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Development of AUC diagrams for analysis of interhemispheric asymmetry of amplitude-frequency characteristics of EEG to detect delayed cerebral ischemia induced by non-traumatic subarachnoid hemorrhage

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Abstract: **The article describes a new type of AUC diagrams intended for the analysis of interhemispheric asymmetry of amplitude-frequency characteristics of electroencephalograms (EEG) of patients with subarachnoid hemorrhage, as well as a new type of head maps named maps of interhemispheric asymmetry of EEG. AUC diagrams are a new statistical tool for identifying regularities in biomedical signals. The idea of AUC diagrams is to visually represent the dependence of the area under the ROC curve (AUC) when comparing data samples from the bounds of the range of given characteristic of this data, for example, frequency or amplitude, etc. The article demonstrates that this principle of data analysis allows us to identify some signs of postoperative complications that may occur in patients undergoing intensive care unit. It is known that the signs of such complications are changes in the amplitude and frequency of EEG oscillations in the neurophysiological frequency ranges delta, theta, alpha, and beta; however, amplitude changes can be caused by other reasons including the state of sleep and exposure to pharmacological drugs. Changes in the amplitude caused by postoperative complications can be revealed by analysis of the interhemispheric asymmetry of the patient's EEG. The developed type of AUC diagrams and interhemispheric EEG asymmetry maps help to automate such EEG analysis. The effectiveness of the developed statistical tools was demonstrated by the analysis of data in two patients with clinically confirmed delayed cerebral ischemia induced by subarachnoid hemorrhage.**

Keywords: **AUC diagrams, ROC analysis, EEG, EEG frequency ranges, interhemispheric asymmetry, head maps, interhemispheric asymmetry maps, delayed cerebral ischemia, subarachnoid hemorrhage, biomedical signals**

UDC 519.67, 612.1, 53.083, 519.24, 004.93

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Contents

1. INTRODUCTION

Delayed cerebral ischemia is a dangerous complication that can occur in the patient a few days after surgical treatment for non-traumatic subarachnoid hemorrhage. Delayed cerebral ischemia causes an immediate threat to the patient's life. Timely diagnosis of this complication is an urgent medical problem. One of the methods for diagnosing delayed cerebral ischemia is continuous monitoring of the patient's condition using electroencephalography (EEG). Currently, EEG analysis is carried out by a doctor. At the same time, the automatic detection of signs of delayed ischemia according to EEG data is considered an open scientific problem. The automation of EEG analysis is a complex problem because the EEG signs of delayed ischemia can be caused by other reasons. For example, an increase in EEG amplitude in the delta frequency band can occur during a patient's sleep, and signs of epileptiform activity can be easily confused with EEG artifacts that occur during chewing. This study aims to create new statistical methods that help to identify EEG signs of delayed cerebral ischemia and automate the continuous analysis of EEG.

The first scientific works that demonstrated the relationship between electrical processes in the cerebral cortex and the work of the circulatory system were made even before the advent of electroencephalography at the end of the 19th century [1]. Even then, researchers noted the complexity of the studied phenomena and the inconsistency of the results of experiments on animal models. After the invention of EEG in 1924 [2], numerous works were published indicating that EEG in different neurophysiological frequency ranges reacts differently to changes in blood flow velocity and the level of blood oxygenation. The fundamental papers of Japanese researchers [3,4] summarized the results of experimental studies and served as the basis for further study in this area. The experimental results described in the neurophysiological literature indicate the possibility of diagnosing delayed cerebral ischemia after subarachnoid hemorrhage using EEG [5-13]. At the same time, however, the problem of clinical diagnosis of delayed ischemia differs from the problem of group analysis of patients. This is caused by different EEG recording conditions leading to a large number of EEG artifacts, individual characteristics of patients, and the need for decision-making on changing the treatment regimen. Currently, EEG is considered a promising tool for diagnosing delayed ischemia but the creation of automatic diagnostic systems requires further research [9].

The most popular regularities of EEG changes caused by delayed cerebral ischemia described in the literature are the increase in the amplitude of the delta rhythm and the decrease in the amplitude of the alpha rhythm [4-6]. The EEG power spectral density (PSD) ratio in the delta and alpha frequency ranges is also widely used [14-16]. The use of the delta/alpha PSD ratio is appropriate when comparing groups of patients because it allows us to increase group differences by combining two regularities of opposite directions in one parameter. However, it should be noted that the problem of identifying regularities in patient groups is fundamentally different from the problem of clinical diagnosis of patients. The use of delta/alpha PSD ratio for individual patient diagnosis may cause erroneous results because the patterns of changes in alpha and delta rhythms may differ in different patients. In particular, in some patients, the alpha rhythm may be absent, which makes the delta/alpha PSD ratio mathematically incorrect.

In studies of EEG in delayed cerebral ischemia, the comparison of the EEG amplitude before and after the onset of ischemia was mainly carried out. Unfortunately, in clinical practice, it is not always possible to start EEG monitoring of a patient immediately after surgery. As a result, the doctor does not have EEG data that could be used to compare the EEG amplitude in case of suspected symptoms of delayed ischemia, which complicates the operational diagnosis based on the regularities described in the literature. Nevertheless, even in this case, signs based on the asymmetry of the EEG amplitude in the affected and contralateral hemispheres can be used for rapid diagnosis. The presence of interhemispheric EEG differences in patients with delayed ischemia is described in [3-6].

The problem of diagnostics based on EEG data obtained on the day of the onset of ischemia can be solved by visualizing interhemispheric EEG differences. One of the means of visual representation of EEG is the head map. Usually, the head map is a two-dimensional diagram on which the EEG amplitude values are displayed in a given frequency range on all EEG electrodes using a color scale (see an example in **Fig. 1**).

Head maps are a useful tool for diagnosing delayed cerebral ischemia if the software implementation of head maps allows displaying the average EEG amplitude over a sufficiently long time (for example, a day). The disadvantage of standard head maps is that different EEG trends are mixed and superimposed on the same diagram even if they are statistically independent. For example, different forms of interhemispheric asymmetry can be observed on different groups of electrodes; the head map will display the overall picture of the EEG amplitude for the entire considered time interval. In addition, all EEG artifacts, which can be quite significant, are also superimposed

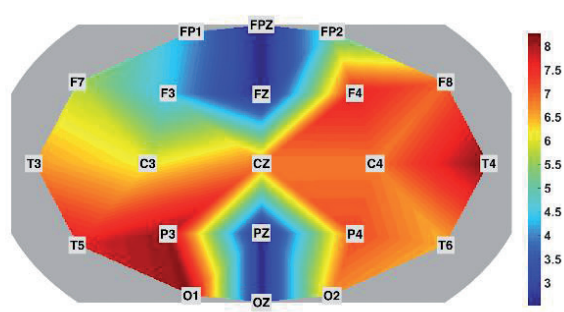

Fig. 1. *An example of a standard head map of* **a patient** *with delayed cerebral ischemia. The delta frequency range (2-4 Hz) is considered. The displayed value is the square root of the median of the square of the instantaneous EEG amplitude over 19 hours. The value is indicated using a color scale. On the head map, various trends in EEG changes are observed simultaneously as well as EEG artifacts. However, based on the head map, it can be concluded that there is interhemispheric EEG asymmetry in the delta frequency range.*

on the overall picture, which complicates the correct interpretation of EEG data. In this paper, we propose statistical tools based on AUC diagrams and the principal component analysis (PCA) that allows us to eliminate these shortcomings of standard EEG head maps. The idea of AUC diagrams is to visually represent the dependence of the area under the ROC curve (AUC) when comparing data samples from the boundaries of the range of given characteristic of this data, for example, frequency. The article proposes a new type of AUC diagram designed to identify interhemispheric EEG differences. The principal component analysis allows us to separate the components of the EEG signals, which are characterized by a correlated change in the signals in some groups of electrodes.

Another problem in using EEG to diagnose delayed cerebral ischemia is the choice of frequency ranges for analysis. The fact is that different authors use different boundaries of the neurophysiological frequency ranges delta, theta, alpha, and beta. Thus, there is an objective problem of determining and verifying the boundaries of the frequency ranges in which the manifestation of the regularities described in the literature on the diagnosis of delayed ischemia using EEG is expected. Frequency ranges must be substantiated and experimentally confirmed. In this work, AUC diagrams are used for this aim.

The article analyzes EEG data of two patients with clinically confirmed delayed cerebral ischemia induced by subarachnoid hemorrhage. Head maps of both patients showed similar patterns of interhemispheric EEG asymmetry in the delta, theta, alpha, and beta frequency ranges. Such asymmetry is not observed in patients before and after delayed ischemia as well as in patients from the control group.

2. DEVELOPMENT OF AUC DIAGRAMS FOR ANALYSIS OF INTERHEMISPHERIC EEG ASYMMETRY

2.1. Principles of constructing and reading AUC diagrams

The idea of AUC diagrams was proposed by the authors for the analysis of wave train electrical activity of the brain in the framework of the problem of diagnosing neurodegenerative diseases [17-21]. In this paper, the method of analyzing wave train electrical activity is not used; however, the principles of constructing and reading AUC diagrams remain the same. The EEG recording is divided into short segments (for example, 10 minutes each). We go through all possible combinations of values of the lower and upper bounds of the EEG frequency range. The average signal amplitude is calculated for each considered frequency range, for each EEG segment, and for each EEG electrode. For each considered frequency range, a matrix is formed:

$$M = \begin{bmatrix} a_{11} & \dots & a_{1k} \\ \dots & \dots & \dots \\ a_{m1} & \dots & a_{mk} \\ \hline b_{11} & \dots & b_{1k} \\ \dots & \dots & \dots \\ b_{m1} & \dots & b_{mk} \end{bmatrix},$$

where a_{ij} is the value of the average EEG amplitude in the considered frequency range in an electrode on the left side of the scalp; b_{ij} is the value of the average EEG amplitude in the considered frequency range in an electrode on the right side of the scalp; k is the number of pairs of symmetrical EEG electrodes; m is the number of short (10 minutes) EEG segments. The principal components of the M matrix are calculated using PCA. The number of components corresponds to the number of pairs of symmetrical electrodes. The projection of the M matrix onto the principal

components is calculated. As a result, *k* vectors are obtained; each vector includes *m* projections of amplitude values in the left hemisphere and *m* projections of amplitude values in the right hemisphere. The ROC curve for comparison of amplitude projection values in the left and right hemispheres is calculated. The area under the ROC curve (AUC) is calculated for a chosen principal component. The AUC values for all considered frequency ranges for the selected PCA component are displayed in the form of a two-dimensional diagram (AUC diagram).

Fig. 2 demonstrates an example of an AUC diagram of a patient with delayed ischemia after a subarachnoid hemorrhage corresponding to the first component of PCA. It is advisable to read the AUC diagram as follows. Let's consider monochromatic color areas adjacent to the diagonal of the AUC diagram. There are two large solid color areas in the diagram; one is cyan and the other is orange. The separation point of these regions, which is closest to the diagonal, approximately corresponds to the frequency of 6 Hz along the abscissa and ordinate axes. The cool colors (blue and cyan) on the diagram correspond to the AUC values < 0.5; the warm colors (red and yellow) correspond to AUC values > 0.5. Therefore, at frequencies below 6 Hz, the average EEG amplitude in the left hemisphere is less than in the right hemisphere, and at frequencies above 6 Hz, the average EEG amplitude, on the contrary, is greater in the left hemisphere. Thus, this patient has a multidirectional interhemispheric asymmetry of the EEG amplitude in different frequency ranges, which corresponds to the regularities of EEG changes in delayed cerebral ischemia described in the literature.

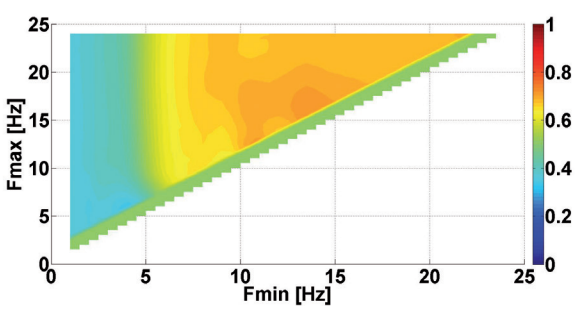

Fig. 2. *An example of an AUC frequency diagram of EEG of* **a patient** *with delayed cerebral ischemia. The displayed value is AUC when comparing the amplitudes of EEG fragments (daily EEG record is divided into 10-minute fragments) in the left and right hemispheres in the frequency range* [F_{min}, F_{max}], *where* F_{min} *is the lower bound of the frequency range, which is indicated by the abscissa, and* F_{max} *is the upper bound of the frequency range, which is indicated by the ordinate. The EEG amplitudes on all pairs of symmetrical electrodes are considered. To reduce the data of all electrodes to a single value, the projection of the amplitude values on* **the first** *component of PCA is calculated. The values are indicated using a color scale. On the AUC diagram, two solid areas are observed: cyan and orange. This is a consequence of the fact that the patient has opposite trends in interhemispheric EEG asymmetry in different frequency ranges.*

According to the literature, it can be expected that the revealed asymmetry of the EEG amplitude can be manifested differently in the areas of the scalp corresponding to different EEG electrodes. The degree of generalization of the revealed differences in the EEG amplitude is also important. To study these issues, we use interhemispheric asymmetry maps, which indicate the values of the PCA coefficients for different EEG electrodes.

2.2. Evaluation of the generalization degree of interhemispheric EEG differences

Interhemispheric asymmetry maps (IAMs) differ from standard head maps in that they reflect the degree of amplitude asymmetry between the corresponding pairs of EEG electrodes in the left and right hemispheres. The degree of asymmetry is displayed using a color scale. Gradations of red and yellow colors indicate electrodes where increased EEG amplitude is observed in comparison with the corresponding electrodes in the contralateral hemisphere. Electrodes in

the contralateral hemisphere are indicated by gradations of blue. IAM is always symmetrical along the vertical axis up to color inversion. This is a consequence of the fact that the information about the cause of the observed asymmetry is discarded. For instance, if the EEG amplitude is greater than normal in the right hemisphere, IAM looks the same as if the EEG amplitude is less than normal in the left hemisphere. This property of IAM allows us to focus on the properties of EEG interhemispheric asymmetry and abstract from the absolute value of the EEG amplitude. If necessary, the doctor can obtain comprehensive information about the EEG amplitude using standard head maps or by directly studying the EEG signals.

Another difference between IAM and standard head maps is that IAM corresponds to a single selected principal component of PCA. Thus, several IAMs correspond to one standard head map in the selected frequency range. When analyzing a patient's EEG, only IAMs corresponding to front components of PCA are usually used because they reflect the most substantial interhemispheric differences. Unfortunately, it is impossible to predict in advance which IAM contains useful diagnostic information. The fact is that some IAMs may correspond to EEG artifacts. Such IAMs are usually easy to recognize by their characteristic appearance which allows us to exclude the influence of EEG artifacts from the analysis and extract important information for the diagnosis of delayed ischemia.

Let us consider an example of IAM of a patient with delayed cerebral ischemia (**Fig. 3**). This IAM corresponds to the first component of PCA in the delta frequency range (2-4 Hz). Interhemispheric EEG asymmetry in the delta frequency range, generalized over the entire surface of the scalp is observed in IAM. Notably, interhemispheric differences are observed in the frontal area of the cortex including electrodes F3 and F4. A possible reason for this difference is that the affected brain region is located near the F4 electrode.

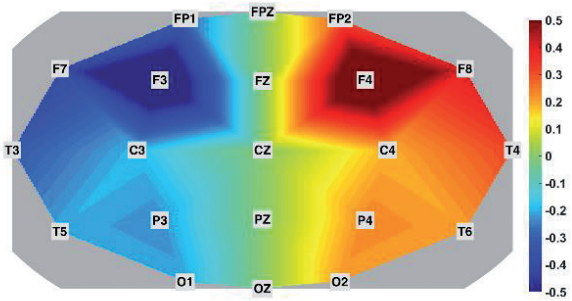

Fig. 3. *An example of an interhemispheric asymmetry map in* **a patient** *with delayed cerebral ischemia. The delta frequency range (2-4 Hz) is considered. The length of the EEG record is 19 hours. The displayed values are the coefficients of* **the first** *component of PCA. The values are indicated by a color scale. Interhemispheric EEG asymmetry in the delta frequency range is observed in IAM. It is generalized over the entire surface of the scalp. Notably, maximal interhemispheric differences are observed in electrodes F3 and F4.*

Note that we observed IAMs similar to Fig. 3 in both patients with delayed cerebral ischemia. At the same time, such IAMs were not observed when delayed ischemia is absent in patients. Below we will demonstrate that the considered patient has other forms of interhemispheric asymmetry corresponding to other components of PCA.

IAMs allow separating and considering one-by-one uncorrelated trends of interhemispheric EEG asymmetry. Next, typical cases of IAMs of the norm (patients not suffering from delayed ischemia) will be considered.

2.3. Examples of normal EEG visualization

Usually, the norm is not characterized by interhemispheric EEG asymmetry. Nevertheless, one can observe various forms of asymmetry in normal IAMs caused by EEG artifacts. **Fig. 4** demonstrates an example of IAM indicating a simple EEG artifact.

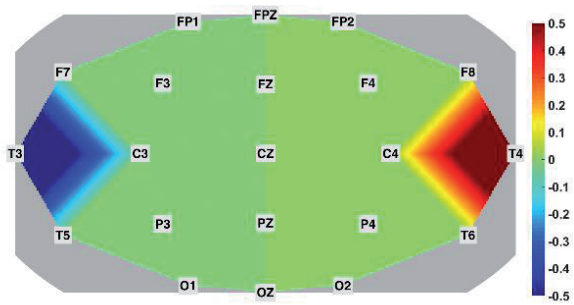

Fig. 4. *An example of an interhemispheric asymmetry map in* **a norm** *(a patient without delayed cerebral ischemia). The delta frequency range (2-4 Hz) is considered. The length of the EEG record is 32 hours. The displayed values are the coefficients of* **the first** *component of PCA. The values are indicated using a color scale. The coefficients of the PCA component under consideration differ from 0 only in electrodes T3 and T4. We can conclude that the observed interhemispheric difference is not generalized and is caused by an EEG* **artifact**.

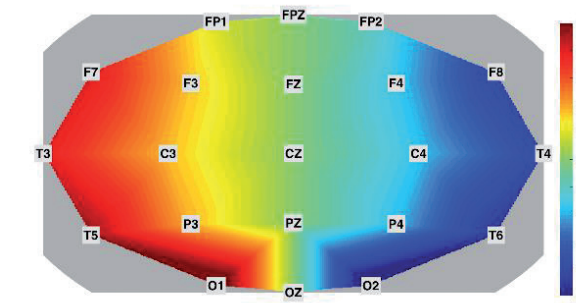

Fig. 5. *An example of an interhemispheric asymmetry map in* **a norm**. *The delta frequency range (2-4 Hz) is considered. The length of the EEG record is 17 hours. The displayed values are the coefficients of* **the first** *component of PCA. The values are indicated using a color scale. Interhemispheric EEG asymmetry in the delta frequency range is generalized over the entire surface of the scalp. Maximal interhemispheric differences are observed in electrodes O1 and O2. This example demonstrates that the presence of generalized interhemispheric asymmetry in itself is not a sign of a disease.*

Electrodes T3 and T4 in IAM are indicated in blue and red respectively. Other IAM electrodes are indicated in green, which corresponds to the coefficient of 0. This means that the observed differences between electrodes T3 and T4 do not correlate with other electrodes. Probably, the observed difference between electrodes is caused by the loss of electrical contact between the T3 electrode and the patient's skin.

Fig. 5 demonstrates a more complex example of a norm IAM. On this IAM, in contrast to the previous example, interhemispheric differences are observed in almost all electrodes located along the edges of the map. Such IAMs display EEG artifacts caused by the penetration of electromyographic signals (EMG) into EEG. The EEG electrodes located along the edges of the IAM are most affected by EMG of the muscles of the neck and face. In the example under consideration, observed EEG artifacts were caused by the patient lying mainly on his left side during the day.

Given examples demonstrate that the presence of amplitude asymmetry in the patient's IAM is not in itself a sign of delayed cerebral ischemia. It is necessary to take into account the form of EEG asymmetry, namely, the relative position and size of the colored area in IAM to diagnose the patient properly. Below, examples of IAMs of patients with delayed cerebral ischemia are given in various frequency ranges.

3. ANALYSIS OF INTERHEMISPHERIC EEG ASYMMETRY IN PATIENTS WITH DELAYED CEREBRAL ISCHEMIA

3.1. Data collection and preprocessing

EEG measurements of patients were carried out in the Department of Neurosurgery of the Sklifosovsky Research Institute for Emergency Medicine using a Mizar-EEG-202 electroencephalograph. Silver Chloride Cup EEG Electrodes were used. The electrodes were installed according to the standard 10-20 system; 21 EEG electrodes were installed. The reference and ground electrodes were placed

along the midline between points Fz and Cz. A high pass filter of 0.5 Hz and a low pass filter of 70 Hz were used. A sampling frequency of 250 Hz was used.

The clinical EEG differs from the laboratory EEG in containing a large number of outliers and significant zero drift. A possible method to improve the quality of EEG signals is the usage of the double banana montage. When using this montage, the computer screen displays the difference in EEG signals measured at nearby electrodes. Double banana montage helps to reduce the zero drift in the EEG signals but the number of outliers in the EEG signals only increases because EEG contains outliers originating from both subtracted EEG channels. In this study, we solve the problem of removing outliers in EEG signals using the X42 statistical method [22] with preliminary trend removal using median filtering. **Fig. 6** demonstrates an example of an EEG signal before zero drift and outliers were removed. **Fig. 7** demonstrates the same signal after removing the outliers.

During the construction of AUC diagrams, the EEG record is divided into segments of 10 minutes. When considering different frequency ranges, the EEG signal is filtered by 8-order Butterworth bandpass filters. The signal is passed through the filter in the forward direction and then in the reverse direction to

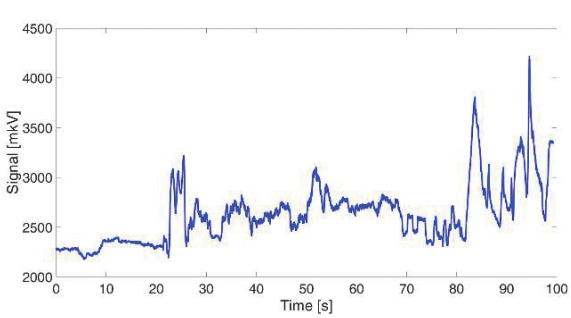

Fig. 6. *An example of a clinical EEG record. The signal contains a significant zero drift which complicates the application of standard outlier removal methods. The abscissa axis is time in seconds. The ordinate axis is the signal in μV.*

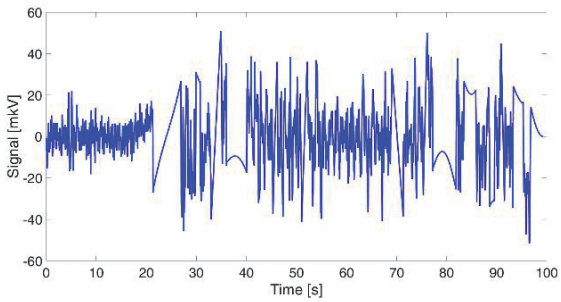

Fig. 7. *An example of a clinical EEG record after the removal of outliers using the X42 statistical method with preliminary removal of zero drift using median filtering. The abscissa axis is time in seconds. The ordinate axis is the signal in μV.*

prevent the phase shift. The instantaneous amplitude of the filtered EEG signal is computed using the Hilbert transform. The square of the instantaneous amplitude of the filtered EEG signal is computed. The average value of the squared instantaneous amplitude is computed. The computed average value is used to compare EEG segments and construct AUC diagrams. When constructing the M matrix, 16 electrodes of 21 were used; thus, 8 pairs of symmetrical EEG electrodes were considered.

3.2. EEG analysis in different frequency ranges

Let us consider examples of IAMs in different frequency ranges. The EEG data in the same patient with delayed cerebral ischemia discussed in Sections 1, 2.1, and 2.2 will be used to construct IAM.

The AUC diagram corresponding to the first component of PCA was considered in Fig. 2. Let us create an AUC diagram corresponding to the second component of PCA (see **Fig. 8**). In the diagram, there is a solid blue area in the delta, theta, alpha, and beta frequency ranges. Note that the abrupt transition from dark blue to dark red in the frequency range above 16 Hz is a computational artifact that does not affect the color of the corresponding IAMs.

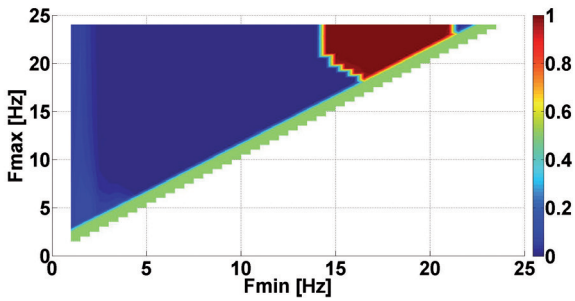

Fig. 8. *An example of an AUC frequency diagram of EEG in* **a patient** *with delayed cerebral ischemia. The displayed value is AUC when comparing the amplitudes of EEG fragments in the left and right hemispheres. The projection of the amplitude values onto* **the second** *principal component is computed. The value is indicated using a color scale. On the AUC diagram, there is a blue area in the delta frequency range of 2-4 Hz.*

The IAM corresponding to the second component of PCA in the delta frequency range (2-4 Hz) is demonstrated in **Fig. 9**. This IAM can be considered as a refinement of IAM corresponding to the first component of PCA demonstrated in Fig. 3. In other words, the relationship between the degrees of interhemispheric asymmetry in different pairs of electrodes is not limited to the correlation

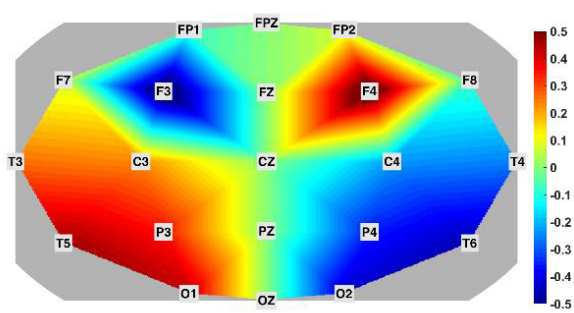

Fig. 9. *An example of an interhemispheric asymmetry map in* **a patient** *with delayed cerebral ischemia. The* **delta** *frequency range (2-4 Hz) is considered. The length of the EEG record is 19 hours. The displayed values are the coefficients of* **the second** *principal component of PCA. The values are indicated using a color scale. Interhemispheric EEG asymmetry in the delta frequency range is generalized over the entire surface of the scalp. There is a correlation between an increase in the EEG amplitude in the affected area (electrode F4) and a decrease in the EEG amplitude in the central and occipital regions of the scalp.*

demonstrated in Fig. 3. There is a weaker trend of the interhemispheric asymmetry demonstrated in Fig. 9 against the background of the trend demonstrated in Fig. 3.

In Fig. 9, there is a correlation between an increase in amplitude in the area of brain damage (electrode F4) and a decrease in amplitude in the central and occipital regions of the scalp. This correlation can be explained by that the increase in the amplitude of the delta rhythm in the F4 electrode is caused by the presence of a breach-rhythm [23] but not only the delayed cerebral ischemia. We observe IAMs, similar to Fig. 9 in both patients with delayed cerebral ischemia. At the same time, such IAM was not observed in patients if the delayed ischemia is absent.

Let us consider frequency ranges. The AUC diagram of the first component of PCA (Fig. 2) demonstrates that the theta neurophysiological range is located on the border between the frequency ranges where different interhemispheric asymmetry is observed. In this situation, we cannot consider the standard theta range (4-8 Hz) as a whole. Below, we consider the upper subrange of 6-8 Hz of the theta range.

The study of IAM in the theta subrange 6-8 Hz demonstrates that IAM in the theta subrange 6-8 Hz is more varied than in the delta range. In particular, we observed a decrease in the theta rhythm on different days in the occipital, central, and frontal parts of the scalp in patients with delayed ischemia in the first component of PCA (see an example in **Fig. 10**).

The high variability of IAM in the theta subrange 6-8 Hz may be caused by that this frequency range is located on the border of the delta and alpha ranges that demonstrate different directions of the change in the EEG amplitude. There is an opinion that the decrease in the alpha and beta rhythms

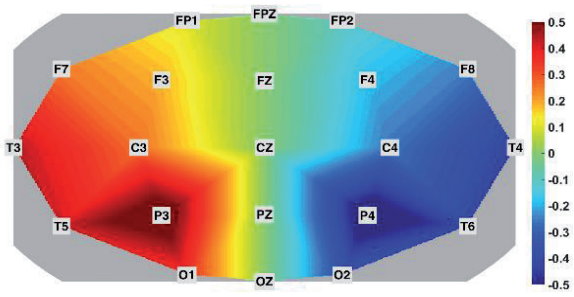

Fig. 10. *An example of an interhemispheric asymmetry map in* **a patient** *with delayed cerebral ischemia. The upper* **theta** *subrange 6-8 Hz is considered. The length of the EEG record is 19 hours. The displayed values are the coefficients of* **the first** *component of PCA. The values are indicated using a color scale. We observe an interhemispheric EEG asymmetry in IAM generalized over the entire surface of the scalp. Notably, maximal interhemispheric differences are observed in the posterior region of the scalp in the electrodes P3 and P4.*

may occur later than the increase in the delta rhythm in patients with delayed ischemia [12, 24]. This issue may also be a reason for the variability of IAM in the theta subrange. Thus, IAM in the theta range may contain important information about the clinical course but this issue requires more detailed study.

In IAM of the first PCA component in the alpha frequency range (8-12 Hz), we observed a decrease in the EEG amplitude in the central and posterior areas of the scalp on the affected hemisphere in one patient with delayed cerebral ischemia (see example in **Fig. 11**). This localization of the interhemispheric asymmetry may relate to the fact that the sources of the alpha rhythm are located in the occipital region of the cortex and the sources of the mu rhythm (at the same frequencies) are located in the central region of the cortex. In the second patient with delayed ischemia, a similar pattern of changes in the alpha rhythm was also observed; however, the corresponding IAM was practically the same as the IAM of the normal alpha rhythm. Thus, alpha IAMs also provide useful diagnostic information but their applicability may be more limited than delta IAMs.

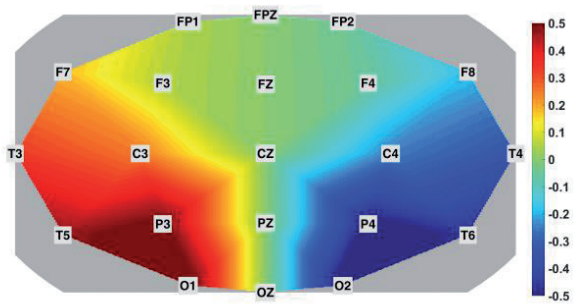

Fig. 11. *An example of an interhemispheric asymmetry map in* **a patient** *with delayed cerebral ischemia. The* **alpha** *frequency range (8-12 Hz) is considered. The length of the EEG record is 19 hours. The displayed values are the coefficients of* **the first** *component of PCA. The values are indicated using a color scale. We observe an interhemispheric asymmetry of EEG in the alpha frequency region generalized in the central and posterior regions of the scalp.*

IAMs of the first component of PCA in the beta-I frequency range (13-15 Hz) in both patients with delayed cerebral ischemia were similar to IAM in the alpha frequency range. Thus, examples of IAMs in the beta-I frequency range are not given for brevity.

Fig. 12 demonstrates an example of IAM of the first component of PCA in the beta-II frequency range (17-24 Hz). Notably, IAM in the beta-II range differs from IAM in the alpha range. This difference can be explained by that the sources of the beta

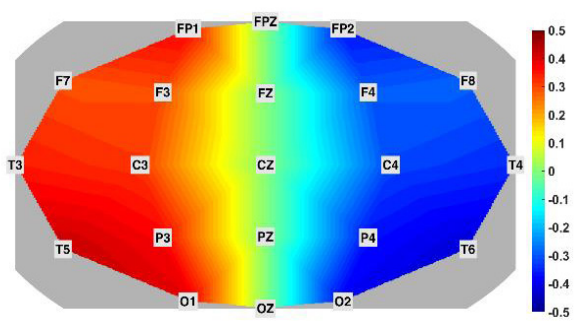

Fig. 12. *An example of an interhemispheric asymmetry map in* **a patient** *with delayed cerebral ischemia. The* **beta-II** *frequency range (17-24 Hz) is considered. The length of the EEG record is 19 hours. The displayed values are the coefficients of* **the first** *component of PCA. The values are indicated using a color scale. We observe the interhemispheric EEG asymmetry in the beta-II frequency range generalized over the entire surface of the scalp.*

rhythm in the cerebral cortex do not have a definite localization. We observe IAMs similar to Fig. 12 in both patients with delayed cerebral ischemia. At the same time, such IAMs were not observed in patients when delayed cerebral ischemia is absent.

Thus, all considered neurophysiological frequency ranges delta, theta, alpha, and beta contain useful information about the clinical course of the disease; however, the diagnostic value of the frequency ranges is different. Let us compare the results of the interhemispheric EEG asymmetry analysis with the data described in the literature.

3.3. Comparison of EEG analysis results in frequency ranges

Research papers studying EEG in patients with delayed cerebral ischemia describe mainly changes in EEG in different frequency ranges over time. In other words, EEG is compared before and after the onset of delayed ischemia [4-6]. In contrast to these studies, we compare EEG in the cerebral hemispheres directly during delayed ischemia. Nevertheless, the results of studies can be compared because EEG changes over time are different in the affected and contralateral hemispheres [3,25-28].

Research papers express different opinions about the diagnostic value of different EEG ranges. For example, [29] demonstrated that the theta and alpha ranges have the highest diagnostic value for the early diagnosis of delayed cerebral ischemia (2-3 days in advance); a 40% decrease within 5-6 hours in focal EEG amplitude was considered as a sign of this complication. The paper [29] notes the importance of removing EEG artifacts and the separation of focal EEG changes and regional EEG changes caused by the status of patients and drug-induced action. In the framework of our method, we use IAMs to detect interhemispheric asymmetry caused by focal EEG changes and PCA to separate uncorrelated focal and regional EEG changes. In addition, we use AUC diagrams to refine the boundaries of the EEG frequency ranges. In most studies, including [29], this check is not implemented; thus, the diagnosis is carried out using incorrect boundaries of the theta range, which simultaneously falls into the regions of an increase and a decrease in the EEG amplitude. This issue allows us to explain the contradictory data on the theta range EEG amplitude changes reported in the literature [4,5].

[30] reports that delta range EEG interhemispheric asymmetry depends on the degree of damage in the cortex and subcortical structures of the brain. Thus, EEG in the delta range may contain additional information useful for diagnosing the patient. We used IAM for analyzing delta range EEG to separate the sign of delayed cerebral ischemia and delta waves caused by sleep. IAMs allow one to abstract from EEG changes caused by sleep because they appear mainly simultaneously on both hemispheres of the brain.

A study of shorter time intervals (about 1 hour) demonstrated that IAMs of patients with delayed cerebral ischemia in some intervals were similar to IAMs of the daily records considered above. However, the estimation of minimal time intervals sufficient for an accurate diagnosis of delayed ischemia is a topic for additional research. The examples of patients with delayed cerebral ischemia considered in this paper are not sufficient to make conclusions about the sensitivity and specificity of the observed interhemispheric asymmetry maps. We can only conclude that the developed visualization tool helps to identify EEG asymmetry patterns that are expected from a neurophysiological point of view.

4. CONCLUSION

A new type of EEG head map named the interhemispheric EEG asymmetry map was developed. The purpose of these maps is to identify signs of delayed cerebral ischemia after subarachnoid hemorrhage. A new type of AUC diagram was developed to check the boundaries of the EEG frequency ranges in which the analysis is carried out. Using AUC diagrams, we have demonstrated that the standard neurophysiological theta range is located on the border between the frequency ranges where the EEG amplitude changes in different directions. This fact allows us to explain contradictory data reported in the literature. IAMs allow us to detect interhemispheric asymmetry caused by focal EEG changes, while PCA is used to separate uncorrelated focal and regional EEG changes. The principles of construction and reading of IAMs and AUC diagrams are demonstrated by the example of analyzing data in two patients with clinically confirmed delayed cerebral ischemia after subarachnoid hemorrhage. EEG changes were demonstrated in the delta, theta, alpha, and beta ranges.

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