CEREBRAL ENERGY EXCHANGE IN EMPLOYEES OF HAZARDOUS NUCLEAR FACILITIES AND PRODUCTIONS WITH THE LOW DEGREE OF PSYCHOPHYSIOLOGICAL ADAPTATION

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Psychophysiological assessment of employees of 10 Russian nuclear power plants revealed a low degree of psychophysiological adaptation (PPA) in 30% of subjects. Studying the fuctional activity (FA) of the brain by EEG revealed the decline in FA in individuals with the low degree of PPA. The impaired cerebral energy exchange could be one of the factors contributing to the decline in the brain functional state. The study was aimed to assess the features of the cerebral energy exchange in the employees of the hazardous nuclear facilities and productions with the low degree of PPA. A total of 159 EEG recordings acquired from individuals with the low degree of PPA (50.8 ± 4.6), and 152 EEG recordings acquired from individuals with the high degree of PPA (48.8 ± 1.5) were studied. Energy exchange was assessed in individuals with the low FA of both brain as a whole and the following conditionally distinguished structural and functional units (SFUs) of the CNS: mainly cerebral cortex (SFU-1), cortical-subcortical interactions (SFU-2), central control of the cardiovascular system (SFU-3). EEG was recorded by standard method using the electroencephalography unit. The magnitude of the hemispheric differences (HD) in the power of biopotentials (BP) between the homologous EEG leads was used to assess the cerebral energy exchange. There is evidence of the cerebral energy exchange increase in the anterior cortical areas of individuals with the low degree of PPA. The increased cerebral energy exchange has been also revealed in SFU-1 and SFU-2 responsible for the mental and psychophysiological functions of the CNS. However, cerebral energy exchange remains unchanged in the SFU-3 reflecting the central control of the CVS.

Keywords: employees, hazardous nuclear facilities and productions, central nervous system, EEG, psychophysiological adaptation, cerebral energy exchange, functional state

Author contribution: Zvereva ZF, Torubarov FS, Vanchakova NP — data processing, manuscript writing; Denisova EA — psychophysiological assessment.

Compliance with ethical standards: the study was approved by the Ethics Commitee of the A. I. Burnazyan Federal Medical Biophysical Center (protocol № 406 dated December 13, 2021).

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Received: 15.04.2022 **Accepted:** 29.04.2022 **Published online:** 03.05.2022

DOI: 10.47183/mes.2022.012

ЦЕРЕБРАЛЬНЫЙ ЭНЕРГООБМЕН У РАБОТНИКОВ ЯДЕРНО ОПАСНЫХ ПРЕДПРИЯТИЙ И ПРОИЗВОДСТВ С НИЗКИМ УРОВНЕМ ПСИХОФИЗИОЛОГИЧЕСКОЙ АДАПТАЦИИ

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В результате психофизиологического обследования работников 10-й АЭС России у 30% обследованных выявлен низкий уровень психофизиологической адаптации (ПФА). Изучение функциональной активности (ФА) головного мозга с помощью ЭЭГ установило ее снижение у лиц с низким уровнем ПФА. Одним из факторов снижения функционального состояния головного мозга может быть нарушение церебрального энергообмена. Целью работы было изучить особенности церебрального энергообмена у работников ядерно опасных предприятий и производств с низким уровнем ПФА. Исследовали 159 ЭЭГ лиц с низким уровнем ПФА (50,8 ± 4,6), 152 ЭЭГ лиц с высоким уровнем ПФА (48,8 ± 1,5). Энергообмен изучали при низкой ФА как мозга в целом, так и отдельных условно выделенных нами структурно-функциональных образований (СФО) ЦНС: преимущественно коры (СФО-1), корково-подкоркового взаимодействия (СФО-2), центральной регуляции сердечно-сосудистой системы (СФО-3). ЭЭГ регистрировали общепринятым способом на электроэнцефалографе. Для оценки церебрального энергообмена использовали показатель величины межполушарных различий (ВМПР) мощности биопотенциалов (БП) ЭЭГ гомологичных отведений. Получены данные об усилении при низком уровне ПФА церебрального энергообмена в передних отделах коры головного мозга. Усиление церебрального энергообмена выявлено также в СФО-1 и СФО-2, ответственных за психические и психофизиологические функции ЦНС. При этом в СФО-3, отражающем центральную регуляцию ССС, церебральный энергообмен не менялся.

Ключевые слова: работники, ядерно опасные предприятия, центральная нервная система, ЭЭГ, психофизиологическая адаптация, церебральный энергообмен, функциональное состояние

Вклад авторов: З. Ф. Зверева, Ф. С. Торубаров, Н. П Ванчакова — обработка данных и написание статьи; Е. А. Денисова — психофизиологическое обследование.

Соблюдение этических стандартов: исследование одобрено этическим комитетом Федерального медицинского биофизического центра им. А. И. Бурназяна (протокол № 406 от 13 декабря 2021 г.)

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Статья получена: 15.04.2022 **Статья принята к печати:** 29.04.2022 **Опубликована онлайн:** 03.05.2022

DOI: 10.47183/mes.2022.012

The work of operating personnel of the hazardous nuclear facilities and productions is associated with severe emotional strain and high responsibility. The employees' top priorities are as follows: timely and accurate perception of complex information, evaluation of information, decision making and adequate response. All the tasks are implemented by the central nervous system (CNS). The impaired functional state (FS) of the CNS resulting in the low degree of psychophysiological adaptation (PPA) affects the professional activities reliability and can lead to the increased risk of accidents being the fault of the staff [1].

Psychophysiological assessment (PA) of employees of the hazardous nuclear facilities and productions performed within the framework of the mandatory annual medical check-ups makes it possible to assess the CNS FS and the degree of PPA [2, 3]. The experience of PA has proven the feasibility of using a comprehensive approach to assess the degree of PPA by methods taking into account human mental, psychophysiological and physiological spheres [1, 3, 4].

Our conceptual model of PA, developed for the personnel of the hazardous nuclear facilities and productions, makes it possible to assess the functional activity (FA) of the allocated conditional structural and functional units (SFUs) of the CNS, the functional state of the entire CNS, and the degree of PPA [5]. The following SFUs of the CNS are considered: primarily cerebral cortex (SFU-1); cortical-subcortical interactions (SFU-2); central control of the cardiovascular system (SFU-3).

The functional activity of the CNS structural and functional units is assessed in the following way:

– SFU-1 is assessed by psychological techniques that reflect the mental sphere: personal characteristics, individual's mental state, character traits, intelligence level, the degree of internality-externality (individual's preparedness to take responsibility for what happens to him/her and around), which are mostly ensured by cerebral cortex [6];

– SFU-2 is assessed by psychophysiological techniques that reflect the dynamics of neural processes, switching between the processes, the level of eye-hand coordination, overall efficiency and activity of the CNS, which are ensured mostly by the cortical-subcortical interactions [7];

– SFU-3 is assessed by physiological technique for determining the heart rate variability (HRV) that reflects the central control of the cardiovascular system (CVS), which is ensured by subcortical structures, the diencephalic region of the brainstem [8].

The FA levels of the CNS SFUs are determined as high, medium or low. This makes it possible to define the degree of PPA as a an integrated indicator, which could also be high, medium or low [2, 3, 4]. PA is performed with the PFS-CONTROL software-hardware complex (SHC) [2, 4].

The previously conducted PA of the operating personnel of 10 Russian nuclear power plants showed that 30% of employees had a low degree of PPA [9, 10]. When assessing the CNS FS in these employees by EEG given the low degree of PPA, abnormal parameters were detected significantly more often than in case of high degree of PPA [11, 12]. This suggested the decline in the CNS FS. The greatest number of abnormalities was revealed in individuals with the low degree of PPA in the SFU reflecting the central control of the CVS [9–12].

In matters of human adaptation to living conditions, including tense and responsible professional activity, studying brain energy metabolism [13] underlying the functional plasticity of the brain [14] is considered important. In the studies unvolving the use of neuroergometry for evaluation of the cerebral energy exchange by recording the brain direct current (DC) potentials [15], alterations in the CNS associated with the harsh living conditions and the development of adaptive response were defined. It was shown that the altered adaptive response in the form of the increased cerebral energy exchange was observed in migrants and individuals permanently residing in the harsh climate of the Arctic Zone of the Russian Federation (RF) [16]. The close correlation between the light pattern, cerebral energy exchange and anxiety was found in the residents of the Arctic Zone of the RF. The seasonal variation of the cerebral energy exchange in the form of the increase during the lighter periods of the year in people with high levels of anxiety is associated with the more prominent increase in energy exchange compared to people with low levels of anxiety [17]. When studying the relationship between the brain activity and the energy metabolism, it was shown that heavier mental workloads were associated with the more prominent increase in the cerebral energy exchange compared to the less heavy workloads [13]. The differences in the cerebral energy exchange increase between various cortical areas under mental workloads of different types were also revealed [18].

Despite their importance, the issues of human brain energy metabolism associated with adaptive response in the employees of the hazardous nuclear facilities and productions are poorly understood. Cerebral energy exchange in the nuclear industry workers with the low degree of PPA has not yet been explored.

For electroencephalography, widely used in studying the mechanisms underlying the normal and abnormal rearrangements in the CNS FS, an indicator, the magnitude of the hemispheric differences (HD) in the power of biopotentials (BP) between the homologous EEG leads, was developed to be used during the study [19]. Matching this indicator with the DC potentials used in neuroergometry has revealed their similarity when assessing alterations in the CNS FS [20] and justified the use of the magnitude of the HD in the power of BP between the homologous EEG leads for analysis of the cerebral energy exchange in individuals with the low degree of PPA.

The study was aimed to assess the features of the cerebral energy exchange in the employees of the hazardous nuclear facilities and productions with the low degree of PPA.

METHODS

Archive EEG recordings obtained from the employees of the hazardous nuclear facilities and productions during the PA performed within the framework of medical check-up were studied. Inclusion criteria: EEG recordings of individuals with no contraindications to further work based on the results of medical check-up and PA. A total of 311 EEG were extracted, of those 159 EEG recordings of individuals with the low degree of PPA (50.8 ± 4.6 years; 146 males, 13 females), and 152 EEG recordings of individuals with the high degree of PPA (48.8 ± 1.5 years; 140 males, 12 females). Due to the low number of female subjects, the groups were recognized as homogenous.

PA was performed using the PFS-CONTROL SHC [2–4]. The following psychological techniques were used:

– multiphasic personality test (MPT; adapted version of MMPI [2, 3, 21, 22]);

– Raymond Cattell's 16 Personality Factors Questionnaire (16PF, form A) [2, 3, 23];

– John Raven's Progressive Matrices Test [2, 3, 24];

– questionnaire of the level of subjective control (USC) [2, 3, 25]; SFU-1 was distinguished based on the methods.

Psychophysiological methods:

– simple visual-motor reaction (SVMR), complex visual-motor reaction (CVMR), reaction to a moving object (RMO); SFU-2 was distinguished based on the methods.

Physiological method: HRV; SFU-3 was distinguished based on the method.

Two groups were formed based on the degree of PPA in order to access the cerebral energy exchange:

– group 1 with the low degree of PPA (n = 159);

– group 2 with the high degree of PPA (comparison group; n = 152).

Two subgroups were also formed based on the FA of the CNS SFUs:

– subgroup 1 with the low FA: SFU-1 (n = 48), SFU-2 (n = 53), SFU-3 (n = 110);

Table 1. HD in the power of BP between the homologous EEG leads acquired from the anterior and posterior cortical areas associated with the high and low degree of PPA

Degree of PPA	HD in the power of BP between the homologous EEG leads (AU)		Test / *p*
	Cortical areas		
	anterior	posterior	
Low *n* = 159	18,1 ± 0,09•*	15,9 ± 0,04•	*t* / 0,0089• *t* / 0,0034*
High *n* = 152	17,3 ± 0,05•*	15,7 ± 0,02•	*t* / 0,0056•

Note: • — significant differences between the anterior and posterior cortical areas; * — significant differences between the high and low degree of PPA.

– subgroup 2 with the high FA: SFU-1 (*n* = 117), SFU-2 (*n* = 71), SFU-3 (*n* = 87).

EEG recording was acquired with the EEGA-21/26 Encephalan-131-03 unit (Medicom MTD; Russia) using the standard 10–20% system with the subject in a state of passive wakefulness. Electrodes were placed over the following cortical zones: Fp1, Fp2, F3, F4, F7, F8, T3, T4, T5, T6, C3, C4, P3, P4, O1,O2. Monopolar montage was used with the reference electrodes placed on the earlobes. The signal digitization rate was 1024, and the reading speed was 30 mm/s. The following ranges were recorded: 0–3.5 Hz — δ; 4.0–7.0 Hz — θ; 8.0–13.0 Hz — α; 14–24 Hz — β1; 25–35 Hz — β2.

To calculate the cerebral energy exchange value:

– the artifact free sections of the recording (1.5–2 min) were processed with the EEGA-21/26 Encephalan-131-03 sotware to obtain the numerical values for 10 fragments of the EEG BP power spectrum in each of the leads placed over the hemispheres;

– to calculate the difference between two values (%), the values of the HD in the power of BP between the homologous EEG leads were calculated using the formula (A-B)/(A+B) — 100%, where A was the power of BP in the EEG lead set up over the left hemisphere, and B was the power of BP in the EEG lead set up over the right hemisphere, based on the conditional mean;

– the absolute values of the HD in the power of BP between the homologous EEG leads were averaged over all the ranges (α, δ, θ, β1, β2) for each electrode pair; the resulting values were considered the indicators of the cerebral energy exchange measured in arbitrary units (AU);

– the average cerebral energy exchange values were calculated for the anterior (Fp1, Fp2, F3, F4, F7, F8, T3, T4, T5, T6) and posterior cortical areas (C3, C4, P3, P4, O1, O2) [19].

Statistical data processing was performed with the STATISTICA 6 for Windows (StatSoft Inc.; USA) and Biostat (AnalystSoft; USA) software. The data set processing with the STATISTICA 6 software involved calculating the mean values (M) and errors (*m*). Student's *t*-test was used to assess the significance of differences between the mean values. The differences in the comparison groups were considered significant at $p < 0.05$. The data set processing with the Biostat software involved applying the χ^2 test, the significance level was set at 0.05 ($p < 0.05$).

RESULTS

Table 1 presents the values of the HD in the power of BP between the homologous EEG leads acquired from the anterior and posterior cortical areas in individuals with the high and low degree of PPA.

The values acquired from the anterior cortical areas were higher than those acquired from the posterior areas in individuals with both high and low degree of PPA. The cerebral energy exchange was higher in anterior than in posterior areas. These ratios are similar to normal ratios of healthy people [19].

In individuals with the low degree of PPA, HD in the power of BP between the homologous EEG leads increased in the anterior cortical areas (in relation to the high degree). There were no differences between the values of the HD in the power of BP between the homologous EEG leads obtained in individuals with the low and high degree of PPA.

From the above, it is clear that in individuals with the low degree of PPA, cerebral energy exchange increased in the

Table 2. HD in the power of BP between the homologous EEG leads acquired from the anterior and posterior cortical areas associated with the high and low degree of PPA

SFU of CNS	FA	HD in the power of BP between the homologous EEG leads (AU)		Test / *p*
		Cortical areas		
		anterior	posterior	
SFU-1	low *n* = 48	18,8 ± 0,07•*	16,1 ± 0,08•	*t* / 0,0062• *t* / 0,0030*"
	high *n* = 117	17,2 ± 0,02•*	15,5 ± 0,05•	*t* / 0,0050•
SFU-2	low *n* = 53	18,2 ± 0,06•*	15,9 ± 0,04•	*t* / 0,0058• χ^2 / 0,046*"
	high *n* = 71	17,0 ± 0,02•*	15,7 ± 0,05•	*t* / 0,0062•
SFU-3	low *n* = 110	17,9 ± 0,04•	15,9 ± 0,06•	*t* / 0,0052•
	high *n* = 87	17,2 ± 0,03•	15,7 ± 0,09•	*t* / 0,016•

Note: • — significant differences between the anterior and posterior cortical areas; * — significant differences between the high and low FA of the SFUs.

anterior cortical areas and remained unchanged in the posterior areas.

Table 2 presents the values of the HD in the power of BP between the homologous EEG leads acquired from the anterior and posterior cortical areas associated with the high and low FA of the SFUs.

In the SFU-1 of individuals with the low FA, the values of the HD in the power of BP between the homologous EEG leads increased (in relation to the high FA) in the anterior cortical areas and remained unchanged in the posterior areas.

Similarly, in the SFU-2 of individuals with the low FA, the values of the HD in the power of BP between the homologous EEG leads increased (in relation to the high FA) in the anterior cortical areas and did not change in the posterior areas.

From the above, it is clear that in the SFU-1 and SFU-2 of individuals with the high FA, cerebral energy exchange increased in the anterior cortical areas and remained unchanged in the posterior areas.

In the SFU-2 of individuals with the low FA, the values of the HD in the power of BP between the homologous EEG leads acquired from the anterior and posterior cortical areas were similar to those acquired from individuals with the high FA. The cerebral energy exchange remained unchanged both in the anterior and posterior cortical areas.

Thus, in individuals with the low degree of PPA and low FA of the SFU-1 and SFU-2, cerebral energy exchange increased in the anterior cortical areas and never changed in the posterior areas. In individuals with the low FA of the SFU-3, cerebral energy exchange remained unchanged both in the anterior and posterior cortical areas.

DISCUSSION

The findings showed that the cerebral energy exchange increased in individuals with the low degree of PPA. In the past electroencephalographic studies of the nuclear power plant personnel it was found that the signs of the CNS FS decline in the form of the increase in indicators recognized as anomalous were found in EEG recordings of individuals with the low degree of PPA [9–12]. According to literature, the types of activity significantly different from normal and showing the CNS FS decline are revealed in EEG recordings of individuals with the low degree of adaptation almost in 80% of observations [9–12]. Based on the data provided it can be assumed that the increased cerebral energy exchange in the employees of the hazardous nuclear facilities and productions with the low level of PPA is the evidence of the CNS FS decline.

PPA is the body's systemic response to the impact of the external and internal factors aimed at adaptation [1, 4, 21, 26]. Stress is considered the main underlying mechanism [27, 28]. It was shown that stress developing as a non-specific body's response to the significant impact of the external and internal factors [27, 28] results naturally in the low degree of adaptation, CNS FS decline, and the increased cerebral energy metabolism [15]. These data have been confirmed by studying the cerebral energy exchange in individuals living in the harsh climate of the Arctic Zone of the RF [16], as well as in the Arctic Zone residents with the high anxiety levels [17]. It can be assumed that the increased cerebral energy exchange in individuals with the low degree of PPA revealed during our study results from stress developing in the nuclear industry workers in response to the significant impact of the external and internal factors during their tense and responsible professional activities.

The increased cerebral energy exchange indicates the probable switching to additional psychophysiological mechanisms allowing individuals with the low degree of PPA to cope with stress. However, this compensatory mechanism is not optimal, it results in fatigue and requires further recovery. That is why the emergence of such alterations should be considered the critical factor for the employees of the hazardous nuclear facilities and productions.

Based on the study results, the cerebral energy exchange increased in individuals with the low FA of the SFU-1 and SFU-2, reflecting human mental and psychophysiological spheres, and remained unchanged in individuals with the low FA of the SFU-3, reflecting human physiology.

In accordance with the conceptual model of PPA, SFU-1 is considered as mainly cortical, SFU-2 as the cortical-subcortical interactions, SFU-3 as the central control of the cardiovascular system [5]. Cerebral cortex is the main area responsible for the functions involving SFU-1 [6]. The cortical-subcortical interactions play a dominant role in the implementation of functions involving SFU-2 [7]. Subcortical structures, the diencephalic region of the brainstem, are the main areas responsible for functions involving SFU-3 [8]. Currently, PPA is believed to be a systemic process based on information processing [29]. Based on the above it can be assumed that the cerebral energy exchange processes are to the greatest extent involved in information processing associated with implementation of functions involving mainly cerebral cortex (SFU-1). The same for functions implemented with the dominant role of the cortical-subcortical interactions (SFU-2). The cerebral energy exchange processes are less involved in information processing associated with implementation of functions involving mostly subcortical structures, the diencephalic region of the brainstem (SFU-3).

It can be also assumed that the increase in the cerebral energy exchange is a compensatory neurochemical process aimed at increasing the FA of the most important SFUs of the brain.

The increased cerebral energy exchange in the anterior cortical areas associated both with low PPA and low FA of the CNS SFUs, involved in mental and psychophysiological functions, is related to the more dynamic nature of these functions in the context of the increased stress compared to physiological functions. SFUs related to regulation of the cardiovascular system are autonomous, and FA of these SFUs seems to involve different mechanisms.

CONCLUSIONS

In the employees of the hazardous nuclear facilities and productions with the low degree of psychophysiological adaptation, cerebral energy exchange increases in the anterior cortical areas and remains unchanged in the posterior areas. In individuals with the low functional activity of the structural and functional units reflecting both mental and psychophysiological spheres, cerebral energy exchange increases in the anterior cortical areas and does not change in the posterior areas. In individuals with the low functional activity of the structural and functional unit reflecting the central control of the cardiovascular system, cerebral energy exchange remains unchanged in both anterior and posterior cortical areas. Advanced research is required to define the cause of no changes in the cerebral energy exchange in this SFU. The findings are important not only for neuroscience but for practical application in medicine.

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