Journal of Physical Education and Sport ® (JPES), Vol. 24 (issue 7), Art 181 pp. 1610 - 1616, July 2024
online ISSN: 2247 - 806X; p-ISSN: 2247 – 8051; ISSN - L = 2247 - 8051 © JPES

Original Article

Neurohumoral regulation of heart rate features in students during physical fitness tests

IVAN BOCHARIN[1], MAKSIM GURYANOV[2], VIKTOR KRAYNIK[3], ATANAS SARANDEV[4], LYAZZAT DYUSSENOVA[5], REGINA KOVYLINA[6], ANTON METALNIKOV[7], INNA CHERDANCEVA[8], NATALYA BALASHKEVICH[9], ANTON VOROZHEIKIN[10], PAVEL TYUPA[11], RUSLAN SADYKOV[12], MAKSIM ANISIMOV[13]
[1,2] Privolzhsky Research Medical University, Nizhny Novgorod, RUSSIA
[1] Nizhny Novgorod State Agrotechnological University, Nizhny Novgorod, RUSSIA
[3] Altai State Pedagogical University, Barnaul, RUSSIA
[4] Faculty of Public health, Medical University – Sofia, BULGARIA
[5] Kazakh National Medical University named after S.D. Asfendiyarov, NCJSC, Almaty, KAZAKHSTAN
[6] Semey Medical University, NCJSC, Semey, KAZAKHSTAN
[7] Altai State Medical University, Barnaul, RUSSIA
[8] Altai State University, Barnaul, RUSSIA
[9] Semey Medical University, NCJSC, Semey, KAZAKHSTAN
[10] Kaliningrad Institute of Management, Kaliningrad, RUSSIA
[11] Immanuel Kant Baltic Federal University, Kaliningrad, RUSSIA
[12] Surgut State Pedagogical University, Surgut, RUSSIA
[13] Saint-Petersburg State Agrarian University, St. Petersburg, RUSSIA

Published online: July 31, 2024
Accepted for publication : July 15, 2024
DOI:10.7752/jpes.2024.07181

Abstract:
Understanding and assessing neural control of the human cardiovascular system during physical activity tests helps identify specific manifestations of this process and enhances training effectiveness. ***Purpose:*** This study evaluates neurohumoral regulation of heart rate in male students performing stress tests based on the European protocol for assessing physical fitness. ***Materials and methods:*** The study involved 75 male students aged 19.3±1.3 years from Volga Research Medical University. Volunteers had no specialized physical training or somatic pathologies. Their body mass index was in the range of 18.7–22.3 kg/m^2. The heart rate variability of students was studied using the MedicalSoft Sports Testing System software and hardware complex. Before and after the exercise test, pulsograms were recorded in a sitting position. The recording duration was at least 5 minutes. Temporal and spectral indicators of heart rate variability and systemic hemodynamic parameters were determined. Physical exercises from European physical fitness tests were used as stress testing. All tests were performed at the maximum power applied by each subject. The duration of the break between exercises was 5 minutes. ***Results.*** It has been established that after performing physical exercises under stress testing conditions, significant shifts in hemodynamic parameters occur, accompanied by increased tension in regulatory systems and increased activity of the central regulatory circuit in terms of heart rate variability. Clustering of the subjects made it possible to identify three groups, among which the second group has the highest level of functional reserves and readiness for physical activity; in the first group, there is an increase in the central regulation of heart rhythm, which is accompanied by a pronounced increase in heart rate. In the third cluster, there is a predominance of low-frequency spectrum power, a significant decrease in temporal indicators of heart rate variability, and a sharp increase in heart rate. This indicates the lowest readiness of the subjects in this group for the presented physical activity. ***Conclusions.*** The use of acquired knowledge can increase the effectiveness of the educational and training process in connection with the individualization of the volume and intensity of physical activity performed by an athlete based on heart rate variability data.
Key Words: **physical education, physical activity, heart rhythms, neurohumoral regulation, functional reserves, neural control of the cardiovascular system**

Introduction

In modern conditions of social development, there is a significant deterioration in the health of people of different ages (Saito et al., 2022; Maloney et al., 2022; Lefaucheur, 2023; Popovych et al., 2024). This causes a decrease in the quality and life expectancy of a person (Metalnikov et al., 2024), deterioration in physical and mental performance (Timnea et al., 2019), tolerance to physical activity and other stress factors (Syamsudin et al., 2021; Mazin et al., 2021). al., 2021; Sokolovskaia et al., 2022;

Corresponding Author: IVAN BOCHARIN, E-mail: bocharin.ivan@mail.ru

The negative vector of changes affects the health and training in the field of vocational training of young people, in particular, university students, where students have to adapt to mental and mental stress (Deschodt-Arsac et al., 2018; Eksterowicz, & Napierała, 2020), other living conditions and everyday life, often isolation from home and relatives.

Regular physical activity associated with physical education or sports also causes adaptation processes in the body (Dupuy et al., 2018). At the same time, the level of adaptive potential of the body for each student is strictly individual and depends on age, gender, state of physical health and other factors (Tiwari et al., 2021; Kolokoltsev et al., 2021). The body's response is to a certain extent determined by changes that arise in the process of complex adaptation to various conditions of the external and internal environment (Guzii et al., 2020).

A universal indicator of adaptation processes that occur in the body includes diverse forms of response from the cardiovascular system (Bocharin et al., 2022). This system plays a primary role in the body's adaptation to both motor activity and mental activity. Adaptive changes in the functioning of this system occur with the active participation of neuroendocrine processes and self-regulation mechanisms (Bocharin et al., 2023). At the same time, an important component of the study of adaptive potential is the assessment of parameters of autonomic regulation, which is necessary to study the balance of consistency in the functioning of this system and diagnose the autonomic relationship (Cid et al., 2019; Kamandulis et al., 2020).

It is known that a simple and informative way to assess the functional state of the human cardiovascular system is the method of assessing heart rate variability parameters (Mejia-Mejia, et al., 2020; Guzii et al., 2020; Christiani et al., 2021). The method is based on determining heart rate. The obtained results of the analysis of heart rate variability make it possible to assess the state of heart activity (Uhlig et al., 2020) and the balance between the sympathetic and parasympathetic parts of the autonomic nervous system. This feature can be a diagnostic tool in managing the training process and helps prevent the development of pathological changes in the body that may be associated with physical activity (Flatt et al., 2020).

Today, there are unified methods for assessing the body's functional tolerance to physical activity and its physical performance (Harvard step test, PWC 170, and others). To monitor the state of a person's physical fitness, motor tests of various types are used, which are included in the European physical fitness tests (PCFSN, 2011). It is known that physical fitness testing is aimed at assessing the development of physical qualities, such as strength, speed, flexibility, endurance and the state of coordination qualities (Abilova, 2021). Their use makes it possible to assess the level of a person's motor qualities and the dynamics of their changes during training or physical education (Wang et al., 2010). Testing physical fitness allows you to make adjustments to the training process, as well as contribute to the effective prevention of maladaptive states from various functional systems of the body in the form of overtraining, acute and chronic overstrain of the body (Losnegard et al., 2021; Lichti et al., 2023). The important role of testing in the prevention of sports injuries. Like any physical activity, with proper dosage, testing helps athletes learn teamwork, organization, discipline and initiative. In addition, the implementation of regulatory tests poses the task of achieving high results in physical activity or sports. At the same time, when performing tests, exercises are performed when "maximum volitional efforts" are achieved, which contributes to pronounced tension in all functional systems of the body.

At the same time, in the scientific literature there are practically no results of analysis of shifts in adaptive potential under the influence of physical activity, which a person performs during motor tests from the European protocol for monitoring physical fitness. Based on this, there is a need to assess the adequacy of the body's adaptation to exercises of various types, which are presented in the monitoring protocol for assessing the athlete's motor qualities and skills.

We believe that identifying the features of neurohumoral adaptation of the human cardiovascular system to test physical loads will make it possible to identify the features of the manifestation of this process in the body. The use of acquired knowledge can increase the effectiveness of the educational and training process in connection with the individualization of the volume and intensity of physical activity performed by the athlete.

Purpose: To evaluate the features of neurohumoral regulation of heart rate when students perform stress tests from the European protocol for assessing physical fitness.

Material & methods

The study involved 75 male volunteers from the Volga Research Medical University (Nizhny Novgorod, Russia). The average age of the subjects was 19.3±1.3 years. The students who participated in the study did not have any diseases or health problems, they were in health group I, and they did not engage in special physical training. The body mass index of the subjects was within normal limits and ranged from 18.7 to 22.3 kg/m2. According to the results of a preliminary oral survey, they had a moderate level of daily physical activity. All study participants gave written voluntary consent to participate in the survey and does not contradict the ethical standards provided for in the 2003 Declaration of Helsinki.

To study heart rate variability (HRV) indicators, we used the "MedicalSoft Sports Testing System" (MS FIT – 01, Russia) software and hardware complex, the work of which is based on the method of assessing variation pulsometry. The pulsogram was recorded for at least 5 minutes while sitting at rest and after performing stress testing, in accordance with the recommendations.

Characteristics were given of the temporal and spectral values of HRV indicators, heart rate (Heart rate, bpm), standard deviation of NN intervals (SDNN, ms), percentage of cardiac intervals with a difference from the previous interval of 50 ms or more (pNN50, %), coefficient vagosympathetic balance (LF/HF, arbitrary units), total power of the heart rate variability spectrum (TP, ms^2), relative power values of the low frequency spectrum (LF, %), super low frequency (VLF, %) and high frequency fluctuations (HF, %), stress index (SI, arbitrary units). Using a hardware and software complex, systemic hemodynamic parameters were determined: stroke volume of the heart (SV, ml) and total peripheral vascular resistance (TPVR, $dyn \cdot s \cdot cm^{-5}$, pascal seconds per centimeter to the minus fifth power). SV was calculated using the Starr formula, and TPVR was calculated using the Poiseuille formula (Spitsin et al., 2018).

As load testing, we used physical exercises of speed-strength, power and speed, which are included in the European tests of physical fitness (PCFSN, 2011). The tests were performed in the following sequence: "standing long jump with a push with two legs", "raising the body from a supine position", "100-meter run" and "pull-up from hanging on a high bar". All tests were performed at maximum applied force. To eliminate the oxygen debt and restore the alactic capacity of energy supply to skeletal muscles, the duration of the break between exercises was 5 minutes. The anaerobic alactic energy system is synonymous with sprint training, weight training, and resistance training (Batacan et al., 2017).

When studying the initial state and changes in indicators after stress testing, statistical processing was carried out using Excel spreadsheets and the Statistica program. The arithmetic mean (M) and its error (m) were determined. To distribute students into groups according to the assessment of their body's tolerance to physical activity and functional reserves, cluster analysis using the K-means method was used. After applying cluster analysis, the indicators in each group are presented as the median and 25 (Q1) and 75 (Q3) quartiles. The significance of the differences between the indicators was checked using the Student t-test and the Mann-Whitney U test. Differences were considered statistically significant at $p<0.05$.

Results

The results of the analysis of hemodynamic parameters and HRV values in students before and after stress testing are presented in Table 1.

Table 1. Values of hemodynamic parameters and HRV in students before and after the stress test, M±m

Parameter/State Status	Состояние		
	Relative physiological rest (n=75)	After performing load testing (n=75)	p<0.05
Heart rate, beats/min	76.2±11.3	143.4±12.7	1-2
Stroke volume, ml	71.5±5.8	105.2±7.9	1-2
Total peripheral vascular resistance, TPVR, $dyn \cdot s \cdot cm^{-5}$	1485.4±110.7	601.7±95.6	1-2
Standard deviation of NN intervals, ms	45.4±7.1	32.7±4.5	1-2
Ratio of cardiointervals differing from the previous interval by 50 ms or more, %	19.7±4.2	11.8±2.5	1-2
Vagosympathetic balance coefficient, arb. units .	1.7±0.4	7.1±0.6	1-2
Total power of the heart rate variability spectrum, ms^2	1739.3±149.7	901.6±138.7	1-2
Relative values of low frequency spectrum powers, %	33.3±4.1	46.8±5.1	1-2
Relative values of powers above the low-frequency spectrum, %	35.8±3.2	44.2±4.2	1-2
Relative values of high-frequency oscillation powers HF, %	30.9±5.3	11.0±4.7	1-2
Stress index, arb. units	101.4±11.5	478.6±17.3	1-2

Note: p – significance of differences between groups 1 (background) and 2 (after stress test) are statistically significant, p<0.05

Statistically significant differences were established between the values of hemodynamic parameters at rest and after performing physical exercises. This is reflected in an increase in heart rate by 88.2%, SV by 47.1% and a decrease in TPVR by 59.5% relative to rest, $p<0.05$.

This is due to the work of the "muscle pump" during muscle contraction, which increases the flow of venous blood to the heart and a more significant ejection of blood from the ventricles. A compensatory decrease in vascular resistance to blood flow caused by physical work also plays a role. The structure of heart rate variability is characterized by an increase in the tension of regulatory mechanisms and an increase in sympathetic and neurohumoral regulation, which may be associated with intense work at the limit of physiological capabilities. This is confirmed by a 38.8% decrease in the standard deviation of NN intervals, a 66.9% decrease in the total spectral power and a 92.2% decrease in the high-wave spectral power after stress testing relative to the values of the indicators at rest, $p<0.05$. In turn, the increased contribution of the central circuit of cardiac rhythm regulation is reflected in a statistically significant increase in the vagosympathetic balance coefficient by 317.6%, in heart rate by 88.2%, and in stress index by 371.9%, $p<0.05$. These indicators characterize a shift in the autonomic balance towards sympathetic stimulation of the myocardium and tension in regulatory systems. This statement is further confirmed by the shift in the relative values of the spectrum power indicators of low-frequency and ultra-low-frequency parameters of the HRV spectral analysis.

When clustering subjects according to the studied indicators using the cluster analysis method, indicators of systemic hemodynamics were used: stroke volume of the heart, total peripheral vascular resistance, as well as HRV parameters. These include heart rate (HR), standard deviation of NN intervals (SDNN), percentage of cardiac intervals with a difference from the previous interval of 50 ms or more (pNN50), relative values of the power of the low frequency spectrum (LF), super low frequency (VLF) and high frequency oscillations (HF), total spectral power (TP) and vagosympathetic balance coefficient (LF/HF).

Before testing students, the obtained indicator values were standardized so that they were located close to zero. To predict the number of clusters, we used the hierarchical clustering method, which demonstrated the possibility of dividing students into 3 groups, and then used cluster analysis using the K-means method. Clustering results using standardized coefficients are presented in Table 2.

Table 2. Values of hemodynamic parameters and HRV in students in clusters on physical activity, M±m

Parameter/Cluster	Cluster			
	1 (n=29)	2 (n=24)	3 (n=22)	p<0.05
LF, %	-0.29±0.17	-1.11±0.26	1.05±0.13	1-2; 2-3; 1-3
HF, %	-0.12±0.36	1.58±0.36	-0.89±0.16	1-2; 2-3; 1-3
VLF, %	-0.25±0.36	-1.21±0.44	1.2±0.33	1-2; 1-3
SDNN, ms	0.08±0.31	1.35±0.51	-1.01±0.26	1-2; 2-3; 1-3
pNN50, %	0.24±0.16	1.28±0.40	-1.17±0.29	1-2; 2-3; 1-3
TP, ms^2	0.16±0.32	1.34±0.14	-1.06±0.41	1-2; 2-3; 1-3
LF/HF, arb. units	-0.69±0.44	-0.48±0.31	1.18±0.41	2-3; 1-3
SV, ml	0.08±0.25	1.38±0.34	-1.05±0.42	1-2; 2-3; 1-3
TPVR, dyn·s·cm^{-5}	-0.15±0.28	-1.34±0.21	1.14±0.32	1-2; 2-3; 1-3
Heart rate, bpm	-0.33±0.13	-1.04±0.22	1.11±0.27	1-2; 2-3; 1-3

Note: p – significance of differences between groups (clusters) 1, 2, 3 by Student's t-test and Mann-Whitney U-test, p<0.05

The results of the analysis of HRV indicators indicate that in the second cluster there is moderate sympathicotonia and centralization of the heart rate. It is accompanied by a moderate inhibition of autonomic circuit activity, a physiological increase in stroke volume, heart rate, and a decrease in total peripheral vascular resistance to prevent an increase in blood pressure. In the first cluster, there is a more pronounced increase in heart rate, multidirectional fluctuations in stroke volume, and preservation of cardiac rhythm centralization according to the values of temporal and spectral HRV indicators.

Students assigned to the third cluster showed a pronounced increase in the sympathetic innervation of the heart and a significant predominance of the activity of the central regulatory circuit. These students show a significant decrease in the values of temporary HRV indicators, a predominance of vasomotor waves of spectral analysis, a sharp increase in heart rate with less pronounced changes in stroke volume. In this group, there is a less active change in total peripheral vascular resistance, accompanied by a sharp increase in blood pressure.

Then the clusters were compared with the native values of hemodynamics and heart rate variability. Data are presented as median and 25-75 percentile for each studied indicator, Table 3.

Table 3. Values of hemodynamic parameters and HRV in students during physical activity, Me, 25-75%

Load/Clusters	Percentile								
	1 Cluster (n=29)			2 Cluster (n=24)			3 Cluster (n=22)		
	25	Me	75	25	Me	75	25	Me	75
LF, %	43.1	44.9	45.9	39.3	40.5	41.4	49.5	52.3	57.3
HF, %	8.9	10.7	11.7	11.7	17.7	18.7	6.0	6.4	7.3
VLF, %	33.6	37.2	42.0	21.0	26.2	28.0	6.0	6.4	7.3
SDNN, ms	32.5	34.7	37.7	43.9	47.2	51.6	22.0	23.5	24.7
pNN50, %	11.6	13.1	14.2	16.8	18.8	21.2	2.6	3.6	5.0
TP, ms^2	891.2	964.0	1056.1	1278.7	1290.7	1350.6	554.3	611.7	673.5
LF/HF, arb. units	5.2	5.4	5.6	5.2	5.5	5.8	7.0	7.5	7.8
SV, ml	100.9	104.4	107.3	127.5	130.9	142.2	65.1	78.9	90.1
TPVR, dyn·s·cm^{-5}	523.0	569.5	617.8	324.2	369.3	417.6	736.8	788.5	857.3
Heart rate, bpm	117.7	122.3	129.6	104.9	108.1	113.5	153.8	165.0	167.7

The results of the analysis indicate that from the data obtained, the maximum level of adaptive reserves and functional tolerance to physical activity, as well as neurohumoral regulation, was established in the second cluster. In this group, the highest level of parasympathetic activity is maintained (according to the values of the HF and pNN50 indicators) against the background of dominant sympathetic stimulation, and the structure of the spectrum corresponds to the expression LF>VLF>HF. According to hemodynamic indicators, the satisfaction of the demand of skeletal muscles with arterial blood to perform physical work is carried out mainly due to an increase in the shock ejection of blood from the left ventricle of the heart. For better oxygen delivery to working muscles, it is achieved by reducing the overall peripheral vascular resistance to blood flow.

In the first cluster, a similar structure of the spectrum is maintained in terms of heart rate variability indicators, and there is also an increase in the centralization of the heart rhythm in terms of time HRV indicators. Higher heart rate values are maintained against the background of less significant changes in stroke volume.

In the third cluster, there is a pronounced increase in sympathetic activity, which is expressed in a high value of the indicator of sympathoadrenal activation of baroreceptor control (LF). In addition, there were maximum intercluster differences in LF and vagosympathetic balance index. This group recorded the lowest values of pNN50 and SDNN, which indicates a significant influence of this physical activity, leading to a state of significant tension in the body's regulatory systems. Noteworthy is the sharp decrease in the overall power of the spectrum, as well as the high level of pulse rate with a slight change in stroke volume relative to other clusters. Total peripheral vascular resistance remains at the highest level in the second cluster.

Dicussion

A marker for assessing human performance is an indicator of the functional state of the body, characterized by the degree of activation of all physiological systems to perform a certain type of activity (Dupuy et al., 2018; Lefaucheur, 2023). Timely control and correction of physical activity allows you to optimize the level of the functional state and tolerance of the body to physical work, which is important when implementing educational training programs and methods (Losnegard et al., 2021; Lichti et al., 2023; Vorozheikin, 2016). At the same time, success in physical culture and sports activities is determined by the dynamism and efficiency of the processes of economization of physiological functions, with their maximum mobilization during exercise and the optimal rate of recovery of indicators (Tiwari et al., 2021; Kolokoltsev et al., 2021).

In recent decades, to assess the adaptive potential, a method for studying heart rate variability with recording a cardiointervalogram and determining temporal and spectral indicators has been used (Mejia-Mejia, et al., 2020; Guzii et al., 2020; Christiani et al., 2021). This provides information for an objective assessment of the functional reserves of the trainee’s body and a forecast of its success. It has been established that performing physical exercises from European physical fitness assessment tests initiates significant shifts in hemodynamic functions and autonomic balance. This is manifested in changes in stroke volume of cardiac blood output, total peripheral vascular resistance, heart rate, temporal and spectral indicators of heart rhythm. This is consistent with the data of researchers (Cid et al., 2019; Kamandulis et al., 2020; Kolokoltsev et al., 2021), whose materials showed that the indicators of spectral analysis of heart rate variability may depend on the direction of the training process, accompanied by physiological changes in parameters systemic hemodynamics, depending on the degree of training.

Under normal conditions, the activity of the heart is carried out through autonomic regulation. When the activity of the cardiovascular system is disrupted, including those caused by powerful physical activity, central control mechanisms are activated to return the body systems to normal and balance it with the external environment. These processes in the body are associated with the tension of all regulatory mechanisms (Guzii et al., 2020). Our distribution of students using cluster analysis allowed us to identify multidirectional groups of young men performing a stress test, which differ in the characteristics of their functional reserves. Taking into account the specificity of the response, the groups recorded multidirectional levels of sympathetic and parasympathetic reactivity, pronounced or moderate activation of the central regulatory circuit and inhibition of the autonomous circuit, as well as shifts in hemodynamic parameters. This makes it possible to determine individual tolerance to physical activity and predict the "price" of adaptation when performing it. We agree with the opinion of R. Tiwari et al. (2021) and M. Kolokoltsev et al. (2021), who showed differences in the values of indicators of adaptation reserve in young people depending on age, gender, body type and other factors.

According to our data, such functional changes, which are associated with significant tension in adaptation mechanisms, were found in students classified in the third cluster. They showed a significant decrease in the values of temporary indicators of heart rate variability and a sharp increase in heart rate. It is known that the greater the process of centralization of the heart control mechanism, the greater the physiological “price” of human adaptation to various factors and volumes of physical activity (Bocharin et al., 2022). There is a trend towards the development of a state of overexertion and overtraining, therefore, in this case, Timely monitoring of the functioning of the regulatory systems of the athlete’s body is necessary. A simple, accessible and informative method can be the method of studying heart rate variability.

Conclusions

The study of the reactivity of the body of students under conditions of stress testing showed that after performing physical exercises, significant shifts in hemodynamic parameters occur, accompanied by an increase in the tension of regulatory systems and an increase in the activity of the central circuit of cardiac regulation in terms of heart rate variability.

Clustering of students made it possible to identify three groups among them, among which the second group has the highest level of functional reserves and readiness for physical activity. In the first group, there is an increase in the central regulation of cardiac rhythm, which is accompanied by a more pronounced increase in pulse rate. In the third cluster, there is a predominance of low-frequency spectrum power, a significant decrease in temporary indicators of heart rate variability, and a sharp increase in heart rate. This suggests the lowest readiness of the subjects in this group for the physical activity performed when testing their physical fitness. The obtained research results can be used to individualize physical activity when planning educational and training sessions.

Conflicts of interest. The authors declare no conflict of interest.

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