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Experience in assessing heart rate variability by smoothed cardiointervalograms

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Abstract. The *objective* of this study is to show the possibility of using the smoothing cardiointervalograms (CIG) method which is solely time domain analysis of CIG to separate and display the influence of various mechanisms of human physiological regulation systems on his heart rate. *Methods.*This paper shows the possibility of using the method of smoothing the cardiointervalogram by means of a moving average for its subsequent decomposition into slow and fast components. Decomposition results are visualized by line graphs and pseudo-phase portraits. Visualization settings allow us to isolate unique transients and calculate its timing. The method is applied to data obtained under different subject functional states and differing in the level of adaptation risks, the presence or absence of stress. For analysis were selected stress episodes detected using the information and telecommunication technology of event-related cardiac telemetry (ITT ERCT) presented by the Internet resource "StressMonitor". *Results.*For the numerical series of RR-intervals, a clear division into fast and slow components is obtained. An algorithm for identifying the frequency content of heart rate variability has been formulated and tested. A visualization method is proposed that is convenient for comparing data obtained for different patients. A pseudo-phase portrait pattern corresponding to the moment of stress onset is found. The proposed method reduced the discreteness of identifying the stress onset moment from 10 seconds to single heart beats. *Conclusion.* The correspondence of the results to the verified ITT ERCT method and the Baevsky–Chernikova concept of adaptive risk has been demonstrated. This confirms the possibility of using the time cardiointervalograms smoothing method for the analysis of heart rate variability.

Keywords: heart rate variability, hierarchy of cardioregulatory times, pseudo phase portrait, stress, time domain analysis heart rate variability, cardiointervalograms smoothing, simple moving average, RR-intervals visualization.

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Introduction

For more than half a century, heart rate variability (HRV) has been used to diagnose and predict human health. HRV is displayed as a time series of RR intervals (intervals between successive heart contractions, intervals between R teeth of an electrocardiogram). Usually, such processing methods as statistical analysis and spectral analysis are applied to it for a certain period of time (usually 5 minutes in standard laboratory conditions) [1–4]. In the spectrum of cardiointervalogram (CIG), frequency ranges are standardly distinguished: high (high frequency, HF), low (low frequency, LF) and very low frequency (very low frequency, VLF). It is believed that these characteristic frequency ranges correspond to various regulatory mechanisms. Since the spectrum is not discrete, the total spectral power and its balance for high and low frequencies, derived indicators are calculated. Spectral and statistical methods are widely used and successfully applied [1–4].

From the time analysis, histograms and scatterograms are used (displaying HRV on the plane in coordinates R_i, R_{i+1}) again for some time interval [3, 4]. Other methods of time analysis have also been proposed, which have not received further development [1].

Back in the mid-19th century, Claude Bernard described the close relationship between the brain and the heart, and in the mid-30s of the 20th century, P., K. Anokhin formulated the theory of functional systems, according to which the central processes of achieving a goal are inextricably linked with the processes of physiological support for its achievement (according to Goldstein) [5]. Nevertheless, instantaneous changes in heart rhythm under cognitive load and stress of various etiologies from this point of view began to be studied only in the last decade [6]. Instantaneous — means momentary, possibly transient changes, possibly transferring the body to a new level of functioning. In spectral analysis, they give a smearing of dominant frequencies or a continuous spectrum. The modern paradigm of HRV models assumes multi-contour control of physiological functions of the body — from two-circuit models, for example R., M. Bayevsky [2], to more complex ones, for example Julian F. Thayer [7]. The review [5] describes a variety of conceptual schemes showing regulatory mechanisms. These regulation schemes reflect the hierarchical structure of vegetative responses. Such a hierarchy of responses obviously corresponds to the hierarchy of regulation and has hierarchically organized characteristic times of adaptation processes. However, this hierarchical temporal organization of the heart rate (HR) is not available for analysis using integral indicators, since they do not reflect and practically do not allow detecting episodes of direct modulation of the rhythm components [8]. In particular, this is not possible with non-periodic modulation of HR. This circumstance limits the study of systemic physiological connections. Obviously, along with the methods of spectral analysis of HRV, the methods of time analysis should also be used. Guided by common sense considerations and the assumption of the existence of a hierarchy of times, we proposed a method for processing cardiorhythmograms related to the time analysis of [8]. Since each level in the management hierarchy (central, metasympathetic, humoral...) has its own pace, it is reasonable to do averaging in a window of moderate duration so that the fast components of regulation are leveled. In this paper, we demonstrate the usefulness of this approach and compare its informativeness with the informativeness of the use of sliding spectral analysis [6] to determine the moment of onset of acute stress. We also demonstrate the possibility of using it to diagnose functional states.

1. Methodology

The creation of any new methods was not the purpose of this work. We use the usual digital filtering method, first used for HRV analysis in space flight in 1965. [9, 10]. The essence of the applied method consists in smoothing the initial sequence of cardiac intervals measured in milliseconds. To do this, a simple moving average is calculated — the average value of the subsequent m values for some n in the original CIG. Denote by RR_i the element of the original sequence of RR intervals. Then the element of the smoothed sequence RR_{S_n} is calculated by the formula

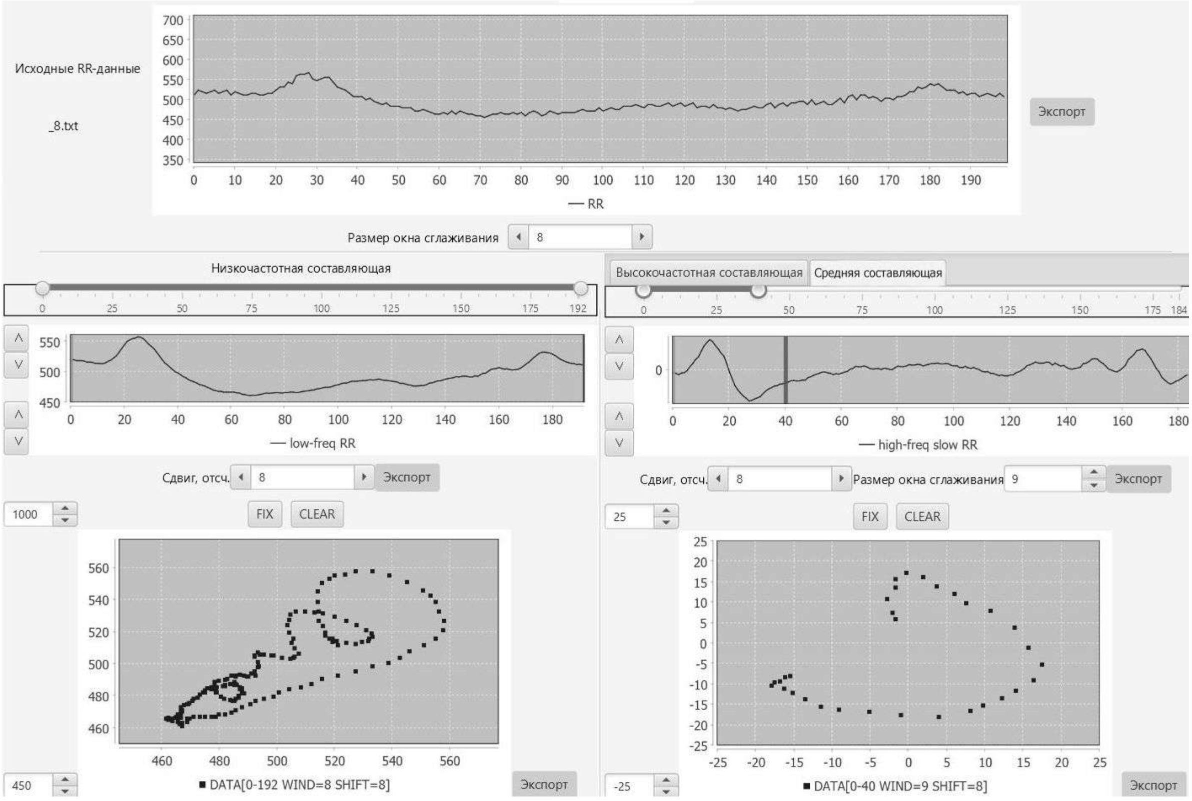
$$RR_{\mathrm{S}_n} = \frac{1}{m}\sum_{n}^{n+m} RR_i,$$

p m — the number of counts of the averaging window. Averaging in the moving average window for m cardiocycles plays the role of a low-frequency filter. The window width is empirically set to be less than half the number of counts, the sum of the durations of which is equal to the time of slow regulation [8]. Due to this, the resulting smoothed sequence $\{RR_{\mathrm{S}}\}$ captures slow heart rate trends.

We assume, as already mentioned above, that significantly different HR change times correspond to different levels of the management hierarchy. That fast (high-frequency) processes of heart rhythm changes are realized against the background of slow (low-frequency) processes of the influence of physiological control on the heart rate. If we further assume that fast and slow mechanisms are independent, then the decomposition of the rhythmogram is additive. The decomposition of BOOKS into slow $\{RR_{\mathrm{S}}\}$ and fast $\{RR_{\mathrm{f}}\}$ components is performed by subtracting $\{RR_{\mathrm{f}}\} = \{RR_i\} - \{RR_{\mathrm{S}}\}$. We subtract the average from the original CIG. The quality of averaging is checked by the proximity to zero of the average value of this difference. This is how the quasi-permanent component is removed. A distinctive feature of this approach is that the values of the smoothed CIG $\{RR_{\mathrm{S}}\}$, as well as the values of $\{RR_i\}$, do not lose their binding to specific points in time, which turned out to be important for the application of the method.

The span of the resulting series $\{RR\}, \{RR_{\mathrm{f}}\}$ [ms] characterizes the intensity of slow and fast regulation. Similarly, averaging in a sliding window is applied to the resulting series $\{RR_{\mathrm{f}}\}$, simulating an average frequency filter. It turns out a number $\{RR_{\mathrm{m}}\}$.

The method was conceived and implemented as interactive. The simplest program was developed «Recon» [8], a user interface that visualizes RR sequences with linear graphs and


Исходные RR-данные

_8.txt

Размер окна сглаживания 8

Сдвиг, отсч. 8

Сдвиг, отсч. 8

Размер окна сглаживания 9

1000

450

25

-25

Fig. 1. Снимок экрана программы «RRecon». Представлены инструменты для декомпозиции исходного ряда RR-интервалов на три выборки: $\{RR_{\mathrm{S}}\}$, $\{RR_{\mathrm{m}}\}$, $\{RR_{\mathrm{f}}\}$ (соответственно вкладки, названные как низкочастотная, средняя и высокочастотная составляющие). На рисунке открыты вкладки медленной и средней компонент ($\{RR_{\mathrm{S}}\}$, $\{RR_{\mathrm{m}}\}$). Для них построены псевдофазовые портреты в осях [мс] (см. объяснения в тексте) [8]

Fig. 1. Screenshot of «RRecon» program. Tools for decomposition of the initial series of RR intervals into three samples are presented: $\{RR_{\mathrm{S}}\}$, $\{RR_{\mathrm{m}}\}$, $\{RR_{\mathrm{f}}\}$ (respectively, the tabs: slow, middle and fast components). The slow and middle frequency tabs are open in the figure ($\{RR_{\mathrm{S}}\}$, $\{RR_{\mathrm{m}}\}$). Pseudo-phase portraits in the ms axes are constructed for them (see explanations in the text) [8]

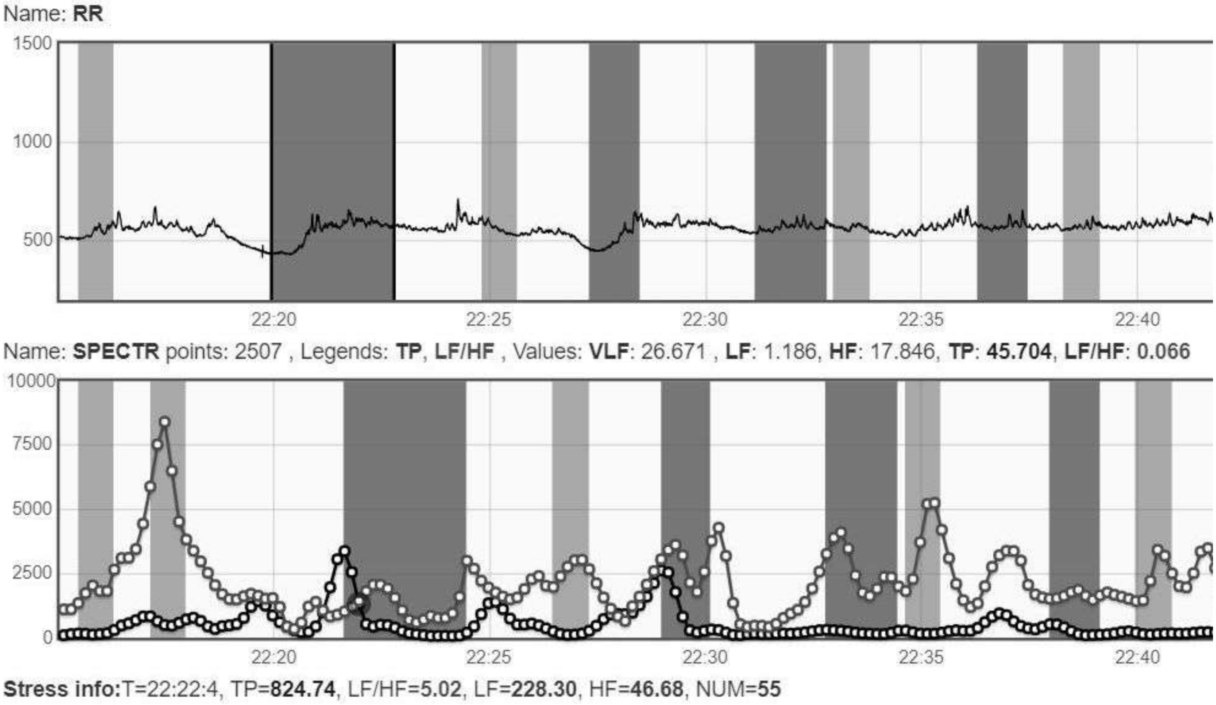
pseudo-phase portraits (Fig. 1).

Each portrait is constructed from pairs of values (RR_n, RR_{n+L}) of the corresponding sequence of RR intervals spaced apart by L counts (with a lag of L). Such portraits make it possible to clearly distinguish the types of aperiodic HRV modes, as well as to determine the period of interval periodic dynamics [11]. The program implements the possibility of changing the shift L (lag). With a shift equal to one, the picture takes the form of a classical tablecloth (correlation rhythmogram). The similarity of the behavior of pseudo-phase portraits with Lissajous figures suggested a method for determining the times of periodic and non-periodic changes CP. The program interface allows you to independently change the width of the smoothing windows of the original CIG and its high-frequency component, change the lags of pseudo-phase portraits, limit the size of the visualized sample, compare the variational range of the series. All this provides the convenience of visual analysis of the trajectories of portraits (see Fig. 1). In fact, we used the well-known method of tablecloths, but we made a shift between the axes such as to ensure that there is no correlation between the counts. As a result, we got a very visual image of clouds corresponding to three frequency ranges.

«To assess individual risks based on HRV analysis in space medicine , it was proposed ...methodological approach of probabilistic assessment of functional reserves (FR) and the degree of stress of regulatory systems (CH)» [12, 13]. «According to the results of the study of vegetative regulation of blood circulation in space flights, the concept of adaptive risk was proposed, which characterizes the adaptive capabilities of the body in terms of the relationship between the functional reserves of the body and the current voltage of regulatory systems (Chernikova A. et al., 2012) according to HRV analysis». «It was confirmed according to studies of vegetative regulation at rest and under functional loads in space flight conditions that the indicators of FR and CH, as well as the magnitude of adaptive risk, are not only related to the current functional state ..., but also are a predictor of a decrease in adaptive capabilities... Adaptive risk ...presents... the probability of developing prenosological and premorbid conditions preceding the disease» [2]. As a result, Baevsky and Chernikova developed a mathematical model for recognizing classes of physiological states [2]. Developers of the Internet resource «StressMonitor» on the *platform www.cogni-nn.ru* we took this model as a basis for determining the quartile of the physiological state and assessing the level of adaptive risk (LAR) in individuals whose HRV records are in the database on the server.

Data in the form of a series of RR intervals are transmitted to the database by means of the information-tele-communiction technology of event-related heart telemetry (ITT ERHT). This technology was developed at the Department of Psychophysiology of the Nizhny Novgorod State University named after N.,I.Lobachevsky [6]. This technology allows in a transparent mode (without attracting the attention of the subject and any restriction of his mobility) continuously, up to 150 hours, to record an electrocardiosignal in conditions of natural human activity. For each rhythmogram, a sliding spectral analysis is performed using the discrete Fourier transform method for non-uniform signals. Further, in accordance with the accepted standards [3, 4], the spectral power in the frequency ranges VLF (0.003...0.040 Hz), LF (0.04...0.15 Hz), HF (0.15...0.4 Hz), total spectrum power $\mathrm{TP} = \mathrm{VLF} + \mathrm{LF} + \mathrm{HF}$ and sympatho-vagal balance index LF/HF. FR, CH, UAR, the probability of the quartile of the functional state are calculated. A screenshot of the Internet resource StressMonitor is shown in Fig. 2. The upper graph is a cardiorhythmogram [ms] with acute stress intervals highlighted by vertical stripes (see below). Lower graphs — calculated spectral parameters of heart rate variability (black color — total spectrum power TP [ms^2], gray color — sympatho-vagal balance LF/HF). Between the graphs — total values of indicators for the visualization interval, at the bottom — values of indicators at the specified time [6]. In a separate report, FR, CH, LAR, and a probabilistic assessment of the functional state are displayed.

At the time of writing, there were about 15 thousand records in the database. We selected records with a high probability related to one of the four physiological states: a— the state



Name: **RR**

Name: **SPECTR** points: 2507 , **Legends: TP**, **LF/HF** , Values: **VLF**: 26.671 , **LF**: 1.186, **HF**: 17.846, **TP**: **45.704**, **LF/HF**: **0.066**

Stress info:T=22:22:4, TP=**824.74**, LF/HF=**5.02**, LF=**228.30**, HF=**46.68**, NUM=**55**

Fig. 2. Снимок экрана Интернет-ресурса StressMonitor. Верхний график — кардиоритмограмма [мс] с интервалами острого стресса, выделенными вертикальными полосами. Нижние графики — расчетные спектральные показатели вариабельности ритма сердца (черный цвет — общая мощность спектра TP [мс^2], серый цвет — симпато-вагусный баланс LF/HF). Между графиками — суммарные значения показателей за интервал визуализации, внизу — значения показателей на момент времени 22:22:04 [6]

Fig. 2. Screenshot of the StressMonitor web resource. Upper graph — heart rate [ms] with acute stress intervals highlighted by vertical bars. Lower graphs — calculated spectral indicators of heart rate variability (black color — total spectrum power TP [ms^2], gray color — LF/HF sympathovagal balance). Between the graphs — the total values of the indicators for the visualization interval, at the bottom — the values of the indicators at the time 22:22:04 [6]

of the physiological norm (FR $>$ 0, CH $<$ 0); b — a prenosological state with a decrease in adaptive capabilities (FR $>$ 0, CH $>$ 0); c— a premorbid state of overstrain (FR $<$ 0, CH $>$ 0); d — pathological state of exhaustion (FR $<$ 0, CH $<$ 0). We built their portraits in the same scale and visualization settings. For greater clarity, the settings for different frequency components differ. For example, in Fig. 3 screenshots of pseudo-phase portraits are presented $\{RR_{\mathrm{S}}\}$, $\{RR_{\mathrm{m}}\}$, $\{RR_{\mathrm{f}}\}$ for 20 rhythmograms, 5 rhythmograms in each quartile states. One can see the change in the area of clouds (the scope of regulation) with a change in the physiological state. There is an advance in the attenuation of the slow and medium components relative to the fast. The positive value of functional reserves (FR) (a, b) is characterized by a larger area of the cloud of fast and medium components, which decreases slightly when the sign of the degree of stress (CH) changes from «+» to «–» (from a to b). When changing the sign of functional reserves from «+» to «–» (from b to c), rigidity is observed in all frequency

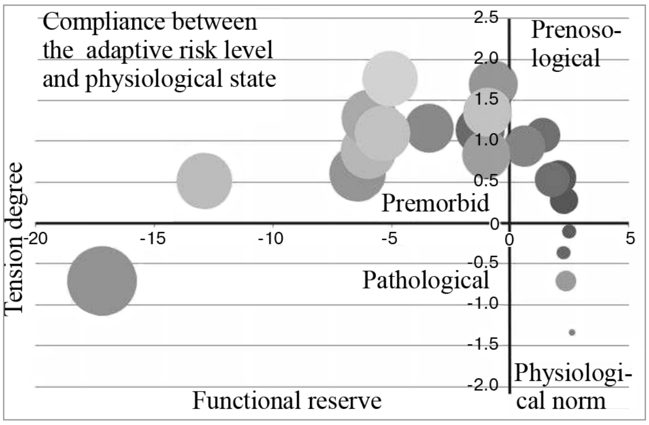


Fig. 4. Траектория состояний спортсмена в пространстве функциональных состояний по Баевскому [2] на основе анализа ВСР. УАР пропорционален диаметру пузырьков

Fig. 4. The trajectory of the athlete's states in the space of functional states according to Baevsky [2] based on HRV analysis. The level of adaptive risk is proportional to the bubbles diameter

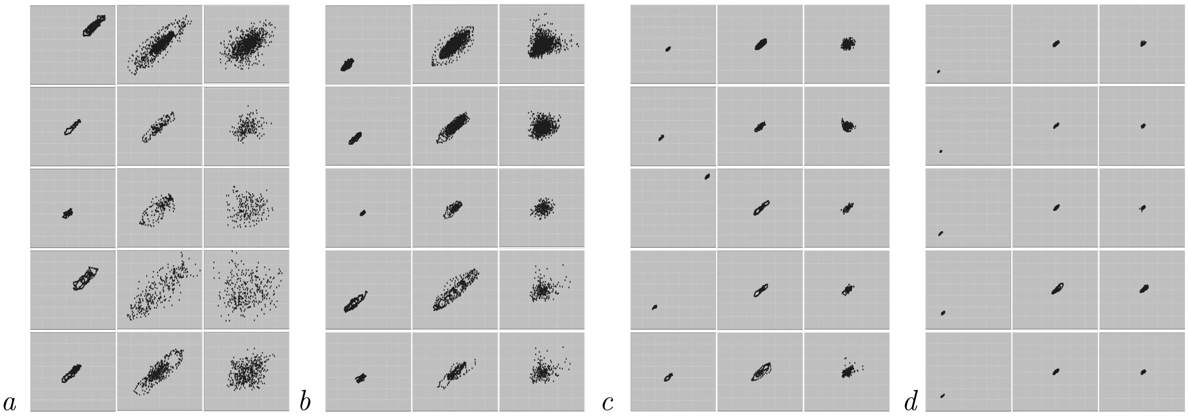


Fig. 3. Псевдофазовые портреты удобны для сопоставления данных, получаемых для разных испытуемых (пациентов). Здесь представлены снимки экрана для каждой из трех компонент (левая колонка — медленная, центральная — средняя, правая — быстрая) для 20 случайных испытуемых, имеющих различное физиологическое состояние. Видно изменение площади облаков (размаха регулирования) с изменением физиологического состояния: *a* — физиологическая норма, *b* — донозологические состояния, *c* — преморбидные состояния, *d* — патологические состояния. Наблюдается опережение затухания медленной и средней компонент относительно быстрой. Настройки визуализации фазовых портретов: скользящее окно усреднения = 30; для медленной компоненты лаг = 8, границы осей 400...1100 мс; для средней компоненты лаг = 4, границы осей ±150 мс; для быстрой компоненты лаг = 8, границы осей ±300 мс

Fig. 3. Pseudo-phase portraits are convenient for comparing data obtained for different subjects (patients). Here are screen shots for each of the three components (left column — slow, center — medium, right — fast) for 20 random subjects with different physiological states. We can see the change in the area of clouds (range of regulation) with a change in the physiological state: *a* — physiological norm, *b* — prenosological conditions, *c* — premorbid conditions, *d* — pathological conditions. There is an pre-attenuation of Slow and Middle relative to Fast. Phase portrait visualization settings: averaging sliding window = 30; for the slow component lag = 8, the boundaries of the axes 400...1100 ms; for the middle component lag = 4, axis boundaries ±150 ms; for the fast component lag = 8, axis boundaries ±300 ms

ranges.

The main purpose of creating an Internet resource «StressMonitor» was, as the name implies, to detect moments of stress [6]. The moments of the onset of acute stress are determined on the basis of the three-component theory of neurochemical mechanisms of stress S. B. Parina [14] by a drop in the total power of the heart rate variability spectrum (TR) against the background of a sharp increase in the sympatho-vagal balance index (LF/HF) [6, 15, 16]. Discreteness of determining the onset of stress — 10 c.

We selected for analysis a 7-hour rhythmogram of a super marathon athlete, characterized by a full spectrum of functional states (FS) and levels of adaptive risk (LAR), which changed during the course of the distance (Fig. 4). The bubble diagram is based on the analysis of this rhythmogram. The diameter of the bubbles corresponds to LAR. The trajectory of the athlete's states is depicted in the space of functional states according to R.,M. Baevsky [2]. The state of stress occurred with all FS. We selected the segments of the CIG corresponding to stress episodes detected by the «StressMonitor» service and sorted them by the level of adaptive risk. These segments were used as input data for the RRecon program (see Fig. 1). The obtained pseudo-phase portraits allowed us to compare the scope and behavior of rhythmograms immediately before and during stress in different physiological states that arose during extreme activity (Fig. 5): in a state of physiological norm (LAR = 1...2), prenosological condition with a decrease in adaptive opportunities (LAR = 3...5), premorbid state of overvoltage of regulatory systems (LAR = 6...8), pathological state of depletion of regulatory systems (LAR = 9...10). In Fig. 5 for 4 values of LAR, the odd columns of the table show portraits during the developed stress, in the even ones — background state. The LAR increases from top to bottom. There is an obvious greater scope of regulation under stress for all components: slow (slow), fast (fast) and medium (middle), despite the drop in the total power of the variability spectrum (TP) under stress. The scope also decreases with the deterioration of the physiological state.

2. Results

The change in the magnitude of the lag L and the boundaries of the observation segment made it possible to graphically isolate non-stationary oscillations. When the lag changes through the program interface, a change in the shape of the pseudo-phase portrait is observed, similar to the modification of Lissajous figures when the phase difference of the signals changes. From a diagonally elongated pseudo-phase portrait (at $L = 1$), which corresponds to a standard tablecloth, the curve unfolds, fills, and takes a rounded shape. With a further increase in the shift, when its the value approaches a quarter of the characteristic regulation time, the curve becomes horizontal (рис. 6).

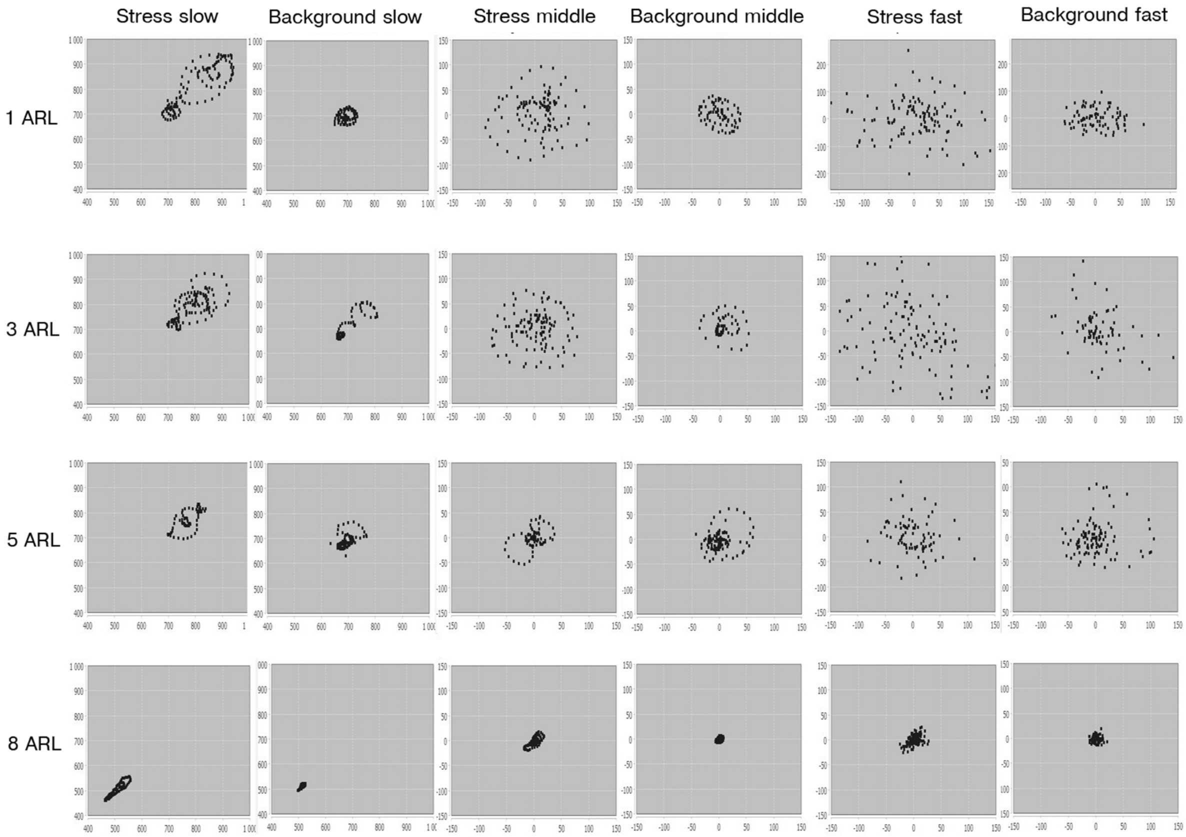


Fig. 5. Ригидизация сердечного ритма (уменьшение размеров облака) при увеличении уровня адаптационного риска (УАР увеличивается сверху вниз) и изменение частотной наполненности при развитии стресса

Fig. 5. Heart rate rigidity (cloud reduction) with an increase of adaptive risk level (ARL) from top to bottom and a change in frequency fullness with the development of stress

Thus, based on this feature and knowing the magnitude of the lag, we are able to determine the characteristic period and frequency of regulation by a simple formula

$$f = 1/(4L \cdot \overline{RR}),$$

where $\overline{RR}$ — is the arithmetic mean of the RR intervals of the considered segment of the CIG. As an example, the Table shows some frequencies of adaptive reactions recognized on the corresponding segments of the initial CIG (UAR = 8) by pseudophase the portrait for the slow component (slow) in Fig. 1 and fig. 6. In particular, in the section RR_{14-102} for the rhythmogram shown in Fig. 1, a damped oscillation is observed $f = 0.02$ Гц.

Таблица

Отрезок RR	Частота, Гц
5–33	0.067
14–102	0.020
31–71	0.017
101–135	0.065

When the size of the sliding averaging window increases, relatively higher frequency elements disappear from the portrait.

A formal comparison of the dynamics inherent in the beginning of stress [6] and pseudo-phase portraits of smoothed CIG on more than 30 episodes for a group of subjects in various functional states, by solving the direct and inverse problems, revealed the characteristic behavior of the tablecloth trajectory (the central part of Fig. 7). There is a sharp change in correlation at the beginning of stress. The sufficiency of this graphic feature for reliable identification of stress requires further study.

Due to the fact that the values of the smoothed CIG do not lose their binding to specific points in time, knowing the number of the stress start point on the pseudo-phase portrait, we can determine the time of its onset with an accuracy of 1-2 heartbeats. This is the maximum possible accuracy, in contrast to the above-described method of information-telecommuniction technology of event-related heart telemetry, which uses integral indicators and determines the occurrence of such events with a discreteness of 10 s.

The proposed approach makes it possible to compare the shape and scope of portraits obtained for different patients. Fig. 3, 5 demonstrate an increase in the rigidity (decrease in the span) of the heart rate with an increase in the level of adaptive risk and a change in frequency fullness with the development of stress.

Conclusion

As a result, a simple method allowed:

- highlight local patterns in the behavior of time series of RR intervals;
- to decompose the cardiointervalogram into slow and fast components;
- determine the frequency of transients;
- localize the moment of the onset of acute stress as accurately as possible;
- compare parameters of different cardiorhythmograms.

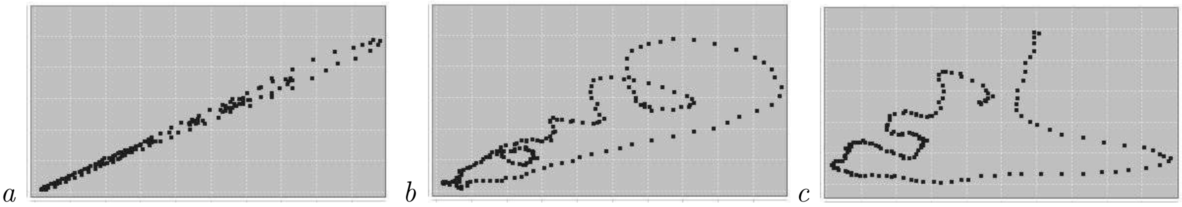


Fig. 6. Изменение формы псевдофазового портрета с изменением величины лага: 1 (a), 8 (b), 25 (c)

Fig. 6. Changing the shape of the table-curve with changing the lag value: 1 (a), 8 (b), 25 (c)

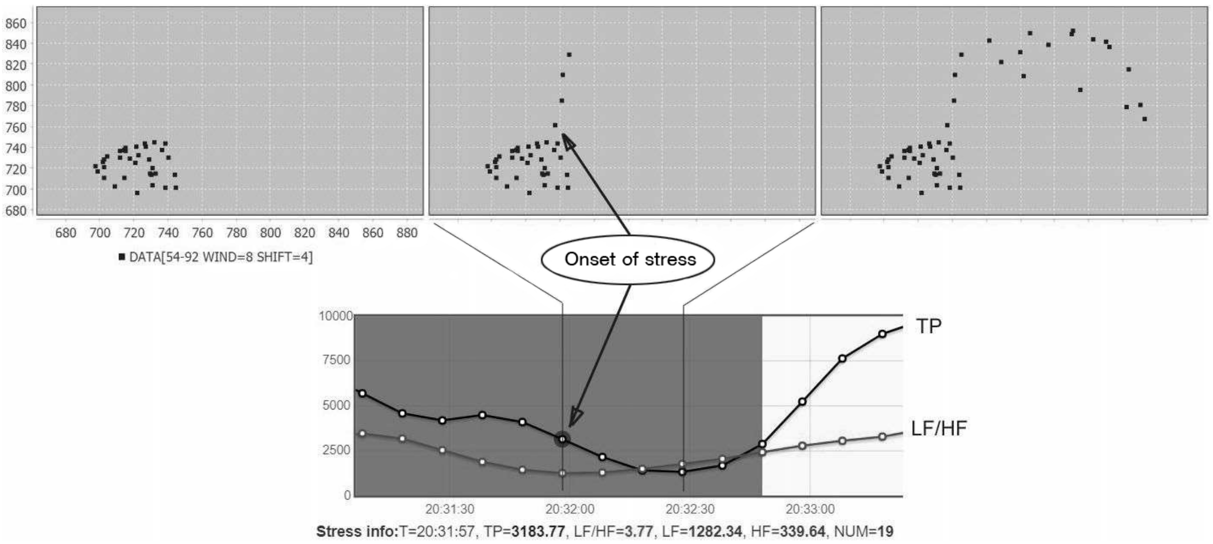


Fig. 7. Паттерн скатерограммы, соответствующий началу стресса

Fig. 7. Scattergram pattern corresponding to the onset of stress

Thus, we have shown new possibilities of using the well-known method. This approach is certainly useful and informative when using it to analyze heart rate variability. We believe that the method of presenting cardiointervalograms in the form of pseudophase portraits may have clinical application. Our proposed method, in the case of updating the program taking into account the competencies of the end user, can be used to quantify the vegetative tone in real time during screening surveys of the population.

References

1. Bayevsky RM, Ivanov GG. Cardiac rhythm variability: The theoretical aspects and the opportunities of clinical application (lecture). Ultrasonic and Functional Diagnostics. 2001;(3):108–127 (in Russian).
2. Baevsky RM, Funtova II, Berseneva AP, Chernikova AG, Luchitskaya ES, Prilutsky DA, Semenov YN, Tank J, Slepchenkova IN, Rusanov VB, Bersenev EY, Ivanov GG. Methods and Instruments of Space Cardiology Aboard the International Space Station: Monograph. Moscow: Tekhnosphera; 2016. 368 p. (in Russian).
3. Baevsky RM, Ivanov GG, Chireikin LV, Gavrilushkin AP, Dovgalevsky PY, Kukushkin YA, Mironova TF, Prilutsky DA, Semenov AV, Fedorov VF, Fleishman AN, Medvedev MM. Analysis of heart rate variability using various electrocardiographic systems (Methodical recommendations, part 1). Journal of Arrhythmology. 2002;(24):65–87 (in Russian).
4. Malik M, Bigger JT, Camm AJ, Kleiger RE, Malliani A, Moss AJ, Schwartz PJ. Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. European Heart Journal. 1996;17(3):354–381. DOI: 10.1093/oxfordjournals.eurheartj.a014868.
5. Goldstein DS, Kopin IJ. Homeostatic systems, biocybernetics, and autonomic neuroscience. Autonomic Neuroscience. 2017;208:15–28. DOI: 10.1016/j.autneu.2017.09.001.
6. Polevaya SA, Eremin EV, Bulanov NA, Bakhchina AV, Kovalchuk AV, Parin SB. Event-related telemetry of heart rate for personalized remote monitoring of cognitive functions and stress under conditions of everyday activity. Modern Technologies in Medicine. 2019;11(1):109–115. DOI: 10.17691/stm2019.11.1.13.
7. Ellis RJ, Thayer JF. Music and autonomic nervous system (dys)function. Music Perception.

2010;27(4):317–326. DOI: 10.1525/mp.2010.27.4.317.

8. Antonets VA, Permiakov SP, Nikulina MV. Applying cardiointervalogram smoothing to analyze heart rate variability. In: Materials of the VII All-Russian Scientific and Practical Conference with International Participation «Heart Rate Variability: Theoretical Aspects and Practical Application in Sports and Mass Physical Culture». 25-26 May 2021, UdSU, Izhevsk. Izhevsk: UdSU; 2021. P. 67–74 (in Russian).
9. Ryabykina GV, Sobolev AV. Analysis of heart rate variability. Cardiology. 1996;36(10):87–97 (in Russian).
10. Baevsky RM, Kirillov OI, Kletskin SZ. Mathematical Analysis of Changes in Heart Rate During Stress. Moscow: Nauka; 1984. 224 p. (in Russian).
11. Shljufman KV, Fishman BE, Frisman EJ. Features of modes for one-dimensional model of ricker. Izvestiya VUZ. Applied Nonlinear Dynamics. 2012;20(2):12–28 (in Russian). DOI: 10.18500/0869-6632-2012-20-2-12-28.
12. Baevsky RM, Chernikova AG. The problem of the physiological norm: a mathematical functional state model based on analysis of the cardiac rhythm variability. Aerospace and Environmental Medicine. 2002;36(6):11–17 (in Russian).
13. Baevsky RM, Chernikova AG. A Method for Assessing the Risk of Development of Donosological, Premorbid and Pathological Conditions in a Long-Term Space Flight. Patent No. 2448644 dated 15.09.2010. Assignee: Institute of Biomedical Problems RAS (in Russian).
14. Parin SB. Humans and animals in extreme situations: Neurochemistry mechanisms, evolutionary aspect. Novosibirsk State University Bulletin. Series: Psychology. 2008;2(2):118–135 (in Russian).
15. Nekrasova MM, Polevaya SA, Parin SB, Shishalov IS, Bakhchina AV. Method for Determining Stress. Patent No. 2531443 dated 11.11.2013. Assignee: Lobachevsky State University of Nizhny Novgorod (in Russian).
16. Grigorieva KA, Grigorieva VN, Polevaya SA. Method for Diagnosing Stress in Humans. Patent No. 2624813 dated 11.08.2016. Assignee: Privolzhsky Research Medical University (in Russian).