THE REACTION OF THE BODY UNDER THE INFLUENCE OF A STRESS STIMULUS

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Abstract: This study examines the dynamics of heart rate variability indices under the influence of a stress stimulus. The most recognized methodological basis for studying and quantifying the system of neurohumoral regulation is the mathematical analysis of heart rate variability (HRV). The first part of the study is based on an analysis of the autonomic nervous system. In the second part, the study presents the cross-analysis of HRV and the variability of the duration of the respiratory cycle. The third part of this study is devoted to the features of the dynamics of indices of autonomous regulation under the influence of mental and physical stress stimuli. The study was conducted during the special training of candidates for cosmonauts. First group - candidates for cosmonauts during maritime training for survival. Second group - instructors and candidates for cosmonauts during special parachute training. The results of the study showed the difference between physical and emotional stress. With physical exertion, the activation of the sympathoadrenal system is accompanied primarily by the release of adrenaline, and when the psychoemotional effect is activated, the activation of the sympathoadrenal system is ensured by the release of norepinephrine, the neurogenic canal.

Key words: stress stimulus, distress, adaptation, neurohumoral regulation, HRV parameters, pathogenetic basis of the development of the disadaptation reaction

Introduction. Stress is the multi-level systemic response of an organism to any exposure that exceeds the capabilities of its selective homeostatic response mechanisms (T.A. Day, 2005). Therefore, quantitative measurement of the human body's physiological response to stress should be based on a multilevel approach and it involves assessment of the following:

A. Influence of the social environment: The following sublevels have the most significant negative influence: low socioeconomic status, adverse life events (including an unpleasant childhood experience), family stress, work stress, and low social support, as well as powerful stressors such as natural disasters or war, which lead to the development of social stress disorders and/or post-traumatic stress disorders.

B. Personal characteristics: anger, hostility, type D personality, and neuroticism.

An unfavorable combination of these social and personal factors leads to such negative effects as depression, anxiety, and emotional burnout. Against this background, a number of somatic and primarily cardiovascular diseases develop (R.von Känel).

The progression of the pathology at the level of organs and tissues is not direct but implemented via the limbic and reticular complex—the vegetative and endocrine systems (K.V.Sudakov). It is no wonder that the binary psychosomatic disorders formula (cortical abnormalities mean somatic pathology) is supplemented by the introduction of the third element (vegetative and endocrine system), allowing it to explain the mechanisms through which a mental effect is expressed in somatic systems and providing a key for a scientific approach to study psychosomatic relationships (A. M. Vein). The important role of the neurohumoral regulation system in the progression of the pathological process was first highlighted by F.Alexander (F.Alexander), who in 1950 offered a theory in which differentiated psychopathological hypotheses were associated with physiological and pathological somatic processes. According to Alexander, vegetative neuroses arise on the basis of unconscious conflict in the process of pathological neurotic progression when emotional tension cannot be suppressed yet its accompanying vegetative changes remain. The emotional state in a particular conflict defines the plan under which the disturbance of vegetative function occurs. In some cases, vegetative reactions manifest in a perverted form that has symptoms of increased parasympathetic excitation. The last effect can lead to involuntary defecation and urination and can be accompanied by paleness of skin integuments (H.F.Ulmer). If the possibilities of competitive and aggressive actions are suppressed, sympathoadrenal system excitation results (V.Bräutigam). At the same time, the excessive activation of only cortical and limbic structures is not enough to cause the disease. Hyperactivity (an inadequate response) at the level of the hypothalamus—the brain stem—is needed. The brain stem is a structure that controls the state of the vegetative nervous system, and the hypothalamus integrates endocrine functions and autonomous regulation. Based on these ideas, the study of the autonomous (vegetative) regulation level involves the assessment of sublevels: parasympathetic and sympathetic divisions of the vegetative nervous system, vegetative reactivity and vegetative activity support, and stem structures (baroreflex regulation).

The concept of "quantitative estimation of the general functional state and adaptive reserves of the organism" in many respects is identical to the quantitative estimation of the state of the neurohumoral regulation system. But how is one to quantify neurohumoral regulation in general and the contribution of each sublevel? There are many approaches to this problem, but uncertainty can be eliminated by applying Newton's strategy, which is to single out a central, well-established, and properly formulated fact and to use it subsequently as the basis of deductions about this circle of phenomena (A.A. Genkin, V.I. Medvedev). This established fact may be the ideas put forward by N. Viner that almost all regulation processes in biological objects are formed as oscillators, and they should be analyzed on the basis of wave theory. The main mediators of the neurohumoral regulation system (noradrenaline (adrenaline) and acetylcholine) are secreted in portions (in quanta). Discontinuous variation of the mediators' concentrations leads to rhythmic fluctuations of the basic vegetative parameters and primarily of the parameters of the cardiovascular system. From a technical point of view, heart rate (HR) fluctuations are the easiest to track. Currently, the most recognized methodological basis for studying and quantifying the neurohumoral regulation system is mathematical analysis of heart rate variability (HRV). The clinical significance of HRV was first noted in 1965, when E.H. Hon and S.T. Lee noticed that fetal distress was preceded by alternation of the intervals between heart contractions before there were any discernible changes in the heart rhythm itself. The idea of the expediency of mathematical methods using heart rhythm analysis to obtain quantitative evaluations of human functional status was implemented by a group of Russian scientists headed by academician V. V. Parin (R.M. Baevsky, O.G. Gazenko). The length of the R-R electrocardiogram (ECG) intervals (the most accessible, informative, and noise-free characteristic of human heart activity) was studied as the initial data for such estimation. Subsequently, in the course of their research, A.D. Voskresensky and M.D. Ventsel formalized a scheme for analyzing and describing heart rhythm that allowed them to abandon uncertain conclusions about its structure that were based on visual observations. They reached an important conclusion about pilots' and cosmonauts' status under the influence of real flight factors in response to ground conditions. Further works of R. M. Baevsky et al. provided a major physiological basis for the observed changes in heart rhythm, associating the detected changes with the regulation system and fundamental ideas about adaptation. An important step in the study of HRV was the adoption of the international standard in 1996 proposed by the North American Society of Pacing and Electrophysiology and the European Society of Cardiology. This unified the approaches to recording methods, analysis, evaluation, and physiological interpretation of HRV.

Having assessed the general functional status of an organism according to its HRV data, we can more accurately predict the probability of regulatory and/or somatic abnormalities' progression during exposure to a stress-excitatory agent, quantify the adaptation reserves of the particular human organism at a particular time, and build the tactics of medical and recreational activities on this basis.

I. Cardiac rhythm variability. Method of vegetative nervous system research

1.1. The definition, physiological classification, and analyzed indices of cardiac rhythm variability

Heart rate variability (HRV) is a method of researching and estimating the current functional status of an organism based on qualitative and quantitative analysis of the variability of the R-R electrocardiogram (ECG) intervals associated with the modulating influence of the vegetative nervous system and humoral factors on the pacemaker activity of a heart sinus node over a period of time.

The registration method of HRV is very simple at first sight and involves ECG recording for a particular established period of time (with a short recording from 2 to 5 minutes), followed by measurement of RR intervals. However, there is a number of significant limitations. Firstly, only sinus heart contractions (RRNN) are subject to analysis. Secondly, the process must be stationary—in other words, the distribution of R-R intervals must be normal. All abnormal contractions (extrasystoles, episodes of pacemaker displacement) and non-stationary areas associated with swallowing, coughing, and external effects are excluded from the analysis.

Both the international standard (of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology) and the Russian recommendations analyze the obtained series of R-R intervals from a mathematical point of view. Consequently, there are methods of time analysis (including geometric construction), spectral analysis, and nonlinear methods of measurement. I do not dispute the importance of the mathematical approach, but it seems more relevant to use physiological classification, as mathematical approaches are just methods allowing one to measure the values of the HRV indices most correctly in a specific situation.

Physiological classification of the HRV indices

In accordance with the physiological classification (V.M. Mikhailov, 2017), the analyzed HRV indices are united based on their ability to measure the physiological correlates, namely:

I.1. The current functional status of the organism.

I.2. The balance of the divisions of the autonomous (vegetative) nervous system.

1.2.1. The status of the parasympathetic division of the autonomous (vegetative) nervous system.

1.2.2. The status of the sympathetic division of the autonomous (vegetative) nervous system.

1.2.3. The balance of the VNS divisions (the ratio of sympathetic and parasympathetic influences)

I.3. The steadiness (stability) of the regulation system.

I.4. The persistence of baroreflex regulation.

1.1. The estimation of the current functional status of an organism is based on the measurement of parameters describing cardiac rhythm variability, namely, average RRNN, R-R-max–R-R-min, SDNN, total spectral power (TP), the area of the scattergram cloud (S), the area of the histogram triangle (the St. George's index—this triangular index is the integral of the frequency function (this is the total number of NN intervals with reference to the frequency function's maximum)). In this case, the histogram is represented in the form of an isosceles triangle. Using the mathematical constructs based on the least-squares method, the histogram's slope is made closer to the rectilinear segment so that the difference between the areas of the simulated triangle and the original histogram is as small as possible. In fact, the triangular index reflects the ratio between the base of the triangle and the mode amplitude of this very triangle, and therefore the interpretation of this index approximately corresponds to the well-known Baevsky tension index (TI).

The St. George index gives the opportunity to estimate cardiac rhythm variability by measuring the area of the frequency distribution histogram, automatically excluding any outliers. The exclusion of abnormal contractions (artifacts and extrasystoles) can be achieved by drawing the tangents from the vertexes of the triangle to the base. The wider the base of the triangle obtained this way, the greater the rhythm variability.

1.2. The balance of the divisions of the autonomous (vegetative) nervous system

1.2.1. Estimation indices of the parasympathetic division of the autonomous (vegetative) nervous system (VNS) status

The mediator of the parasympathetic division of the VNS is acetylcholine. It is rapidly destroyed by acetylcholinesterase, and it leads to rapid changes (oscillations) in the heart rate. Thus, a wave with a short period and, consequently, a high frequency of oscillations of more than nine per minute (> 0.15 Hz) (high-frequency oscillations [HF]) is formed. The activity of the parasympathetic section of the VNS mainly depends on respiration (it provides cardiorespiratory synchronization). Since the human respiration rate is often 9-24 breaths per minute, changes in cardiac rhythm oscillations occur in the frequency range from 0.15 to 0.4 Hz. When recording cardiorhythmography, these waves look like fast (high-frequency) oscillations (HF-component) of HRV (Fig. 1).

Fig. 1. High-frequency oscillations (fast waves) on (a) rhythmogram (top);
(b) spectrogram (bottom left); (c) scattergram (bottom right)
(TP = 1787 ms^2/Hz; VLF = 248 ms^2/Hz; LF = 185 ms^2/Hz; HF = 1354 ms^2/Hz; LF/HF = 0.14;
L, ms = 127; w, MS = 131; L/w = 0.97; S, ms^2 = 26120.)

The high-frequency oscillations can also be measured using such indices as

— RMSSD—the square root of the average of squares of differences between adjacent NN intervals.

— NN50—the number of cases in which the difference between the duration of successive NN exceeds 50 ms. In some cases, it is expedient to use other differences of normal RRNN intervals' duration. In this case, the question is about the NN-intervals family (NNx [ms]), where x is a different duration of NN intervals that is used when the average heart rate differs greatly from the accepted reference values. For example, when examining newborns during physical exercise and emotions, if the average heart rate significantly exceeds 100 beats/min, the use of pNN50 always gives zero value. In these cases, the use of pNN15 allows the use of this index (V.M. Mikhailov et al., 2006).

— pNN50 (%) (pNNx [%])—percentage (share) of successive NN intervals, where the difference between them exceeds 50 ms (x ms).

— On a scattergram, parasympathetic activity is characterized by the indices of the cloud width (w).

— On a spectrogram, parasympathetic activity is reflected by the high-frequency oscillations (HF)—it is a part of the spectrum in the frequency range 0.15–0.40 Hz (oscillation frequency: 9–24 cycles per minute). The power in this frequency range is associated mainly with respiratory movements and reflects the vagal control of the heart rate (modulation effect of the parasympathetic division of VNS).

— Power in the high-frequency range is expressed in normalized units (HF, n. u.), calculated by the formula HF, n. u. = HF / (Total – VLF) × 100.

When conducting functional tests of the parasympathetic activity/reactivity of the VNS, the parasympathetic division can be defined according to the following indices:

— 30:15 coefficient—calculated during the orthostatic sampling;

— breathing coefficient for sampling with deep controlled respiration (six per minute) (the ratio between the average duration of the maximum length of the RR intervals on the exhalation and the average duration of the minimum length of the RR intervals on the inhalation);

— speed of heart rate recovery at 1 and/or 2 minutes after the maximum loading test.

1.2.2. Estimation indices of the sympathetic division of the autonomous (vegetative) nervous system (VNS) status

The mediator of the parasympathetic division of the VNS is noradrenaline. The main mechanism of formation of low-frequency oscillations (LF-component) is recurrent outbreaks of sympathetic vasomotor activity (own rhythm of vasomotor center), which lead to a rise of blood pressure (BP). Increased blood pressure reflexively slows the heart rate (HR) via a baroreflex mechanism, so we can see specific slow waves (low frequency oscillations) in the rhythmogram shown in Fig. 2.

Fig. 2. Rhythmogram and HRV spectrogram with the predominance of activity of the sympathetic division of the VNS: TP = 1579 ms^2/Hz; VLF = 198 ms^2/Hz; LF = 1286 ms^2/Hz; HF = 95 ms^2/Hz; LF/HF = 13.5; L, ms = 122; w, ms = 41; L/w = 2,98; S, ms^2 = 7806.

In addition, the baroreflex activity of efferent influence is represented by other cerebral ergotropic brain structures. Spectral analysis is mainly used to estimate sympathetic activity.

— Low-frequency oscillations (LF) are a part of the spectrum in the frequency range of 0.04–0.15 Hz (oscillation frequency is 2.4 to 9 cycles per minute). Power in the low frequencies is expressed in normalized units (LF, n. u.), calculated by the formula LF, n. u. = LF / (Total – VLF) × 100.

— With some reservations, the rate of the cloud length on the scattergram also allows the estimation of the state of sympathetic and adrenal activity.

When conducting functional tests, sympathetic and adrenal activity is expressed by

— Chronotropic index (CI): the ratio of the increase of the heart rate at the peak load to the heart rate at rest (at maximum loading test).

— The coefficient of increase in the heart rate at 1 minute of load compared to the heart rate at rest (Fig. 3). The index is considered to be "soft" psychic (mental) stress. In the Paris study (Jouven et al., 2009), which lasted more than 20 years, 7,746 Frenchmen from 42 to 53 years of age were supervised. The threshold values of soft mental stress were set to < 4 beats/min and > 12 beats/min. Data for men of 52.4 ± 6.6 years of age: the difference in the heart rate (Me [25;75]) at 1 minute of load – the heart rate when lying = 24(21;29); the difference in the heart rate at 1 minute of load – the heart rate when sitting (on bicycle ergometer) = 12(9;16) beats/min.

Figure 3 shows the rhythmogram of the loading test (bicycle ergometry, ramp protocol) of a patient passing a medical flight commission. The heart rate at rest, sitting = 80 beats/min. The heart rate at 1 min of load (25 W) = 125 beats/min, representing an increase of 45 beats/min. In 2 minutes (120 s), against a background of increasing load, the heart rate decreased to 110 beats/min, then rose in parallel to load.

Fig. 3. Load test rhythmogram. Excessive heart rate response to soft mental stress.

1.2.3. The balance of the VNS divisions (the ratio of sympathetic and parasympathetic influences) is characterized by the following:

— The ratio of LF to HF. LF and HF are measured in relative units that represent the percentage contribution of each oscillating component in the spectrum's total power, from which the power of the VLF-component is subtracted, i.e., HF, n. u./LF, n. u.

— The width of the scattergram "cloud" (w) is associated mainly with high-frequency oscillations (equivalent of HF-component), and the length (L) is mainly related to the general variability of the cardiac rhythm and predominantly slow modulations and reflects sympathetic and adrenal activity. In Figure 1 (Parasympathicotonia), "the cloud" is almost in the form of a circle. In Figure 2 (Sympathicotonia), "the cloud" is stretched along the bisectrix. Accordingly, the ratio L/w is equal to the ratio LF/HF, which allows one to characterize the sympathetic and parasympathetic balance. The index L/w is expedient in cases when HRV recording register extrasystoles.

— R.M. Baevsky's tension index (TI) of regulation systems characterizes the activity of the autonomous regulation mechanisms and the state of regulation of the central contour. This index is calculated based on analysis of the histogram's RR-interval distribution. Amplification of the sympathetic regulation manifests in the stabilization of the rhythm, a reduction of the

RR-intervals' durations' scatter, and an increase in the number of intervals with the same duration (an increase of the mode amplitude in the number of intervals corresponding to the mode value—the most frequent value). The mode amplitude is increased, whereas the base of the histogram becomes narrow. In quantity, this can be expressed by the ratio of the histogram's height to its width. The index is very sensitive to the slightest deviations of the RR intervals' duration from the normal distribution. Even single episodes of spontaneous prolongation of the RR duration lead to an excessive decline in TI values. Conversely, an increase in the heart rate and reduction of the RR-intervals' durations' scatter (for example, during functional tests) sharply increase TI in disproportion. As with other geometric methods, the correct interpretation of the results is possible given a relatively long recording (optimally, at least 20 minutes).

— Very low-frequency vibrations (VLF)—the frequency range is from 0.003 to 0.04 Hz (the oscillation frequency is 0.2 to 2.4 cycles per minute). Physiological factors influencing them are numerous and cannot always be reliably interpreted. Presumably, the spectral power in this range is affected by the renin-angiotensin-aldosterone system, catecholamine concentration in plasma, the thermoregulation system, and other cerebral ergotropic structures and various factors leading to the instability of the recording process. Some authors have summarized the values of the LF and VLF-components, and the sum of these values is considered to be a measure of sympathetic and adrenal activity. This approach can be accepted in individual cases only.

1.3. The characteristics of the complexity and stability of the system can be given using nonlinear methods of analysis such as entropy, fractal, periodic oscillations, bifurcation, and chaos.

How can we understand the phrase "the inner stability of the system"? Ideas about systems' internal stability arose from chaos theory, one of the founders of which is Edward Lorenz. In 1972, Lorenz published the scientific article whose title became a household word: "About the Possibility of Predictions: Can the Flapping of a Butterfly's Wings in Brazil Cause a Tornado in Texas?" This wording illustrates the essence of chaos theory.

Is it possible to predict a predisposition and a readiness for sudden changes in health status? Using mathematical models from chaos theory, with a certain probability, they undoubtedly can be predicted. There are cases of sudden death that did not have a direct connection to any disease or genetic abnormality, but they are not common. With proper dynamics monitoring of HRV and with the appropriate mathematical software, it is possible to predict the probability of sudden and abrupt deviations in heart rate and, as a consequence, health status in general. These mathematical models are used by ratings agencies when making decisions about expediency and investment risks and by financiers when predicting the fluctuations of currencies.

1.4. The indices characterizing the state of baroreflex regulation

Ideally, the measurement and estimation of baroreflex indices are based on the cross-correlation ratio between the heart rate (RR interval) and arterial pressure at rest or in response to exposure to an excitatory agent. One of the most frequently used methods of baroreflex function estimation is to compute the angle between the changes in the heart rate and blood pressure. Cross-spectral analysis for the heart rate and blood pressure can also be used to estimate baroreflex activity. One can improve the accuracy of the result with functional tests. In terms of response dynamics, one can judge how synchronously the indices of the heart rate and blood pressure change. For this purpose, one can use a Valsalva test, a passive tilt test, artificial creation of negative pressure in the area of carotid bodies, a test with physical loading, or pharmacological influence by injection of drugs that quickly increase or lower blood pressure.

II. Cross-analysis of the heart rate variability and respiratory cycle duration variability (HRV/RCDV) and the limits of the spectral analysis frequency ranges

The close relationship between the respiratory and cardiovascular systems was established by S. Hales (1677–1761), who was the first to notice that heart rate varies depending on breathing. In 1847, the photographer C. Lugwig (1816–1895) recorded respiratory sinus arrhythmia. An inhalation increased heart rate, and an exhalation slowed it. What gives us the record of the breathing pattern (pneumogram) and the calculation of cross-correlation relationships of HRV/RCDV?

1. Breathing pattern estimation contributes to a more complete clinical characterization of patients with psycho-emotional and psycho-vegetative disorders when complaints of rapid breathing, feeling short of breath, and breath dissatisfaction—the desire and the need to take a deep breath periodically (the so-called "dreary neurotic breath") are bright and almost obligatory.

2. The breathing pattern may indirectly contribute to diagnosis and functional evaluation of a number of other pathologies, primarily obstruction of the respiratory system and some mitochondrial diseases.

3. To change the limits of the frequency ranges correctly, and in some cases quite significantly, which allows one to rightly judge the balance of the VNS divisions and to clarify the quantitative values of spectral power indices.

4. In some cases, when myocardial electrical instability manifests in the form of rapid changes in the RR-intervals' duration, which looks like high-frequency oscillations, breath recording contributes to the recognition of a pathology.

The pattern of a single respiratory cycle and a pneumogram itself can provide diagnostic value in general and should at least be taken into consideration while interpreting the results of HRV.

A normal pneumogram has a steep upward curvature; in the upper part, breath speed slows down slightly and then goes into a downward curvature, almost without an inspiratory plateau (without delay). The expiratory flow rate slows to end in an expiratory plateau. Ventilation pattern features can contain important information and should be considered in the analysis of cardiac rhythm. For example, regularly recorded "steps" on the rising curvature of the inhalation curve are evidence of emotional (panic) disorders (Fig. 4). From the point of view of psychosomatic medicine, they can be interpreted as a reaction of rejection (not letting in).

Fig. 4. Pneumogram pattern for anxiety disorders. On the rising curvature of the pneumogram, notches are clearly visible, which are considered as "unit setting" and representative of the unwillingness to let someone or something into one's inner world.

It is sometimes possible to identify the breathing pattern specific to obstructive sleep apnea (OSA). Typically, such a breathing pattern with typical snoring and episodic apnea is recorded only in case of explicit OSA when symptoms of chronic fatigue (daytime sleepiness) clearly manifest.

Fig. 5 shows a rhythmogram that presents single periodic deep breaths accompanied by visibly increased heart rate and recurrent retraction. In his day, E. Fromm very brightly described such breaths as "dreary neurotic breaths." Surely, this conclusion looks more justified in cases when we not only visually observe the influence of breathing pattern features from the rhythmogram but have also recorded a pneumogram.

Fig. 5. Cardiorhythmography pattern in case of "dreary neurotic breaths." The arrows indicate the changes in the rhythmogram caused by deep breaths.

Deep breaths significantly increase cardiac rhythm variability and the SDNN indices in particular and significantly change the spectral characteristics. The amplitude of slow waves increases artificially, and as a result, the spectral power of the waves of low and very low frequency increases. As a result, the share of the VLF-component and the LF-component in the structure of HRV spectral power becomes disproportionately large. Although the conclusion about the prevalence of "cerebral ergotropic effects in the cardiac rhythm modulation" in such a situation essentially seems to be correct, the real situation is not reflected. Only synchronous recording of a pneumogram or constant monitoring of the patient during ECG recording allows one to adequately interpret the results and provide sound recommendations.

The following are widely used ways of quantifying the correlation relationship (HRV–RCDV) or cardiorespiratory synchronization indices (CSI):

— time domain analysis, when the amplitude of oscillations in heart contractions is analyzed in connection with each respiratory cycle (for example, the difference between the fastest heart rate during inhalation and the slowest heart rate during exhalation) (P. Grossman et al., 1990);

— calculation of correlation coefficients;

— coherence analysis of the heart rate variability spectral power and the respiratory cycle's duration variability (L.J. Bard et al., 2001; D. Widjaja et al., 2013);

— nonlinear dynamics methods, which allow one to estimate such properties of physiological processes as entropy, which characterizes the information uncertainty level (the system stability), and fractality, reflecting the degree of process self-similarity.

The use of standard statistical correlation coefficients in cross-analysis of HRV–RCDV (time domain analysis) requires preliminary confirmation of the normal distribution of both samples, calculation of the confidence limits of the correlation coefficient, and evidence of the processes' stationarity, and it is difficult to observe for short recording.

Spectral power coherence estimation (cross-correlation relations of the heart rate and respiratory rate in the frequency domain) has a number of advantages. The main ones are spectral characteristics providing for selective analysis of the relationship (coherence) between the duration of the respiratory cycle and the high-frequency (HF) component of HRV. From the point of view of a system approach, the desynchronization of cardiorespiratory relations is one of the symptoms allowing one to diagnose a maladjustment state (pre-existing disease). In particular, K. V. Sudakov (1997, 1998) and E.A.Yumatov (1983), researching the cross-correlation heart rate–respiratory rate relationships during psycho-emotional stress, found the relationship of changes of the correlation coefficients of the heart rate and respiratory rate with the nature of the individuals' achievement of adaptive results. High cross-correlation of the HRV–RCDV ratios is observed in persons who have reached good results in work, in those successfully studying in educational institutions, and in athletes showing consistently high results. A separate issue is how to make a cross-correlation analysis of HRV/RCDV relatively simple (for the user of computer programs) and clear to understand while providing maximum information and being easily applicable in practice.

In 2002, I proposed a way of estimating human functional status based on the analysis of the heart rate variability and variability of respiratory cycle duration (invention No. 2195163 of 27.12.2002). The essence of the proposed method can be presented as follows.

The standard examination protocol includes a 5-minute synchronous recording of ECG and a pneumogram. The estimation of the spectral power in each frequency range is carried out in accordance with the international standard. A histogram of the respiratory cycles' duration, which is graphically superimposed on the HRV spectrogram, is built based on the pneumogram. In a typical case, the following results shown in Fig. 6 are obtained.

Fig. 6. The sequence of graphical representation of an HRV spectrogram and respiratory cycle duration histogram: (A) ECG and respiratory curve recording (v = 5 mm/s); (B) pneumogram (top) and rhythmogram (bottom); (C) the HRV spectrogram with superimposed respiratory cycle duration histogram.

The base of the respiratory cycle duration histogram is in the range of 0.3 to 0.38 Hz, which corresponds to a respiratory rate equal to 18–23 breaths per minute. In this case, the base width of the respiratory cycle duration histogram coincides with the frequency characteristics of the HF-component, and recalculation of the spectral power indices is not required. A normal respiratory cycle duration histogram should coincide with the HF-component of HRV.

The following indices are analyzed:

— respiratory rate and RCDV spread;

— HRV spectral analysis parameters—the HF-component is corrected considering the position of the respiratory cycle duration histogram (in Hz);

— cardiorespiratory synchronization and/or correlation coefficient.

2.1. Estimation of the frequency ranges' limits depending on the respiratory rate

During the development of the International standard (1996), the limit of the frequency range between the HF-component and the LF-component was defined as 0.15 Hz, which corresponds to the respiratory rate of 9 breaths per minute. The limit was chosen arbitrarily without considering the actual respiration rate (respiratory cycle duration). It was assumed that the normal respiratory rate could not be less than 9 breaths per minute. But what if the respiratory rate is less than 9 breaths per minute? At the respiratory rate of 6–9 breaths per minute, the severity of respiratory sinus arrhythmia and, hence, the cardiac rhythm variability are maximized. The answer is simple: one needs to shift the HF-component limit to the left limit of the respiratory cycle duration histogram or to increase the respiratory rate to > 9 per minute (Fig. 7).

Fig.7. Spectrogram and respiratory cycle duration histogram. Measurement of HF-components:

(A) respiratory rate = 9 per minute; standard measurement range 0.15–0.40 Hz: **TP, ms^2 = 5657;** LF, ms^2 = 3364; HF, ms^2 = 1474; **LF/HF = 2.3**

(B) respiratory rate = 9 per minute; the measurement range is shifted to the left limit of the respiratory cycle duration histogram—0.12–0.20 Hz: **TP, ms^2 = 5651**; LF, ms^2 = 1035; HF, ms^2 = 3926; LF/HF = **0.26**

(C) the measurement range of the respiratory cycle duration histogram limits against the background of hurried respiration (16 per minute): **TP, ms^2 = 2325**; LF, ms^2 = 319; HF, ms^2 = 1168; LF/HF = **0.27**

Moving the HF-component limit to 0.12 Hz (the left limit of the respiratory cycle duration histogram) led to a significant change in the sympathetic and parasympathetic balance indices (from 2.3, which corresponds to hypersympathicotonia, to 0.26, which corresponds to frank parasympathicotonia).

The wordings of the conclusion were changed accordingly:

(A) The variant without correction (as is): "The total spectrum power of neurohumoral modulation is moderate. The balance of the vegetative nervous system divisions is characterized by a predominance of sympathetic division activity. Cardiorespiratory synchronization is maintained. The current functional status is slightly reduced."

(B) The variant after correction of the HF-component's left limit (for 0.12 Hz): "The total spectrum power of neurohumoral modulation is moderate. The balance of the vegetative nervous system divisions is characterized by a predominance of parasympathetic division activity. Cardiorespiratory synchronization is maintained. The current functional status is satisfactory."

(C) The variant when the respiratory rate is increased to 16 per minute: "The total spectrum power of neurohumoral modulation is low. The balance of the vegetative nervous system divisions is characterized by a predominance of parasympathetic division activity. Cardiorespiratory synchronization is maintained. The current functional status is reduced."

In the first case (A), the decline of the current functional status (FS) is conditioned upon hypersympathicotonia. In the second case (B), the current functional status is considered satisfactory, but the characteristic of the VNS division's balance reversed, and it in fact "improved" the FS. Finally, in the third case (C), after the increase in the respiratory rate, the VNS division's balance again changed to "the predominance of the parasympathetic division activity," while the current FS was "reduced," but this time by reducing the total spectrum power of neurohumoral modulation.

Where is the truth? Which conclusion can be regarded as correct? It is possible to offer an approximate algorithm for recording and forming the opinion.

— Background recording should be carried out as usual without bringing the patient's attention to his or her respiratory rate and respiration depth.

— If from the original recording we see that the respiratory rate is outside the established standard range (less than 0.15 Hz or more than 0.4 Hz), we carry out the recording with metronomic breathing (the optimal respiratory rate is from 14 to 18 per minute).

— When interpreting results, the structure of spectral power and, accordingly, the balance of the VNS divisions are calculated according to the recording with metronomic breathing.

— The estimation of the total spectrum power (TP index) is carried out depending on the peculiarities of the patient's normal breathing pattern. If the examined patient breathes slowly and deeply for the sake of improving the index, then the TP index of metronomic breathing is considered. If it is the patient's normal breathing pattern, it is possible to take the values obtained in the first recording.

When the respiratory rate is more than 24 breaths per minute (more than 0.4 Hz), one should extend the calculation limit of the HF-component to the right limit of the respiratory cycle duration histogram.

2.2. Cardiorespiratory synchronicity (CRS)

The synchronization of breathing and cardiac rhythm is of great importance in human life. The proposed approach in which the HRV spectrogram is superimposed with the respiratory cycle duration variability histogram is matchless for its simplicity and descriptiveness. The picture of CRS is so obvious that, as a rule, it does not require special explanations and comments. In Fig. 8, an example is shown of a well-expressed cardiorespiratory synchronization on the left and the almost complete absence of CRS on the right.

Fig. 8. Spectrogram and RCDV histogram. Left: good cardiorespiratory synchronization (CRS = 51); Right: cardiorespiratory desynchronosis (CRS = 2.6)

Important note: with age, during a pathology, when there is an "escape" of the cardiovascular system under the modulating influence of the vegetative nervous system, cardiorespiratory synchronization is also reduced. Accordingly, the diagnostic value of respiratory samples is reduced as well.

2.3. High-frequency oscillations of cardiac rhythm that are not caused by breathing and are not related to electrophysiological instability of the myocardium

In some cases, usually during pathology, the rhythmogram shows high-frequency oscillations (the HF-component) that are not related to breathing and therefore should not be considered as the HF-component in the estimation of total spectral power and in calculation of the VNS division's balance. On an ECG, these heart rate oscillations look like frequent and rapid changes of RR-intervals' duration but do not meet the extrasystoles criteria. Figure 9 presents an example that shows how cross-analysis of HRV–RCDV allows one to identify such high-frequency waves caused by electrophysiological features of the sinoatrial zone.

Fig. 9. Spectrogram for high-frequency oscillations. Left: the peak of high-frequency oscillations (0.15–0.25 Hz). When superimposing the respiratory cycle duration histogram, the peak of the HRV spectrogram is not related to breathing (RCDV is in the range of 0.23 to 0.40 Hz). Thus, the presented high-frequency oscillations are not related to respiration and most likely reflect the electrical instability of the sinoatrial zone. Top: pneumogram and rhythmogram.

When comparing the ECG with the respiratory curve (Fig. 9 A) and the cardiorhythmogram with the pneumogram (Fig. 9 B), it is obvious that high-frequency oscillations do not depend on the heart rate and the main peak of the HF-component is located outside the RCDV histogram. Therefore, these waves do not reflect the state of the VNS parasympathetic division. In this case, the most probable genesis of cardiorespiratory desynchronosis is electric instability in the area of the right atrial pacemaker.

III. Peculiarities of autonomous regulation dynamics during exposure to mental and physical stress excitatory agent

3.1. The dynamics of HRV indices during the survival and the parachute training of cosmonaut candidates

The research was conducted during special training of cosmonaut candidates.

The first group comprised the cosmonaut candidates during the sea survival training.

The second group comprised instructors and cosmonaut candidates during the special parachute training. Besides, for cosmonaut candidates, this training was valid.

The main feature of the research was the fact that all experiments were included in the real training process. The additional exasperating stress excitatory agent and the motivation for high-quality task performance was the fact that, in almost all cases, there was a professional selection. On the one hand, this fact significantly complicated the organization of the experimental material collection and restricted the set of methodological tools and the selection of medical monitoring equipment, but on the other hand, it eliminated most of the disadvantages of a laboratory experiment, especially the low activity motivation for the participants of the experiment.

In the first group, the research was carried out at the Russian training bases of the Yuri A. Gagarin Research and Testing Cosmonaut Training Center. High-quality performance by the cosmonaut candidates during the survival training is a prerequisite for admission to flights. The purpose of the sea training is to simulate extreme conditions of autonomous existence in case of the emergency landing of the flight crew at sea and to form professionally important qualities in the cosmonauts.

Materials and methods: The first group includes 12 practically healthy cosmonaut candidates, 11 men and one woman (mean age = 37.4 ± 5.8 years). The recording and estimation of HRV were conducted in accordance with the international standard of 1996 with 5-minute recordings. Additionally, pneumograms were recorded using the Poly-Spectrum-12 hardware and software complex of Neurosoft LLC (the city of Ivanovo).

The electrocardiograms (ECG) and pneumograms were recorded from the capsule of a lander by means of a medical monitoring system (MMS) with radio-telemetric transmission of information by Poly-Spectrum-Radio (Neurosoft LLC, the city of Ivanovo). The first rhythmogram (RG) recording was performed onboard the ship in a separate cabin immediately prior to training, and the second one was performed within 5–10 minutes after the training, conditioned upon the process's stationarity.

During the training, participants had to perform a number of tasks in the lander capsule. The most significant factors affecting the current functional status during the sea training are excessive motion sickness, overheating, dehydration, hypoxia, and hypercapnia. A significant factor in the negative psycho-emotional modulation of FS during the sea training is emotions (N. A.Filatov et al., 2003; V. M.Mikhailov et al., 2004; V. M.Mikhailov et al., 2006; V. M.Mikhailov, 2008).

Skydiving was intended to give trainees work skills under conditions of emotional and physical stress. ECG (rhythmogram) recording and radio-telemetric transmission of information immediately during the descend were performed using the Poly-Spectrum-Radio hardware and software complex. The first examination was performed in the morning in prone position before the first jump, and then in an upright position, the standing active orthostatic test (AOT) was performed. The repeated recording (in prone and upright positions) was performed 5–15 minutes after landing (after a fixed period determined visually in the rhythmogram).

In the second group, 17 people aged 30 ± 4 years were examined.

Recording and analysis of HRV was performed on the hardware and software complex Poly-Spectrum-8 (12) (Neurosoft LLC) in accordance with the International standard of 1996.

Fig. 10 presents photographs of the field testing of cosmonaut candidates during the special sea training.

Fig. 10 A. Simulation of a lander capsule falling in the sea.

Fig. 10 B. Recording of HRV and parameters of central and cerebral hemodynamics ("REO-Spectrum" hardware and software complex) 5–10 minutes after finishing the training.

The current functional status was assessed by the TP (total spectral power) indicator, considering the contributions of fast oscillations (HF-component) as reflecting the activity of the vegetative nervous system's (VNS) parasympathetic division, slow fluctuations (LF-component) as a marker of sympathetic activity effects, and very slow oscillations (VLF-component) as conditioned upon humoral, metabolic, and cerebral ergotropic influences to a certain extent. The LF/HF ratio is regarded as the sympathetic and parasympathetic balance.

The reactivity of the VNS parasympathetic division during the AOT was determined by the 30:15 coefficient (C 30:15). Vegetative maintenance of activity was estimated according to the degree of activation of the sympathetic and adrenal systems in response to orthostasis (the dynamics of the LF/HF percentages ratio was considered with regard to changes in the absolute values of the LF-component).

Additionally, the pneumogram was recorded, the respiratory cycle duration (RCD) was determined, and the limit of the HF-component was adjusted if necessary with regard to width and position on the x-axis of the RCD histogram's base. The results of the research were processed using Microsoft Excel 7 and Biostat 3.03 statistical software packages. Data are presented as the median and 25th and 75th percentiles (Me [25%; 75%]). The differences' validity was estimated by the non-parametric Wilcoxon test.

The results of the research on cosmonaut candidates before and after the sea training

The results of HRV mathematical analysis before and after the sea training of cosmonaut candidates are given in Table 1. As can be seen from the data presented in Table 1, after the sea training, the variability of cardiac rhythm significantly decreased at rest: the total spectrum power (TP) decreased at the expense of VLF- and HF-components, and the SDNN indices decreased. In the structure of spectral power, HF (%) indices and time indices evidently significantly decreased, characterizing parasympathetic activity (RMSSD, pNN50 [%]). Against this background, the contribution of the slow component (absolute values of LF-component spectral power were not changed) increased, which reflects the relative increase in the sympathetic and adrenal systems' activity.

As a result, the ratio of LF/HF, characterizing sympathetic and parasympathetic balance, evidently increased. The above-mentioned changes can be interpreted as follows: After the sea training, a decrease in current functional status (mainly due to the VNS parasympathetic division) and a relative increase in sympathetic and adrenal activity were observed. Please note that the increase in sympathetic and adrenal activity is not absolute but relative.

Table 1. HRV indices before and after the sea training (background recording and AOT)

Index	background recording		AOT	
	Before	after	before	After
RRNN, ms	948 (846; 1034)	694 (625; 747)***	754 (707; 878)	585 (516; 616)***
SDNN, ms	54.0 (40.7; 64.3)	27.0 (23.5; 43.8)*	47.5 (42.3; 51.5)	27.0 (23.5; 32.0)**
RMSSD, ms	42.0 (28.0; 50.8)	27.0 (23.5; 43.8)*	20.5 (17.0; 25.8)	12.0 (7.5; 13.0)***
pNN50, %	21.6 (6.0; 30.1)	0.49 (0.00; 3.02)*	2.68 (1.25; 4.80)	0.53 (0.00; 1.05)**

TP, ms²/Hz	2775 (1717; 4080)	655 (475; 1659)*	2234 (1781; 3291)	677 (489; 957)**
VLF,ms²/Hz	934 (614; 1540)	302 (222; 610)*	852 (675; 1424)	240 (192; 344)**
LF, ms²/Hz	683 (380; 987)	318 (177; 785)n	982 (587; 1636)	472 (201; 551)**
HF, ms²/Hz	583 (371; 1234)	38 (34; 89)*	123 (69; 272)	14 (8; 33)***
LF/HF	1.8 (0.6; 2.7)	8.4 (4.8; 8.9)***	8.3 (4.1; 16.0)	23.2 (16.6; 25.1)**
% VLF	39.9 (26.9; 48.1)	43.4 (35.0; 49.7)n	38.9 (31.3; 51.3)	46.1 (33.3; 57.3)n
% LF	34.2 (18.1; 45.6)	47.3 (35.0; 52.8)**	42.8 (30.7; 61.9)	50.7 (41.1; 60.5)n
% HF	22.8 (15.0; 34.4)	6.1 (5.6; 9.1)***	5.6 (3.4; 10.7)	2.1 (1.5; 3.5)**
C 30:15			1.54 (1.36; 1.79)	1.15 (1.10; 1.21)***

^{n}— : inaccurate; *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$.

Even more clearly are the above shifts identified when carrying out the active orthostatic test. The total power of the spectrum evidently decreases firstly due to the high-frequency component. Against this background, the sympathetic and adrenal activity relatively increase, and, importantly, the reactivity of the VNS parasympathetic division decreases to a high degree of accuracy (C 30:15).

The dynamics of the HRV indices are shown clearly in Fig.11.

Fig.11. The HRV spectral power indices (median) before and after the sea survival training

The LF/HF index reflects the balance of the VNS sympathetic and parasympathetic divisions, and the index C 30:15 characterizes the reactivity of the VNS parasympathetic division during AOT. The decrease of C 30:15 not only reflects the decreased reactivity of the VNS parasympathetic division but also indicates the breakdown of mechanisms that return to the normal state. Low values of C 30:15, along with the suppression of parasympathetic activity (HF-component), are a sign of the low resilience of the vagus nerve to the exposure to stress excitatory agent.

An increase in the LF/HF ratio reflects the adequacy of the vegetative provision of activity. Normally, when stress resistance is good and the stress excitatory agent's intensity is relatively low, sympathetic and adrenal activity must be increased. Lack of growth indicates depletion of adaptive capacity. However, the limits of the physiological fluctuations of these indicators are currently not reliably identified, and, apparently, intragroup norms in the solution of each specific task need to be worked on.

The above-mentioned arguments are consistent and to some extent explain the ideas of H. Selye about superficial adaptation energy.

If we discard mystical ideas, it is quite obvious that the depletion of superficial adaptation energy is a decrease in the regulatory capabilities of the vegetative nervous system. Besides, in the first turn, the VNS parasympathetic division depletes faster as a system of rapid response.

Prolonged stress involves the deep adaptation energy that is identified with the humoral regulation system (pituitary gland–adrenal glands axis), then with the immune system, and subsequently, structural changes of organs and systems are developed.

The results of the research on parachutists before and after the jump

The continuous ECG transmission during the jump was achieved through the Poly-Spectrum-Radio hardware and software complex of Neurosoft LLC (the city of Ivanovo). During descent, the average heart rate (HR) was 160 ± 20.3 beats/min. An example of a rhythmogram and a fragment of an ECG with recorded extrasystole during the descent and in the first minutes after landing are shown in Fig. 12.

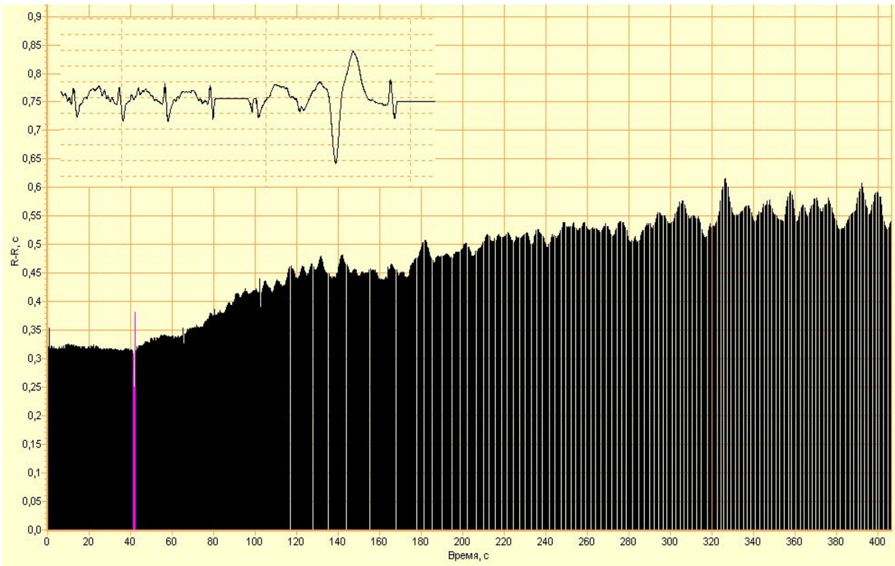

Fig. 12. A fragment of the ECG, polytopic group extrasystoles (in the upper left corner). and rhythmogram during the descent and in the first minutes after the jump.

The heart rate at the time of landing was 180 beats/min. At the 40th second (just before touching land), the group extrasystoles were recorded. Immediately after landing, the slowing of the heart rate was observed. After about 300 seconds, the heart rate decreased to 110 beats/min, a well-expressed wave structure of cardiac rhythm appeared, and the process became stationary. After landing, the stationarity of the cardiac rhythm wave process was usually recovered within 5–10 minutes to almost the initial level. The average heart rate before the jump was 72 ± 13.7 beats/min, and 5–10 minutes after the jump, during the HRV recording, it was 80.1 ± 14.9 beats/min.

The recovery of the wave structure of cardiac rhythm is an important quality characteristic. Since the heart rate modulation is under the VNS's control, it can respond adequately to changing external effects. The recovery time of the cardiac rhythm's wave structure after exposure to a stress excitatory agent is important when estimating an organism's adaptive reserves, especially in the labor physiology of professional groups whose activity has a high degree of risk.

The results of HRV mathematical analysis before and after the parachute jump are presented in table 2.

Table 2. HRV indices before and after the parachute jump (background recording and AOT)

Index	**background recording**		**AOT**	
	before the jump	**After**	**before the jump**	**after**

RRNN, ms	885 (762; 915)	769 (693; 903)**	702 (637; 760)	639 (592; 674)**
SDNN, ms	69.5 (47.0; 90.3)	38.0 (26.3; 48.0)***	55.0 (28.0; 61.5)	35.5 (29.5; 46.8)*
RMSSD, ms	48.0 (27.8; 82.5)	21.0 (11.5; 32.5)***	25.0 (10.0; 32.5)	17.0 (10.8; 23.0)**
pNN50, %	21.2 (7.1; 47.4)	3.6 (0.3; 12.4)***	5.0 (0.4; 7.8)	2.2 (0.3; 3.5)**
TP, ms^2/Hz	5189 (3000; 6928)	1791 (873; 3169)***	3730 (1240; 5652)	1925 (1361; 3161)**
VLF, ms^2/Hz	1509 (876; 2723)	734 (559; 1285)**	1160 (523; 2125)	763 (419; 923)n
LF, ms^2/Hz	1176 (841; 1750)	688 (283; 863)**	1446 (613; 3468)	1144 (590; 2098)n
HF, ms^2/Hz	1752 (643; 2753)	239 (116; 558)***	280 (135; 743)	146 (90; 428)*
LF/HF	0.8 (0.4; 1.1)	2.0 (1.4; 3.0)***	5.5 (3.7; 7.4)	6.4 (5.0; 9.0)n
% VLF	37.6 (26.0; 53.3)	49.3 (34.9;57.9)n	36.5 (29.7; 53.9)	40.1 (24.1; 48.1)n
% LF	22.2 (18.3; 33.2)	33.1 (25.6; 40.3)n	54.4 (37.4; 61.4)	52.2 (44.9; 65.1)n
% HF	32.8 (20.2; 48.3)	16.9 (13.0; 23.0)**	8.5 (6.6; 14.3)	8.9 (5.5; 12.0)n
C 30:15			1.35 (1.26; 1.52)	1.20 (1.09; 1.27)**

*^{n}: inaccurate; *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$.*

In the analysis of the obtained data, the same dynamics of HRV indices for cosmonaut candidates after the sea training are observed. After the parachute jump, general cardiac rhythm variability decreases (decrease in the TR and SDNN indices), a frank oppression of activity and reactivity of the VNS parasympathetic division are observed (decrease in RMSSD indices, pNN50 [%]), and the HF-component power is at rest, along with C 30:15 and the specific contribution of the high-frequency component (HF) in response to orthostasis. Against this background, a relative increase in the activity of the sympathetic and adrenal systems is observed (the LF/HF ratio increased).

3.2. Dynamics of HRV indices during exposure to physical stress excitatory agent

The dynamics of HRV after physical training (exposure to a mainly physical stress excitatory agent) differed significantly from the dynamics of the index during exposure to psycho-emotional (mental) stress. As an example, I present the results of examination of hockey players, the youth national team candidates, passing the training camp before the World Cup. Trainings were run twice a day, in the morning and in the evening. The HRV research was conducted twice a day, in the morning before waking up and in the evening in 2–2.5 hours after the training (before going to sleep). The dynamics of the HRV spectral analysis indices of teenage hockey players, recorded in prone position, are presented in Table 3 and in Figs. 13 and 14.

Table 3. HRV indices before and after hockey players the training (background recording and AOT)

Index	**background recording**		**AOT**	
	before the training	**After**	**before the training**	**After**
RRNN, ms	1025 (946; 1202)	906 (852; 933)*	755 (654; 821)	754 (738; 781)n
SDNN, ms	94.0 (46.5; 135.5)	47.0 (39.3; 66.1)***	71.0 (60.0; 109.5)	65.5 (56.2; 94.8)n
RMSSD, ms	91.0 (37.5; 150.0)	52.2 (36.5; 59.5)**	33.0 (23.0; 61.5)	38.1 (32.8; 55.0)n
pNN50, %	51.6 (18.6; 63.2)	33.9 (14.2; 49.8)*	10.0 (3.4; 23.3)	13.7 (10.5; 26.1)*
TP, ms^2/Hz	8743 (2104; 18001)	2072 (1427; 3641)***	4746 (2898; 9868)	13928 (2885; 8740)**
VLF, ms^2/Hz	2492 (989; 6369)	536 (439; 627)**	1621 (905; 3549)	1144 (948; 1851) n
LF, ms^2/Hz	1422 (696; 5231)	516 (452; 1397)***	2165 (1617; 4860)	2119 (1358; 4698)n
HF, ms^2/Hz	2903 (567; 8054)	840 (648; 1616)***	257 (100; 1070)	383 (365; 779)n
LF/HF	0.94 (0.69; 1.21)	0.75 (0.63; 0.86)n	9.0 (3.8; 10.4)	5.6 (2.4; 7.5) *
C 30:15			1.7 (1.4; 1.9)	1.62 (1.40; 1.77)n

^{n}: inaccurate; *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$.

Fig. 13. Comparative estimation of the spectral analysis indices of the hockey players before and after the training (background recording at rest in prone position) (1 – VLF; 2 – LF; 3 – HF [ms^2/Hz]).

As can be seen from the presented data, the spectral power of all components dramatically decreased after the training and, consequently, more than four times, the total spectrum power (TP) decreased. Thus, we can mention a significant decrease in the level of the current functional status. But please note that there are no significant dynamics of the LF/HF ratio in this group. Once again, let me restate the explanation of this phenomenon: during intensive physical loading, the increase of sympathetic and adrenal activity is caused mainly by catecholamines' secretion (the pituitary gland–adrenal glands axis "works"). During stress-loadings of less intensity but with a big contribution from the psycho-emotional component, the activation of sympathetic and adrenal activity occurs mainly at the expense of noradrenaline secretion by the sympathetic nervous system, and as a result, there is a more significant increase in the LF/HF ratio. While the secretion of adrenal hormones has a significant stabilizing effect on the myocardium, the secretion of noradrenaline during psycho-emotional stress leads to an electrical defragmentation of the myocardium and can provoke the occurrence of arrhythmia. This explains why psychological stress can have a negative impact on the human body and why physical stress of moderate intensity is beneficial.

The dynamics of the spectral analysis indices during the active orthostatic test before and after the training is presented in Fig. 14.

Fig. 14. The spectral analysis indices of the hockey players' HRV before and after the training during AOT (1 – VLF; 2 – LF; 3 – HF [ms^2/Hz]).

Unlike in the background recording, the dynamics of spectral analysis indices (before and after the training) are inaccurate during AOT and should be interpreted as the preservation of the organism's adaptive reserves against the background of the current FS decrease.

The severity of the decrease in spectral power indices at rest reflects the so-called physiological cost of activity—the physiological cost of the training, in this case. The diagnostic value of such research is that it allows one to estimate in repeated recordings how much lower the current functional status and adaptive reserves of the body are or how fully they have recovered. In terms of high-volume and -intensity training loadings, the estimation of the body's current FS makes it possible to run the training process properly and prevent the transition of adaptive changes beyond the limits of expedient adaption. The lack of HRV spectral power indices' recovery on the next day after the training, the excessive increase in sympathetic and adrenal activity, and the insufficient reactivity of the VNS parasympathetic division when carrying out an active orthostatic test defined by the 30:15 coefficient allow one to diagnose such conditions as fatigue and overtraining early.

IV. Conclusion

In response to the influence of stress excitatory agents, adaptive systemic reactions occur that are compensatory in nature. Along with systems specifically responsible for adaptation to these injuries, the system of neurohumoral regulation plays an important role as a non-specific system of adaptation to exposure to stress -excitatory agents. In practically healthy persons exposed to a stress-excitatory agent, the non-specific system of adaptation (neurohumoral regulation system), which can be adequately estimated in the HRV research, is in the foreground.

Comparison of the research groups (a) with predominant influence of the psycho-emotional component (cosmonaut candidates during the survival training, parachutists during and after jumps) and (b) with predominant influence of the physical component (hockey players) makes it possible to establish the typical HRV indices' dynamics under exposure to a stress excitatory agent:

— Cardiac rhythm variability (indices: total spectral power (TP), standard deviation (SDNN), square "cloud" on the scatter gram (S)) is reduced.

— Parasympathetic effects (indices: the HF-component of spectral power, pNN50 [%], rMSSD, the width of the "cloud" on the scattergram [w]) are reduced.

— Indices characterizing the activity of the sympathetic and adrenal systems (the LF-component of spectral power, the length of the "cloud" on the scatter gram (L)) are also reduced, but to a lesser degree. As a result, the balance of the VNS divisions is relatively shifted in the direction of sympathetic and adrenal activity (indices: LF/HF, L/w).

— The absolute spectral power of the waves of a very slow period (VLF-component) does not change significantly, and they become dominant in the spectral power structure.

— In an active orthostatic test, the 30:15 coefficient significantly decreases, representing the breakdown of mechanisms as they return to their normal states. The decrease in the 30:15 coefficient and the HF-component's spectral power indicates the predominant effect of the VNS parasympathetic division under stress.

The decrease of the current functional status (the cardiac rhythm variability), the decrease of VNS parasympathetic division activity (tone), and the relative activation of the sympathetic and adrenal systems are pathogenic bases for the development of disadaptation reactions.

When pneumogram recording detects an abnormality of cardiorespiratory synchronization, it should also be regarded as a characteristic symptom of distress. The abovementioned HRV dynamics in response to a stress excitatory agent are more typical for a group with predominant exposure to the psycho-emotional component. As for the group with predominant exposure to the physical component, the suppression of parasympathetic influences is expressed to a lesser degree, and more often, not only a relative but also an absolute increase in sympathetic and adrenal activity is observed.

This observation confirms the existence of a fundamental difference between physical and emotional stress. During physical loadings, the activation of the sympathetic and adrenal systems is accompanied by the secretion of adrenaline, predominantly—the humoral channel. The even effect of adrenaline on the heart's beta-receptors through the blood does not cause electric defragmentation of the myocardium and even has a stabilizing effect. Under psycho-emotional exposure, the activation of the sympathetic and adrenal systems is largely supported by the secretion of noradrenaline - the neurogenic channel. The predominantly modulating effect of noradrenaline (neurogenic channel) under certain conditions (decrease of affinity and density of cardiac beta-receptors due to apoptosis, cicatricial changes of the myocardium, neurodegenerative processes) can be potentially dangerous, as it leads to electric defragmentation of the myocardium. The suppression of parasympathetic activity additionally increases the risk.

— Online HRV recording during full-scale testing allows one to give a quantitative characterization of the concept of the "physiological cost of activity" to correct the intensity of the training and work processes in a timely manner, if necessary, and thus to implement the concepts of occupational health while practicing extreme activities.

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