal (Fig. 2). However, the procedure for removing artifacts using the method of Gram-Schmidt orthogonalization was done for this stage of the experiment. Thus on (Fig. 2, b) shows the initial EEG signals to the application of the procedure removal of the oculomotor artifacts, and (Fig. 2, c) given EEG signals after applying the method of Gram-Schmidt orthogonalization. From (Fig. 2, b) and (Fig. 2, c) it shows that the the original EEG signals is no different from the EEG signals, after the application of the procedure removal of the oculomotor artifacts. In this case distribution of the original signals and signals after using the Gram-Schmidt procedure shown on Figure 2d have identical shapes, close to a normal distribution.This result allows to say that the proposed method can be easily implemented to remove oculomotor artifacts in EEG recordings in the automatic mode, since developed method does not distort the original signal in the absence of artifacts.

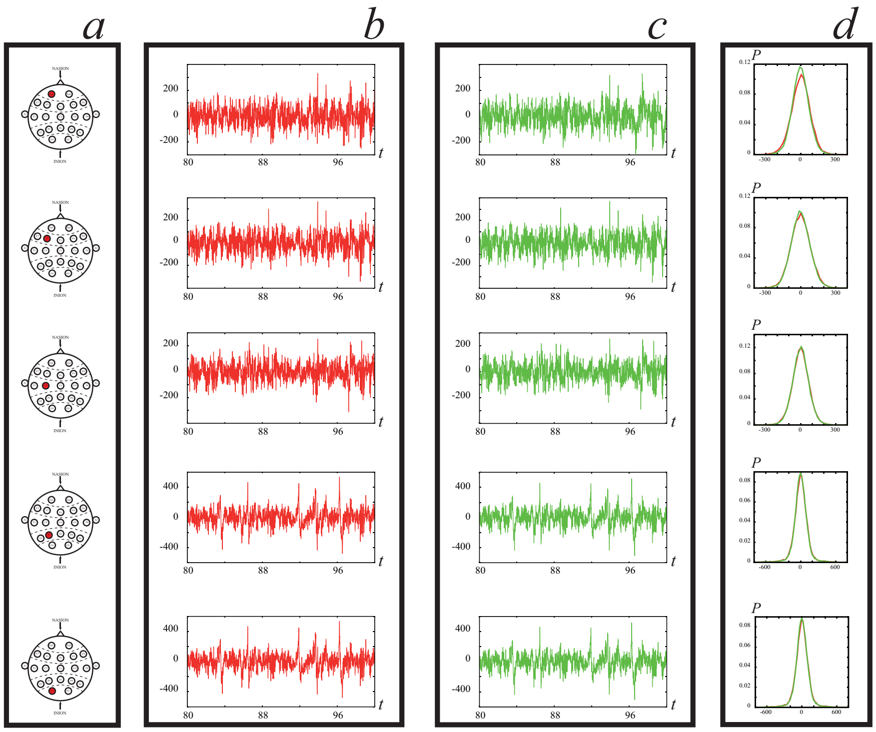

Figure 2. EEG fragments registered on the first stage of the experiment, illustrating the result of applying the orthogonal transformation procedure to remove the oculomotor artifacts of different types: (a) international EEG electrode placement scheme "10 – 20"; (b) the original EEG data; (c) EEG data after using the Gram-Schmidt procedure; (d) signal distribution with the original data (red line) and the signal after using the Gram-Schmidt procedure (green line).

In the second stage of the experiment (EEG and EOG registration in subjects with eyes open) procedure Gram-Schmidt orthogonalization was used to remove the oculomotor artifacts caused by the horizontal and vertical movements of the eyeballs, and also due to blinking. On (Fig. 3, b) shows the initial EEG signals for the different channels. Is clearly seen that in the frontal channels eye movement artifacts are more pronounced than the the occipital. On rises shown EEG signals for the different channels after application of the Gram-Schmidt orthogonalization. From (Fig. 3, b), (Fig. 3, c), (Fig. 3, d) and clearly shows that the use of Gram-Schmidt orthogonalization to remove oculomotor artifacts is effective enough.

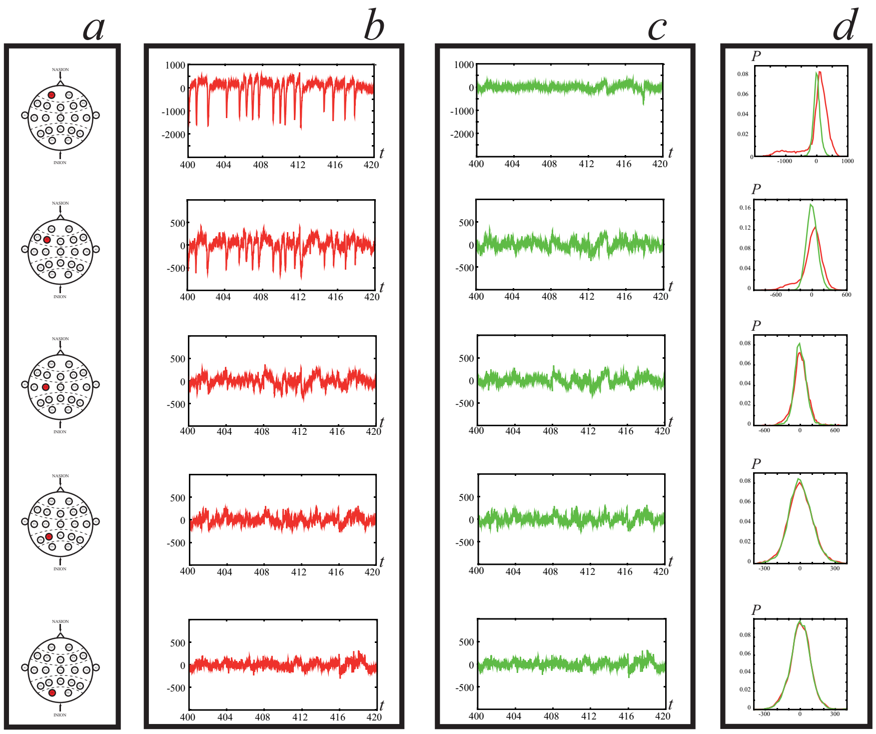

Figure 3. EG fragments registered in the second stage of the experiment, illustrating the result of applying the orthogonal transformation procedure to remove the oculomotor artifacts of different types: (a) - International EEG electrode placement scheme "10 – 20"; (b) - the original EEG data; c - EEG data after using the Gram-Schmidt procedure; c - signal distribution with the original data (red line) and the signal after using the Gram-Schmidt procedure (green line).

5. CONCLUSION

In the paper we have considered the novel method for the removing oculomotor artifacts from EEG data. This method is based on the orthogonal Gram-Schmidt transformation, and the use of established techniques has demonstrated the high efficiency removing of artifacts, caused by the spontaneous movements of the eyeballs (on average from 94.9 to 97.9% in different EEG channels). This procedure does not lead to a breach of the EEG patterns and is a simple, effective and reliable way to remove oculomotor artifacts in the multichannel EEG data. Thus, the proposed method for removing oculomotor artifacts can be easily implemented to remove artifacts in EEG recordings in the real time.

6. ACKNOWLEDGMENTS

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