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Physiological interpretation of heart rate variability spectral analysis data

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Despite the widespread use of the spectral analysis of heart rate variability (HRV) in biology and medicine, today questions about the physiological interpretation of frequency ranges remain unsolved. The combined recording of the electrocardiogram and registration of the amplitude and frequency of displacement of the chest during breathing allowed us to estimate the contribution of the act of breathing on HRV in the HF range and to determine the leading role of mechanical contraction of the diaphragm in the formation of respiratory arrhythmia. We also determined experimentally that, depending on the frequency and strength of the mechanical effect on the aorta of animals, it is possible to obtain corresponding peaks in the spectrogram. In humans, a test with swallowing at varying the frequency of swallowing allows obtaining a peak in any area of the spectrogram. The results obtained with the contraction of the muscles of the anterior abdominal wall indicate the effect of a rhythmic increase in intra-abdominal pressure on the formation of the spectrum. Based on the obtained results, we can assume that the peaks in the LF-range, not related to the arterial pressure waves, are due to the mechanical effect on the aorta of the peristaltic waves of the digestive tract organs. The results of studies, conducted when changing the position of the body in space, showed that hydrodynamic changes in the venous system largely determine the very slow-wave component of the spectrum.

Keywords: spectral analysis; heart rate variability; physiological interpretation.

INTRODUCTION

Due to the use of high-resolution electrocardiographic devices in medical practice, it has been possible to discover that the intervals between the QRS complexes are uneven. The first results on studying the heart rate variability (HRV) were achieved by E.H. Hon and S.T. Lee. in 1965 after investigation of the fetus intrauterine lesion [1]. They concluded that as strong disorder of the fetus heart rhythm was caused by the changes in the rhythm structure. In 1978 M. Wolf et al. [2] for the first time found that the incidence of death of the patients after myocardial infarction was higher if they had a reduced HRV.

Under the physiological conditions, the heart rhythm regulation is the result of the rhythmic activity of the sinus node automatic cells [3]. Changes in the duration of cardio intervals should be considered as the consequence of the influence of a multi-contour, hierarchically organized multi-level system for controlling the physiological functions of the body [4]. This approach to the study of HRV is based on the provisions of biological cybernetics, developed in 1966 by V.V. Parin and R.M. Bayevsky [4].

In 1996 the European Society of Cardiology and the North American Society of Pacing and Electrophysiology released the guidelines, describing the measurement standards and methods for analyzing the HRV, as well as the fields of application of HRV analysis in practical medicine [5]. Five-minute and daily electrocardiogram (ECG) records are used for the analysis. [5]. In clinical practice and experimental studies, the frequency non-parametric method of calculating the spectral density is widely used, due to which a basic information about HRV can be obtained [3].

Spectral analysis is based on the Fourier theory, according to which any periodic curve, even of a complex shape, can be represented as the sum of several sinusoids having their own amplitude, phase and frequency [6]. In the spectrogram obtained using the Fourier transform, there are three frequency ranges (5-minute ECG recordings), i.e. 0.015–0.4 Hz total power (TP); 0.4–0.15 high frequency (HF);0.15–0.04 low frequency (LF); 0.04–0.015 very low frequency (VLF) [5].

This choice of frequency ranges for human HRV was confirmed by the method of spectral analysis of independent components (Spectral independent component analysis) [7]. It is important to underline that the “Standards” do not provide the convincing data regarding the physiological processes and phenomena which underlie each frequency range. The results of clinical and experimental studies determined that efferent vagal activity determines the high-frequency HF component [8]. The interpretation of the LF component is more contradictory, some authors regard it as a marker of sympathetic modulation (especially in normalized units) [9], and others as a parameter that includes both sympathetic and vagus effects on HRV [8]. There is an opinion that the LF / HF ratio (sympathovagal balance) makes it possible to determine the prevailing link of regulation. However, this point of view was criticized [10].

We should notice that the physiological explanation for the VLF components is virtually absent. The publications provide an extremely scarce information that the very low frequency area of the spectrum is due to the thermoregulation, the functioning of the renin-angiotensin and sympathetic nervous systems [3]. As some scientists believe, the physiological bases of HRV concept, which are often used in the studies of cardiovascular system, are not fully verified provisions and require critical rethinking [10, 11].

The “Standards” states that «… Heart-Rate-Variability (HRV) represents one of the most promising such markers… However, the significance and meaning of the many different measures of HRV are more complex than generally appreciated and there is a potential for incorrect conclusions and for excessive or unfounded extrapolations» [5]. Based on all stated above, it is obvious that it is necessary to study the physiological mechanisms underlying the regulation of HRV.

The research aim was to determine the physiological processes that underlie each component of the HRV spectrum.

METHODS

The studies were performed in 7-month outbred male rats (n = 80) in the standard animals house conditions. In addition, 10 human volunteers participated in the experiment with their informed consent.

Manipulations with animals were carried out in accordance with the Law of Ukraine “On the Protection of Animals from Cruel Treatment: Law of Ukraine No. 3447-IV dated February 21, 2006). and following the requirements of the Committee in Bioethics of the Institute for Problems of Cryobiology and Cryomedicine of the National Academy of Sciences of Ukraine, agreed with the provisions of the European Convention on the Protection of Vertebrate Animals, used for experimental and other scientific purposes (Strasbourg, 1986).

Various methodological approaches were required to perform the experiments in animals, including superficial and ultra-deep anesthesia, carried out by means of an inhalation method, and deep anesthesia did by intramuscular administration of 5 mg / kg Telazol (US Zoetis Inc.). Mechanical pressure on the abdominal aorta was performed with an interval of 10 s (0.1 Hz) and 15 s (0.067 Hz).

Human breath test was performed at 6 and 30 respiratory movements / minute (0.1 and 0.5 Hz). The effect of nicotine on HRV was assessed after smoking a cigarette containing 0.3 mg nicotine. The frequency of swallowing movements was 2 sips per minute (0.035 Hz);

3.5 (0.056 Hz); 5.5 (0.09 Hz); 7.3 (0.137 Hz). The frequency of muscle tension in the anterior abdominal wall corresponded to the frequency of 0.161; 0.033; 0.05 Hz.

ECG was recorded during 5 min with Poly-Spectrum 8/V and Poly-Spectrum 12 hardware-software using Poly-Spectrum-Rhythm software version 4.8 (all - Neurosoft, Russia) in standard (I, II, III) and additional (avL, avR and avF) leads. The parameters of the spectral analysis of HRV in rats were equal to those previously determined: TP — 0.015–3 Hz; VLF - 0.015–0.04 Hz); LF (0.05-0.79 Hz); HF (0.8–3 Hz) [12], the results of analysis in humans, are described in “Standards” [5]. The influence rate of postural loads on HRV was assessed according to ECG data in wedge (supine), ortho- (vertical – with head up) or anti-orthostatic- (with head down) body positions. To determine the frequency of respiration and the amplitude of the chest displacement, we used a DAP-1 sphygmosensor connected to an electrocardiograph (NeuroSoft, Russia), which was fixed on the lateral surface of the animal or human chests. Indices were recorded in the SFG1 lead.

The non-parametric method MANOVA was used to process the results statistically. Quantitative data were presented as mean values and mean square deviations. Indices were calculated with the “SPSS 17.0” (USA) software for Windows.

RESULTS AND DISCUSSION

In experimental studies aimed at investigation of the physiological processes of HRV regulation, it is necessary to use an integrated approach based on the applying of available methods and techniques, enabling to determine the conditions that qualitatively change the spectrum. The data obtained under fixed and non-fixed conditions for ECG recording will contribute to a deeper understanding of the mechanisms underlying HRV. In addition, to study this problem, it is important to determine the anatomical and physiological features of the organs and systems involved into the HRV regulation. Since three frequency ranges exist on the spectrum, the physiological processes behind them should be studied separately.

HF waves. High-frequency HF-waves are closely related to the act of breathing, therefore the range of this component in humans is 0.4–0.15 Hz (Table 1), which corresponds to 9-24 oscillations (respiratory movements per minute) [4]. In small mammals (rats) this range is 0.8–3 Hz (48–180 oscillations per minute) in the waking state [12, 13]. With shallow irregular breathing, the peak of HF waves is “blurred”, but at regular breathing, it corresponds to the frequency of breathing [13]. In animals in a state of superficial anesthesia, the frequency of respiratory movements (NPV) slightly increases while keeping a normal heart rate (HR), and in deeper anesthesia, the NPV decreases by 40% relative to the norm. The ratio of heart rate / NPV in rats under deep anesthesia is increased from 4.3 up to 6.5 (Table 1).

The introduction of animals into ultra-deep anesthesia (stage 3) caused very deep breathing, evidenced by a pronounced increase in the volume of the chest during inhalation, while the NPV was reduced down to 33 per minute. In the

Table 1. Indices of heart and respiratory rates in rats

Group	HR per minute	RR per minute	HR/RR
Conscious animals (the norm)	403.4 ± 7.3	97.2 ± 6.1	4.3
Surface anesthesia	384.9 ± 8.4	115.3 ± 6.9	3.4
Deep anesthesia	394.9 ± 9.2	61.4 ± 3.2*	6.5*
Ultra Deep Anesthesia	419.4 ± 12.5	33.7 ± 4.1*	12.6*

Note: * – differences are statistically significant if compared with the norm, $P \leq 0.05$

spectrogram within the range of low-frequency waves, we noted a high peak corresponding to the breathing frequency and the appearance of additional "damped" harmonics (Fig. 1).

The total power of the spectrum during ultra-deep anesthesia decreased from 171 ms² to 12.3 ms². We also noted the rhythmogram rigidity: (R – Rmin = 140 ms; R – Rmax = 147 ms). The obtained results show that HRV is sharply reduced, and all 2095 R – R intervals have only eight values. To avoid the mathematical errors, we analyzed the experimental data with the Kubios HRV Version 2.2 software (Biosignal Analysis and Medical Imaging Group, Finland) and obtained a similar result. Consequently, the appearance of harmonics in the spectrogram is associated with physiology, and in this certain case it is done with the pathophysiological processes in the body in a state of super-deep anesthesia.

It is known that the diaphragm is a pectoral septum, with openings of the aorta, inferior vena cava and esophagus in it. Due to deep breathing, aortic mechanical compression occurs between the legs of the diaphragm, which probably leads to an activation of nerve endings located in the adventitia and the appearance of a reflected hydrodynamic wave, which is perceived by the baroreceptors of the aortic arch. In the epigastric region, the aorta is braided by mixed nerves of the celiac plexus (*Plexus coeliacus*). The irritation of the aortic receptors, as well as the epigastric interoreceptors, has a reflex effect on HRV (Goltz reflex) [14]. In addition, hydrodynamic changes that occur during mechanical pressure on the aorta may cause the appearance of "damped" harmonic peaks in the frequency ranges 1–1.1 and 1.5–1.7 Hz (see Fig. 1) in the spectrogram. The compression of the main vessel leads to the appearance of waves of blood going in the proximal and distal directions. The baroreceptors of the aortic arch and the carotid arteries react to hydrodynamic waves, the signals along the nerve fibers are transmitted to the vegetative centers. We observed similar changes in people with shallow and deep breathing samples (Fig. 2).

Fig. 2, A, demonstrates that at a hallow breathing, the peak of respiratory arrhythmia (0.5 Hz) is mild. At the same time, the size of the chest excursion is small, and, accordingly, the pressure on the aorta is minimal. Deep breathing led to an increase in the chest excursion rate, and it caused the appearance of high peak at 0.1 Hz (Fig. 2, B). Mean while the total power of the spectrum increased by 4 times. The high amplitude of this peak can be explained by the resonance between various oscillatory processes in the cardiovascular system (imposing a respiratory rhythm on the peak of LF waves at

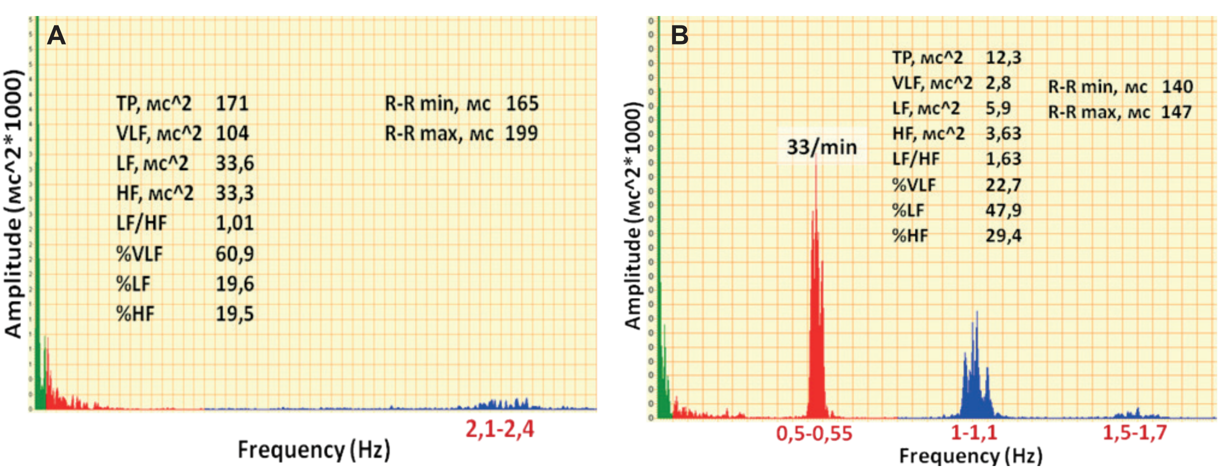

Fig. 1. Spectrum HRV in rats: A – state of wakefulness. (Respiratory rate – 132 breaths per minute); B – state of super-deep anesthesia. (Respiratory rate – 33 breaths per minute). The presence of harmonics (1–1.1 and 1.5–1.7 Hz)

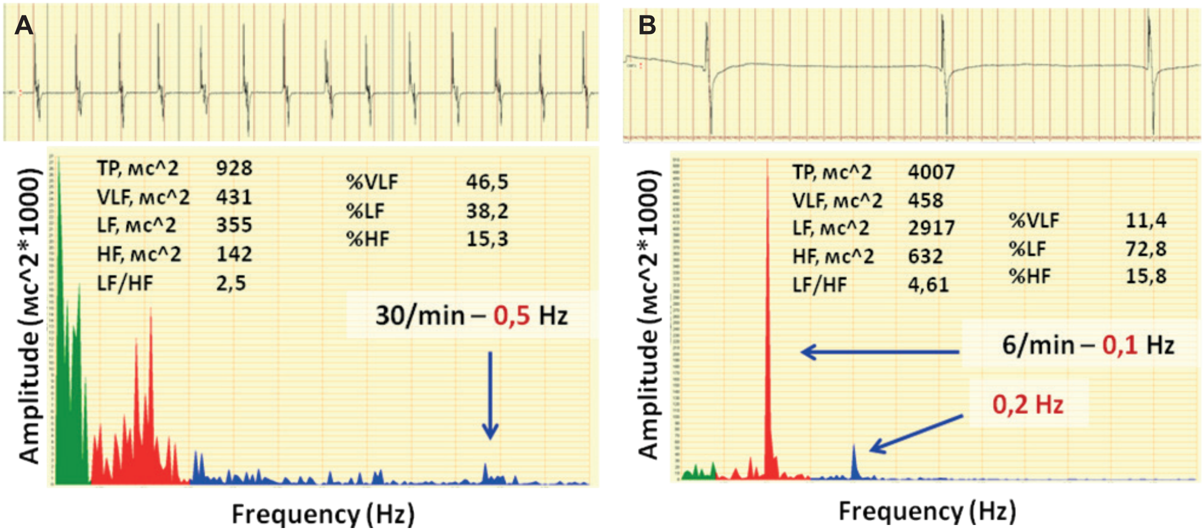

Fig. 2. Breathing tests in humans (breathing curve and spectrogram): A - shallow breathing. (HR - 82 beats per minute, NPV - 30 breaths per minute). In the spectrogram, a low peak of respiration (0.5 Hz); B - deep breathing. (HR - 76 beats per minute, NPV - 6 breaths per minute). In the spectrogram, the presence of a harmonic peak at 0.2 Hz

0.1 Hz). The appearance of a "fading" harmonic peak at a level of 0.2 Hz is similar to the one recorded in a state of super-deep anesthesia in rats (see Fig. 1 B).

To confirm the hypothesis about the influence of biomechanics on the formation of HRV, we conducted an experiment in rats, which were pressed on the abdominal aorta with a period of 10 sec. (0.1 Hz) and 15 sec. (0.067 Hz) (Fig. 3).

Depending on the frequency of mechanical effects on the abdominal aorta, the rhythm of cardiac activity also reflexively changed, and peaks with "damped" harmonics appeared on the spectrogram (Fig. 3). In both cases, the peaks associated with respiratory arrhythmia were located independently, 1.6 Hz (96 breaths per minute) and 1.75 Hz (105 breaths per minute). With pressure on the anterior abdominal wall,

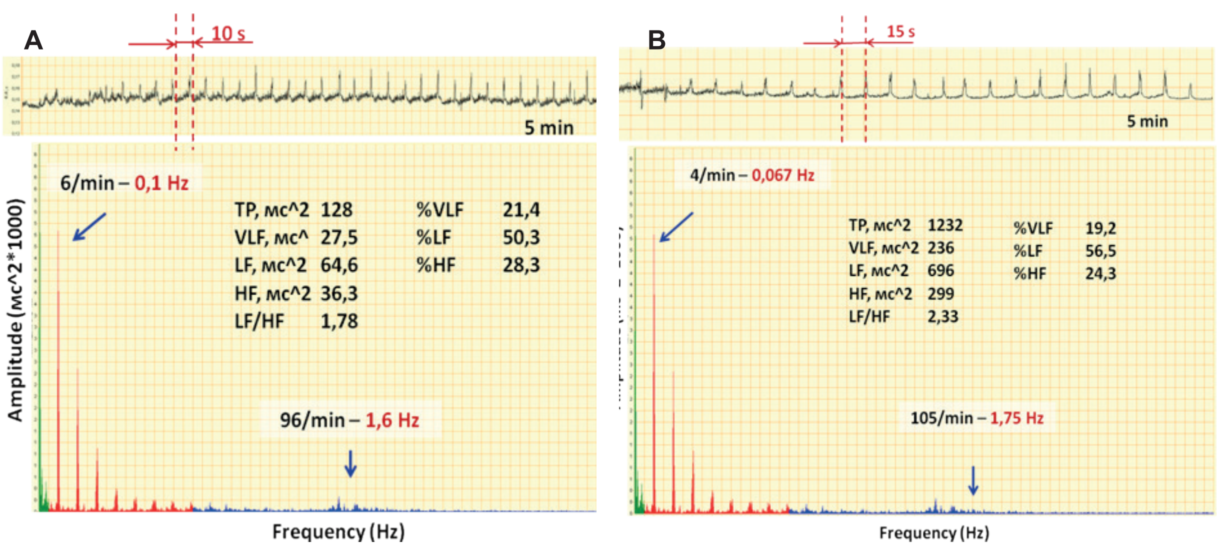

Fig. 3. Mechanical pressure on the rat aorta (rhythmogram and spectrogram): A - 6 presses per minute. (NPV - 96 breaths per minute); B - 4 presses per minute. (NPV - 105 breaths per minute)

the aorta was pressed against the spine, therefore the amplitude of the peaks on the rhythmogram and on the spectrogram was rather high (Fig. 3). After both types of rhythmic effects on the aorta (with a period of 10 and 15 sec.), the total power of the spectrum increased 10 times. After processing the obtained results using the software Kubios HRV Version 2.2 (Biosignal Analysis and Medical Imaging Group, Finland), similar results were obtained.

LF waves. Waves of blood pressure (BP) with a period exceeding the respiratory one are named after the German physiologist S. Mayer, who discovered and described them in 1876 [15]. Earlier, in 1865, a German physician L. Traube discovered non-respiratory waves of blood pressure oscillations with a period of about 10 s. Professor W.D. Halliburton based on the results of historical analysis (1919), proposed in his paper "Traube waves end Mayer waves" to coin these waves in honor of their first discoverer Traube [16].

There are two main theories which explain the nature of slow fluctuations in blood pressure levels: pacemaker and baroreflex. According to the pacemaker theory, the presence of an autonomous generator in the region of the central brain structures, involved into the formation of sympathetic tone is considered to be the source of oscillations. These fluctuations along sympathetic efferent nerve fibers are transmitted to the heart and vessels, activating cardiac metasympathetic structures that carry out the basic innervation of the organ. The result of the described mechanism, is that BP rhythms are formed, having a frequency of 0.1 Hz [17].

Based on the provisions of the baroreflex theory, the regulation of heart rate is based on the analysis of multiple afferent signals from the baro- and chemoreceptors of the aortic arch, carotid arteries, respiratory neurons and higher nerve centers. We should mention that the vasomotor and respiratory centers function with each other consistently in time as a complex non-linear system [17]. In addition, there is a hypothesis that the rhythm with a frequency of 0.1 Hz is a consequence of the myogenic reaction of arterioles, which, according to the baroreflex mechanism, changes the heart rate. It is possible that the level of CO_2 in the blood has a huge impact on maintaining blood pressure and other hydrodynamic characteristics in the arterioles of the microvasculature. However, to prove this assumption, it is necessary to use special equipment with high resolution, since the available instruments for measuring saturation reveal the association of HRV with CO_2 levels only in deep disorders, for example, in severe form of obstructive sleep apnea [18].

One of the main methods of studying physiological processes is turning off or stimulating one of the parameters of the system [19]. To enhance the sympathetic effects at the ganglia level, we conducted a test with tobacco smoking. At low concentrations, nicotine increases the activity of nicotinic receptors and increases the amount of stimulating hormone adrenaline (epinephrine), which is reflected in a decrease of total power of the spectrum by 2.8 times and an increase in the spectral power of LF waves from 42.9 up to 53.5%. After smoking, breathing becomes more superficial, the peak of HF waves is less pronounced and shifts to the high-frequency area from 0.2 up to 0.3 Hz. The action of nicotine leads to a spasm of arterioles and, accordingly, to a higher blood pressure, which is largely due to the activation of the sympathetic autonomic system.

As can be seen in the spectrogram (Fig. 2), in addition to the main 0.1 Hz peak in the slowly wave region of the spectrum, we can determine other peaks, which are recorded both in the norm and other states. It is possible that organs located in the thoracic and abdominal cavities, which are characterized by oscillatory processes with a frequency characteristic of the LF range, can have a mechanical effect on the aorta. To understand this phenomenon, it is necessary to investigate HRV not only in stationary conditions.

Unsteady condition during ECG recording

may be an act of swallowing. Since the esophagus is located near the aorta, the mechanical pressure of the esophagus on the aorta occurs during the passage of a peristaltic wave through the tendon center of the diaphragm, which causes irritation of the receptors and changes hemodynamics. In addition, the branches of the vagus nerve pass through the tendon center of the diaphragm, which can also “receive” impulses from any mechanical stimulation. On the rhythmogram, the act of swallowing is indicated as single waves of tachycardia, which from time to time turns into short-term bradycardia. S. Melzer described this phenomenon in 1883 and G.Y. Priyma called this reaction as a pharyngeal-cardiac reflex [20]. The results of the swallowing test showed that, by varying the frequency of swallowing, a peak can be obtained in any region of the spectrogram (Fig. 4).

In this experiment, HRV was studied during voluntary swallowing, but at rest the involuntary contraction of the esophagus can take place due to “cleansing” peristalsis that is not associated with swallowing and which is a reaction to the irritation of the esophagus wall with food residues with the frequency of the peristaltic wave that is in the LF range [21]. However, the amplitude of such a wave is much lower,

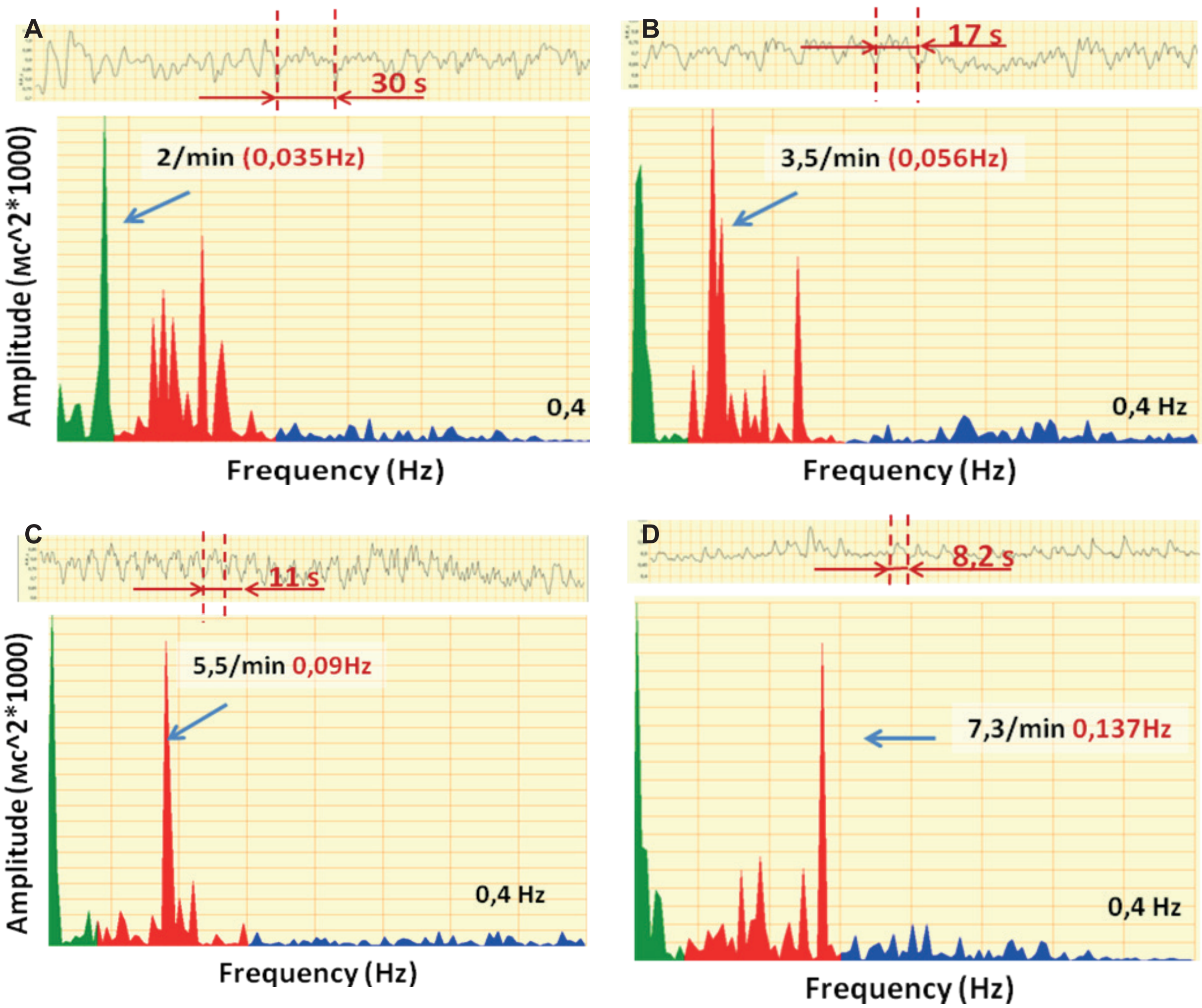

Fig. 4. Effect of swallowing frequency on HRV in humans (rhythmogram and spectrogram): A - 2 sips per minute; B - 3.5 sips per minute; C - 5.5 sips per minute; D - 7.3 sips per minute

so the effect on the aorta and hemodynamics will be minimal, and therefore the peaks on the spectrum will be low. Perhaps, abdominal organs that exert mechanical pressure on the aorta, can also affect the spectrum, in addition to the waves of blood pressure.

When studying the motor-evacuation function of the digestive tract using the Gastroscan-GEM gastroenteromonitor (JSC RPE Istok-Sistema, Russia), the frequency of gastric and intestinal peristalsis was found to be within the 0.01–0.25 Hz range, namely 0.01–0.03 for large intestine; 0.03–0.07for stomach; 0.07–0.13 for Ileum; 0.13–0.18 for jejunum 0.18–0.25 for duodenum [22]. Based on the results of a combined study of ECG recording and electrogastroenterography, it is possible to calculate the correlation coefficient of the HRV frequency spectra and the peristaltic waves of the gastrointestinal tract, which will allow us to determine the origin of the low peaks of the LF range.

VLF waves. In the formation of this component of the spectrum, the humoral-metabolic system plays an important role, but its contribution to rhythmic and non-rhythmic processes and reactions occurring in the body may be secondary. To clarify this phenomenon, it is also necessary to study HRV in non-stationary conditions. It is known that any changes in any link of the cardiovascular system lead to hemodynamic rearrangements of the entire system [23]. Based on the results of the studies, it was determined that a change in the body position from the wedge to orthostatic does not significantly affect the indices of the spectral and temporal analysis of HRV in rats (Table 2). Perhaps this is due to the rapid recovery of hydrodynamic parameters (heart rate, blood pressure, central venous pressure (CVP)), since *in vivo* the body of the rat is oriented in space between the wedge and orthostatic position. On the contrary, if the body of the rat is in the antiorostatic position, then the total power of the spectrum increases by 5.2 times (from 19.8 to 184.2 ms^2) due to a rise in the frequency of VLF waves (Table 2).

When a human body position changes from a horizontal position to a vertical one, the heart rate increases, resulted from an altered hydrodynamics and the associated redistribution of blood [19]. Due to decrease in the total power of the spectrum, the VLF component decreases from 40 to 30% (Fig. 5 A, B).

It is known that when changing the body position from horizontal to vertical, the change in hydrostatic pressure and the redistribution of blood associated with it are of the greatest importance for maintaining hemodynamic equilibrium. In the capacitive vessels of the lower extremities 400–600 ml of blood are

Table 2. HRV of rats when changing the body position

Indices	Body position		
	Clinostatic position	Ortostatic position	Anti-ortostatic position
TP, ms^2	52.9 ± 19.2	36.8 ± 8.7	278.8 ± 75.1*
VLF, ms^2	19.8 ± 10.3	16.6 ± 4.5	184.2 ± 64.4*
LF, ms^2	21.8 ± 9.2	13.0 ± 4.3	72.5 ± 13.8*
HF, ms^2	11.2 ± 2.4	7.2 ± 0.5	22.0 ± 6.3*
LF/HF	2.3 ± 0.7	1.8 ± 0.5	4.3 ± 0.7*
%VLF	32.1 ± 5.7	42.8 ± 3.9	60.2 ± 7.0*
%LF	39.2 ± 5.3	32.2 ± 4.2	28.3 ± 2.5*
%HF	28.8 ± 6.7	25.1 ± 6.1	11.5 ± 4.9*
HR	528.0 ± 8.3	534.6 ± 8.4	495.6 ± 6.9*

Note: * – differences are statistically significant in comparison with the indices, corresponding to clinostatic body position of rat, $P \leq 0.05$

accumulated and therefore venous return, the CVP, stroke volume and systolic pressure are decreased [19]. During the transition of a person to the antiorthostatic position, we noted an increase in the VLF component up to 70% due to reverse hydrodynamic changes.

Active adaptive hemodynamic reactions are triggered by the signals from arterial baroreceptors and stretching receptors of intrathoracic vessels. Since the baroreceptors are located in the aortic arch and the carotid sinus, then when a person comes back into a vertical position, the hydrostatic pressure in the area of these receptors will decrease. The decrease of the baroreceptors impulses will lead to the launch of reflex adaptive reactions: the narrowing of resistive and capacitive vessels; increasing heart rate; augmented concentration of catecholamines in the adrenal medulla; activation of the renin-angiotensin system; enhanced production of vasopressin and aldosterone. At the same time, the hormonal effect will manifest itself after the latent period. On the contrary, the transition to the antiortostatic position of the body in humans is accompanied by a change in hydrostatic pressure, which leads to an increase in venous return and an increase in CVP. On the spectrogram, this is reflected as an increase in VLF waves up to 70% (Fig. 5, C).

In addition, hemodynamic changes (redistribution of blood) of the body, associated with a decrease in CVP, are observed after a meal. In our previous work, it was shown that postprandial load in rats led to a decrease in the VLF component of HRV from 63.1 to 45.2%, which confirms the existence of a relationship between the very slow-wave component and CVP [24]. The change of body position affects the interposition of internal organs and the degree of tension in the muscles of the abdominal wall. In the "standing" position, intra-abdominal pressure in the lower abdomen increases, in the "sitting" position it decreases due to relaxation of the anterior abdominal wall, and in the "lying" position on the back gets even lower [25]. The physiological causes of increasing intra-abdominal pressure are abdominal muscle contraction, pregnancy, etc. Depending on the frequency of contractions of the abdominal muscles, as well as during swallowing the peaks were recorded in the spectrogram in all frequency ranges.

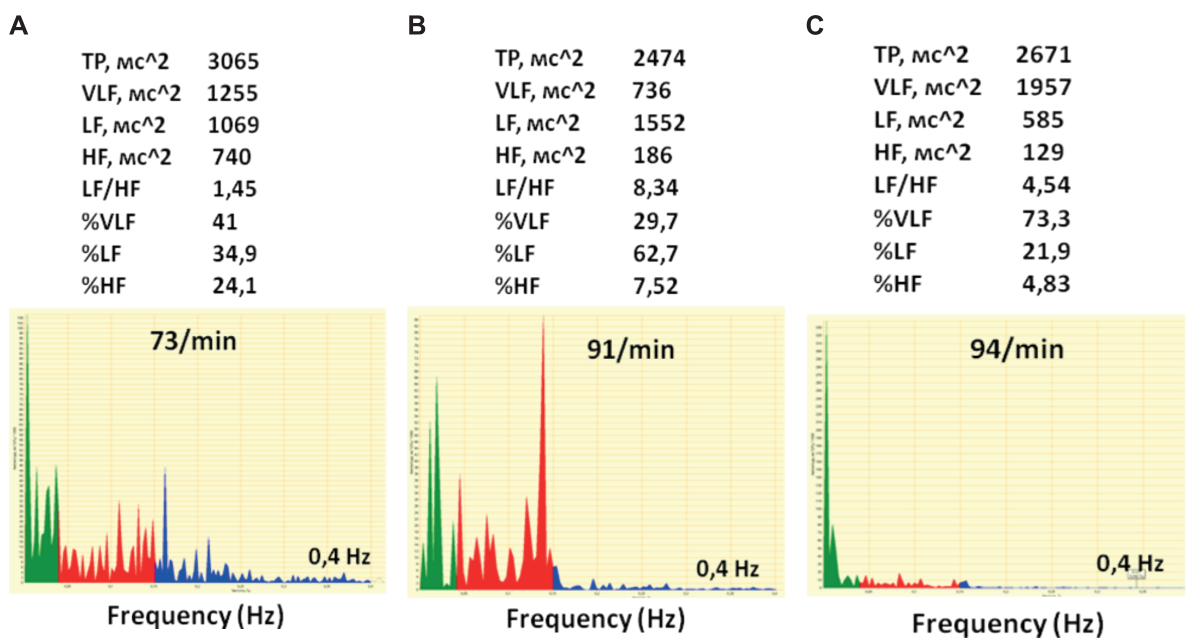

Fig. 5. The effect of a change in body position on human HRV: A - clinostatic; B - orthostatic; C - antiorthostatic

Published data and the results of our own research indicate that the dynamic changes in the indices of the cardiovascular system, including HRV, should be considered from the point of the theory of functional systems. We can consider the indicators of the spectral analysis of HRV as the result of the joint work of various systems (respiratory, cardiovascular, endocrine, etc.), the main function of which is to ensure the homeostasis of the body [26]. According to the theory of P.K. Anokhin, one of the important conditions for the integrity of the functional system as an integrative formation of the organism is the inverse afferentation of the achieved final adaptive effect. This allows us to consider the functional system as a closed formation with continuous inverse information about the success of this adaptive action [26]. Such an information is transferred by the vegetative nervous system (ANS), which is actively involved into the heart rhythm modulation. Meanwhile it is important to mention that the degree of contribution of each of the ANS departments to the formation of HRV has not yet been determined and requires further research.

As we know from the physiology of the nervous system of the heart, the impulses from the baroreceptors of the aortic arch and carotid sinus are transmitted along the parasympathetic fibers of the sinus branches of the glossopharyngeal nerve to the centers of the vagus nerve via the medulla [27]. Then the signals are transmitted to the cortical and subcortical regulation centers and through the efferent neurons into sympathetic and parasympathetic divisions of the ANS.

Based on the results of our analysis of HRV, we can estimate the degree of influence of internal and external factors on the state of the hemodynamic system of the body. At the same time, it is not possible to determine the nature of the ANS influence (sympathovagal balance), since the sympathetic and parasympathetic divisions of the ANS in most cases function in an inseparable relationship. The HRV spectrum mostly reflects the result of the functional system of the body involved into maintaining the vital indices of the cardiovascular system (heart rate, blood pressure, CVP) at the required physiological level with the presence of feedback. It is aorta that plays the main role in the cascade of signal transmission. The baroreceptors of the aortic arch, carotid sinus, and nerve plexus around the aorta are the main receptors that perceive any fluctuations during its mechanical stimulation.

Considering aorta as one of the main objects involved in the formation of HRV allows us to answer the question of why the total power of the spectrum decreases with age. First, age-related changes in the body not only affect the hormonal status, but also reduce the number and sensitivity of receptors, including the vascular wall, baroreceptors [28]. Secondly, atherosclerotic lesion of the aorta in all the areas and in all the layers of the vessel (from intimal to adventitia) reduces the number of receptors [28, 29]. In addition, an acquired rigidity of arteries occupies a special place in the pathogenesis of atherosclerosis and its associated pathological conditions [28, 29]. As a result of qualitative changes in the walls of blood vessels, which reduce their elasticity, the aorta is transformed into a rigid vessel, which conducts a pulse wave with disturbances, and this affects the spectrum. Thus, the results of our research aimed at elucidation and detailed study of processes reflecting the spectrum of HRV can later be used in clinical practice to determine the effect of various physical factors on the hemodynamics of the organism as a whole.

CONCLUSIONS

1. The data of the spectral analysis of HRV are one of the main indices in demonstrating how strong are the influences of internal and external factors on the state of the hemodynamic system of the body, but they are insufficient for assessing the nature of ANS effects (determination of sympathovagal balance).

2. Rhythmic movement of the diaphragm, which exerts mechanical pressure on the aorta, playes on of the main roles in the formation of HF waves and, depending on the strength and frequency of the effect, peaks with a corresponding amplitude are displayed on the spectrogram.

3. We discovered that the mechanical effect on the abdominal aorta reflex affect the rhythm of cardiac activity, as evidenced by the appearance of peaks corresponding to the frequency of pressure, with "damped" harmonics on the spectrogram.

4. Based on the results of the swallowing test, we can assume that the peaks in the LF-range, which are not associated with the arterial pressure waves, are caused by the mechanical effect of the peristaltic waves of the digestive tract organs on the aorta.

5. The change in the spatial position of the body, which is accompanied by hemodynamic changes in the body, including a decrease / increase in venous return, CVP, affects the very slow-wave component of the HRV spectrum.

The authors of this study confirm that the research and publication of the results were not associated with any conflicts regarding commercial or financial relations, relations with organizations and/or individuals who may have been related to the study, and interrelations of coauthors of the article.

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ФИЗИОЛОГИЧЕСКАЯ ИНТЕРПРЕТАЦИЯ РЕЗУЛЬТАТОВ СПЕКТРАЛЬНОГО АНАЛИЗА ВАРИАБЕЛЬНОСТИ СЕРДЕЧНОГО РИТМА

Несмотря на широкое использование в биологии и медицине метода спектрального анализа вариабельности сердечного ритма (ВСР), на сегодняшний день остаются нерешенными вопросы, касающиеся физиологической интерпретации частотных диапазонов. Сочетанная запись электрокардиограммы и регистрация амплитуды и частоты смещения грудной клетки при дыхании позволила оценить вклад акта дыхания на ВСР в HF-диапазоне и определить ведущую роль механического сокращения диафрагмы в формировании дыхательной аритмии. Экспериментально установлено, что в зависимости от частоты и силы механического воздействия на аорту животных можно получить соответствующие пики на спектрограмме. У людей проба с глотанием при варьировании ее частоты позволяет получать пик в любой области спектрограммы. Результаты, полученные при сокращении мышц передней брюшной стенки, свидетельствуют о влиянии ритмичного увеличения внутрибрюшного давления на формирование спектра. На основании полученных результатов можно предположить, что пики в LF-диапазоне, не связанные с волнами артериального давления, обусловлены механическим действием на аорту перистальтических волн органов пищеварительного тракта. Результаты исследований, проведенных при смене положения тела в пространстве, показали, что гидродинамические изменения в венозной системе, во многом определяют очень медленно-волновую компоненту спектра.

Ключевые слова: спектральный анализ; вариабельность сердечного ритма; физиологическая интерпретация.

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ФІЗІОЛОГІЧНА ИНТЕРПРЕТАЦІЯ РЕЗУЛЬТАТІВ СПЕКТРАЛЬНОГО АНАЛІЗУ ВАРІАБЕЛЬНОСТІ СЕРЦЕВОГО РИТМУ

Незважаючи на широке використання в біології та медицині методу спектрального аналізу варіабельності серцевого ритму (ВСР), нині залишаються невирішеними питання, що стосуються фізіологічної інтерпретації частотних діапазонів. Поєднаний запис електрокардіограми та реєстрації амплітуди і частоти зміщення грудної клітки при диханні дали змогу оцінити внесок акту дихання на ВСР в HF-діапазоні і визначити провідну роль механічного скорочення діафрагми в формуванні дихальної аритмії. Експериментально встановлено, що залежно від частоти і сили механічного впливу на аорту тварин можна отримати відповідні піки на спектрограмі. У людей проба з ковтанням при варіюванні її частоти дає можливість отримувати пік у будь-якій ділянці спектрограми. Результати, отримані при скороченні м'язів передньої черевної стінки, свідчать про вплив ритмічного збільшення внутрішньочеревного тиску на формування спектра. Можна припустити, що піки в LF-діапазоні, які не пов'язані з хвилями артеріального тиску, зумовлені механічним впливом на аорту перистальтичних хвиль органів травного тракту. Результати досліджень, проведених при зміні положення тіла в просторі, показали, що гідродинамічні зміни в венозній системі, багато в чому визначають дуже повільно-хвильову компоненту спектра.

Ключові слова: спектральний аналіз; варіабельність серцевого ритму; фізіологічна інтерпретація.

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