УДК 612.824+612.172.2]:612.821-055.1
DOI: https://doi.org/10.17816/PAVLOVJ109281

Особенности гемодинамики головного мозга и вариабельности сердечного ритма у молодых мужчин при выполнении моделируемой когнитивной деятельности с неодинаковой результативностью

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АННОТАЦИЯ

Введение. Целенаправленная когнитивная деятельность человека зависит от кровоснабжения клеток коры головного мозга (ГМ), а также от её вегетативного обеспечения.

Цель. Выявить особенности гемодинамики ГМ и вариабельности сердечного ритма (ВРС) у молодых мужчин, выполняющих когнитивные задачи с неодинаковой результативностью.

Материалы и методы. В исследовании приняли участие 42 практически здоровых молодых мужчины (средний возраст 19,40 ± 1,20 года). Гемодинамику ГМ изучали с использованием реографа Рео-Спектр-2 (ООО Нейрософт, Россия) в исходном состоянии относительного покоя и во время моделирования целенаправленной когнитивной деятельности. Синхронно с записью реоэнцефалограммы проводили регистрацию ритмокардиограммы с помощью аппаратно-программного комплекса Варикард 2.51 (ООО Рамена, Россия). Целенаправленную когнитивную деятельность реализовывали при помощи программы для проведения психофизиологических исследований Физиотест с использованием поведенческой модели: тест «Таблицы Шульте» в двухцветной модификации «Шульте–Горбова». При статистической обработке данных использовались кластерный и корреляционный анализ.

Результаты. По показателям результативности теста «Таблицы Шульте–Горбова» выборка испытуемых была разделена на два кластера (n = 28 и n = 14). При сравнении кластеров в исходном состоянии относительного покоя и во время когнитивной деятельности были выявлены различия по реоэнцефалографическим показателям, что отражает неодинаковый характер гемодинамического обеспечения ГМ у представителей данных кластеров. Выявлены различия по показателям ВСР, отражающие отличия в уровне напряженности функционирования адаптационных механизмов как в исходном состоянии, так и во время когнитивной деятельности. Результаты корреляционного анализа продемонстрировали неодинаковую зависимость между показателями реоэнцефалограммы, ВСР и показателями результативности выполнения теста «Шульте–Горбова» у представителей разных кластеров.

Выводы. «Высокорезультативные» испытуемые характеризуются меньшим временем распространения реографической волны и большим временем медленного кровенаполнения в бассейне правой вертебральной артерии, а также большим коэффициентом асимметрии реографического индекса в бассейне левой внутренней сонной артерии и бассейне вертебральных артерий обоих полушарий во время когнитивной деятельности по сравнению с «низкорезультативными» испытуемыми. Физиологическое обеспечение целенаправленной деятельности человека с неодинаковой результативностью решения когнитивных задач характеризуется не только различными уровнями показателей гемодинамики ГМ и активности регуляторных механизмов автономной нервной системы, но и определенным характером корреляционных взаимосвязей данных показателей с параметрами целенаправленного поведения, в частности, с общим временем выполнения задания и коэффициентом полезного действия.

Ключевые слова: *целенаправленное поведение; результативность решения когнитивной задачи; реоэнцефалография; кардиоинтервалография; кластерный анализ; корреляционный анализ*

Для цитирования:
Кулагин П.А., Лапкин М.М., Трутнева Е.А. Особенности гемодинамики головного мозга и вариабельности сердечного ритма у молодых мужчин при выполнении моделируемой когнитивной деятельности с неодинаковой результативностью // Российский медико-биологический вестник имени академика И. П. Павлова. 2023. Т. 31, № 1. С. 79–88. DOI: https://doi.org/10.17816/PAVLOVJ109281

Рукопись получена: 10.07.2022 **Рукопись одобрена:** 04.10.2022 **Опубликована:** 31.03.2023

DOI: https://doi.org/10.17816/PAVLOVJ109281

Peculiarities of Brain Hemodynamics and Heart Rhythm Variability in Young Men in Performing Modeled Cognitive Activity with Unequal Effectiveness

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ABSTRACT

INTRODUCTION: Purposeful cognitive brain activity of an individual depends on blood supply to the cells of the cerebral cortex (CC), and on their autonomic innervation.

AIM: To identify peculiarities of the brain hemodynamics and heart rhythm variability (HRV) in young men performing cognitive tasks with unequal effectiveness.

MATERIALS AND METHODS: The study involved 42 practically healthy young men (mean age 19.40 ± 1.20 years). The brain hemodynamics was studied using Reo-Spektr-2 rheograph (Neurosoft, Russia) in the initial condition of relative rest and in modeled purposeful cognitive activity. Synchronously with record of rheoencephalogram, rhythmocardiogram was recorded using Varicard 2.51 hardware-software complex (Ramena, Russia). Purposeful cognitive activity was modeled in Physiotest program for psychophysiological studies with use of behavioral model: Schulte Table Test in a two-color Schulte–Gorbov modification. In statistical data processing, cluster and correlation analyses were used.

RESULTS: Based on the effectiveness of Schulte–Gorbov Table Test, the sample of subjects was divided to two clusters (n = 28 and n = 14). Comparison of clusters in the initial condition of relative physiological rest and during cognitive activity revealed differences in rheoencephalographic parameters, which reflects unequal hemodynamic supply of the brain in representatives of the given clusters. Differences in HRV parameter were found reflecting the different levels of tension of adaptation mechanisms in the initial condition and in cognitive activity. The results of the correlation analysis demonstrated different dependence between the parameters of rheoencephalogram, HRV and parameters of the effectiveness of Schulte-Gorbov Test in representatives of different clusters.

CONCLUSIONS: (1) 'High-effective' subjects are characterized by shorter time of propagation of the rheographic wave and longer time of slow blood filling of the right vertebral artery basin, and by higher rheographic index asymmetry coefficient in the basin of the left internal carotid artery and of vertebral arteries of both hemispheres during cognitive activity compared to 'low-effective' subjects. (2) Physiological support of purposeful activity of an individual with unequal effectiveness of salvation of cognitive tasks is characterized not only by different levels of brain hemodynamics and activity of autonomic regulatory mechanisms, but also by certain type of correlation relationships of these parameters with parameters of purposeful behavior, in particular, with the total time of fulfilment of the task and efficiency coefficient.

Keywords: *purposeful behavior; effectiveness of salvation of cognitive task; rheoencephalography; cardiointervalography; cluster analysis; correlation analysis*

For citation:
Kulagin PA, Lapkin MM, Trutneva EA. Peculiarities of Brain Hemodynamics and Heart Rhythm Variability in Young Men in Performing Modeled Cognitive Activity with Unequal Effectiveness. *I. P. Pavlov Russian Medical Biological Herald.* 2023;31(1):79–88. DOI: https://doi.org/10.17816/PAVLOVJ109281

Received: 10.07.2022 **Accepted:** 04.10.2022 **Published:** 31.03.2023

ECO•VECTOR

LIST OF ABBREVIATIONS

AA — ratio of amplitude of maximal systolic value of venous component to maximal wave amplitude
C — rheographic index asymmetry coefficient
D — dicrotic index
DIA — diastolic index
EC — efficiency coefficient
Fmd — right fronto-mastoid lead
Fms — left fronto-mastoid lead
HR — heart rate
HRV — heart rate variability
MT — mean time of number selection
Omd — right occipito-mastoid lead
Oms — left occipito-mastoidal lead
pHF — spectrum power in high frequency range
pLF — spectrum power in low frequency range
PP — performance power
pVLF — spectrum power in very low frequency range
pvo — parameter of venous outflow
REG — rheoencephalography
RI — rheographic index
RU — relative units
SI — stress index
TPT — total performance time
V_{av} — average slow filling velocity
V_{max} — maximal rapid filling velocity
α — time of rising edge of wave
α1 — rapid blood filling time
α2 — slow blood filling time
Q_x — time of propagation of rheographic wave

INTRODUCTION

One of tasks of modern physiology of human behavior is investigation of the role of physiological support of purposeful activity in formation of unequal effectiveness [1–3].

Cognitive activity of a human is directly related to functioning of cells of cerebral cortex, whose adequate vital activity depends of the level of their supply with blood [4, 5]. A widely known inexpensive noninvasive method of studying regional cerebral circulation is rheoencephalography (REG) [6–8].

Besides, according to the modern data, important factors that determine the effectiveness of human purposeful activity are its autonomic support and physiological cost reflecting consumption of physiological resources [9–11]. One of methods to evaluate the physiological costs of human activity, is mathematical analysis of heart rate with evaluation of its variability [12]. Heart rate variability (HRV) may serve as a parameter of tension of adaptation mechanisms in realization of different forms of behavior with different effectiveness [13, 14].

The **aim** of this study to identify peculiarities of hemodynamics of the brain and variability of heart rate in young men performing cognitive tasks with unequal effectiveness.

MATERIALS AND METHODS

The study involved 50 practically healthy young men. All participants gave written Informed consent to participate in the study (the study Protocol was approved by the Local Ethics Committee of Ryazan State Medical University (Protocol No. 2 of 2020, October 07).

Exclusion criterion was deviation of more than two REG parameters from average standard values (M ± 2SD). Based on this criterion, a final sample of 42 male individuals aged 18 to 23 years (average age 19.40 ± 1.20 years) was formed.

The hemodynamics of the brain was studied in the first half of the day in the sitting position of a test subject using a Reo-Spektr-2 computer multifunctional rheograph (Neurosoft, Russia) in the initial state of relative rest and during modeling of purposeful cognitive activity. The positions of the head, neck and torso of the subjects were controlled and did not change throughout the study. The rheoencephalogram was recorded in the fronto-mastoid leads on the left (Fms) and on the right (Fmd) and in the occipito-mastoid leads on the left (Oms) and on the right (Omd), which permitted to assess the state of blood flow in the systems of the internal carotid and vertebral arteries [15]. The obtained data were automatically analyzed and interpreted using software Reo-Spektr.NET (Neurosoft, Russia). In the analysis, the following REG parameters were used:

- time of propagation of rheographic wave (Q_x, s);
- time of rapid blood filling (α1, s);
- time of slow blood filling (α2, s);
- time of rising edge of the wave (α, s);
- rheographic index (RI, relative units (RU));
- rheographic index asymmetry coefficient (C, %);
- maximal velocity of rapid filling (V_{max}, Ohm/s);
- average velocity of slow filling (V_{av}, Ohm/s);
- dicrotic index (D, %);
- diastolic index (DIA, %);
- ratio of amplitude of maximal systolic value of venous component to maximal wave amplitude (AA, %);
- parameter of venous outflow (pvo, %).

Synchronously with rheoencephalogram, rhythmocardiogram was recorded using Varicard 2.51 hardware-software complex (Ramena, Russia). Rhythmograms were processed and analyzed by the following parameters using the included ISKIM 6.1 software:

- heart rate (HR, 1/min);
- stress index (SI, RU);
- spectral characteristics of the curve enveloping a dynamic row of cardiointervals:
  - spectrum power in high frequency range (pHF, %);
  - spectrum power in low frequency range (pLF, %);
  - spectrum power in very low frequency range (pVLF, %).

Duration of record of REG and rhythmocardiogram in the initial condition of relative rest was 5 minutes; in modeling the purposeful cognitive activity record was limited by the time of performing cognitive activity and was on average 2.20 ± 0.90 minutes.

Purposeful cognitive activity was realized using a program for psychophysiological studies in Physiotest system (Russia) [16] with a behavioral model: Schulte Tables Test in Schulte-Gorbov two-color modification. In analysis of the effectiveness of cognitive activity, the following parameters were used:

- total performance time (TPT, s);
- average time of number selection (AT, s);
- efficiency coefficient (EC, %, calculated by the formula: *EC = ((total presented numbers–errors)) / (total presented numbers);*
- power of performance (PP, RU, calculated by the formula: *pp = (EC × total performance time) / (60 sec).*

Accumulation, correction and primary descriptive statistical processing of the initial data were carried out using Microsoft Office Excel 2016 spreadsheet (Microsoft, USA). Statistical analysis was performed in Statistica 13 program (Stat Soft Inc., USA, license JPZ811I521319AR25ACD-W). The obtained results were visualized in GraphPadPrism 8.0.1 program (GraphPad Software Inc., USA). Quantitative parameters were evaluated for correspondence to the normal distribution by using Shapiro–Wilk test. Due to the absence of signs of normal data distribution, nonparametric statistical methods were used. Cluster analysis was used to identify homogeneous groups based on the criterion of different effectiveness of cognitive activity. Differences between the two compared paired samples were checked by Wilcoxon's W-test. Mann–Whitney U-test was used to compare independent totalities (groups). To study the relationship between the parameters, correlation analysis was performed using Spearman's rank correlation method. The data are presented in the form of median (Me), lower (LQ) and upper (UQ) quartiles. The critical significance level was considered to be $p < 0.05$.

RESULTS

By parameters of efficiency of Schulte–Gorbov Test, the sample of subjects was divided to 2 clusters (Figure 1a) using cluster analysis by method of k-means: cluster 1 (n = 28) and cluster 2 n = 14). In comparison of clusters by effectiveness, the differences in all criteria were statistically confirmed (Figure 1b).

In realization of the cognitive activity, the subjects of the first cluster showed reduction of the time of rapid blood filling in Fmd, Fms, Oms leads; reduction of the time of slow blood filling in Oms lead; reduction of the rheographic index in Oms lead; reduction of the average velocity of slow filling in Omd lead (Figure 2) in comparison with the initial level.

In the cognitive activity, the subjects of the second cluster showed reduction of the time of propagation of the rheographic wave in Emd and Omd leads; increase in the diastolic index in Oms lead; reduction of time of slow blood filling in Omd and Oms leads (Figure 3).

In comparison of clusters by hemodynamic parameters of the brain in the initial condition of relative rest and in cognitive activity, differences in a number of parameters of REG were found (Table 1).

The subjects of the first cluster, relative to the second one, demonstrated a shorter time of propagation of the rheographic wave in all four leads at rest, and also in Omd lead in cognitive activity; a longer time of rapid blood filling in Fms, Omd, Oms leads at rest; a longer time of slow blood filling in Omd lead in cognitive activity; a higher diastolic index in Oms lead at rest; also a higher rheographic index asymmetry coefficient in Fms, Omd, Oms leads in cognitive activity.

In analysis of cardiorhythmograms, SI parameter in the initial condition and in cognitive activity and pLF parameter in cognitive activity in the representatives of the first cluster were lower than in those of the second cluster (Figure 4).

Differences in the character and expression of correlation relationships between parameters of the purposeful activity and its physiological support in subjects of clusters 1 and 2 are presented in the form of correlation pleiads (Figure 5).

DISCUSSION

In the conducted study, the subjects of the first cluster demonstrated shorter total time of test performance, shorter average time of number selection, lower performance power and higher efficiency compared to the subjects of the second cluster, which permits to characterize them as ‘high-effective’. The representatives of the second cluster can be considered ‘low-effective’ in solving the given cognitive task.

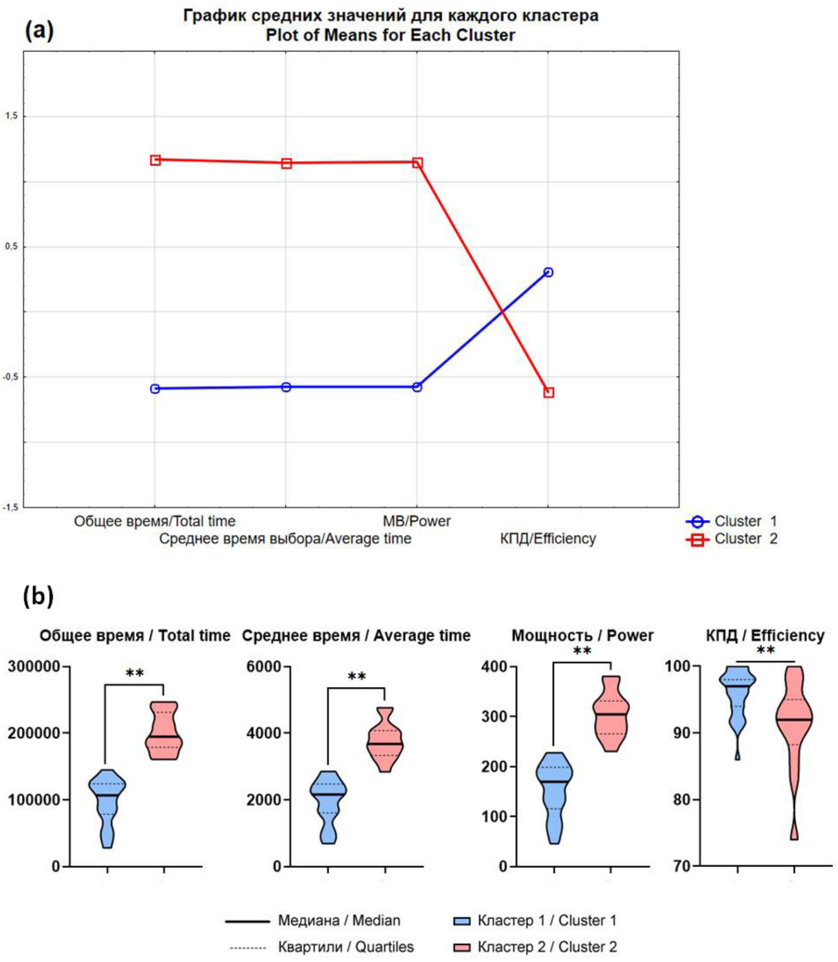

Fig. 1. Comparison of clusters by effectiveness of performing Schulte–Gorbov Test.
Notes: ** — p < 0.01 for Mann–Whitney test; EC — efficiency coefficient; PP — performance power.

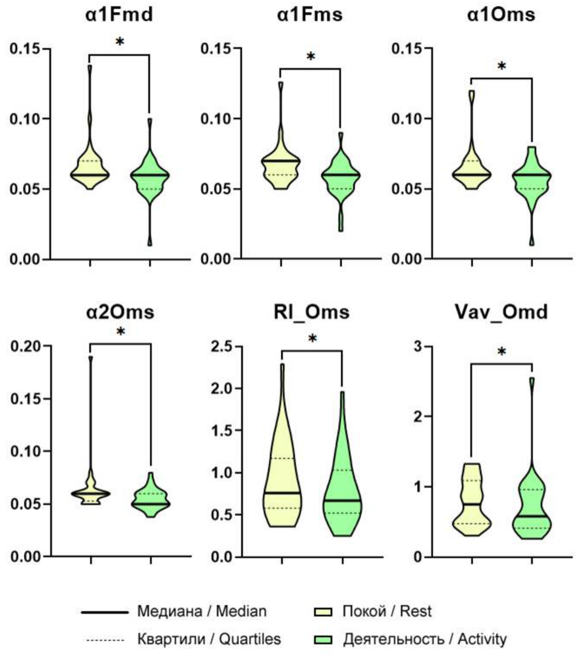

Fig. 2. Dynamics of results of rheoencephalography in representatives of cluster 1 in performing Schulte–Gorbov Test in comparison with the initial level.
Notes: α1 — time of rapid blood filling; α2 — time of slow blood filling; RI — rheographic index; Vav — average velocity of slow filling; Fms — left fronto-mastoid lead; Fmd — right fronto-mastoid lead; Oms — left occipito-mastoid lead; Omd — right occipito-mastoid lead; * — p < 0.05 — for Wilcoxon W-test.

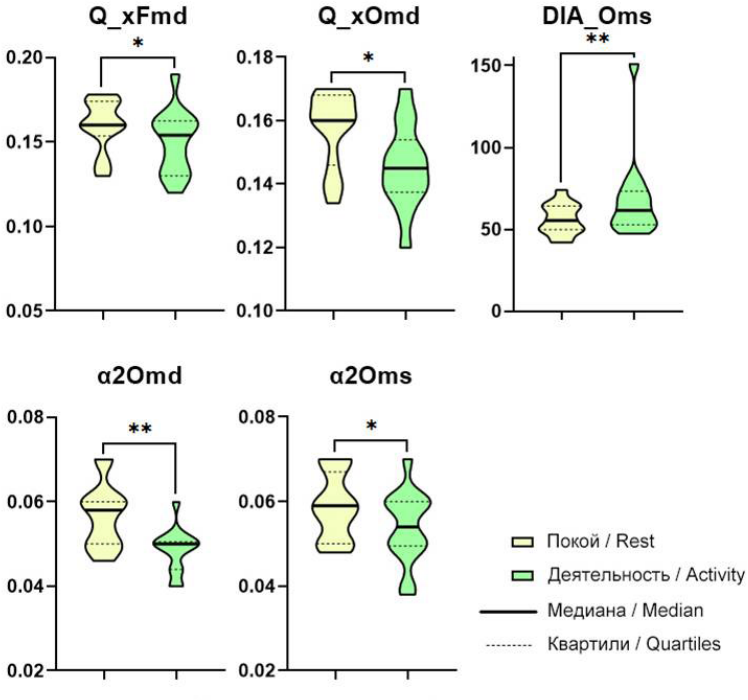

Fig. 3. Dynamics of results of rheoencephalography in representatives of cluster 2 in performing Schulte-Gorbov Test in comparison with the initial level.

Notes: α1 — time of rapid blood filling; α2 — time of slow blood filling; RI — rheographic index; Vav — average velocity of slow filling; Fms — left fronto-mastoid lead; Fmd — right fronto-mastoid lead; Oms — left occipito-mastoid lead; Omd — right occipito-mastoid lead; * — $p < 0.05$ — for Wilcoxon W-test.

Table 1. Initial Differences in Parameters of Rheoencephalography at Rest and in Cognitive Activity Between Clusters (Me (LQ; HQ))

Condition	Parameter	Cluster 1	Cluster 2	p
	n	28	14	
Initial level	Q_xFmd	0.15 (0.13; 0.16)	0.16 (0.16; 0.17)	0.00765
	Q_xFms	0.14 (0.13; 0.16)	0.17 (0.16; 0.17)	0.00886
	Q_xOmd	0.14 (0.13; 0.16)	0.16 (0.15; 0.17)	0.01165
	Q_xOms	0.13 (0.13; 0.15)	0.16 (0.15; 0.16)	0.00689
	α1Fms	0.07 (0.06; 0.07)	0.06 (0.05; 0.07)	0.03399
	α1Omd	0.06 (0.05; 0.07)	0.05 (0.05; 0.06)	0.01289
	α1Oms	0.06 (0.06; 0.07)	0.06 (0.05; 0.06)	0.04572
	DiaOms	65.00 (58.75; 75.25)	55.50 (50.00; 63.75)	0.00526
Cognitive activity	Q_xOmd	0.13 (0.12; 0.14)	0.15 (0.14; 0.15)	0.02525
	α2Omd	0.06 (0.05; 0.07)	0.05 (0.05; 0.05)	0.00605
	KFms	26.5 (10.75; 37.00)	9.50 (1.50; 18.50)	0.02947
	KOmd	35.00 (16.75; 69.75)	5.50 (-2.00; 20.00)	0.00732
	KOms	35.00 (16.75; 69.75)	5.50 (1.25; 22.25)	0.03065

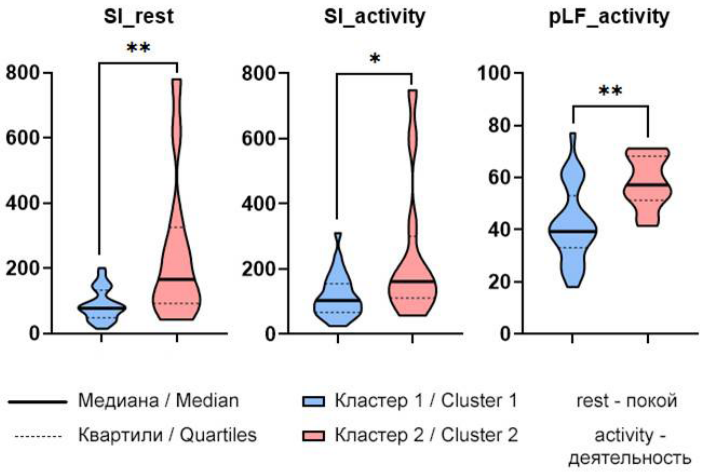

Fig. 4. Comparative analysis of the parameters of heart rate variability between clusters.
Notes: SI — stress index; pLF — spectrum power in the low frequency range; * — $p < 0.05$, ** — $p < 0.01$ for Mann-test.

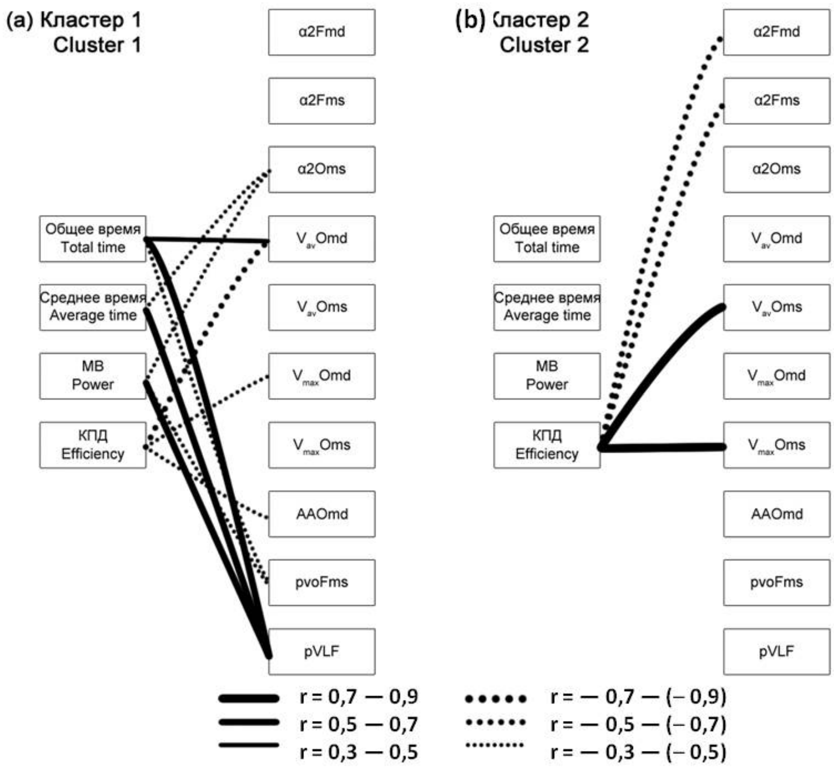

Fig. 5. Correlation pleiads reflecting interrelations of the parameters of rheoencephalography and heart rate variability with parameters of efficiency of cognitive activity of representatives of the compared clusters.
Notes: Solid line shows positive (direct) relationships, dotted line shows negative (inverse) relationships. Line thickness reflects the strength of correlation relationship (on Chaddock scale) [17]. AA — ratio of the amplitude of maximal systolic value of venous component to maximal wave amplitude; pvo — parameter of venous outflow; PP — performance power, EC — efficiency coefficient; Fms — left fronto-mastoid lead; Fmd — right fronto-mastoid lead; Oms — left occipito-mastoid lead; Omd — right occipito-mastoid lead; α2 — slow blood filling time; V_{av} — average velocity of slow filling; V_{max} — maximal velocity of rapid filling.

In comparison of hemodynamic parameters recorded under different conditions, significant changes were revealed in both clusters. However, the nature of the changes is different. A common change is a decrease in the time of slow blood filling in the left occipito-mastoid lead (α2Oms), which is probably due to a change in the tone of medium- and small-caliber vessels in the left vertebrobasilar system. The identical phenomenon is confirmed in the works of other authors [18].

When comparing clusters in the initial state of relative rest and in cognitive activity, significant differences were revealed in a number of REG parameters, which reflects the unequal hemodynamic support of the brain in representatives of these clusters. The shorter propagation time of the rheographic wave at rest in all four leads and in Omd lead during cognitive activity in subjects of the first cluster is probably associated with a higher tone of extracranial vessels. The longer time of rapid blood filling in the representatives of the first cluster in Fms, Omd, Oms leads at rest may reflect the higher elasticity of the walls of large cerebral arteries: the left internal carotid artery and vertebral arteries. It is also worth noting that 'high-effective' subjects are characterized by a higher coefficient of asymmetry of the rheographic index during workload, which indicates significant asymmetry of blood filling (C > 26%). However, a number of previous studies demonstrated asymmetry of blood filling in subjects with low-effective performance of a cognitive task on Stroop test model [4, 5], which does not agree with the results of our study and confirms the need for further research in this area on different behavioral models.

The obtained results also indicate a possibility of determining parameters of the cerebral blood flow with high-frequency probing current used in REG research.

The identified differences in HRV parameters demonstrate a lower level of tension of the regulatory mechanisms of the sympathetic division of the autonomic nervous system in representatives of cluster 1 both in the initial state and during cognitive activity. High pLF values during cognitive activity in representatives of cluster 2 seem to show relatively higher activity of the sympathetic division of the autonomic nervous system.

The results of the correlation analysis reflect unequal dependences between the parameters of REG, HRV and the parameters of effectiveness of Schulte–Gorbov Test in representatives of different clusters. It is worthy to note peculiarities of the relations between the parameters of the maximum velocity of rapid filling (V_{max}, reflects the tone of large arteries), the average velocity of slow filling (V_{av}, reflects the tone of medium and small arteries) and the efficiency coefficient. In cluster 1, a weak negative correlation was found between V_{max}Omd and EC (r = -0.38) and a moderate negative correlation between V_{av}Omd and EC (r = -0.56). The representatives of cluster 2 showed a strong positive correlation between V_{max}Oms and EC (r = 0.71), and between VavOms and EC (r = 0.72). It is also important to note the direct correlation between the velocity of slow filling in the occipito-mastoid right lead (V_{av}Omd) and the total time of Schulte–Gorbov Test performance (r = 0.39) in representatives of the 'high-effective' cluster. This parameter in the subjects of the given cluster reliably decreased in the test compared to the initial level. E. S. Olenko, et al. in their work (2021) also revealed direct correlations of V_{av} parameter with the time of performing Stroop test, but these correlations were found with V_{av} parameter recorded in the fronto-mastoid right and left leads (V_{av}Fmd and V_{av}Fms, respectively) in individuals with low performance of cognitive tasks [5].

CONCLUSIONS

1. The effectiveness of cognitive activity of an individual is associated with the peculiarities of cerebral hemodynamics, in particular, with changes in velocity characteristics of blood filling: maximal velocity of rapid filling and average velocity of slow filling, and also with peculiarities of the autonomic regulation of heart activity.

2. 'High-effective' subjects are characterized by shorter time of propagation of rheographic wave and a longer time of slow blood filling in the system of the right vertebral artery, and also by a higher coefficient of rheographic index asymmetry in the system of the left internal carotid artery and the system of vertebral arteries of both hemispheres in the cognitive activity, compared to 'low-effective' subjects.

3. Physiological support of the purposive activity of humans with unequal effectiveness of performing cognitive tasks is characterized not only by different levels of cerebral hemodynamic parameters and activity of autonomic regulatory mechanisms, but also by certain relationships of these parameters with parameters of the purposeful behavior, in particular, with the total time of task performance and efficiency coefficient.

ADDITIONALLY

Funding. This study was not supported by any external sources of funding.

Conflict of interests. The authors declares no conflicts of interests.

Contribution of the authors: *P. A. Kulagin* — collection and statistical analysis of material, writing the text of the article; *M. M. Lapkin* — research concept and design, editing; *E. A. Trutneva* — research design, correction of research methods. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

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

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов: *Кулагин П. А.* — сбор и статистическая обработка материала, написание текста статьи; *Лапкин М. М.* — концепция и дизайн исследования, редактирование; *Трутнева Е. А.* — дизайн исследования, коррекция методов исследования. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

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