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RESEARCH ARTICLE

Local spatial analysis of EEG signals using the Laplacian montage

Andrey A. Slezkin [1, 2, @],
Svetlana P. Stepina [3],
Namik G. Gusein-zade [2, 4]

[1] *Institute of Higher Nervous Activity and Neurophysiology, Russian Academy of Sciences, Moscow, 117485 Russia*
[2] *MIREA – Russian Technological University, Moscow, 119454 Russia*
[3] *Patrice Lumumba Peoples' Friendship University of Russia (RUDN university), Moscow, 117198 Russia*
[4] *Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, 119991 Russia*
[@] *Corresponding author, e-mail: com2274@yandex.ru*

Abstract
Objectives. One pressing problem when recording brain activity signals by electroencephalography (EEG) is the need to reduce the effect of interference (artifacts). This study presents a method for resolving this problem using the Laplace differential operator. The aim is to determine the number of electrodes included in the Laplacian montage, as well as to clarify the requirements for the geometric shape of their placement, in order to ensure the best quality of EEG signal processing.
Methods. The Laplacian montage method is based on the use of individual electrodes to determine the second derivative of the signal, proportional to the electric current at the corresponding point on the surface of the head. This approach allows the potential of neural activity of the source located in a small area limited by the electrode complex to be evaluated. By using a small number of equidistant electrodes placed around the target electrode, the Laplacian montage can produce a significantly higher quality signal from the area under the electrode complex.
Results. Among all the methods for constructing the Laplacian montage discussed in the article, a complex consisting of 16 + 1 electrodes was shown to be preferable. The choice of the 16 + 1 scheme was determined by the best compromise between the quality of EEG signal processing and the complexity of manufacturing the electrode complex with given geometric parameters. The quality assessment was carried out by simulating the interference signal which allowed the correctness of the choice of installation design to be evaluated.
Conclusions. The use of the Laplacian montage method can significantly reduce the effect of artifacts. The proposed montage scheme ensures a good suppression of interference signals, the sources of which are located far beyond the projection of the electrode complex. However, not all interference arising from sources deep inside the brain, can be effectively suppressed using the Laplacian montage scheme alone.

Keywords: electroencephalography, EEG signals, artifact, reference montage, Laplacian montage, electrode placement scheme, electrode complex

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НАУЧНАЯ СТАТЬЯ

Локальный пространственный анализ ЭЭГ-сигналов с помощью лапласиановского монтажа

А.А. Слезкин [1, 2, @],
С.П. Степина [3],
Н.Г. Гусейн-заде [2, 4]

[1] *Институт высшей нервной деятельности и нейрофизиологии, Российская академия наук, Москва, 117485 Россия*
[2] *МИРЭА – Российский технологический университет, Москва, 119454 Россия*
[3] *Российский университет дружбы народов, Москва, 117198 Россия*
[4] *Институт общей физики им. А.М. Прохорова, Российская академия наук, Москва, 119991 Россия*
[@] *Автор для переписки, e-mail: com2274@yandex.ru*

Резюме
Цели. Одной из актуальных задач, возникающих при регистрации сигналов мозговой активности с помощью электроэнцефалографии (ЭЭГ), является уменьшение влияния помех (артефактов). В данном исследовании рассматривается один из способов решения данной задачи с помощью дифференциального оператора Лапласа. Цель работы – определение количества электродов, входящих в лапласиановский монтаж, а также выяснение требований к геометрической форме их расположения для обеспечения наилучшего качества обработки сигналов ЭЭГ.
Методы. Метод лапласиановского монтажа основывается на использовании отдельных электродов для определения второй производной сигнала, которая пропорциональна электрическому току в соответствующей точке поверхности головы. Этот подход позволяет оценить потенциал нейронной активности источника, находящегося в малой области, ограниченной комплексом электродов. При использовании небольшого количества равноудаленных электродов вокруг целевого электрода при лапласиановском монтаже удается получить значительно более качественный сигнал из области, находящейся под электродным комплексом.
Результаты. Для всех рассмотренных в статье способов построения лапласиановского монтажа, было показано, что комплекс, состоящий из 16 + 1 отдельных электродов, является наиболее предпочтительным для использования. Выбор схемы 16 + 1 обусловлен наилучшим компромиссом между качеством обработки сигналов ЭЭГ и сложностью изготовления электродного комплекса при заданных геометрических параметрах. Оценка качества проводилась моделированием сигнала помехи, с помощью чего удалось оценить правильность выбора схемы построения монтажа.
Выводы. Установлено, что применение метода лапласиановского монтажа способно значительно уменьшить влияние артефактов. С помощью предложенной схемы монтажа обеспечивается высокий уровень подавления помеховых сигналов, источники которых находятся далеко за пределами проекции электродного комплекса. Однако не все помехи, источники которых лежат в глубине мозга, могут быть эффективно подавлены с помощью одной лишь схемы лапласиановского монтажа. Необходимо использовать различные цифровые методы обработки сигналов, учитывающие их статистические свойства.

Ключевые слова: электроэнцефалография, ЭЭГ-сигналы, артефакт, референтный монтаж, лапласиановский монтаж, схема наложения электродов, электродный комплекс

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INTRODUCTION

Electroencephalography (EEG) is one of the most common methods for studying the electrical activity of the brain which helps to determine the functional state of the brain. When registering electrical potentials on the surface of the head, the useful signal is often noisy due to artifacts of various nature. In order to obtain adequate information about the functioning of brain structures, various radiophysical methods are used. These consist of hardware and are based on approaches known from signal processing theory and statistical radiophysics.

Hardware methods for improving the quality of the EEG signal are primarily based on the use of new types of electrodes, as well as electrode montage and arrangement schemes. A lead montage is a system of connections between electrodes, the most common of which are described in the review [1]. The number of electrodes included in the montage can vary from 2 to 20 depending on the purpose of recording. The use of different types of montage in EEG studies allows more accurate data on the electrical activity of the brain to be obtained, as well as specific electrical events which may be important for the diagnosis and treatment of various diseases [2]. There are variants of montage, some of which will be described below.

Monopolar montage in which the potential difference between one electrode and a reference point (usually located behind the ear) is recorded. ***Bipolar montage*** records the potential difference between two electrodes located on neighboring areas of the head. In the case of ***monophasic montage***, only positive or only negative half-waves of the EEG signal are recorded. This type of montage is used to detect specific electrical events such as misalignment or synchronization between different areas of the brain.

Reference montage uses an additional electrode located away from the brain regions of interest. The total electrical activity recorded with this additional electrode helps to account for the effects of artifacts arising, for example, from eye movements or muscle activity (particularly facial muscles).

The purpose of using the reference montage is to record the EEG signal without the influence of interfering sources and noise, i.e., in relation to an electrically neutral electrode. However, due to the conductivity of biological tissues, it is impossible to place on the surface of the head a reference electrode which retains electrical neutrality. In theory, this condition is met at an infinite distance from the source. In the 1950s. [3], a method known as the ***common average reference montage*** was developed. In this method, electrode potentials are measured relative to a common average reference, i.e., the potential obtained by averaging the values recorded from all electrodes. With random signals at all electrodes, the average potential, i.e., the potential of the common reference electrode, would be zero. However, the activity of neuronal ensembles is spatially distributed quite widely, and the signals at the electrodes are not independent. In order to address this problem, ***local averaged reference montage*** was developed, in which a small number of electrodes near the target electrode are used to compute a complex reference. There are several types of averaged reference montage—Laplacian, Lemos, and Hjorth montages [4, 5].

LAPLACIAN REFERENCE MONTAGE

In the present work, the Laplacian local averaged reference montage will be used. This is based on the fact that the second spatial derivative of EEG signals is proportional to the electric current in the corresponding point of the head surface. This allows the value of the underlying neural activity source potential to be estimated.

The potential field gradient at any given electrode is calculated by measuring the difference between the voltage at the electrode of interest and the voltage of each of its nearest neighbors. If the potential field gradient at an electrode is calculated, there is no need for a common reference comparison electrode.

The currently used modification of the Laplacian montage for surface potentials was developed under the assumption of homogeneous cortical conductivity [2]. In this method, the second spatial derivative of the potential field is defined by the electric current perpendicular to the cortical surface.

There are a number of limitations associated with the Laplacian montage. The accuracy with which this montage represents the signal strongly depends on the interelectrode distance. In the first Laplacian scheme, no additional electrodes were used, and only the standard EEG electrode arrangement scheme was used. In this method, data from the nearest 8 grid electrodes was used to obtain the value of the local averaged reference electrode (for lead C4, for example) (Fig. 1). The general idea of the montage is based on the fact that the target electrode, at which the resulting signal is determined, is assigned a weight of +1. The other electrodes are assigned weights based on their distances from the target electrode location, such that each weight is proportional to the inverse of the distance squared and scaled such that the sum of these weights equals −1. Thus, the sum of all weights is zero, which makes the differential operation indifferent to the choice of the reference electrode location [4].

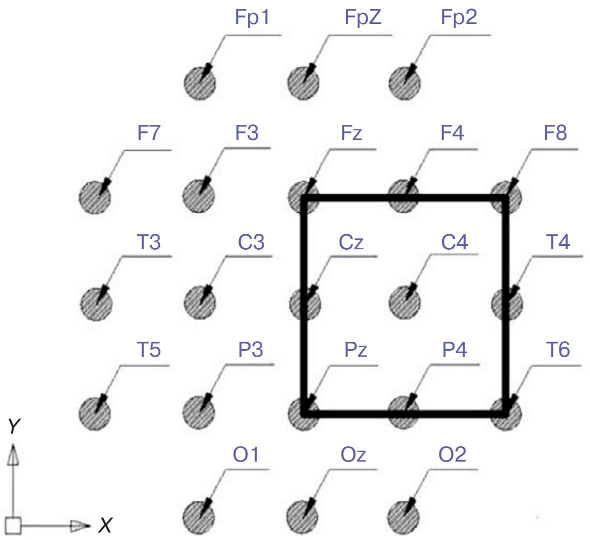


Fig. 1. Display of the EEG 10–20 electrode placement scheme on the plane

The following formula [1] is used to obtain the electrode C4 value using a locally averaged reference electrode:

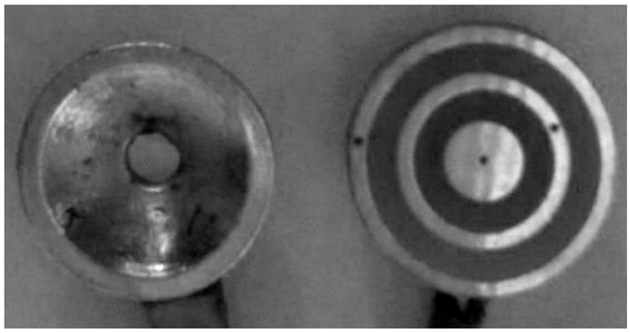
$$C4 = (Fz + F4 + F8 + Cz + T4 + Pz + P4 + T6)/8. \quad (1)$$

This scheme works relatively well for medial and central electrodes in standard EEG circuits. However, the fulfillment of these assumptions is rather problematic with regard to peripheral electrodes. In this case, weighting coefficients are introduced for edge electrodes, for example, the formula [2] is taken for T3:

$$T3 = (2 \cdot F7 + 2 \cdot T5 + C3)/5. \quad (2)$$

This Laplacian scheme, as can be seen, uses data from electrodes located at different distances from the center electrode which may require the selection of weights for them and introduces distortions in the resulting signal.

Another way of constructing a Laplacian montage is to use solid electrically conductive concentric rings as electrodes (Fig. 2), as presented in [6, 7].



(a) (b)

Fig. 2. Conventional electrode (a) and tripolar electrode (b) consisting of three concentric rings (photo from [2])

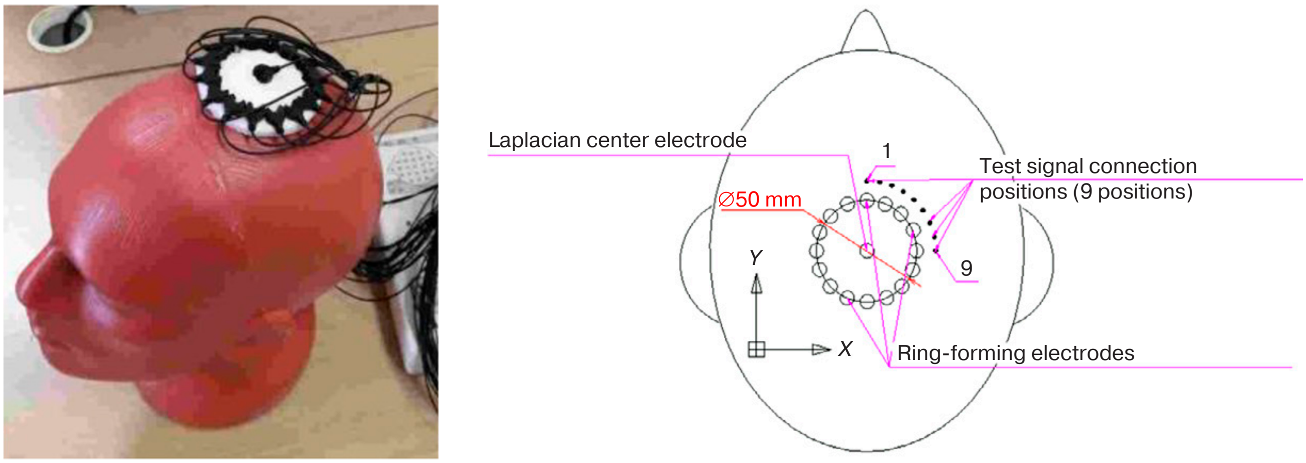
This method has its advantages and disadvantages in use. For example, with best signal accuracy, it is quite difficult to ensure a uniform fit of the ring to the scalp. This ring montage cannot be converted to a different signal processing scheme, as opposed to a montage based on individual electrodes.

In addition, an EEG signal whose source is not a point, but a scalp, scattered (diffuse) electric charge will also be distorted when processed by Laplacian. Laplacian is best suited for working with relatively focal sources, i.e., concentrated in a small area compared to the size of the electrode complex included in the montage [8].

Our choice in favor of the ring shape of the electrode complex consisting of individual electrodes was determined by consideration of the computational problems of the Laplacian method associated with different electrode configurations and interelectrode distances [9], as well as the problem of ensuring uniform adherence of electrodes to the scalp. For such a shape, the finite difference method is the simplest way of signal processing. As will be shown below, when using a small number of equidistant electrodes around the target electrode in the Laplacian montage, a much better signal from the area under the electrode complex may be obtained.

(16 + 1)-ELECTRODE LAPLACIAN MONTAGE SCHEME

In the scheme (Fig. 3) of the (16 + 1)-electrode Laplacian Montage, as proposed by the authors, the distance from the circle on which the peripheral electrodes of the complex are located to the central electrode was 25 mm. This corresponds approximately to the average interelectrode distance for the 10–20 EEG overlay scheme. A diameter of 50 mm was determined



(a) (b)

Fig. 3. Montage scheme of the (16 + 1)-electrode complex: (a) picture of a dummy head with a set of electrodes, implementing the Laplacian montage; (b) sketch of the electrode complex (top view)

based on the area under the electrode complex required to analyze the cortical structures of interest. Taking into account the size of a single electrode, the total number of electrodes placed on a circle of this diameter was $N = 16$.

The most convenient location of the (16 + 1)-electrode complex to study the properties and to illustrate the operation of the Laplacian assembly is the sensorimotor area of the cerebral cortex. The location of the electrode complex is a relatively flat surface in this region of the head and corresponds to the lead Cz in the standard scheme of electrode placement 10–20.

For such Laplacian montage, the value of the resulting S_{lap} signal with respect to the local averaged reference electrode is calculated using the following formula:

$$S_{\text{lap}} = \frac{1}{N}\sum_{i=1}^{N}(S_0 - S_i), \quad (3)$$

where S_0 is the signal at the central electrode of the Laplacian; S_i are the signals at the electrodes included in the ring complex; N is the number of electrodes included in the ring complex.

EXPERIMENTAL SCHEME

In order to understand the processes of information acquisition and processing performed by the brain, the initial shape of the signal arising in the source of interest in the brain's neural activity needs to be known. However, the presence of many activity centers in the human brain does not allow the shape of the signal to be described with a given accuracy. In order to clarify the result of the multi-electrode complex, an interfering test signal was used which was transmitted to different points of the scalp surface (Fig. 3), after which the potentials of this signal on all electrodes of the complex was measured. The source of the test signal in the experiment was a generator of sinusoidal oscillations with an amplitude of 50 mV and a frequency of 130 Hz. The Laplacian method for (4 + 1), (8 + 1), and (16 + 1)-electrode ring montages was used to process the potentials. In EEG measurement, this test signal is an interfering signal. The application of the Laplacian should reduce, and ideally completely suppress, this interfering signal. We will evaluate the effectiveness of a particular montage by comparing the power attenuation coefficients of the signal source external to the perimeter of the electrode complex. Thus, we can experimentally determine the number of N electrodes included in the $(N + 1)$-electrode mounting scheme at which the interfering signal is effectively suppressed, and the mounting is not hindered.

A generator signal was sequentially applied to the scalp (9 positions) located at a distance of 40 mm from the central electrode of the complex (Fig. 3). These 9 points are located at a distance of 1/8 quarter of the circumference length from each other. In the monopolar withdrawal mode, the amplitude of the signal recorded at the center electrode was 40 mV in all cases. The signals obtained by the Laplacian method for all three types of mounting considered (4 + 1, 8 + 1, and 16 + 1) are shown in Fig. 4 and have different amplitudes, different from zero.

The ratio of signal powers at the central electrode to the signal power obtained using the Laplacian was calculated by the formula:

$$R_{\text{m}} = \frac{\sum_{t=0}^{T} x_{S_0\_\text{pos}}(t)^2}{\sum_{t=0}^{T} x_{\text{lap}\_\text{m}\_\text{pos}}(t)^2}, \quad (4)$$

where R_m is the power ratio for the Laplacian of type m; m is the type of Laplacian (4 + 1, 8 + 1, or 16 + 1); $x_{\text{lap\_m\_pos}}$ is the amplitude of signal samples after processing by the Laplacian of type m for the electrode position of the test signal generator pos; $x_{S_0\_pos}$ is the amplitude of signal samples at the center electrode of the Laplacian for the position of the test signal generator electrode pos; T is the total signal recording time.

Figure 5 shows that increasing the number of electrodes in the ring from 4 to 16 contributes to better attenuation of interference signals. However, the characteristics obtained with (8 + 1) and (16 + 1)-electrode montages are already very close. A further increase in the number of electrodes in the ring complex to more than 16 can be considered inexpedient, since it will not lead to a significant improvement of the signal. However, it will unnecessarily complicate the montage scheme [10].

APPLICATION OF THE (16 + 1)-ELECTRODE MONTAGE AND DISCUSSION ON THE RESULTS

The main objective of the proposed Laplacian montage is to suppress EEG artifacts which may distort the structure of the electroencephalographic signal. Such interference includes, for example, oculographic and myographic artifacts associated with eye movements and muscle work at the moment of EEG recording. Figure 6 shows the effect of such interferences on the signal recorded on the lead (electrode) Cz in the standard scheme 10–20.

When using a multi-electrode (16 + 1) Laplacian montage in this case, oculographic interference (from

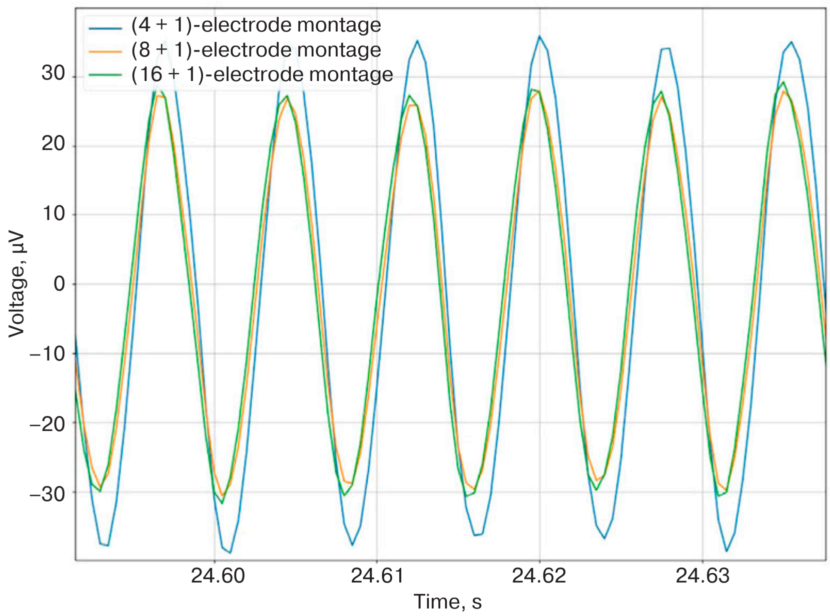


Fig. 4. Fragment of the result of test signal processing by Laplacian montages

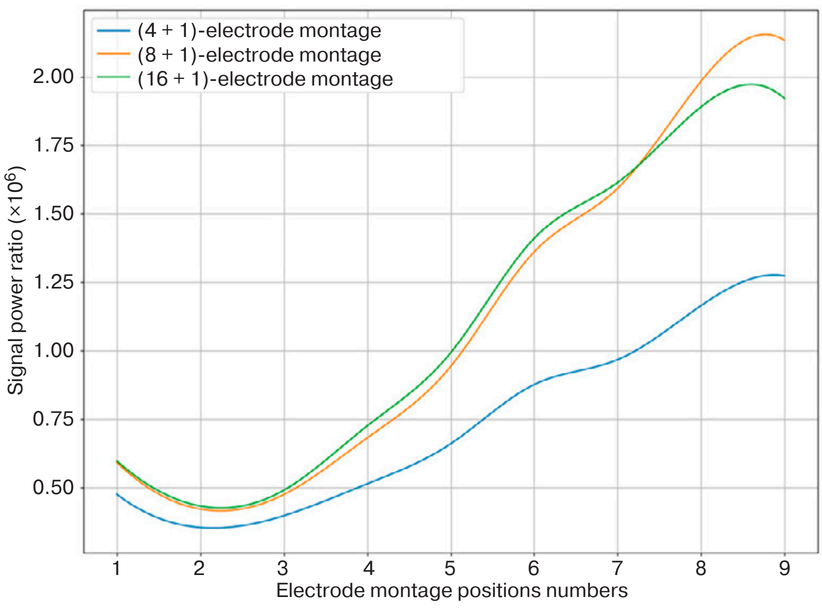


Fig. 5. Ratios of the power of the original signal to the powers of the signals obtained by Laplacian montage

eye blinking) has been almost completely leveled out (Fig. 7a).

The disadvantages of Laplacian montage of any configuration include the fact that it processes signals of neural activity sources located not only on the surface of the head, but also inside the brain volume. Consequently, if a source of interference/artifacts falls within the projection of the electrode complex, it is difficult to reduce it by Laplacian, as can be seen in Fig. 7b. In this case, the ring electrode complex is installed in the temporal region (lead T3). Therefore, the source of oculographic artifacts/interference (from eye blinking) falls in the projection of the Laplacian. In this case, inversion occurs in addition to a slight attenuation of the signal. It is not possible to eliminate interference in such a case. This is also true for another type of artifacts: myographic artifacts. They have a diffuse nature, and in the event of hitting the projection of the electrode complex, they cannot be completely suppressed either.

In order to counteract this phenomenon, other processing methods [11, 12] need to be used, including those not related to the types of electrode mounting [13]. A range of digital signal processing methods need to be used which take into account their statistical properties [14–16]. Since the artifact signal and the signal of interest related to neural activity are of different nature, they are uncorrelated. This allows statistical filtering methods to be used, such as Wiener filter and similar methods in order to separate them.

CONCLUSIONS

The studies confirmed the assumption that the applied Laplacian assembly provides good suppression of interference signals whose sources are far beyond the projection of the electrode complex. However, not all interference signals from sources deep in the brain, can be effectively suppressed with the help of the Laplacian montage scheme alone.

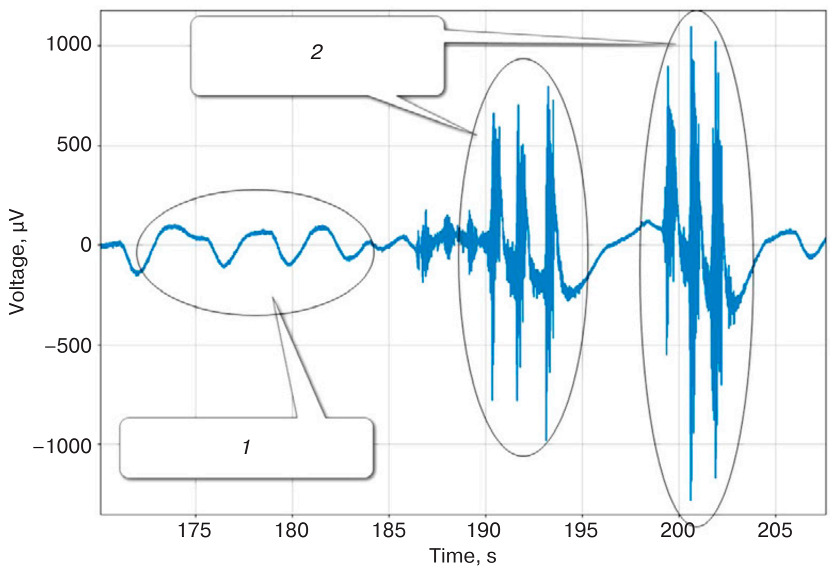


Fig. 6. Impact of the oculographic artifacts of blinking (*1*) and myographic artifacts of jaw muscle movements (*2*) on the EEG signal

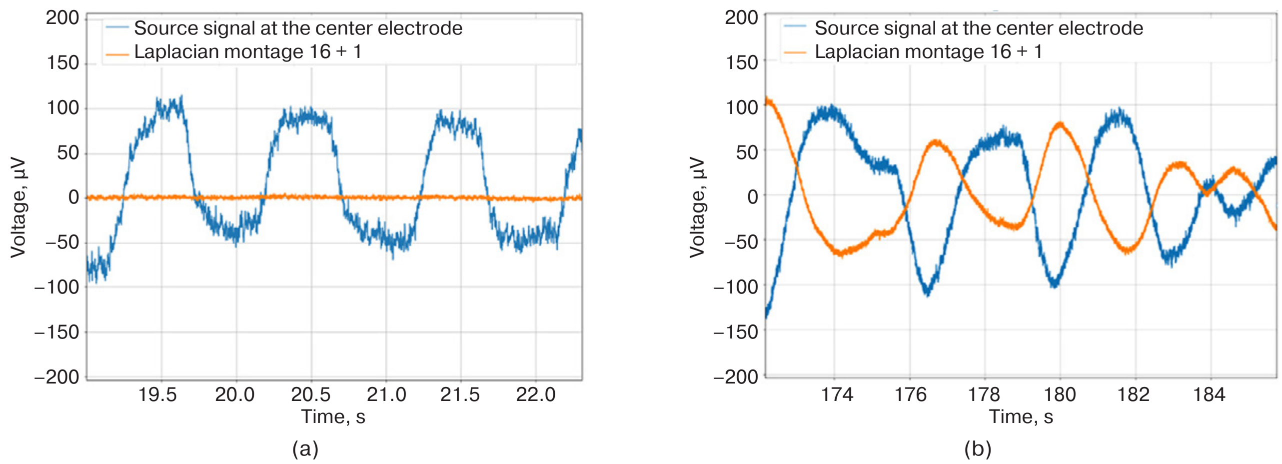


Fig. 7. Fragment of the signal noisy with oculographic artifacts and its corresponding fragment after Laplacian processing (16 + 1): (a) obtained in the parietal region Cz; (b) obtained in the temporal region (T3)

For all the methods of construction of the Laplacian montage considered in the article, in which the 4 + 1, 8 + 1, and 16 + 1 separate electrodes were used, the complex consisting of 16 + 1 electrodes is preferable. A further increase in the number of electrodes in the ring is inexpedient, since it will not lead to a significant improvement of the obtained signal but will unnecessarily complicate the mounting scheme. The choice of the 16 + 1 scheme is conditioned by the best compromise between the quality of EEG signal processing and the complexity of electrode complex manufacturing at the given geometrical parameters.

The use of the Laplacian montage method can significantly improve the quality of EEG signals and, therefore, increase accuracy when detecting various pathologies.

Authors' contributions

A.A. Slezkin—setting the problem, developing the design of the experiment, conducting the experiment, analyzing the results obtained, and formulating conclusions.

S.P. Stepina—conducting the experiment and writing the text of the article.

N.G. Gusein-zade—setting the problem, analyzing the results obtained, and formulating conclusions.

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About the authors

Andrey A. Slezkin, Engineer, Laboratory of General and Clinical Neurophysiology, Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences (5A, Butlerova ul., Moscow, 117485 Russia); Postgraduate Student, Department of Modeling of Radiophysical Processes, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia). E-mail: com2274@yandex.ru. http://orcid.org/0000-0003-1230-8347

Svetlana P. Stepina, Cand. Sci. (Phys.-Math.), Associate Professor, Scientific Educational Institute of Physical Research and Technology, Patrice Lumumba Peoples' Friendship University of Russia (RUDN University) (6, Miklukho-Maklaya ul., Moscow, 117198 Russia). E-mail: stepina_sp@pfur.ru. Scopus Author ID 8937542900, ResearcherID E-7025-2018, http://orcid.org/0000-0002-3900-0329

Namik G. Gusein-zade, Dr. Sci. (Phys.-Math.), Professor, Head of Department of Modeling of Radiophysical Processes, Institute of Radio Electronics and Informatics, MIREA – Russian Technological University (78, Vernadskogo pr., Moscow, 119454 Russia); Chief Researcher of Theoretical Department, Prokhorov General Physics Institute of the Russian Academy of Sciences (38, Vavilova ul., Moscow, 119991 Russia). E-mail: ngus@mail.ru. Scopus Author ID 6506825772, ResearcherID S-7407-2016, http://orcid.org/0000-0001-8000-1107

Об авторах

Слезкин Андрей Александрович, инженер, лаборатория общей и клинической нейрофизиологии ФГБУН «Институт высшей нервной деятельности и нейрофизиологии Российской академии наук» (117485, Москва, ул. Бутлерова, д. 5); аспирант, кафедра моделирования радиофизических процессов Института радиоэлектроники и информатики ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78). E-mail: com2274@yandex.ru. http://orcid.org/0000-0003-1230-8347

Степина Светлана Петровна, к.ф.-м.н., доцент, Научно-образовательный институт физических исследований и технологий ФГАОУ ВО «Российский университет дружбы народов им. Патриса Лумумбы» (РУДН) (117198, Россия, Москва, ул. Миклухо-Маклая, д. 6). E-mail: stepina_sp@pfur.ru. Scopus Author ID 8937542900, ResearcherID E-7025-2018, http://orcid.org/0000-0002-3900-0329

Гусейн-заде Намик Гусейнага оглы, д.ф.-м.н., профессор, заведующий кафедрой моделирования радиофизических процессов Института радиоэлектроники и информатики ФГБОУ ВО «МИРЭА – Российский технологический университет» (119454, Россия, Москва, пр-т Вернадского, д. 78); главный научный сотрудник теоретического отдела ФГБУН ФИЦ «Институт общей физики им. А.М. Прохорова Российской академии наук» (119991, Россия, Москва, ул. Вавилова, д. 38). E-mail: ngus@mail.ru. Scopus Author ID 6506825772, ResearcherID S-7407-2016, http://orcid.org/0000-0001-8000-1107

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