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Quantitative electroencephalography analysis data in outpatient patients with psychosomatic manifestations following COVID-19

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Abstract. ***Introduction.*** The electroencephalography is considered as the most important tool for assessing the spatiotemporal features of the electrical activity of the brain in the examination of patients with neurological manifestations of COVID-19, especially in cases of encephalopathy, seizures and epileptic status. ***Aim.*** It was planned to identify various electroencephalography patterns characteristic of the COVID-19 group of patients with visual electroencephalography analysis and to evaluate possible focal changes using quantitative methods such as spectral and coherent analysis. ***Materials and methods.*** The electroencephalography of 125 outpatient patients aged 16 to 68 years who were under observation at a neuropsychiatric dispensary with a history of COVID-19 and psychosomatic complaints at the time of the examination was recorded. The control group consisted of 45 healthy subjects. ***Results.*** The obtained results made it possible to divide the results of electroencephalography registration and analysis into three types of patterns: polymorphic low-frequency activity; low-frequency polymorphic activity with a predominance of slow waves (delta and theta bands); high-frequency electroencephalography with a dominant in the beta1 band. ***Conclusions.*** The formation of focal changes of a slow-wave nature with a characteristic localization in the right temporal region is noted in 20% of patients. The correlation index in the alpha range is stable for the electroencephalography of the control group, where 90% of the subjects had correlation coefficients in the alpha range of more than 0.6. On the contrary, a polymorphic pattern is observed among patients, stable indicators with a coefficient of more than 0.6 for all studied connections, both between the hemispheres and within the hemispheres, were recorded only in 25% of cases. The analysis of coherence coefficients in patients, on the contrary, shows a higher stability of interhemispheric connections and various options for reducing connections within the hemispheres, which often have a mirror character.

Keywords: electroencephalography, post-COVID condition, EEG spectral analysis, EEG coherence analysis

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Количественный анализ электроэнцефалографии у амбулаторных пациентов с психосоматическими проявлениями после COVID-19

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Резюме. ***Введение.*** Электроэнцефалографию рассматривают как наиболее важный инструмент для оценки пространственно-временных особенностей электрической активности мозга при обследовании пациентов с неврологическими проявлениями COVID-19, особенно при проявлении энцефалопатии, судорог и эпилептического статуса. ***Цель исследования*** — выделить различные паттерны электроэнцефалограммы, характерные для группы пациентов, перенесших COVID-19, при визуальном анализе электроэнцефалограммы и с помощью количественных методов — спектрального и когерентного анализа, оценить возможные очаговые изменения. ***Материалы и методы.*** Регистрировали электроэнцефалограмму 125 амбулаторных пациентов в возрасте от 16 до 68 лет, находящихся под наблюдением в психоневрологическом диспансере с COVID-19 в анамнезе и психосоматическими жалобами на момент обследования. Контрольную группу составили 45 здоровых испытуемых. ***Результаты.*** Данные регистрации и анализа электроэнцефалограммы были разделены на три типа паттернов: полиморфная низкочастотная активность; низкочастотная полиморфная активность с преобладанием медленных волн (дельта- и тета-диапазоны); высокочастотная электроэнцефалограмма с доминантой в бета-1-диапазоне. ***Выводы.*** Отмечено формирование очаговых изменений медленноволнового характера с характерной локализацией в правой височной области у 20% пациентов. Индекс корреляции в альфа-диапазоне стабилен для электроэнцефалографии контрольной группы, где у 90% испытуемых коэффициенты корреляции в альфа-диапазоне были более 0,6. Напротив, среди пациентов наблюдалась полиморфная картина, стабильные показатели с коэффициентом более 0,6 для всех изученных связей как между полушариями, так и внутри полушарий были зарегистрированы только в 25% случаев. При анализе коэффициентов когерентности у пациентов отмечены более высокая стабильность межполушарных связей и различные варианты ослабления связей внутри полушарий, которые часто носят зеркальный характер.

Ключевые слова: электроэнцефалография, ЭЭГ, постковид, спектральный анализ, когерентный анализ ЭЭГ

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Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

INTRODUCTION

The period of the spread of coronavirus infection (COronaVIrus Disease 2019, COVID-19) was marked by an explosive surge in research across virology, epidemiology, infectious diseases, clinical physiology, and pharmacology. It became evident that the changes induced by the infection pertain to the interests of the most diverse, and often highly specialized, fields of medical science. Numerous specialists in laboratories around the world are observing a variety of specific and nonspecific manifestations of the consequences of coronavirus infection, both proximate in the history and quite remote. Scientific debate continues as to whether the nonspecific, yet similar, findings in a series of published cases of COVID-19-associated encephalopathy (disorganized background activity with diffuse slowing and frontal predominance, accompanied by low reactivity) can be considered distinctive features of COVID-19 or whether, conversely, these findings stem from a multifactorial origin not directly caused by the virus [1–7]. Furthermore, the interest in electroencephalography (EEG) findings in COVID-19 is driven by analogous results observed in a number of neurological conditions — viral encephalitis/encephalopathy associated with COVID-19, epilepsy, as well as demyelinating and neurodegenerative processes [1, 8, 9]. Neurological complications arise in one-third (34.6%) of patients with severe COVID-19 and include stroke, headache, and seizures [10]. In publications addressing EEG in COVID-19, the number of patients ranges from isolated cases [8, 11, 12] to 100 [13, 14]. The findings of these studies are heterogeneous, encompassing both normal EEG [15] and diffuse slowing in all cases [16–18]. Some works have demonstrated a predominance of frontal changes [1, 7, 19, 20].

The most common EEG finding, observed in two-thirds (68.6%) of patients, is a generalized reduction in the mean frequency of oscillations [21–23]. This may serve as a marker of diffuse nonspecific encephalopathy, the most prevalent brain abnormality in this disease. Other EEG signs indicative of diffuse encephalopathy include generalized rhythmic delta activity and generalized periodic discharges with triphasic morphology [24–26]. Lateralized periodic and rhythmic patterns, characteristic of concomitant focal dysfunction in some patients, are also recorded. Epileptiform abnormalities are not uncommon in the studied EEGs (13.0%), suggesting heightened cortical excitability preceding seizure events. Indeed, 5.5% of patients experienced seizures or status epilepticus [27, 28]. Studies occasionally note characteristic frontal abnormalities, which correlates with the presumed entry of COVID-19 into the brain [8, 16, 17, 19, 20].

Early clinical manifestations of COVID-19, such as anosmia and ageusia, are thought to be linked to viral entry into the nasal and oral mucosa, a process facilitated by ACE-2 receptors (angiotensin-converting enzyme 2) [27–29]. Subsequent spread to the orbitofrontal region [29] via afferent nerves leads to predominant involvement of the olfactory bulb and orbitofrontal/frontal areas, which may explain the emergence of focal EEG changes in frontal leads [28]. Several authors have proposed frontal epileptiform discharges as biomarkers of COVID-19 [8, 12, 16, 32, 33]. Approximately half of all recorded epileptic events (10 of 22) originate in the frontal lobes, compared with 18% (4 of 22) in the occipital lobe. Beyond the frontal lobe, COVID-19 may also affect the piriform cortex, limbic structures, thalamus, hypothalamus, brainstem, and autonomic structures [30, 31, 34–36]. Investigators have sought to link diverse EEG findings in patients with prior COVID-19 to other factors, such as lung injury with subsequent hypoxia, cardiac arrest, metabolic derangements, systemic inflammatory response syndrome, hypercoagulability, vasculitis, and stroke, among others. Evidence indicates that the severity of EEG abnormalities correlates with blood oxygen saturation upon hospital admission, though this relationship has yet to be confirmed by neuroimaging data [37]. In addition, EEG changes may also be attributable to pre-existing neurological conditions, such as epilepsy [19, 38, 39]. Thus, to date, no single EEG pattern has been identified that would develop within a short time frame from the onset of COVID-19 spread. The spectrum of neurophysiological changes will undoubtedly be very broad and polymorphic; however, a statistically robust analysis of large datasets will reveal avenues for further investigation. Furthermore, intriguing incidental findings remain a distinct possibility.

AIM

The aim of this study was to identify EEG patterns characteristic of the patient group by means of both classical visual EEG analysis and quantitative methods — spectral and coherence analysis — and to detect possible focal changes emerging on EEG as sequelae of COVID-19.

MATERIALS AND METHODS

Outpatient patients undergoing routine diagnostic workup and treatment at the Saint Petersburg State Budgetary Healthcare Institution “Psychoneurological Dispensary No. 1” (PND) were examined. Two groups, A and B, were formed for the analysis. Group A comprised 125 patients (age range 18–68 years, 68 women

and 57 men) who had sustained COVID-19 3 to 12 months prior to examination and presented with various psychosomatic complaints that had prompted them to seek psychotherapeutic care. Group B (control) consisted of 45 healthy subjects (with an age and sex distribution matching that of Group A) undergoing fitness-for-duty evaluation with no history of coronavirus infection.

EEG was recorded in accordance with the international 10–20 system using 16 monopolar leads (Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, T5, T6, P3, P4, O1, O2) in a standard reference montage (the reference electrode was placed over the subjects' left zygomatic region). EEG recordings were obtained using the Mitsar-EEG-202 hardware-software system. Routine functional tests were performed during the examination, including eyes-open and eyes-closed tests, intermittent photic stimulation at varying frequencies (1–15 Hz range), and a three-minute hyperventilation test with forced breathing.

Computer analysis was performed using WinEEG 2.1 and Loreta-Key Viewer 04 software. EEG recordings were initially assessed visually with respect to frequency and amplitude parameters, rhythm distribution over the convexital surface, and the degree of rhythm desynchronization upon eye opening and/or the appearance of single photic stimuli. Using quantitative EEG methods, spectral power was determined in the main frequency bands, with correlation coefficients taken into account when comparing intrahemispheric and interhemispheric interactions.

The parameters for spectral power estimation were as follows: an epoch of 10 s duration was selected, with an analysis period of 5 s. The following additional parameters were applied: 50% overlap between analysis periods, a Hann window, and a low-frequency signal filter in the 0.25–1.25 Hz range. Furthermore, the mean power spectrum was calculated for all recording channels of the selected artifact-free EEG segments. The results obtained were converted into percentages such that the total sum across all frequency bands for each lead under study equaled 100%.

Local changes in spectral power were visualized by means of low-resolution electromagnetic tomography (LORETA), the results of which were presented as two-dimensional maps of distribution across anatomical structures. Statistical data processing was carried out using Microsoft Office Excel, SPSS, and Statistics 17.0 software. The reliability of the findings was assessed using Student's t-test. Differences were considered statistically significant at a significance level of $p < 0.05$.

RESULTS

Visual analysis of EEG recordings from COVID-19 convalescent outpatients revealed a tendency toward diminished alpha rhythm expression. Alpha activity emerged with a delay both at recording onset and upon resumption following the eyes-open/eyes-closed test or single photic stimuli. It is well established that in healthy individuals, the emergence of a stable, high-amplitude alpha rhythm at the beginning of an EEG recording under standard conditions (dimmed light, muscle relaxation, silence) varies temporally (from 1 s to 1 min in 90% of those examined).

For data comparison, we employed the alpha rhythm recovery test after eye opening followed by eye closure, with the «eyes closed» timestamp in the EEG file serving as the reference point. Among healthy participants (control group), a stable alpha rhythm emerged within 1–2 s in 80% of cases. In study Group A, alpha rhythm recovery occurred within 5–10 s in 60% of participants.

Fig. 1 presents a fragment of the baseline EEG illustrating this phenomenon. The patient, a 48-year-old man, complained of poor sleep, inability to concentrate, and impaired attention and memory. He had sustained coronavirus infection 4 months prior, had been managed on an outpatient basis, with an acute phase lasting no fewer than 20 days; computed tomography revealed pneumonia typical of COVID-19. Notably, Group A participants exhibited a reduction in alpha rhythm amplitude. Concurrently, the frequency values of this rhythm in these patients lay closer to the upper boundary of the range (11–12 Hz versus 9–10 Hz in the control group).

In the present study, comparison of EEG spectral power between the two groups revealed a consistent reduction in the alpha-band index in patients who had sustained COVID-19, whereas the EEG of healthy individuals demonstrated a clear predominance of the alpha rhythm on both visual analysis and spectral power estimation. Fig. 2 shows a "brighter" red-to-yellow spectrum corresponding to a high level of alpha-band oscillations, together with its symmetrical distribution and a maximum value in the occipital region. This pattern of spectral power distribution is characteristic of 70% of healthy individuals. Visually, such EEG recordings are assessed as patterns with a dominant alpha rhythm.

In Group A (outpatients), a broader distribution of spectral power variants across different EEG frequency bands is observed, satisfying the criterion of statistical significance ($p < 0.05$) relative to the spectral power data from the healthy group. The traditional



Fig. 1. **Electroencephalogram of a 48-year-old man who recovered from COVID-19. Delayed alpha rhythm recovery after eye closure. Markers indicate a steady increase in the alpha frequency range index from the 5th second (photo from the archive of PND No. 1, 2022–2023)**

Рис. 1. Электроэнцефалограмма мужчины, перенесшего COVID-19, 48 лет. Замедление восстановления альфа-ритма после закрытия глаз. Маркеры указывают на устойчивое увеличение индекса альфа-диапазона с 5-й секунды (фото из архива ПНД № 1, 2022–2023 гг.)

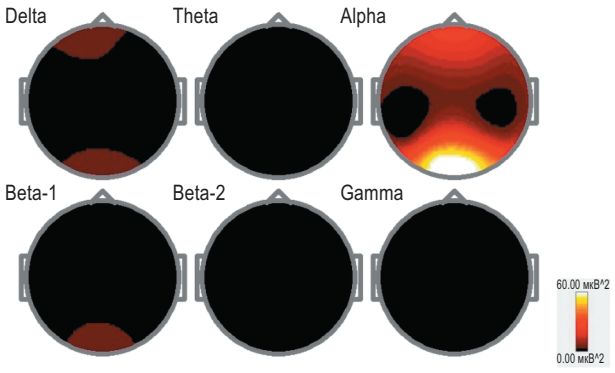


Fig. 2. **Distribution of electroencephalogram spectral power in a healthy subject (male, 45 years old) from control group B (photo from the archive of PND No. 1, 2022–2023)**

Рис. 2. Распределение спектральной мощности при выполнении электроэнцефалографии у здорового испытуемого (мужчина, 45 лет) из контрольной группы В (фото из архива ПНД № 1, 2022–2023 гг.)

alpha rhythm dominance occurs considerably less often (20%). In the majority of patients (62%), the EEG is characterized by a distribution of biosignals spanning all bands from delta to beta-2 waves. In such cases, no stable dominant rhythm can be identified (Fig. 3).

Figs. 3 and 4 present EEG frequency analysis maps along with the electromagnetic brain tomography results of a 50-year-old male patient who had sustained moderate COVID-19. Six months earlier, he had been treated in a general hospital with subsequent transfer to an infectious disease unit. Although the patient considers himself recovered and has resumed work, he complains of persistent signs of asthenia with autonomic dysfunction: general weakness, excessive sweating, and, consequently, a loss of vital energy.

Analysis of the data revealed the formation of a localized focus of slow-wave activity in the delta range (and, to a lesser extent, in the theta range) in the right cerebral hemisphere, with the greatest prominence in the temporal region. This local phenomenon is clearly visualized on the two-dimensional map generated by low-resolution electromagnetic tomography (LORETA): the red arrow marks a zone of increased spectral power in the right temporal lobe (see Fig. 4). Such focal dominance was recorded in 20% of the patients comprising Group A. Notably, on visual assessment, EEG recordings of this type are classified as low-amplitude polymorphic activity.

The third EEG variant observed in the patient group (approximately 20%) is characteristic of a broad range of psychosomatic patients and is therefore regarded as nonspecific. This variant is distinguished by a shift of spectral power into the beta-1 and beta-2 bands, with the emergence of two “centers of activity” — in the alpha and beta regions (Fig. 5). Visually, such EEG variants are assessed as high-frequency patterns with a noticeable beta-1 band dominance and fragmentary, weakly expressed alpha activity. In their reports, specialists frequently employ the phrase “flat EEG”.

Table 1 presents summarized data on spectral power (μV) across the frequency bands studied. Cells demonstrating an accent of spectral power in the right temporal region are highlighted.

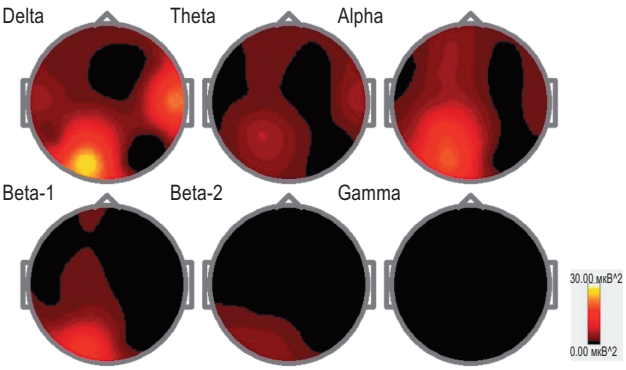


Fig. 3. **Spectral power of the electroencephalogram in the subject of the experimental group A (male, 55 years old). The signal distribution is visible in all ranges from delta to beta-2 (photo from the archive of PND No. 1, 2022–2023)**

Рис. 3. Спектральная мощность электроэнцефалографии у испытуемого опытной группы А (мужчина, 55 лет). Видно распределение сигнала по всем диапазонам от дельта до бета-2 (фото из архива ПНД № 1, 2022–2023 гг.)

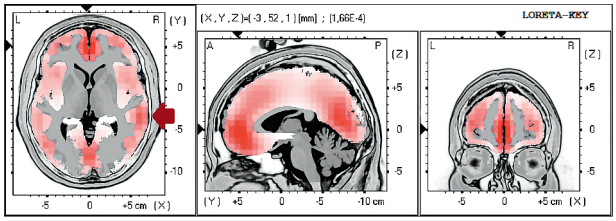


Fig. 4. **Low-resolution electromagnetic tomography of the LORETA — visualization of local changes in the right temporal region (the same subject, Fig. 3) (photo from the archive of PND No. 1, 2022–2023)**

Рис. 4. Электромагнитная томограмма низкого разрешения LORETA — визуализация локальных изменения в правой височной области (тот же испытуемый, рис. 3) (фото из архива ПНД № 1, 2022–2023 гг.)

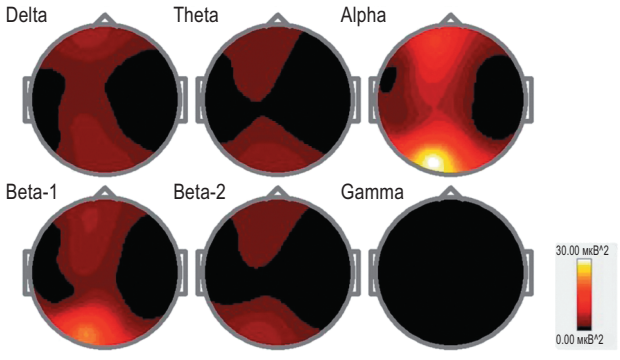


Рис. 5. **Распределение спектральной мощности у пациента группы А (женщина, 38 лет). Отмечается формирование двух акцентов в бета-1- и альфа-диапазонах (фото из архива ПНД № 1, 2022–2023 гг.)**

Fig. 5. Spectral power distribution in a patient, group A (female, 38 years old). Two accents in the beta-1 and alpha bands are noted (photo from the archive of PND No. 1, 2022–2023)

Among the systemic findings, the considerable divergence in EEG spectral power between patients and healthy subjects with respect to oscillations in the slow bands — delta and theta rhythms — is particularly noteworthy. Although the amplitude of these rhythms is reduced in patients, their spectral expression is considerably higher. A certain predominance in the right temporal EEG recording sites is also notable. The spectral power of the alpha rhythm is higher in healthy individuals than in patients; however, substantial differences are recorded only in the frontal and occipital regions. Following the determination of EEG spectral power, coherence analysis was performed to compare interhemispheric and intrahemispheric interactions. In healthy subjects (Group B), high correlation coefficients are consistently observed both between hemispheres (in the Fp1–Fp2, C3–C4, F7–F8, T3–T4, T5–T6, P3–P4, and O1–O2 pairs) and within hemispheres (in the Fp1–T3, Fp1–C3, Fp2–C4, Fp2–T4, T3–O1, C3–O1, T4–O2, and C4–O2 pairs) (Fig. 6).

In the control group, the alpha correlation index remained stable throughout the 10-second EEG segment selected for analysis. In 90% of the subjects in this group, alpha rhythm correlation coefficients exceeded 0.6. By contrast, the patients exhibited a heterogeneous EEG picture. Stable values with a coefficient above 0.6 across all interhemispheric and intrahemispheric connections studied were recorded in only 25% of participants, a statistically significant difference from the control group ($p < 0.05$). In the majority of the remaining cases, weakened interaction between individual pairs of leads was noted, predominantly in the temporal regions (T3 and/or T4).

As an illustration of coherence analysis, we present the case of Patient S., a 50-year-old man who sustained moderate COVID-19 requiring hospitalization and intensive care unit treatment (Fig. 7). Six months after recovery, the patient complained of intermittent muscle pain, reduced work capacity, and poor sleep. EEG analysis revealed a decreased interhemispheric correlation coefficient at T3–T4, along with reduced intrahemispheric interactions in the Fp1–T3 and T4–O2 derivations.

Examination of coherence measures in Group A patients demonstrated enhanced stability of interhemispheric interaction against a background of diverse manifestations of weakened intrahemispheric connectivity, often exhibiting mirror symmetry. As an example of coherence analysis, Fig. 8 presents the case of Patient K., a 55-year-old woman who had sustained moderate coronavirus infection approximately six months earlier, with initial admission to a general hospital and

Table 1

Electroencephalography spectral power (μV) in delta, theta, and alpha bands

Таблица 1

Спектральная мощность электроэнцефалографии (мкВ) в дельта-, тета- и альфа-диапазонах

ЭЭГ-отведение EEG-Ableitung	Опытная группа (A) An experienced group (A)			Контрольная группа (B) The control group (B)		
	дельта delta	тета theta	альфа alpha	дельта delta	тета theta	альфа alpha
Fp1	5±1,2**	10±4,2**	12±4,5**	0,2±0,1	5±2,2	21±7,8
Fp2	6±2,1**	11±4,6**	17±6,4	0,3±0,1	5±2,3	19±7,5
F3	5±2,2**	9±3,9**	16±5,4	0,1±0,1	4±1,9	17±6,8
F4	4±1,9**	10±4,1**	17±6,5	0,2±0,1	3±1,6	19±7,6
F7	5±2,3**	11±4,5**	15±5,0	0,3±0,1	3±1,7	16±6,5
F8	4±1,7**	8±3,8*	19±7,9	0,3±0,1	4±1,8	22±8,1
C3	2±1,4*	10±4,1**	11±3,9	0,3±0,1	3±1,6	12±4,7
C4	1±0,6*	9±3,7**	10±3,6	0,2±0,1	3±1,6	10±4,4
T3	3±1,6**	11±4,3**	16±5,6	0,3±0,1	2±1,4	17±6,7
T4	6±4,5**	15±5,9**	14±4,8	0,4±0,1	3±1,5	15±4,3
T5	3±1,7**	10±4,5**	18±7,6	0,3±0,1	3±1,6	20±7,5
T6	7±5,6**	14±5,7**	16±5,4	0,2±0,1	2±1,4	18±6,9
P3	4±1,9**	9±3,8**	19±7,8*	0,4±0,2	3±1,6	25±10
P4	4±1,9**	10±4,1**	20±8,1	0,3±0,1	3±1,5	22±9,5
O1	6±4,3**	11±4,4**	22±8,8**	0,2±0,1	4±1,8	35±11,3
O2	6±4,5**	10±4,2*	24±10,1**	0,3±0,1	5±2,0	32±11,1

Reliability * p <0.05; **p <0.01.
Достоверность * p <0,05; **p <0,01.

The table is prepared by the authors
Таблица составлена авторами

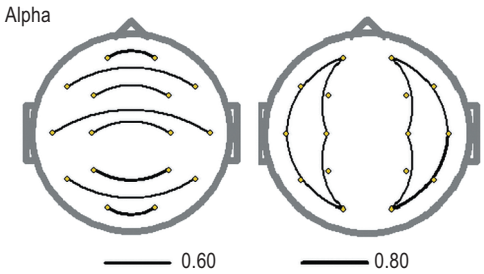


Fig. 6. **The ratio of interhemispheric and intrahemispheric interaction between points according to the 10/20 system in the alpha band in the studied control group (female electroencephalogram, 35 years old) (photo from the archive of PND No. 1, 2022–2023)**

Рис. 6. Соотношение межполушарного и внутриполушарного взаимодействия между точками в соответствии с системой 10/20 в альфа-диапазоне в исследуемой контрольной группе (электроэнцефалограмма женщины, 35 лет) (фото из архива ПНД № 1, 2022–2023 гг.)

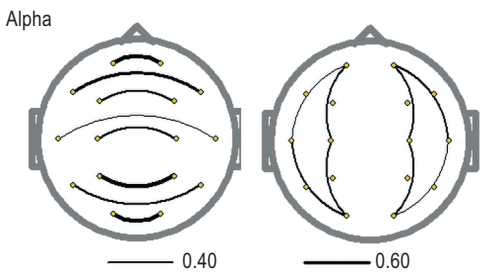


Fig. 7. **Ratio of interhemispheric and intrahemispheric interaction between leads according to the 10/20 system in the alpha band, patient C. (male electroencephalogram, 50 years old) (photo from the archive of PND No. 1, 2022–2023)**

Рис. 7. Соотношение межполушарного и внутриполушарного взаимодействия между отведениями в соответствии с системой 10/20 в альфа-диапазоне, пациент С. (электроэнцефалограмма мужчины, 50 лет) (фото из архива ПНД № 1, 2022–2023 гг.)

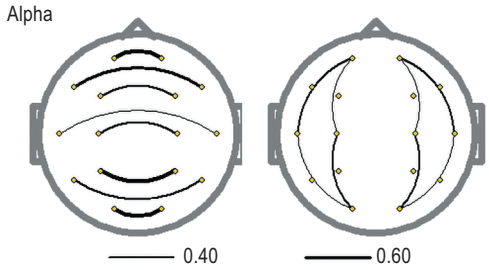


Fig. 8. **The ratio of interhemispheric and intrahemispheric interaction between the leads according to the 10/20 system in the alpha range. Group A, electroencephalogram of a woman, 55 years old (photo from the archive of PND No. 1, 2022–2023)**

Рис. 8. Соотношение межполушарного и внутриполушарного взаимодействия между отведениями в соответствии с системой 10/20 в альфа-диапазоне. Группа А, электроэнцефалограмма женщины, 55 лет (фото из архива ПНД № 1, 2022–2023 гг.)

subsequent transfer to an infectious disease unit. The patient rates her condition as "recovered" and has returned to work; however, she complains of symptoms of asthenia with autonomic dysfunction, namely loss of strength, excessive sweating, and, consequently, diminished interest in life. A reduction in the interhemispheric coherence coefficient is observed exclusively in the T3–T4 derivation, whereas weakened intrahemispheric interactions are evident in four lead pairs: Fp1–C3, T3–O1, Fp2–C4, and T4–O2.

DISCUSSION

Analysis of the EEG findings in patients with COVID-19, together with data from the literature spanning 2020–2025, indicates that the principal EEG observations center on reduced voltage (amplitude) of biosignals and various patterns of polymorphic activity, with a predominance of particular EEG rhythms in localized areas of the convexital surface. In patients with a neuropsychiatric profile, sustained coronavirus infection is characterized on EEG by a number of distinctive features. These include diminished cortical reactivity and, most notably, altered alpha rhythm parameters [40]. A marked shift in the EEG spectral power picture is observed, driven by an expansion of the dominant frequency bands to encompass those closest to the alpha range — namely, the beta and theta bands. Coherence analysis reveals that high interhemispheric correlation coefficients are preserved, whereas intrahemispheric connections, by contrast, are reduced in number, often involving the temporal leads.

As an intriguing and potentially specific feature of the analysis, we highlight a characteristic shift in spectral power within the slow-wave bands, accompanied by a phase of excitation in the right temporal region. Low-amplitude EEG patterns are recorded in approximately 10% of normal healthy individuals [27, 41]. These patterns do not exhibit the generation of a dominant alpha rhythm, show reduced reactivity, and display an intermingling of beta and alpha frequencies. In a series of studies, an EEG amplitude not exceeding 20 μV, with rare instances of reactivity, has been documented in 100% of patients.

During standard sleep EEG recording, it has been demonstrated that, upon spontaneous sleep onset, sleep spindles are either absent or poorly expressed. Follow-up examinations of patients with a favorable COVID-19 outcome have revealed a posterior dominant theta rhythm, thereby ruling out a physiological absence of the posterior alpha rhythm [15, 27, 29, 42–44].

Low-voltage EEG patterns, or those of generalized suppression, are frequently associated with extensive cortical and subcortical injury, such as anoxic encephalopathy or severe traumatic brain injury. This pattern has been found to precede an unfavorable prognosis (a score of 4 on the 11-grade qualitative EEG classification scale) or irreversible processes [45, 46]. Similar findings have been reported in ischemic encephalopathy [47, 48], with the notable exception of hypothyroid encephalopathy, which is considered reversible [27]. Low-voltage EEG has also been described in cases of diffuse neuronal dysfunction induced by hypothermia or intoxication with central nervous system depressants [48].

A review of the literature reveals a substantial body of fragmented data on the sensitivity of spectral power in both acquired and congenital conditions that pathologically alter brain activity. In particular, increased power in the slow delta and theta bands has been demonstrated in patients with acute cerebrovascular accidents, with clear positive dynamics by day 14 in the absence of localized foci of slow activity [44, 49]. Several authors report increased delta band spectral power in patients with concomitant organic brain lesions [9, 44, 49]. At the same time, significant changes in the spectral characteristics of the EEG in schizophrenia have been identified solely through the analysis of responses to auditory or visual stimuli [42, 43].

It must be borne in mind that the brain cannot function in "isolation" from the rest of the body. Alterations in the functioning of multiple internal organs influence brain activity via psychosomatic connections, which implies corresponding changes in EEG spectral power. For instance, increased spectral power in the beta-1 and alpha bands has been described in various endocrine pathologies [27]. A number of articles on EEG and COVID-19 make reference to background stress arising from physi-

cal activity [50–52]. Some authors detect low-amplitude EEG oscillations yet attribute these to metabolic or ischemic changes.

One particular concern is that EEG studies are at times conducted using a methodology that deviates from the standard—specifically, employing fewer than 10 electrodes rather than the recommended 21 (to reduce the risk of COVID-19 transmission). According to currently accepted normative amplitude values, as well as the criteria set forth by the American Clinical Neurophysiology Society for the standardization of EEG terminology, 21-electrode EEG caps are employed in intensive care settings and are regarded as the "gold standard". It is well established that interelectrode distance influences oscillation amplitude; consequently, recordings obtained with fewer electrodes double the interelectrode spacing and yield higher amplitudes, and should therefore be interpreted against their own normative values [37, 53]. These considerations, however, pertain more to bipolar than to monopolar recordings [54].

Nonspecific EEG changes have also been described in patients with COVID-19, distinct from those seen in other infectious or metabolic encephalopathies. A reduction in spectral power has been documented as a distinguishing feature, resembling the pattern observed in severe encephalopathic states associated with a poor prognosis. This picture was noted both in intensive care units and on standard wards, and in patients with either favorable disease progression or progressive deterioration alike. At the same time, among patients with a favorable outcome, these changes tended toward EEG normalization. On the basis of these EEG findings, a metabolic/hypoxic mechanism appears improbable. The low EEG amplitude, possibly attributable to desynchronization, may account for the minimal prevalence of epileptiform activity reported in patients with COVID-19 [28].

Thus, EEG represents an important tool in the management and diagnosis of patients with neurological manifestations of COVID-19, particularly in those with encephalopathy, seizures, and status epilepticus. Abnormalities, where present, encompass slowing, periodic discharges, epileptiform discharges, seizures, and status epilepticus—findings indicative of localized dysfunction, nonspecific encephalopathy, and cortical hyperexcitability in this condition. The extent of EEG abnormalities depends on the diagnosis of COVID-19, the duration of follow-up, pre-existing neurological conditions such as epilepsy, and disease severity. EEG abnormalities affecting the frontal lobes appear to be prevalent in patients with COVID-19-associated encephalopathy and may be proposed as a potential biomarker, provided they are consistently documented.

CONCLUSION

1. Visual EEG analysis permits the classification of post-COVID-19 sequelae into three distinct groups. In the majority of those examined (62%), the EEG demonstrates a uniform distribution of bioelectrical activity across all frequency bands studied, from delta to beta-2 waves. In such instances, clear identification of a dominant frequency proves challenging. This phenomenon may be interpreted as a variant of polymorphic low-frequency activity.

2. The EEG recordings of the second group are characterized by polymorphic low-frequency activity with prominent delta and theta rhythms.

3. The third group comprised EEG recordings marked by a predominance of the high-frequency beta-1 band and minimal alpha rhythm presence, a pattern designated as "flat EEG".

4. Focal slow-wave changes with a characteristic localization in the right temporal region are noted in 20% of patients.

5. In the control group, the alpha band exhibits stable correlation coefficients, with correlation coefficients exceeding 0.6 in the overwhelming majority (90%) of participants. By contrast, the patients present a heterogeneous picture: consistently high values (above 0.6) across all connections studied—both interhemispheric and intrahemispheric—were recorded in only a quarter (25%) of subjects. Coherence analysis in patients revealed an inverse trend: enhanced stability of interhemispheric connections accompanied by variable attenuation of intrahemispheric interactions, often exhibiting mirror symmetry.

ADDITIONAL INFORMATION

Author contribution. N.Yu. Kipyatkov — collection of materials, writing the original text; S.A. Lytayev — development of the research concept, scientific and technical editing; N.V. Skrebtsova — analysis of the obtained results, performing statistical analysis; V.V. Gaivoronskaia — analysis of the obtained results, selection of literary sources; K.A. Belskaya — selection of literary sources, performing statistical analysis.

All authors made a substantial contribution to the conception of the study, acquisition, analysis, interpretation of data for the work, drafting and revising the article, final approval of the version to be published and agree to be accountable for all aspects of the study.

Competing interests. The authors declare that they have no competing interests.

Consent for publication. Written consent was obtained from the patient for publication of relevant medical information within the manuscript.

ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. Н.Ю. Кипятков — сбор материала, написание исходного текста; С.А. Лытаев — разработка концепции исследования, научное и техническое редактирование; Н.В. Скребцова — анализ полученных результатов, выполнение статистического анализа; В.В. Гайворонская — анализ полученных результатов, подбор литературных источников; К.А. Бельская — подбор литературных источников, выполнение статистического анализа.

Все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией.

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

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