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Cardiac Telemerty for Stress Assessment

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Abstract—**The use of stress assessment is receiving increasing attention. However, assessment approaches and methods this far are limited to static contexts. Scholars have raised questions concerning the validity of laboratory measurement results for stress detection in everyday life. The paper presents the results of developing a new method of stress assessment in real-life scenarios. This method is based on the noninvasive continuous cardiac rhythm monitoring. It is shown that the results obtained in the laboratory stress-related contexts have poor correlation with the results of the similar real-life scenarios. In this connection, the principal requirements for stress monitoring solutions are listed, and the architecture of the cardiac telemetry complex for continuous stress measurement is described. Drawing on experimental data over a 5-year period, we identify a stress-specific context-invariant HRV pattern. The theoretical and application perspectives for cardiac telemetry are presented for discussion. The progress achieved in the research and the ways for further investigation are outlined in the conclusion.**

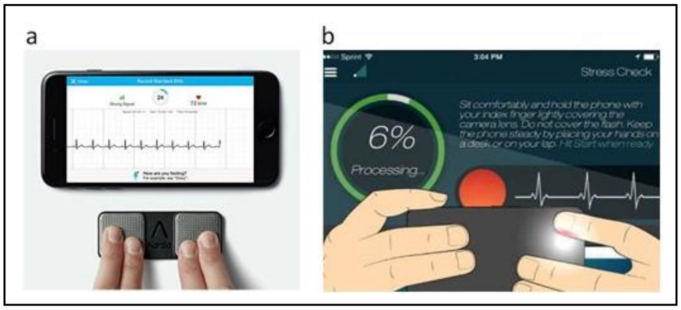
Keywords- stress; heart rate variability; autonomic nervous system; wireless technology.

I. INTRODUCTION

This paper is an extended presentation of [1], an experimental and theoretical justification for the role of endogenous opioid system in autonomic regulation of stress.

Stress reaction is a physiological response to factors perceived as challenging, demanding or threatening. Extensive scientific literature shows that stress can be associated with adverse health outcomes, e.g., an increased risk of severe chronic diseases, illnesses such as cardiovascular and immunological diseases - contributing to poor relationships and lost productivity at work, reduced quality and duration of life [2-4]. The overall burden of stress-generating lifestyles is heavy both at individual and at the societal level [5].

Measuring and monitoring stress is a key to identifying the main stressors and understanding the lifestyle-related choices and behaviors that make for healthy life and well-being. There is a dramatic growth of solutions for stress assessment over the past five years - from portable ambulatory diagnostics to home appliances, where the most advanced technologies investigate the potential of a modern smartphone and a wearable HR monitor [6] (see Figure 1). They allow to measure stress in a wide range of laboratory and ambulatory contexts, or static real-life scenarios like sleep. However, such approach greatly narrows the scope of application of the technology and questions its predictive validity, since the human regulation is a dynamic process.



Sit comfortably and hold the phone with your index finger lightly covering the camera lens. Do not cover the flash. Keep the phone steady by placing your hands on a desk, or on your lap. Hit Start when ready

Figure 1. Modern approaches to cardiac activity monitoring: (a) a pocket-sized healthcare gadget (2017); (b) measuring stress through a built-in smartphone camera and flash (2015).

This article introduces a cardiac telemetry solution for stress assessment in dynamic real-life scenarios and presents the results of its implementation in various experimental contexts. The developmental work is based on a combination of mathematical modeling and algorithm development with extensive empirical physiological and behavioral research. The datasets for developing the method include 7 432 field and laboratory assessments in 4 619 people. The technology described in this paper can be utilized widely in different types of healthcare studies, wellbeing and health promotion services, and consumer products such as chest belts, smart watches, as well as professional sports coaching and coaching amateur athletes.

The article is organized as follows: Section II presents a brief description of the stress phenomenon and introduces related works; it is followed by Section III, dedicated to the concepts and implementation details of our cardiac telemetry solution. Section IV addresses the evaluation results. Section V ends the paper with a look to future work.

II. RELATED WORK

This section starts with a brief definition of the stress phenomenon and an overview on Heart rate variability (HRV) analysis approaches that are relevant in the context of stress detection. Finally, a short sub-section gives an overview on mathematical methods for stress modeling.

A. *Definition of Stress*

Stress is one of the most common extreme regimes for the living. According to the three-component theory, stress is a nonspecific protective systemic reduced response to damage or threat of damage [7-8]. That is, stress is not an adaptive, but a maladjustment process.

The stress-launching factor is a disagreement between the current state and the necessary state [9]. Then, in accordance with the theory of functional systems (FS) [10], we can assume that the occurrence of excessive mismatch in any of the modules of the acting FS leads to stress activation, which realizes the protective mechanism. The stress activation involves a combination of certain physiological (neurochemical, immune, vegetative, etc.) mechanisms [7-8, 11]. The same load can be optimal (or within the boundaries of the adaptation range) or stressing (beyond the adaptation range) for different people.

B. *Stress Recognition using HRV*

Autonomic nervous system (ANS) plays a key role in maintaining physiological functions of the body, including flexible and appropriate modification of the cardiac activity according to need. According to Baevsky et al., cardiac rhythm regulation can be represented as a double-circuit model with the central and autonomous circuits, with feedforward and feedback links (see Figure 2). In this case, the effect of the autonomous circuit is connected with respiratory arrhythmia, and the central circuit - with non-respiratory arrhythmia [12].

HRV analysis - determining the degree of variability in consecutive RR intervals or instant heart rate (HR) in a cardiogram - has become an important tool for assessing stress. A wide range of mathematical tools includes statistical, geometric, spectral, and nonlinear algorithms. Evolution of the mathematical apparatus for R-R intervals analysis is demonstrated by George E. Billman [13] (Figure 3). At the same time, the whole set of mathematical methods of HRV analysis is redundant [14]. However, it is important to note that each method has its own limitations in application. The most accurate method in terms of the time resolution is spectral analysis of RR-intervals. The selection of HRV periodic components allows us to determine the current state of the neuro-humoral regulation system. For the first time, different types of sequences of RR-intervals were described by Fleisch and Beckman in 1932 [15]. Rhythmic activity of pacemaker cells of the sinus node is interrelated with endocrine and humoral processes that change the threshold of spontaneous depolarization of pacemaker sinus node [16-18]. This leads to an increase or decrease in the interval between heart cycles and, consequently, a decrease or increase in heart rate. The factors that regulate HR will also affect HRV. An important feature of this process is that the activity of these factors varies periodically [19-20]. However, it should be noted that in addition to periodic modulations of various factors in HRV, there are also non-periodic components.

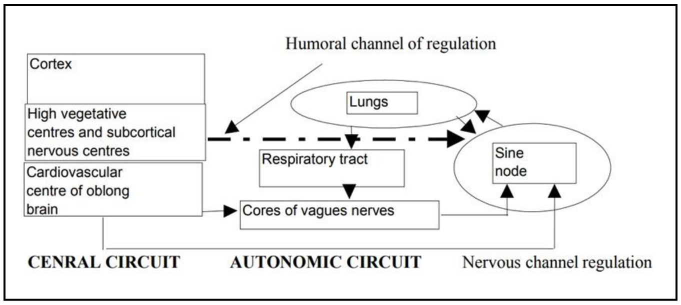


Figure 2. Scheme of double-circuit model for cardiac rhythm regulation.

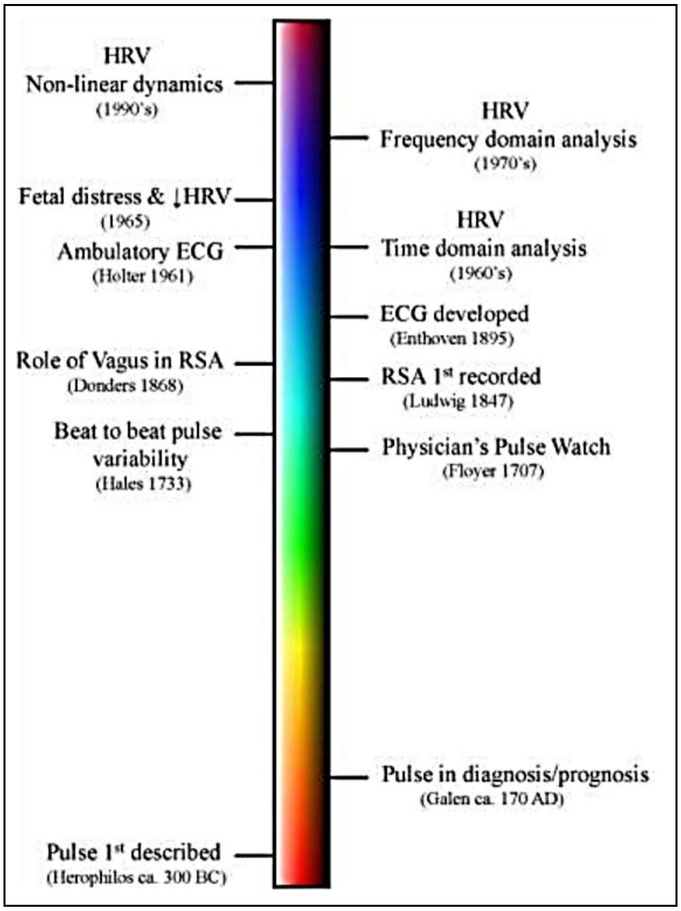


Figure 3. The temporal sequence of some of the most important events in HRV research history [13].

The traditional analysis of RR-intervals divides the HRV frequency spectrum into three ranges, (a) high-frequency (HF) oscillations (0.15-0.4 Hz); (b) low-frequency (LF) oscillations (0.04-0.15 Hz); (c) very low frequency (VLF) oscillations (0.015-0.04 Hz). However, in addition to the classical frequency ranges listed above, a number of authors indicate very high frequency (VHF) oscillations (0.6-2 Hz). Experimental data show the presence of VHF-components in the structure of the HRV spectrum in patients and in healthy people [21-22]. Table I shows the most relevant frequency ranges for spectral analysis of HRV.

TABLE I. THE FREQUENCY RANGES FOR SPECTRAL HRV ANALYSIS

Title of the Spectrum Component	Frequency Range (Hz)	Time Period (Sec)
HF	0,4 – 0,15	2,5 – 6,6
LF	0,15 – 0,04	6,6 – 25,0
VLF	0,04 – 0,015	25,0 – 66,0
ULF	Below 0,015	Over 66,0

The first studies of the impact of the information load on the functional state of a person using cardiovascular indicators are mentioned in the work of Winkler [23], who demonstrated that performing an arithmetic test leads to an increase in HR. Accumulated empirical evidence indicates that the LF spectrum is the most sensitive to the effect of cognitive loads. As a result, it was concluded that the suppression of LF (0.1Hz) HRV component reflects the effort of the subject required to perform a cognitive task, while the restoration of the spectral power during the relaxation period after completion of the cognitive task reflects the degree of previous efforts [24]. Some examples of empirical studies are listed in Table II.

TABLE II. EXAMPLES OF HRV SPECTRAL ANALYSIS UNDER COGNITIVE LOAD

Author	Experimental Problem	Selected HRV Indices	Trend
Egelund, 1982 [61]	Fatigue spectral HRV indices in drivers	LF (0,1 Hz)	Decrease
Kaplan, 1999 [62]	The change in the spectral indices in response to an erroneous action	HF (0,15-0,4 Hz)	Decrease
Mulder, 2000 [63]	The change in the spectral indices under cognitive load	LF (0,1 Hz)	Decrease
Brinkman, 2004 [64]	The change in the spectral indices during transition from solving simple equations to the complex ones	LF (0,1 Hz)	Decrease

The autonomic HRV regulation reflects the level of the adaptive resources of the organism [12; 25]. Studies have shown that emotions, cognitive processes, and physical activity are closely related to the dynamics of autonomic HRV regulation [26-27]. The research into stress provides an extensive HRV database for different groups of subjects in clinical and laboratory contexts: patients with depressive disorders, post-stroke patients with diabetes, etc. [28-30]. Vegetative correlates of fatigue, overexertion and various types of stress are actively studied [31-34]. Integration of the available data leads to the conclusion that the autonomic HRV regulation is sensitive to changes in emotional, cognitive and physical activity and is informative for the study of adaptation and maladjustment processes.

The data on the dynamics of HRV during stress are contradictory. Some studies demonstrate no changes in HRV [35] and the severity of respiratory arrhythmia in HR [36] in the presence of stress factors, while other authors show a high degree of variability in LF, HF, LF/HF spectral HRV parameters [37] (see Table III). Such contradictions could be explained by different software and hardware base of researchers.

TABLE III. SELECTED EMPIRICAL STUDIES OF HRV IN STRESS-RELATED CONTEXTS

Author	Context	LF Trend	HF Trend
T. Chandola et al., 2008 [34]	Working stress	Decrease	Decrease
J. Taelman et al., 2011 [26]	Intellectual load and/or physical load	Decrease	Decrease
N.I. Shlyk, 2011 [56]	An intensive training	Increase	Increase
H. Che-Hao et al., 2012 [57]	Inhalation anesthesia	Increase	N/D

For decades stress could be evaluated at rest only [38] with sitting or lying position of the subject being mandatory, and a great risk to damage the data by any external irritant stimuli [39]. All the mentioned restrictions greatly narrow the scope of contexts for research and make stress measurement in real-life scenarios impossible. Since the autonomic HRV regulation is dependent on the target function and varies greatly in accordance with the context [25, 40], static measurements in the laboratory do not always agree with the principle of ecological validity [15, 30, 41-42].

Currently, the problem of stress-specific HRV parameters is still unsolved. The definition of such parameters is complicated by the presence of individual optimum indices for a particular person, which do not always coincide with the average statistical results. This conditions the use of correlation of the HRV parameters along with the absolute values.

C. Neurohumoral HRV Regulation

More than 150 years ago, Claude Bernard denoted the existence of close connections between the brain and the heart [43]. Practical implementation of this concept is characterized by a number of important advantages. First, the methods of measuring the parameters of the functioning of the cardiovascular system (minute and stroke volume, pulse rate, arterial pressure) are well-known and generally available. Secondly, cardiovascular variability data can be used to evaluate the system of neurohumoral regulation of the heart and blood vessels, of which HR is the most simple and accessible for analysis.

Baro- and chemoreceptors control various parameters of the blood circulation in the vascular bed and heart, and as a result, the information about the ongoing endogenous changes enters the central nervous system (CNS). This ensures the lability of the adaptation of the heart-vascular system (HVS) to continuously changing environmental conditions. Thus, by controlling the processes of HVS regulation, it is possible to obtain information on the effectiveness of adaptive mechanisms in response to stress conditions.

As a theoretical approach, the neurovisual integrative model (NVM) is considered, according to which changes in HR are generally related to the state of the brain more, than to the state of the heart [44]. A number of nerve structures associated with heart rhythm are described within the framework of NVM. The data on these results are based on animal studies, studies of people with local cerebral lesions, physiological and pharmacological analysis, and work with methods of neuroimaging (PET, fMRT) [45-46].

HR is determined by the property of automatism, i.e., the ability of the cells of the conduction system of the heart to spontaneously activate and cause a contraction of the myocardium. Automatism is caused by the appearance of spontaneous depolarization of cells of the sinus node. The usual frequency is 60-80 pulses per minute. The fluctuations of HR are connected, on the one hand, with the intrinsic activity of the sinus node (intracardiac reflexes), and on the other hand with the influence of the higher centers of regulation [8]. HRV analysis, which is determining the degree of variability of consecutive R-R intervals or instant HR, has become an important tool for risk assessment.

HF oscillations of HR reflect the connection between the vagus nerve and the sinus node and the exerted neuromuscular influences. Therefore, the spectral power (density) in the HF range of the HRV spectrum is related to the activity of the parasympathetic link of the vegetative nervous system [11].

The LF range of the HRV spectrum when analyzing the records of the R-R intervals measured at rest (lying, sitting) is usually represented by a single peak at a frequency of 0.1 Hz. In fact, a wave peak with a frequency of 0.1 Hz in the spectrum of HRV means that the body has mechanisms for modulating HR with a period of 10 s. Oscillations with the same period are recorded in the rhythm of blood pressure. It can be assumed that the formation of a 0.1-Hz rhythm of RR-interval oscillations is the result of the participation of three mechanisms: baroreflex, central, and myogenic. For practical use, it is important that LF modulation of HR is associated with the activity of postganglionic sympathetic fibers, and their spectral power (density) reflects the activity of the sympathetic link of the VNS in the regulation of the heart rhythm [50].

As a rule, an increase in the power of LF oscillations is accompanied by a decrease in the power of HF oscillations, which may be the result of the existence of special mutual-reciprocal relations between them. Such interactions are also observed between the parasympathetic and sympathetic contours of the VNS, which determine the presence of these wave oscillations in HRV. This substantiates the usage of the LF/HF ratio power ranges of the HRV spectrum (also called the vegetative balance index, or VBI) for assessing the autonomic balance level [34, 39].

D. *Stress Research Issues*

The development of mathematical processing of ECG naturally led to the discovery of a large number of indicators (statistical, geometric, frequency), which, on the one hand, closely correlate with each other, making the entire set redundant, and on the other hand, are suitable for interpreting and evaluating the cardiac signal only in stationary conditions [14].

The key issues of autonomic regulation research are the following:

- What factors are responsible for autonomic responses in the context of daily-life activity?
- What psychophysiological processes underlie the HRV regulation in the context daily-life activity?
- Is it possible to predict HRV response in daily-life activity context from laboratory measurements?

For accessing physiological stress, a neurophysiologic index is a simultaneous increase of LF/HF values with the fall in the total power spectrum of HRV [11-12, 31, 33-35, 39-40].

The relationship between laboratory and field indices of vegetative regulation of the heart rhythm has been studied for more than 30 years.

Public speaking seems to be the most realistic natural activity context for stress study, along with an examination, an interview, etc. All of these real-life scenarios remain relatively manageable [42]. However, when public speech context was used as a component of the laboratory model of stress in the Trier Social Stress Test (TSST) [47], the later comparison of the results with 41 trials of natural public speaking HRV records showed no correlations [48]. Numerous studies show much more pronounced changes in HR when performing in public in the natural activity context as compared to laboratory experiments [49-51]. The review [41] concludes that there are weak correlations between HRV measurements produced in laboratory and field contexts, although some positive correlations are found.

Another approach to the problem of real-time stress diagnostics in natural dynamic contexts is the development of a new instrumental method. The method should allow recording of biophysical signals to provide personalized monitoring and remote diagnostics of stress without restrictions on the duration of recording. The California Institute of Technology and the Georgia Institute of Technology have made significant progress in this respect. They developed a clothing fabric with an incorporated network of contactless capacitive sensors to allow continuous HRV monitoring in real-life contexts [52].

In our work, we analyze HRV patterns from normal healthy people in various real-life contexts, e.g., stressful tasks, intensive physical activities, sudden maneuver while driving, etc. In order to do that, we use an unobtrusive HRV measuring device that can be easily worn long-term (24-hours). Such approach will allow us to identify the stress-specific HRV pattern for dynamic real-life scenarios.

III. CARDIAC TELEMETRY SOLUTION

The cardiac telemetry technology was designed for stress detection in dynamic real-life scenarios. The basic data for analysis are R-R intervals of the electrocardiogram (ECG) obtained in real time from a wireless sensor. The StressMonitor client application allows preliminary processing of the data and its representation in the form of a dynamic graph with indicated HRV spectral values. All the data is stored in a cloud. The solution is already in demand by medical institutions and scientific laboratories, professional coaches, and health-conscious people.

A. *Solution Requirements*

Since the operation of the human body is a dynamic process, due to high lability and the contextual dependence of HRV, special requirements are imposed on the technology for stress measurement in real-life scenarios. Among such requirements we list the following: safety and convenience for use in everyday life; mobility, i.e., the signal source can be remote from the signal receiving unit; continuous recording of signal; low power consumption; autonomous mode of HRV diagnostics; automatic processing of interrupts; sustainability to external interference; ability to accumulate data in off-line mode.

B. *Solution Arcitecture*

Cardiac telemetry is a monitoring solution that allows continuous HRV monitoring while the volunteer remains active without the restriction of being attached to a bedside cardiac monitor. A three-module wireless technology has been developed [53-55].

ZephyrTM HxMTM Smart (HxM, Zephyr Technology) sensor platform combines optimal size and energy consumption as well as quality of receiving and transmitting radio signals not sacrificing the comfort of the use. The platform is 65x32 mm in size and 17 grams in weight. Its design ensures reliable fixation of sensors on the human body. The platform combines a microprocessor, a radio signal reception and transmission unit, a low-power ECG sensor, an acceleration sensor, and a distance sensor. The device works for 150 hours without recharging. The signal transmission range is 10 m. The data transfer to a smartphone or a tablet PC is organized via Bluetooth SPP - 2,4 GHz. Packets of raw data are transmitted every second, where each dataset contains a unique device identifier, 15 last R-R intervals, and the start time of the recording.

For temporary accumulation and preprocessing of data, a StressMonitor application for Android-operating smartphone is used. Further the data is transmitted via GSM channels to a special server (see Figure 4). The star-shaped topology of the sensor network ensures the efficient use of hardware in case of collective monitoring.

The StressMonitor application displays real-time RR-graphs with spectral frequency-related HRV indices [10] (see Figure 5). It was developed with the use of MySQL 5.5 database, Python 2.7 programming language, Django 1.8 development framework, the Flot 8.2 library, a framework for creating a BootStrap 3.2 site design, NumPy, JQuery 2.1 library, Yandex API Maps.

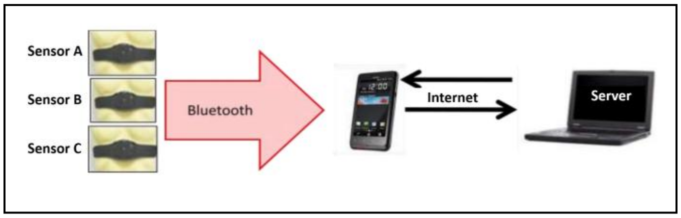


Figure 4. Architecture for wireless registration of HRV in a group of volunteers.

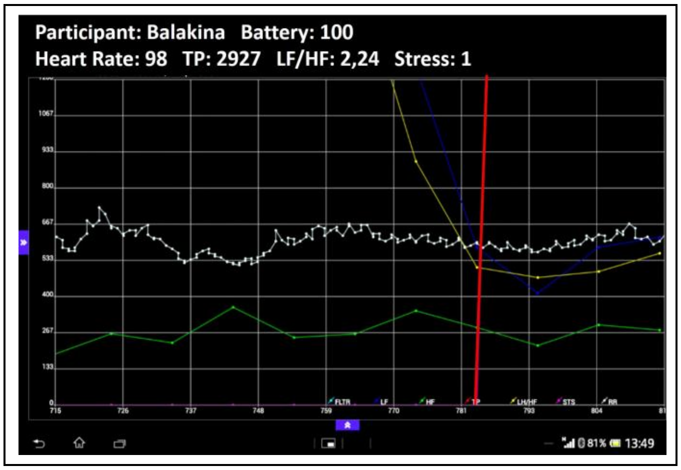

Participant: Balakina Battery: 100
Heart Rate: 98 TP: 2927 LF/HF: 2,24 Stress: 1

Figure 5. Graphical representation of RR-intervals with calculated HRV spectral indices; the red vertical bar indicates the onset of the stress episode.

The server database works on MySQL 5.5 software. The received RR signal is cut by a time window for 100 seconds with a time shift of 10 seconds. For the resulting windows, the discrete Fourier transform for uneven signals calculates the spectrum. For the purpose of analysis the spectrum is divided into the following ranges: VLF (0.003-0.04 Hz), LF (0.04-0.15 Hz), HF (0.15-0.4 Hz). The algorithm also uses frequency-related HRV indices: total power (TP) which is a sum of VLF, LF, and HF; vagally-sympathetic balance (LF/HF). As a result, we receive spectral HRV values, GSM coordinates, the time and events associated with stress in a particular person during real-life activity [10].

C. *Mathematical Methods for HRV Analysis*

For the data processing, spectral periodogram method and statistical methods for analysis of HRV, as well as the continuous wavelet transformation were used.

Spectral analysis is one of the most important types of time series analysis, which allows to determine the effect of autonomic regulation on HRV.

When constructing the spectrum of the rhythmogram, it is important to take into account that the signal itself is not a time series of amplitudes of a physical quantity, but a number series of time intervals between adjacent QRS events in a cardiogram. Fundamentally, the Fourier transform cannot be performed because of the unevenness of the QRS events time scale. It is necessary either to convert a number of intervals into a time series, or to adapt a transformation for a non-uniform series.

Taking into account the specificity of the cardiac signal obtained in real-life contexts, namely, the presence of a nonstationary property and a large number of transition regions, a set of specialized spectral methods for signal processing is suggested:

- Continuous wavelet transform (CW method, or Morlet wavelet) for analysis of amplitude modulations of RR-intervals and spectral components of rhythmograms.
- Dynamic spectral analysis, which synthesizes Fast Fourier transformation algorithms and Lomba-Scargla periodograms, for analysis of rapid changes in the structure of HR. In our case dynamic spectral analysis was performed in a specialized program built in the LabVIEW environment.

As a result, we analyze the temporal dynamics of the power characteristics of the vibration spectra of the RR-intervals, namely: the total power of the HRV spectrum (TP, ms^2); LF, ms^2; HF, ms^2; the ratio of the power of the rhythmogram spectrum (LF/HF).

D. Solution Validation

The validity of the cardiac telemetry complex has been tested by the simultaneous recording with the two certified ECG clinical solutions: AIP Poly-Spectrum (Neurosoft) and Ankar-131 (Medicom) (see Figure 6), and statistical analysis of the HRV patterns and the time sequences of R-R intervals. There is a high correspondence of the time sequences for R-R intervals and the HRV patterns (p = 0.995, Student's test).

IV. RESULTS AND DISCUSSION

In this section, our selected studies are considered. All the subjects gave informed written consent to participate in the research. Trials with deviation over 10% were removed from the data prior to the analyses. R-R intervals of less than 300 or more than 1500 ms were considered as deviations. Overall, data loss was below 3% across all measurements for each participant group. For all other trials, median filtering was performed prior to spectral analysis.

A. Participants

362 healthy people from Nizhny Novgorod (179 men and 183 women, with a mean age of 21.5 (±1.3)) took part in the experiment. All participants had no heart condition. All of the participants gave an informed consent to stimulation by electrical impulses. All of the participants were naïve regarding the purpose of the experiment.

B. Research Contexts

The data for the research was gathered both in laboratory contexts and in real-life scenarios.

The laboratory contexts were:

- Students during public speaking.
- Students playing a race computer game.
- Sportsmen playing chess with a computer.

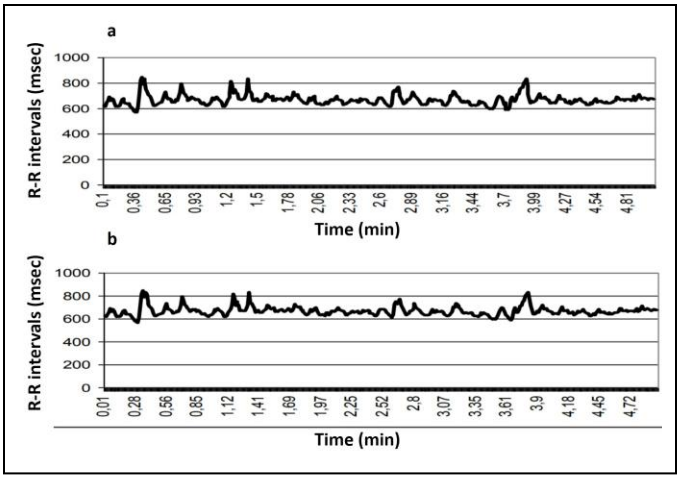


Figure 6. Comparison of synchronized R-R records: (a) Cardiac Telemetry Solution; (b) Poly-Spectrum Analyzer.

The real-life contexts were:

- Drivers of public transport during a sudden maneuver.
- Athletes during an intensive training.
- Firefighters during training in the gas-smoke chamber.

C. Procedure

Volunteers underwent research both individually and collectively, depending on the context.

Before the test, a participant was asked to wear ZephyrTM chest belt. The person responsible for the experiment ran the SmartMonitor app and entered the participant’s name, age, and gender. Then the participant was instructed to start the experimentation activity.

Research contexts could take from 30 minutes to several days depending on an activity. All this time, the volunteers wore ZephyrTM chest belt and their data was transferred to the cloud.

After the tests, the lab technician downloaded data from the cloud. HRV spectral analysis was carried out automatically directly in the cloud with the use of a special program complex. Statistical processing of data within each context and between contexts was carried out manually in the program STATISTICA 10.

D. Results

When analyzing spectral HRV indices during public speaking, it was revealed that a decrease in TP with simultaneous increase in LF/HF is a typical pattern for the context (76% of cases).

In the context of computer race game, the moments of mismatch and errors were also characterized by a decrease in TP and an increase in LF/HF values.

During the game of chess in 77% of cases there was a decrease in TP and an increase in LF/HF at the time of a loss (see Figure 7).

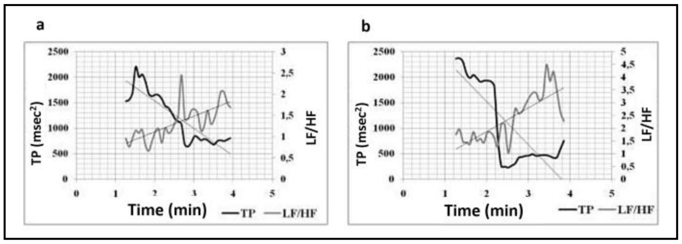


Figure 7. TP and LF/HF HRV spectral values during a game of chess: (a) the player attacks with a subsequent defeat; (b) the player loses the initiative and the game ends in defeat.

In public transport drivers, a sudden maneuver was accompanied by an increase in TP and LF/HF, followed by a decrease in TP with an increase in LF/HF.

HRV spectral analysis in the process of intensive training showed a statistically significant decrease of TP, LF, and HF values after the training load, as well as an increase in LF/HF (p<0,05) (see Figure 8). Table IV represents a comparison of the HRV spectral values for warm-up, where optimal HRV values for effective training are identified (see also Figure 9).

TABLE IV. THE OPTIMAL SPECTRAL HRV PARAMETERS DURING WARM-UP

HRV Indices	Mean Value	Standard Error of the Mean
HR, beats per minute	78,40	± 4,53
TP, msec2	3653,82	± 211,81
LF, msec2	1604,49	± 87,59
HF, msec2	573,29	± 61,01
LF/HF	3,09	± 0,86

When analyzing the spectral HRV dynamics in firefighters during training in a gas-smoke chamber, a characteristic R-R pattern was also found: the decrease of TP with an increase in LF/HF (97% of cases).

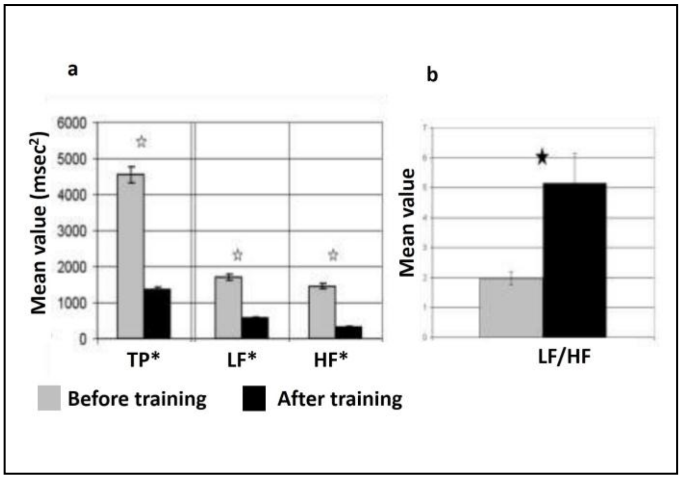


Figure 8. Mean values of spectral HRV parameters before and after exercise: (a) TP, LF, HF (msec2); (b) LF/HF (*p <0.05, Student's test).

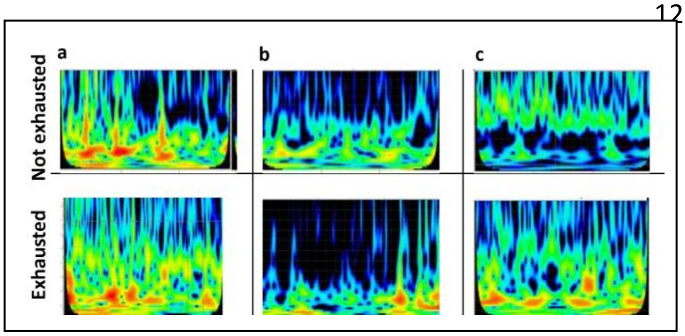


Figure 9. Wavelet analysis of rhythmograms (Morlet wavelets) in athletes at different stages of training: (a) warm-up; (b) training process; (c) rest.

V. CONCLUSION AND FUTURE WORK

To summarize, we undertook an investigation of HRV dynamics during stress in various laboratory contexts and real-life scenarios with the use of cardiac telemetry. We found evidence that there is a dynamic pattern of RR-intervals characteristic for stress, which is the decrease of TP values with the increase of LF/HF values. Therefore, stress is physiologically manifested by increased sympathetic and diminished parasympathetic activity of the ANS.

The main objective of the study was to analyze the continuous dynamics of autonomic regulation of HRV in heterogeneous laboratory and real-scenarios and to identify the dynamic structures of autonomic regulation indices specific for the stress response.

The results of the study of the HRV autonomic regulation dynamics under variousloads reproduce and confirm data on the high sensitivity of the regulation system to various changes in the internal and external contexts of a living system [25].

Using the new wireless cardiac telemetry solution that was developed specifically for the task of measuring living systems in the real-life scenarios opened new opportunities for research [51-52].

As the result of experimental series, it is shown that the dynamics of the HRV autonomic regulation parameters is nonlinear, quasi-periodic, and does not have direct relationships with the autonomous regulation measurements in stationary contexts like sitting or lying. There are no grounds to deny the possibility of revealing the dependencies between the indices of the autonomic regulation at rest and in the context of natural activity. However, they seem to be individual. Therefore, an appropriate experimental design presupposes repeated long-term monitoring of a person in a rich set of real-life scenarios.

Use of spectral analysis algorithms for uneven time series, such as the sequence of RR-intervals, made it possible to reveal VHF spectrum of HRV that was not considered in classical physiology and medicine.

Mathematical methods of dynamic spectral analysis allow scaling the discreteness of the received parameters, so there is an opportunity to observe real-time changes in the structure of the autonomous regulation of HR in the course of real-life events. This makes it possible to use 15-second rhythmograms for analysis instead of 300-second rhythmograms as in the classical HRV analysis.

The novelty of the study is the approach with the loads differing not in the complexity, but in the very nature of the target task.

In general, the decrease in HRV as a sign of the presence of a disease is discussed in many works [58-60]. The list of diseases is very wide, including cardiovascular system disorders (myocardial dysfunction, tetraplegia, hypertension, congestive circulatory insufficiency, chronic mitral regurgitation, cardiomyopathy, ventricular arrhythmias, supraventricular arrhythmias, etc.); psychoneurological disorders (posttraumatic stress disorder, depression, anxiety), oncological diseases, infectious diseases (influenza, ARVI). Apparently, the decrease in HRV is a nonspecific marker of the presence of a disease. Then, it is debatable that the famous Selye triad, which is a complex of three stress-specific symptoms (hypertrophy of the adrenal glands, thymus involution, ulceration in the digestive tract), can be extended. In order to introduce the decrease in HRV as the dynamic marker of stress, we need to reproduce pharmaco-physiological responses associated with stress reaction.

The HRV data obtained in athletes during physical load represents a fundamentally new context for research of stress. An important result was obtained when trying to reveal the coordination between the initial states of athletes with their performance in the context of uninterrupted monitoring of their training activities from warm-up until rest.

According to the 3-component theory of stress [8] and empirical data, we assume that the first phase of stress-related HRV pattern dynamics is associated with the activation of all regulatory loops, and especially the sympathetic component of the autonomic nervous system. The second phase of HRV dynamics may be associated with the activation of the endogenous opioid system (EOS) (see Figure 9).

A contradiction in interpretation may arise when comparing the two indices of the sympathetic activity, which is the power of the LF component of HRV and HR spectrum. It is commonly believed that an increase in HR and an increase in the LF index reflect the activity of the sympathetic system. In our case, the increase in HR values is combined with the decrease of the LF component (i.e., training load effects in athletes). That is, the two indices contradict each other.

However, experimental data on the LF component dynamics were historically obtained in static contexts, that is, active contexts were not considered. At rest, there is a direct correlation between the power of LF and HR.

As a result, changes in HR and LF power are not always associated with the activity of the sympathetic subsystem. Apparently, they reflect different regimes of sympathetic influence on the heart rhythm. The LF component reflects the phasic modulation of the HR in the context of rest. The increase in HR is a single strong increase associated with sympathetic activation in the dynamic real-life context.

The results of the use of the cardiac telemetry in numerous experiments justify its potential for application in further research into stress phenomenon, health promotion services, consumer wellness devices, professional sports, and amateur training.

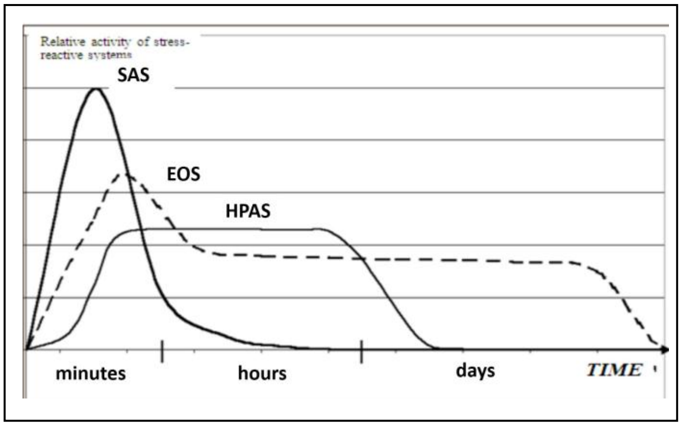


Figure 10. The dynamics of the stress-protection systems SAS, HPAS, and EOS during stress.

In future researches we would like to focus on defining the best practices for stress management. Research into neurobiological mechanisms of stress at the cell level is planned for further technology development.

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REFERENCES

[1] S.B. Parin, S.A. Polevaia, and A.V. Polevaia, “A Neurochemical Framework to Stress and the Role of the Endogenous Opioid System in the Control of Heart Rate Variability for Cognitive Load,” in COGNITIVE 2017: 9th International Conference on Advanced Cognitive Technologies and Applications, IARIA, pp. 16–20, 2017.

[2] E-M. Backe, A. Seidler, U. Latza, K. Rossnagel, and B. Schumann, “The role of psychosocial stress at work for the development of cardiovascular diseases: a systematic review,” International Archieves of Occupational and Environtal Health, vol. 85, pp. 67–79, 2012.

[3] S. C. Segerström and G. E. Miller, “Psychological Stress and the Human Immune System: A Meta-Analytic Study of 30 Years of Inquiry,” Psychological Bulletin, vol. 130(4), pp. 601–630, 2004.

[4] N. Schneiderman, G. Ironson, and S. D. Siegel “Stress and Health: Psychological, Behavioral, and Biological Determinants,” Annual Review of Clinical Psychology, vol. 1, pp. 607-628, 2005.

[5] World Health Organization, “Charting the way to well-being,” The European Health Report, 2012.

[6] A. Muaremi, B. Arnrich, and G. Troster, “Towards Measuring Stress with Smartphones and Wearable Devices During Workday and Sleep,” Bionanoscience, vol. 3, pp. 172–183, May 2013, doi:10.1007/s12668-013-0089-2.

[7] H. Selye, “The story of the adaptation syndrome,” Montreal: ACTA, Inc., Medical Publishers, 1952.

[8] S. B. Parin, “Humans and animals in emergency situations: neurochemical mechanisms, evolutionary aspect,” Vestnik NSU, vol. 2(2), pp. 118–135, 2008.

[9] S. B. Parin and S. A. Polevaya, “Features of information transformation under stress and shock,” VIII All-Russian

Scientific and Technical Conference "Neuroinformatics-2006", Moscow: MEPhI, pp. 165-171, 2006.

[10] P. K. Anokhin, "Essays on the Physiology of Functional Systems," Moscow: Medicine, pp. 17-59, 1975.

[11] S. A. Polevaya, S. B. Parin, and E. G. Stromkova, "Psychophysical mapping of human functional states," Experimental Psychology in Russia: Traditions and Perspectives, pp. 534-538, 2010.

[12] R. M. Bayevsky, "Analysis of heart rate variability: history and philosophy, theory and practice," Clinical informatics and telemedicine, vol. 1(1), pp. 54-64, 2004.

[13] G. E. Billman, "Heart rate variability–a historical perspective," 2011, doi:10.3389/fphys.2011.00086.

[14] A. S. Ban, N. A. Paramonova, G. M. Zagorodnyi, and D. S. Ban, "Analysis of the interrelation between heart rate variability indices," Military medicine: a scientific and practical peer-reviewed journal, vol. 4, pp. 21-24, 2010.

[15] V. A. Barabanschikov, "Experimental Psychology in Russia," Moscow: Institute of Psychology RAS, pp. 13-18, 2010.

[16] H. Bonnemeier, G. Richardt, J. Potratz, U. K. Wiegand, A. Brandes, N. Kluge, and H. A. Katus, "Circadian profile of cardiac autonomic nervous modulation in healthy subjects: differing effects of aging and gender on heart rate variability," J. Cardiovasc. Electrophysiol, vol. 14(8), pp. 791-799, 2003.

[17] G. B. Stanley, K. Poolla, and R. A. Siegel, "Threshold modeling of autonomic control of heart rate variability," IEEE Trans Biomed Eng, vol. 47(9), pp. 1147-1153, 2000.

[18] A. Zaza and F. Lombardi, "Autonomic indexes based on the analysis of heart rate variability: a view from the sinus node," Cardiovasc Res, vol., 50(3), pp. 434-442, 2001.

[19] R. M Baevsky and G. G. Ivanov, "Heart rate variability: theoretical aspects and possibilities of clinical application," Ultrasound functional diagnostics, vol. 3, pp. 108-127, 2001.

[20] D. Singh, K. Vinod, and S. C. Saxena, "Sampling frequency of the RR interval time series for spectral analysis of heart rate variability," J. Med. Eng. Technol, vol. 26(6), pp. 263-272, 2004.

[21] E. Toledo, I. Pinhas, D. Aravot, and S. Akselrod, "Very high frequency oscillations in the heart rate and blood pressure of heart transplant patients," Med. Biol. Eng. Comput, vol. 41, pp. 432-438, 2003.

[22] S. V. Bozhokin, E. M. Lecova, V. O. Samoilov, and P. I. Tolkachev, "Wavelet analysis of non-stationary heart rate variability during passive orthostatic test," Biophysics, vol., 4, pp. 696-712, 2012.

[23] C. Winkler, "Attention and respiration," Proc. Acad. Sci. Amsterdam, vol. 1, pp. 121-138, 1899.

[24] V. A. Mashin, "Three-factor model of heart rate variability in psychological research of functional systems of human operator," Moscow, 2010.

[25] V. V. Parin and F. Z. Meerson, "Essays on the clinical physiology of blood circulation," Moscow: Medicine, 1960.

[26] J. Taelman, S. Vandeput, E. Vlemincx, A. Spaepen, and S. Van Huffel, "Instantaneous changes in heart rate regulation due to mental load in simulated office work," Eur J Appl Physiol, vol. 111(7), pp. 1497-1505, 2011a.

[27] J. Taelman, U. Katholieke, L. B. Leuven, S. Vandeput, I. Gligorijevic, and A. Spaepen, "Timefrequency heart rate variability characteristics of young adults during physical, mental and combined stress in laboratory environment," Conf Proc IEEE Eng Med Biol Soc, pp. 1973-1976, 2011b.

[28] E. K. S. Hanson, G. L. R. Godaert, C. J. M. Maas, and T. F. Meijman, "Vagal cardiac control throughout the day: the relative importance

[29] of effort-reward imbalance and within-day measurements of mood, demand and satisfaction," Biol. Psychol, vol. 56, pp. 23-44, 2001.

[30] A. Collins, A. Karasek, and K. Costas, "Job strain and autonomic indices of cardiovascular disease risk," American Journal of Industrial Medicine, vol. 48, pp. 183-193, 2005.

[31] P. Melillo, M. Bracale, and L. Pecchia, "Nonlinear Heart Rate Variability features for real-life stress detection. Case study: students under stress due to university examination," Biomed. Eng.Online, vol. 10(1), pp. 96, 2011.

[32] T. W. Buchanan and D. Tranel, "Stress and emotional memory retrieval: effects of sex and cortisol response," Neurobiol. Learn. Mem, vol. 89, pp. 134-141, 2008.

[33] R. Nikolova, L. Tzaneva, and S. Danev, "Investigation of noise exposure effect on heart rate variability parameters," Cent Eur. J. Public Health, vol. 9(3), pp. 130-132, 2001.

[34] T. Chandola, A. Britton, E. Brunner, H. Hemingway, M. Malik, M. Kumari, E. Badrick, M. Kivimaki, and M. Marmot, "Work stress and coronary heart disease: what are the mechanisms? ," Eur Heart J, vol. 29, pp. 640-648, 2008.

[35] T. Chandola, A. Heraclides, and M. Kumari, "Psychophysiological biomarkers of workplace stressors," Neurosci. Biobehav. Rev, vol. 35(1), pp. 51-57, 2010.

[36] N. Rohleder, J. M. Wolf, E. F. Maldonado, and C. Kirschbaum, "The psychosocial stress-induced increase in salivary alpha-amylase is independent of saliva flow rate," Psychophysiology, vol. 43, pp. 645-652, 2006.

[37] M. Altemus, L. S. Redwine, Y. Leong, C. A. Frye, S. W. Porges, and C. S. Carter, "Responses to laboratory psychosocial stress in postpartum women," Psychosom. Med, vol. 63, pp. 814-821, 2001.

[38] H. Lackschewitz, G. Hüther, and B. Kröner-Herwig, "Physiological and psychological stress responses in adults with attention-deficit/hyperactivity disorder (ADHD)," Psychoneuroendocrinology, vol. 33, pp. 612-624, 2008.

[39] M. Malik, J. T. Bigger, A. J. Camm, R. E. Kleiger, A. Malliani, A. J. Moss, and P. J. Schwartz, "Heart rate variability: Standards of measurement, physiological interpretation, and clinical use," Eur. Heart J, vol. 17(3), pp. 354-381, 1996.

[40] R. M. Baevsky, "Prediction of states on the verge of norm and pathology," Moscow: Medicine, 1979.

[41] P.K.. Anokhin, "Fundamental questions of the general theory of functional systems of the principles of the system organization of functions", Moscow: Science, pp. 5-61, 1973.

[42] J. R. Turner, D. Carroll, S. Dean, and M. G. Harris, "Heart rate reactions to standard laboratory challenges and a naturalistic stressor," International Journal of Psychophysiology, vol. 151, pp. 151-152, 1987.

[43] C. Bernard, "The physiology of the heart and its relation to the brain: lecture," N. Solovyov, Ed. St. Petersburg, 1867.

[44] J.F. Thayer, F. Åhs, Fredrikson, M.J.J Sollers, and T.D. Wagere, "A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health," Neuroscience and Biobehavioral Reviews, 36, pp. 747–756, 2012.

[45] J.F. Thayer and R.D. Lane, "A model of neurovisceral integration in emotion regulation and dysregulation," J. Affect. Disord., 61, pp.201–216, 2000.

[46] J.F. Thayer and R.D. Lane, "Claude Bernard and the heart–brain connection: further elaboration of a model of neurovisceral integration," Neurosci. Biobehav. Rev, 33, pp.81–88, 2009.

[47] Y. J. Zanstraa and D. W. Johnston, "Cardiovascular reactivity in real life settings: Measurement, mechanisms and meaning," Biol. Psychol, vol. 86(2), pp. 98-105, 2011.

[48] C. Kirschbaum, K. M. Pirke, and D. H. Hellhammer, "The 'Trier Social Stress Test'—a tool for investigating psychobiological stress responses in a laboratory setting," Neuropsychobiology, vol. 28, pp. 76-81, 1993.

[49] J. R. Turner, S. S. Girdler, A. Sherwood, and K. C. Light, "Cardiovascular responses to behavioral stressors: laboratory-field generalization and inter-task consistency," Journal of Psychosomatic Research, vol. 34(5), pp. 581-589, 1990.

[50] L. Warwick-Evans, J. Walker, and J. A. Evans, "A comparison of psychologically-induced cardiovascular reactivity in laboratory and natural environments," Journal of Psychosomatic Research, vol. 32, pp. 493-504, 1988.

[51] L. J. Van Doornen and R. W. Van Blokland, "The relation to type a behavior and vital exhaustion with physiological reactions to real life stress," Journal of Psychosomatic Research, vol. 3, pp. 715-725, 1989.

[52] J. P. Davig, K. T. Larkin, and J. L. Goodie, "Does cardiovascular reactivity to stress measured in the laboratory generalize to thesis and dissertation meetings among doctoral students? ," International Journal of Behavioral Medicine, vol. 7, pp. 216-235, 2000.

[53] E.V. Runova, S.B. Parin, M.M. Nekrasova, A.V. Bakhchina, A.V. Kovalchuk, I.S. Shyshalov, and S.A. Polevaya, "Monitoring and distant diagnostics of sportsment's functional state based on information technologies and telemetry in the conditions of natural activity," Int J Psychophysiology, vol. 85(3), pp. 420– 421, 2012.

[54] S. A. Polevaia, S. B. Parin, A. V. Bakhchina, M. M. Nekrasova, I. S. Shishalov, E. V. Runova, and V. V. Kozhevnikov, "Determination system of functional state of a group of people," Patent RF №129680, 2013.

[55] S. A. Polevaya, S. B. Parin, A. V. Bakhchina, M. M. Nekrasova, I. S. Shishalov, E. V. Runova, and V. V. Kozhevnikov, "Determination system of functional state of a group of people with feedback," Patent RF №129681, 2013.

[56] N. I. Shlyk, A. E. Alabuzhev, N. Z. Feofilaktov, and A. O. Sleptsov, "Dynamic studies of heart rate variability in mid-season athletes in the training process in mid-mountain conditions," Materials of the 5th All-Russian Symposium with international participation: Variability of the heart rhythm. Theoretical aspects and practical application, pp. 384-389, 2011.

[57] H. Che-Hao, T. Ming-Ya, H. Go-Shine, L. Tso-Chou, C. Kuen-Pao, H. Shung-Tai, S. LiangYu, and L. Chi-Yuan, "Poincaré plot indexes of heart rate variability detect dynamic autonomic modulation during general anesthesia induction," Acta Anaesthesiologica Taiwanica, vol. 50, pp. 12-18, 2012.

[58] K. Becker, I. Görlach, and T. Frieling, "Häussinger, D. Characterization and natural course of cardiac autonomic nervous dysfunction in HIV-infected patients," AIDS, vol., 11(6), pp. 751-757, 1997.

[59] S. Cohen and N. Weinstein, "Nonauditory effects of noise on behavior and health," Journal of Social Issues, vol. 37, pp. 36-70, 1981.

[60] M. De Couck, D. van Brummelen, D. Schallier, J. De Grève, and Y. Gidron, "The relationship between vagal nerve activity and clinical outcomes in prostate and non-small cell lung cancerpatients," Oncology reports, pp. 2435-2441, doi:10.3892/or.2013.2725.

[61] N. Egelund, "Spectral analysis of heart rate variability as an indicator of driver fatigue," Ergonomics, vol. 25(7), pp. 663-672,1982.

[62] A.Y. Kaplan, "Heart rate variability and the nature of feedback upon the result of operational activity in a human," Zh Vyssh Nerv Deiat I P Pavlova, vol.48(6), pp.345-350, 1999.

[63] G. Mulder, L.J.M. Mulder, T.F. Meijman, J.B.P. Veldman, and A.M. Van Roon, "A psychophysiological approach to working conditions," in Engineering Psychophysiology: Issues and Applications, R.W. Backs, W. Boucsein, Eds. pp. 139-159,2000.

[64] W.P. Brinkman, R. Haakma, and D.G. Bouwhuis, "Memory Load: a Factor that Links the Usability of Individual Interaction Components Together," Proc. the Conference HCI: Design for Life, vol.2, Leeds, UK, pp.165-168, 2004.