HRV Analysis under the usage of different electrocardiography systems (Methodical recommendations)

These methodical recommendations are prepared according to the order of the Committee of Clinic Diagnostic Apparatus and the Committee of New Medical Techniques of Ministry of Health of Russia (protocol №4 from the 11-th of April, 2002) by the following authors: R.M.Bayevsky (Chair), G.G.Ivanov (Chair Deputy), L.V.Chireykin (Chair Deputy), A.P.Gavrilushkin, P.Ya.Dovgalevsky, U.A.Kukushkin, T.F.Mironova, D.A.Priluzkiy, U.N.Semenov, V.F.Fedorov, A.N.Fleishmann, M.M.Medvedev (Secretary General)

Annotation

Current methodical recommendations on HRV analysis conclude perennial experience of the domestic research in this area. Presented materials are also considering some foreign experience. These recommendations are relevant only for the so-called "short" records of heart rhythm (from few minutes to few hours) and should not be used for the 24-hour records.

Here are presented generic working definitions and theoretical foundations HRV Analysis' method. Also shown areas of method's application and reasons for its usage. Standard methods of information gathering and recommendations on the following analysis are also proposed. Description of the basic methods HRV analysis are also given and shown the ways of their standardization and further development.

Some basic methods of HRV Analysis' results evaluation are also presented, including clinical-physiological interpretation and functional states evaluation. Aspects discussed of reproduction and comparability of received results. Also discussed the prospects of following development of the methods of HRV Analysis.

Introduction

HRV Analysis has started to develop in USSR at the beginning of the 60s. One of the most stimulating reasons for its development was the success of space medicine research (ParinV.V., Baevsky R.M.,Gazenko O.G., 1965). In 1966 in Moscow the first symposium on HRV took place (on the mathematical analysis of heart rhythm) (ParinV.V., Baevsky R.M.,1968). Maximum activity of the research in HRV area in the USSR was noticed at the beginning of 70s- 80s (Zhemajtite D.I., 1965, 1970; Nidekker I.G., 1968; Vlasov Yu.A. and oth.,1971; Kudryavceva V.I., 1974; Voskresenskij A.D., Ventcel M.D., 1974; Nikulina G.A., 1974, Baevsky

R.M., 1972, 1976, 1979; Vorobev V.I., 1978; Kletskin S.Z., 1978; Bezrukih M.M., 1981; Gabinsky Ya.L., 1982).

The results of all those researches were gathered in 1984 monograph (Baevsky R.M., Kirillov O.I., Kletskin S.Z., 1984). The fast increase of the number of HRV researches was noticed during the last fifteen years in Western Europe and USA. For the last 5-6 years annually there were published up to few hundred works. In Russia after noticeable decrease of research activity in HRV Analysis at the end of 80s - beginning of 90s, the last few years also admitted growing attention to this method.

However in present time most of the Russian researchers use standards of measurements, physiological interpretations of HRV, and recommendations on the usage of this method, developed in 1996 by European Cardiology Society and North-American Electrophysiology Society, which are completely ignore enormous experience of domestic science.

Analysis of the considerable amount of publications in Russian magazines, materials of many conferences and symposiums show that studies of Russian scientists in HRV Analysis area are not only keeping pace with the western researchers, but in many points are being on the leading edge. Only for last few years in Russia have been published 4 monographs on HRV (Ryabikina G.V., Sobolev A.V., 1998, 2001; Mironova T.F., Mironov V.A., 1998, Flejshman A.F., 1999; Mihajlov V.M., 2000). Periodics regularly publish reviews on different aspects of HRV analysis (Ryabikina G.V., Sobolev A.V., 1996, YavelovI.S., Graciansky N.A., Zujkov Yu.A., 1997; Baevsky R.M., Ivanov G.G., 2001). Results of the studies of Russian scientists on HRV are regularly presented at the Russia-wide and International Cardiology congresses and symposiums (1996, 1997, 1999, 2002).

Current recommendations are developed on the basis of accumulation of experience of domestic researches in this area with consideration of the data received abroad. These recommendations are not to be a literature review and completed with a very limited number of references, used in the text. Recommendations do not include materials on the clinical usage of the method. Their major goal is to standardize methods of research and the ways to analyze data that is results of different studies could be comparable to each other.

Considerable amount of tools for HRV analysis have been developed and published by different firms and companies in Russia. Unfortunately, each of producers has tendency to use its own standards, based either on standards given in European-American recommendations, or developed by certain medical customers. This situation makes impossible to compare results of researches done with the usage of different tools. Considering that there is a high probability of active and wide implementation of HRV analysis in Russia in the nearest future, we should think of the certain measures to standardize the method.

According to the decision of Commission of the diagnostic tools and equipment of the Committee on the new medicine technique of Russian Ministry of Health (protocol No 4 of 11.04.2000) there was created a group of experts to develop methodical recommendations on the methods of HRV Analysis. The following recommendations are the one of results produced by this group and are relevant only to analysis of so-called "short" records of the heart rhythm using serial electro-cardilographical systems produced in Russia. Major items of this medical instruction realized in the following serial electrocardilographical systems produced in Russia:

1. Hardware-software complex "Varicard" (Institute of implementation of the new medical technologies, Ryazan);
2. Computer systems "Vita-Rhythm", "VNS-Rhythm", "VNS-Vita", and "VNS-Spectrum" (firm "Neurosoft", Ivanovo)
3. Computer electrocardiograph "Kardi" (firm "Medical Computer Systems", Zelenograd)
4. Hardware-software complex APK-RKG ("Mikor" company, Chelyabinsk)
5. Electrocardiographical complex "MKA01" and reograph tool "RP-KA2-01" with cardiograph channel ("Medass", Moscow)
6. Complex of daily monitoring ECG "Cardiotechnika"("INCART", St Petersburg).

All above-mentioned hardware-software complexes suppose to work along with computer and provide generation of dynamical series of cardiointervals with the signal sampling rate up to 1000 Hz and higher. The accuracy of duration measurements is +-1 ms.

1. Basic working definitions.

HRV Analysis is a method of evaluation of the state of the mechanisms of the regulation of physiological functions in human organism and animals, partially of the common activity of regulatory mechanisms of the neurohumor regulation of heart correlations between sympathetic and parasympathetic departments of vegetative nerve system.

Current activity between sympathetic and parasympathetic departments is a result of the reaction of multi-contour and multi-circle blood system regulation, changing its parameters for achievement of optimal adaptive response, which reflects adaptive reaction of whole organism.

Adaptive reactions are individual and can be realized for different persons with different level of participation of functional systems, which possess in their turn the backward connectivity, changing in time and having changeable functional organization. The method is based on the recognition and measurement time intervals between R-picks ECG (R-R intervals), building dynamic series of cardiointervals and following analysis omitted numerous lines with the different mathematical methods. Dynamic series of cardiointervals are called as cardiointervalogramm (CIG).

A dynamical series can be considered as stationary and nonstationary. Random processes are called stationary if they proceed approximately homogeneously and look like continuous oscillations about a mean position. Stationary processes are characterized by ergodicity, i.e., averaging over time corresponds to averaging over an ensemble. In other words, we should obtain identical parameters at any time interval. Virtually each time interval contains some elements of nonstationarity (fractal components). In these methodical recommendations cardiointervalogramm is considered as a steady-state random process with the relevant interpretation of the data resulted from its analysis. In the recent years, the methods of nonlinear dynamics have been extensively applied to evaluate the fractal components of time intervals (Goldberger A., 1991; Fleishmann A. N., 1999, 2001; Gavrilushkin A.P., Masluk A.P., 2001).

During the analysis of the dynamic series of cardiointervals we should distinguish between short-time ("short") and long –time ("long") records. Under the last, as a rule, meant data received from 24-hour and 48-hour monitoring ECG (Holters monitoring). Under so-called "short" records meant data received during the researches lasting minutes, tens of minutes, or hours.

Dynamic series of cardiointervals can be obtained from analysis of any of cardiographical records (electrical, mechanical, ultrasound, etc), however in the current document we are focused only at the data resulting analysis of electrocardiosignals.

VHR Analysis includes three stages:

1. Measurement of the length of R-R intervals and presentation of the dynamic series of cardiointervals in a form of cardiointervalogramm.
2. Analysis of the dynamic series of cardiointervals.
3. Evaluation of the results of VHR analysis.

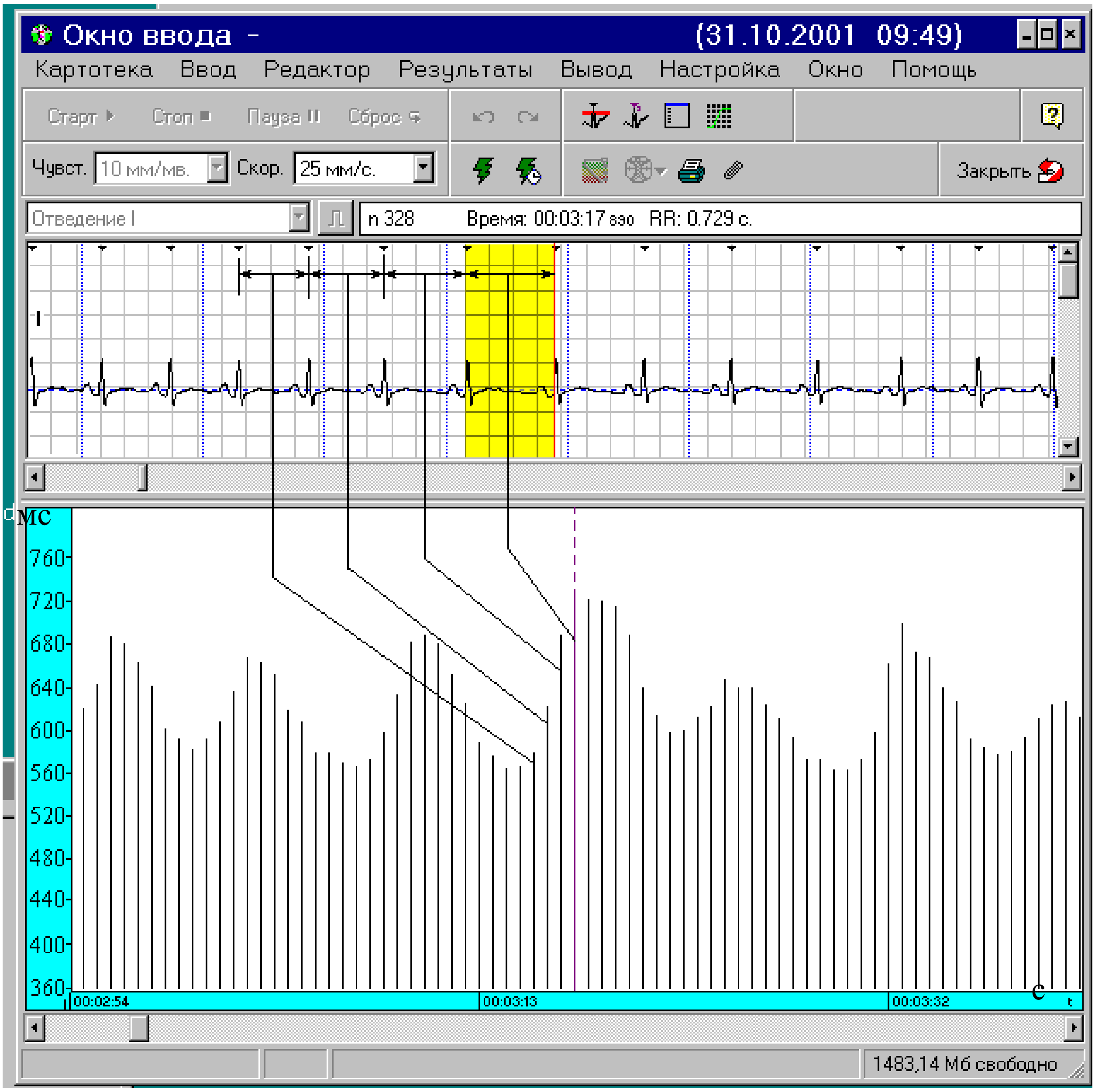
Measurement of the length of R-R intervals is executed by hardware or software methods with the accuracy up to 1ms. The problem of recognition R-picks of ECG in different hardware-software complexes is solved differently. The presentation of dynamic series of cardiointervals can be realized in the numeric or graphical view.

The methods of analysis of dynamic series of cardiointervals can be divided into visual and mathematical. Visual analysis of cardiointervalogramms (rhythmogramm) has been developed by D.Zhemajtite (1965, 1972). The classification of rhythmogramms proposed by her has being actual up-to-date (T.V.Mironova, V.A.Mironov, 1999). The mathematical methods of the analysis can be divided into three large classes:

- general variability research (statistical methods or analysis in time domain).
- research of HRV periodic components (frequency analysis).

• research of internal organisation of a dynamic sequence of cardiointervals (autocorrelated analysis, correlation rhythmography, methods of non-linear dynamics).

Numerous values (parameters of HRV) obtained as a result of HRV analysis are estimated in different ways by various explorers depending on the scientific-theoretical concept used.



Pic.1. Formation of cardiointervalogram (CIG) while inputing electrocardiography signal. Upper curve represents electrocardiogram (ECG), bottom curve shows CIG (ordinate axis represents duration of cardio intervals in milliseconds; abscissa axis represents check-in time of cardio intervals (hours, min, sec.). Points mark elements of CIG corresponding to intervals between RR-fingers of the ECG.

2. SCIENTIFIC AND-THEORETICAL BASIS OF A METHOD

The main information about systems regulating a heart rhythm is included in «dispersion functions» of cardio intervals durations. It is necessary to take into account current level of blood circulation function system. Analysing HRV the question is a so-called sinus arrhythmia, which represents complex processes of interaction of different circuits of cardiac rhythm regulation. If a rhythm disturbance of different origin appears the application of special methods on recovery of stationarity of studied process is required or it is necessary to use the special analytical approaches.

A dynamic sequence of cardio intervals can be analysed and estimated on the basis of different scientific and theoretical conceptions. Depending on scientific or practical tasks it should be recommended to use one of the following three approaches:

1. To consider the changes of a cardiac rhythm in connection with adaptive reaction of an organism as a whole, i.e. like a development of different stages of a general adaptation syndrome (G.Selie, 1961).

2. To consider the oscillations of cardio intervals durations as an outcome of influence of multi-circuit, hierarchically organized multi-level managing system of physiological functions of organism. This approach is based on principals of biological cybernetics (V.V. Parin, R.M. Bayevski, 1966) and on theory of functional systems (P.K. Anokhin, 1975). In that case it is possible to consider changes of

heart rate variability parameters to be specified by formation of different functional systems which coincide to outcome required at the moment.

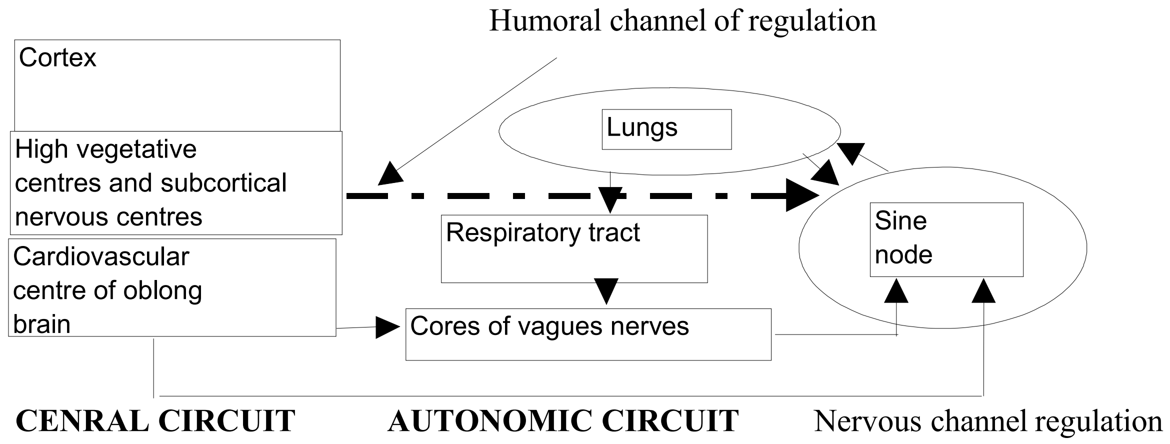
3. To consider the changes of cardiac rhythm in connection with activity of neurohormonal regulation mechanisms as a result of activity of different links of vegetative nervous system.

Nowadays the theory of adaptation is one of the fundamental directions of modern biology and physiology. The adaptive activity of human and animal organism provides not only survival and evolutional development but daily adaptation to changes of environment as well.

G.Selie's theory on common adaptation syndrome describes phase nature of adaptive reactions and founds a leading role of consumption regulatory systems under acute and chronic stress in development of majority of pathological conditions and diseases. Blood circulation can be considered as the sensing indicator of adaptive reactions of organism as a whole (V.V.Parin and co-authors, 1967). Variability of cardiac rhythm represents well degree of regulatory systems strain corresponded by both activation of pituitary gland – adrenal system and reaction of sympathoadrenal system arising in reply to any stress effects.

Detailed study of HRV by using methods of autocorrelated and spectral analysis has resulted in developing the approach based on postulates of biological cybernetics and theory of functional systems. The concept of heart rhythm variability as a result of influence of numerous regulatory mechanisms (nervous, hormonal, humoral) on blood circulation is in the basis of this approach.

Functional system of regulation of blood circulation represents multiple-circuit, hierarchically organized system in which the predominant role of separate links is determined by current needs of organism. The most simple double-circuit model of regulation of cardiac rhythm is based on the cybernetic approach which suppose that system of sine node regulation can be represented by two interdependent levels (circuits) namely central and autonomous with direct coupling and feedback loop (see pic.2). In that case the effect of autonomous level (circuit) is identified with respiratory arrhythmia and the effect of central circuit is connected with nonrespiratory arrhythmia.



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

The working structures of autonomous circuit of regulation are: sine node (SN), vague nerves and their cores in medulla (circuit of parasympathetic regulation). Thereby breathing system is considered as a member of a feedback loop in autonomous circuit of cardiac rhythm (CR) regulation.

The activity of central regulation circuit, which is identified with sympathoadrenal influences on a heart rhythm, is connected to non-respiratory sinus arrhythmia (SA) and is characterized by different slow-wave components of cardiac rhythm. The direct coupling between central and autonomous circuits is fulfilled due to nervous (basically sympathetic) and humoral communications. The feedback is provided by afferent impulsation from baroreceptors of heart and vessels, from chemoreceptors and vast receptor zones of different organs and tissues.

Autonomous regulation in the state of rest is characterized by availability of expressed respiratory arrhythmia. Respiratory waves strengthen during the dream when the central influences on autonomous circuit of regulation decrease. Different loadings on organism, which require engaging of central circuit of regulation in CR control procedure, lead to the attenuation of respiratory component of SA and to the intensification of its non-respiratory component.

Central circuit of CR regulation is a complex multi-level system of neuro-humoral regulation of physiological functions, which includes numerous links from subcortical centres of oblong brain up to hypothalamus-pituitary level of vegetative regulation and brain cortex. Structure of this system of regulation can be schematically represented by consisting of three levels. Certain functional systems or levels of regulation correspond to these levels rather then anatomic-morphological structures of brain. Those systems or levels are as follows:

1-st level provides organization of co-operation of organism with an environment (adaptation of organism to exposures). The central nervous system, including cortical mechanisms of regulation, which synchronize functional activity of all systems of organism according to effect of environmental factors, fall into this level (level A).

2-d level executes equilibrium between different systems of organism and provides an intersystem homeostasis. The basic role in this level is played by highest vegetative centres (including hypothalamic-pituitary system), which provides hormone-vegetative homeostasis (level B).

3-rd level provides intrasystem homeostasis in different systems of organism, in particular in cardio-respiratory system (the system of blood circulation and system of breathing can be considered as one functional system). Here the leading role is played by subcortical nervous centres, in particular by vasculomotor centre as a part of subcortical cardiovascular centre stimulating or depressing heart by means of fibres of sympathetic nerves (level C).

Non-respiratory SA represents oscillations of CR with the periods bigger than 6-7 seconds (below 0,15 Hz). Slow (non-respiratory) oscillations of cardiac rhythm correlate with similar waves of arterial pressure (AP) and of plethysmogram. Slow waves of 1-st, 2-nd and higher orders are distinguished by observers. CR structure includes not only vibrational components in the form of respiratory and non-respiratory waves but also non-periodic processes (so-called fractal components).

Origin of these CR components is being connected with multi-level and non-linear nature of processes of cardiac rhythm regulation and with availability of transient processes. The heart rhythm is not strongly stationary casual process with ergodic properties, what entail repetition of its statistical characteristics on any arbitrary taken stretches.

Heart rate variability reproduces complex picture of diverse control influences on system of blood circulation with interference of periodic components of different frequency and amplitude and also with non-linear co-operation of various control levels.

By using CR records with duration less than 5 minutes we artificially limit the number of regulatory mechanisms (control circuits) studied, we narrow down range of studied control influences. The longer is the sequence of cardio intervals being analysed, the bigger the number of regulatory mechanism levels could be investigated.

Approach to the HRV analysis is based on the idea of concerning mechanisms of neurohormonal regulation and is the closest and clearest to the physiologists and especially clinicians. It is known, that heart rhythm is regulated by vegetative, by central nervous system and by several humoral and reflex effects. Parasympathetic and sympathetic nervous systems are in certain co-operation and both are affected by central nervous system and several humoral and reflex factors.

There is a permanent effect of sympathetic and parasympathetic influences at all levels of regulation. The real relations between two departments of vegetative nervous system are complex. As a matter of fact is that there is a different degree of activity of one of the departments of a vegetative system while changing activity of another. It means, that actual heart rhythm can sometimes be the simple sum of sympathetic and parasympathetic stimulation, but sometimes sympathetic or parasympathetic stimulation can interact in a complicated way with origin parasympathetic or sympathetic activity.

The decrease of activity in one part of autonomic nervous system and increase it in another is observed at achievement useful adaptative result.

For example, excitement of baro-receptors with increase of arterial pressure results to decrease of frequency and force of intimate reductions. This effect is caused by increase of parasympathetic and reduction of sympathetic activity. Such type of interaction corresponds to a principle "functional synergy". It is necessary to emphasize, that the described various approaches to the analysis HRV are complementary. The current activity of sympathetic and parasympathetic parts of autonomic nervous system is system reaction of multiplanimetric and multilevel system of regulation.

3. Basic areas of application of the method and indication to its use

During 40-year's term of application of various methods of HRV in the different areas of physiology and clinical medicine, the sphere of their use continues to extend with each year. It is essentially important that the analysis of HRV is not specialized method of diagnostic. It is possible to list some examples, where it is applied to specification of the diagnosis of the certain diseases. In particular, it is diagnostics of neuropathy at diabetes mellitus. In many cases it is study of nonspecific reactions of organism on influence of the various factors or at the certain diseases. Preceding from the submitted scientific - theoretical rules it is possible to allocate conditionally four directions of application of methods of the analysis HRV:

1. Estimation of functional condition of the organism and its changes on the basis of definition of parameters autonomic balance and neurohumoral regulation;
2. Estimation express of the adapted answer of organism at influence various stresses;
3. Estimation of a condition of separate parts vegetative regulation of circulation of blood;

4. Development prognosis on the basis of an estimation of the current functional condition of organism, express it the adapted answers and condition of separate parts regulation of the mechanism.

The practical realization of the specified directions opens a boundless field of activity, both for the scientist, and for physicians. The rough and rather incomplete list of areas of use of methods of the analysis HRV and indications to their application made on the basis of the analysis of the modern domestic and foreign publications is offered below.

1. Study of autonomic regulation of heart rhythm at the practically healthy people (initial level vegetative regulation, vegetative reaction, vegetative providing with activity);
2. Estimation vegetative regulation of a rhythm of heart at the patients with various diseases (change vegetative balance, degree of prevalence of one of the departments vegetative of nervous system). Reception of the additional information for diagnostics of some forms of diseases, for example, independent neuropathy at diabetes mellitus.
3. Estimation of functional condition of the regulation systems of organism on the basis of the integrated approach to system of circulation of blood as to the indicator adaptation of activity all organism.
4. Definition of vegetative regulation (vago-, norma- or sympathotonia).
5. Prognosis of risk of sudden death and fatal arrhythmias at a heart attack myocardium and IDH, at the patients with gastric infringements of a rhythm, at chronic intimate insufficiency caused arterial hypertension, cardiomiopathy.
6. Allocation of groups of risk on development of menacing life of the raised stability of an intimate rhythm.
7. Use as a control method at realization of various functional tests.
8. Estimation of efficiency of medical-preventive and improving measures.

9. Estimation of a level of stress, degree pressure of regulation systems at extreme and subextreme influences on organism.
10. Estimation of functional condition of the man - operator.
11. Using for estimate of functional condition at mass preventive inspections of different quota of the population.
12. Prognosis of a functional condition (stability organism) at professional selection and definition professional of suitability.
13. Monitoring HRV in surgery with the purpose of the express objectivity of operational stress and control of adequacy anaesthesia, and also for a choice such as and dosages of anesthetic protection and for the control in after surgical operation period.
14. Estimation of reactions autonomic nervous system at influence on organism of electromagnetic fields, intoxications and others pathogenic factors;
15. Choice of optimum therapy in view of a background of autonomic heart regulation, in the control of efficiency of treatment, correction of doze of preparation;
16. Estimation and prognosis of mental reactions by expressed vegetative background;
17. Using this method in neurology for an estimation of a condition autonomic nervous system at various diseases;
18. Control of a functional condition of the organism in sports;
19. Estimation of the vegetative regulation during development of children and teenagers. Application as a control method in school medicine for social - pedagogical and medical psychological researches;
20. Control of the functional condition of a foetus in obstetrics. Application in the neonatal period of development of the organism.

The above-mentioned list is not exhaustive. It will constantly increase. The basic affidavit to the application of methods of HRV analysis is probable changes of organism's system regulation, in particular changes of vegetative balance. As there are practically no such functional conditions or diseases, in which the mechanisms of vegetative regulations would take part, then the sphere of application of HRV analysis is really inexhaustible. It means, that nowadays this method is the only available, non-invasive, simple enough and relatively cheap method for estimation of vegetative regulation. Taking into consideration the vast perspectives of the development of the method, it is important to provide its standards and comprehension of data obtained by different researches.

4. Main medical and technical conditions.

4.1. Conditions for continuity of registration of heart rhythm.

The continuity of CR registration depends on purposes of research. The duration of records can be at range from several minutes to several hours. For instance, at mass prophylactic examination or at preliminary policlinic and clinic researches 5-minutes registration of ECG is applied. At functional tests the continuity of registration can be at range from 10-15 minutes to 1.5-2 hours. Control tests from 3 to 5 hours can be in need during the surgical operations, and at last the continuity of persistent registration can reach 10-12 hours in resuscitation departments and at research of a dream. It is supposed to be pointed four kinds of HRV investigation:

1. Transitory (operative or survey) records (standard continuity – 5 minutes)
2. Records with middle continuity (up to 1-2 hours)
3. Long records (up to 8-10 hours)
4. Daily records (24 hours and more continuing)

Definite tasks can require shorter periods of time records (1-2 minutes). In these guidelines long and daily records are not studied. As for the records of middle continuity, in this case their application is supposed in the frames of holding the functional tests.

In spite of continuity of registration during the data analysis as basic selection, it is recommended to use 5-minutes segments of record. In separate cases it is allowed to use shorter selection by work with highly stationary processes (emotional stress, steady phase of physical training). It is worth to use in each stationary stage

5-minute standard segments of record and sum up in a proper way the results of analysis of these segments, if the necessity of estimation of cardiointervalogram by continuing observation will arise. The analysis of more prolonged segments of record require special elaboration, because while estimating them one must take into account presence of periodical components in their contain, reflecting the state of higher level regulation and it is also important to pay special attention to the stability of functional condition and transitional processes.

4.2.The methods of HRV investigation.

The investigation of HRV can be parallel or specialized. In first case it is held simultaneously with ECG registration, EHO-CG for the purposes of diagnosis and medical control or during Holter monitoring. In the second case it is purposeful investigation of HRV with utilization of specialized systems.

According to this, four kinds of investigations can be pointed:

a) operative investigations in condition of relative rest;
b) investigations during functional tests;
c) investigations in condition of usual activity;
d) investigations in clinical conditions.

Each of these kinds of investigations is characterized by peculiarities of methods.

4.2.1. Operative investigations in condition of relative rest.

ECG signal is registered in one of the standard (better in the 2-d or 3-d) chest sections. The duration of record must be not less than 5 minutes. It is better to hold record not less than 10 minutes, if there are disorders of rhythm. Analysis of the 2-d, 3-d consistent 5-minutes' records confirms the state of physiological status stability. HF must be known in experimental and clinical investigations for proper comparison of receiving data.

HRV investigation must be held not earlier than in 1.5-2 hours after meal in a quiet place, constant temperature of which is 20-22°. It is necessary to revoke physical and therapeutic procedures and treatment with medicine before investigation.

Before the beginning the investigation, 5-10 minutes period of adaptation will be necessary.

The record of ECG is being made in lying position, with calm breath. The surrounding during the investigation must be calm. It is desirable to hold the investigation with women during the mensal period, as hormonal changes in organism reflect themselves at cardiointervalogram. It is necessary to dismiss all obstacles leading to emotional excitement, not to speak with investigated and other, expel telephone calls and appearance of other persons including medical workers. During HRV investigation Patient must breathe without taking deep inhale, coughing and swallowing saliva.

4.2.2. Investigations at functional tests.

Functional test is an important part of HRV investigation. The main aim is to estimate of functional supplies of mechanisms of vegetative regulation. Different links of system of management of physiological functions can be tested depending on kind of functional work.

Sensibility and reactivity of vegetative nervous system, its sympathetic and parasympathetic sections under the influence of one or another testing factor can serve as diagnostic and prognostic criteria.

For example, in the case of diabetic neuropathy the reaction of parasympathetic link of regulation on the trial with fixed tempo of breathing (6 breathes per minute) is one of the most important diagnostic signs. The schedule of functional tests, most often used in researches of HRV, is presented below:

a. Active and passive orthostatic test (when it is needed clinoorthostatic test).
b. Test with the fixed breathing tempo.
c. Valsaw's test.
d. Tests with maximal breathing delay on inhale and exhale.
e. Isometric cargo test.
f. Cargo tests at veloergometre.

g. Pharmacological tests (with β-blocators, atropine and other drugs).

h. Ashner's test.

i. Sinocarotid test.

j. Psychophisiological test.

Represented schedule of functional tests is not full. Each of pointed tests is led by its own special method. Depending on the type of test used the length of recording CR can hesitate from some minutes (during the test of fixed breathing tempo) to some hours (during pharmacological tests).

It is necessary to point out next specialities of HRV analysis during functional tests:

• Background (initial) record must be led in condition of the rest (see above) during not less than 5 minutes. For comparison with background record analogous by length records, received on different stages of function test must be used.

• Transitional process during functional tests must be analyzed by special methods (these methods are not looked through here). In this case it must be pointed out from the record visually or automatically with the use of appropriating algorithm, registrating instationarity and non-linearity of the process. The analysis of transitional processes can have independent diagnostic and prognostic sense. Transitional process, depending on the type of functional tests can take shorter or longer time.

• The estimation of changes of indices HRV by functional tests must be done with the registration of data received by other methods of research.

4.2.3. The researches in conditions of ordinary activity or in the case of making professional work.

The using of analysis HRV as the method of estimation of adapting possibilities of the organism or current stress stage occur practical interest for different domains of applied physiology, professional and sport medicine and for socio-ecological researches. The development of donosologic diagnosis made it possible to point out almost wealthy people, enormous group of people with high and very high tension of regulatory systems, with heightened risk of disruption of adaptation and appearing of pathologic deviation and diseases. Such people need regular control of stress stage and recommendations for wealthy preservation.

The problem of chronic stress when there is constant elevating tension of regulating systems concern almost all the population, but particularly important for separate professional groups, whose work is united with the influence of complex of stress factors. They are, in particular, operators of computer systems, controllers, drivers and also businessmen and administrator-commanding apparatus. The analysis of HRV is an adequate method of the estimation of the stress stage of their everyday work. Here depending on target the using of every of three types of researches (short-time, middle-time or long-time) is possible.

Short-time or operative researches with the recording lengths of 5-15 minutes may take place in the system of common investigations when it is necessary to estimate the group's of people state and to point out persons with elevated risk of pathologic process. In such researches parallel gathering of anamnesis, registration of complaints, manner of life and anthropometric dates are important. The recording must take place in the conditions of relative calm in laying or sitting position.

Middle-time records (till one hour) are expediency to carry out using to separate stages of work. For instance, at the beginning and at the end of working day, during the lesson, during making concrete working operation. In sport medicine such records can take place before and after competitions, during making individual physical trainings (only stationary sections of record). In the case of operator work, it is controlled before and after relay.

Long time records are researches during working relay, during working day and during night sleep.

The analysis of HRV in middle and long-time records is recommended to take place using 5-minutes segments for the learning of the dynamics of adaptation process. The checking of every analyzing segment on stationarity has essential sense. The sections of record reflecting transitional processes must be analyzed with the use of special methods. When the results of HRV analysis are estimated, conditions of records, reaction factors and the position of investigated person (laying, sitting, moving, etc.) must be registrated.

4.2.4. Researches in clinical conditions.

In application to clinical conditions it is also important to differ above-mentioned kinds of researches. Short-time researches must be inspected as operative, reviewing and previous. They can take place at the beginning and at the end of treatment or regularly at the process of treatment for the definition of functional patient's state. The middle-time records, which are led because of functional tests, are the most adequate to clinical conditions.

Moreover, such records take place in function with control of treating procedures, for example, in the case of physiotherapeutic reaction. Researches from surgery and anesthesiologic fields also concern to middle-time records. They are as records made directly during surgery operations for the control of adequacy of anesthesia, as the control of the patient's state at the nearest after-operation period.

Long-time operations are used for the HRV analysis at the after-operation period and in resuscitation practice. The estimate of the stress level and opportune exposition of overloading and exhaustion of regulatory mechanisms plays the most important role for prevention of menace states and death. The researches of sleep led in neurology and psychology are also the example of long-time records.

It is important to underline, that the specialty of HRV analysis in the case of using this method in clinical practice is, that the physicians have to understand clearly nonspecialty of results received and not to try to look for of HRV pathognomic to one or another form of pathology. The dates of HRV analysis have to be compared with other clinical data, instrumental, biochemical, anamnesis.

4.3. The requirements for software, standards of processing.

1. The presentation of previous data in a way of cardiointervalogram with possibility of editoring (remove of arthefacts and extrasystols) has to b provided;

2. It is recommended to provide automatic discretion of arythmics and their interpolation without breach of stationarity of dynamic row of cardiointervals;
3. It is recommended to provide the possibility of reform of dynamic row of cardiointervalsto equidistant row with the frequency of quoting 250,500…..or 1000 (possibility to choose the frequency);
4. Possibility of choosing the analysis method;
5. Representing the results of analysis in a graphic way (varying pulsograms, scaterograms, spectrums, etc.);
6. Forming of the table of results of analysis and appropriate graphic representing by all methods chosen of analysis;
7. It is recommended to provide the possibility of automatic estimate of analysis' results (mainly for commercial programs and mass consume);
8. Database for keeping of initial information (desirable also initial ECG-signal) and results of analysis;
9. The possibility of receiving information (after the user's inquiry) concerned of structure of program, rules of working with it and interpretation of calculating exponents must be provided;
10. Complementary requires can include the possibility of:

a) estimate of stationarity of dynamic row and rejecting of instationary sections;
b) successive analysis of selections of proposed capacity with proposed pace (continuously sliding method);
c) the identification of cogs P, Q, S, T and segments PQ, ORS, QT and ST in ECG and also lining up the dynamic row of meanings by set exponents.

5. Essential methods of HRV analysis.

5.1. Statistical methods.

These methods are used for direct amounting of estimation of HRV at investigated period of time. During their use the cardiointervalogram is inspected as the collection of successive time intervals, namely intervals RR. Statistic characteristic of dynamic row of cardiointervals include: SDNN, RMSSD, PNN50, CV.

SDNN or CKO is a summarized index of variability of quantities of RR intervals of all investigated period (NN means a row of normal intervals "normal to normal" except extrasystols);

CKO is neuter quadrate deviation (conveys in ms);

SDNN is standard deviation of NN intervals (CKO analog);

SDANN is standard deviation of neuter meanings SDNN from 5-minutes segments for middle-time records, long-time records or 24 hour records. Also standard deviations of neuter meanings of other exponents can be reviewed by the same way;

RMSSD is quadrate root from the sum of quadrates from the difference of quantities of successive pairs of NN intervals (normal RR intervals);

NN50 is number of pairs of successive NN intervals, which differ for more than 50 milliseconds, received for all the record period;

PNN50 (%) is percent NN50 from the common number of successive pairs of intervals which differ for more than 50 milliseconds received for all the record period;

CV is coefficient of variation. It is favorable for the practical use it constitutes an estimation CKO;

CV=CKO/M*100, where M is a neuter meaning of RR intervals;

D, As, Ex are second, third and fourth statistic moments. D is CKO in quadrate, it reflects summary power of all periodic and non-periodic fluctuations. As is a coefficient of asymmetry, it let us judge about the stationarity of investigated dynamic row, presence and expression of transitional processes including trends. Ex is a coefficient of excessiveness, reflects the rapidity (precipice) of change of casual non-stationed components of dynamic row and presence of local non-stationarity.

5.2. Geometric methods (variable pulsometry).

The essence of varying pulsometry confines in learning the allocation law of cardiointervals as casual quantities. A variable curved line (curved line of allocation of cardiointervals is histogram), is lining up in this case and its main characteristics are definite by: Mo (Mode), Amo (Model's amplitude), MxDMn (variable range).

Mode is a most often met meaning of cardiointerval in this dynamic row. Mo differs a little from mathematic expectation (M) in the case of normal allocation and high stationarity. Amo (Model's amplitude) is the number of cardiointervals appropriated to the quantity of Mode in percent to the capacity of selection. Variable range (MxDMn) reflects the grade of variability of cardiointervals' meanings in researched dynamic row. It is calculated by the difference of maximal (Mx) and minimal (Mn) meanings of cardiointervals and that's why it can be distorted in the case of arythiyes and arthefacts.

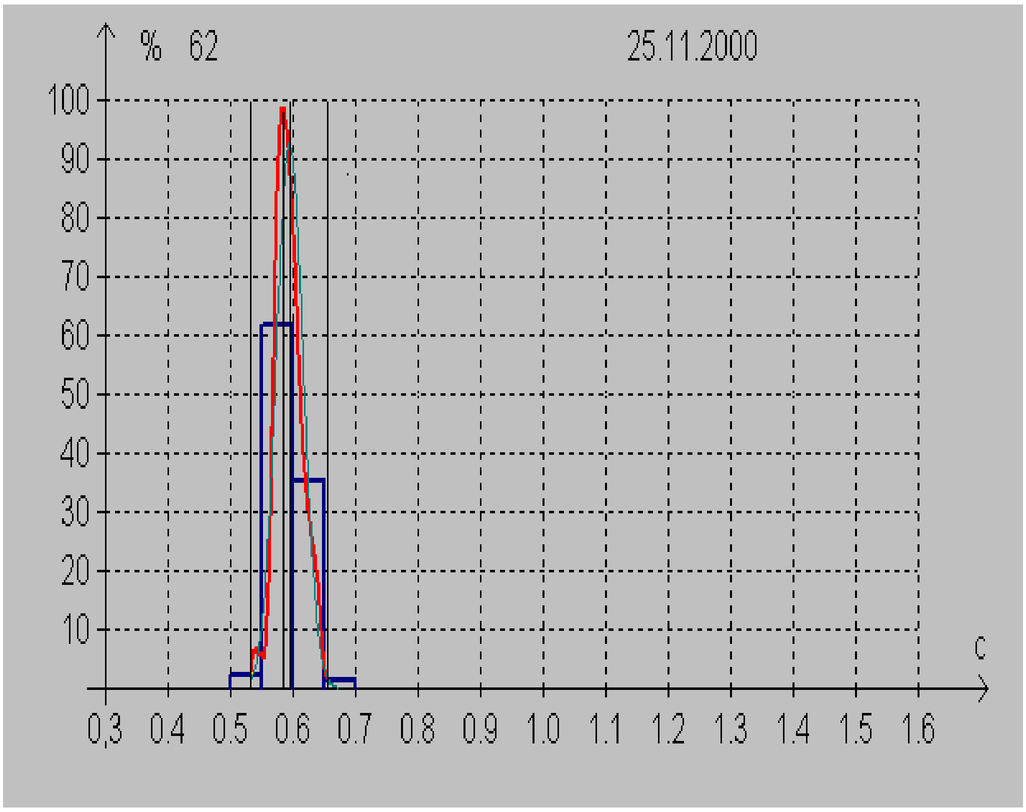
During lining up histograms (or variable pulsograms) the choosing method of gathering data has the major meaning. A traditional manner of grouping cardiointervals is the range from 400 to 1300 ms with the intervals of 50 ms was constituted in perennial practice. Thus, 20 fixed ranges of cardiointervals' length are pointed which let us to compare variable pulsograms received by different researchers at different groups of researches. In this case the selection capacity, in which the grouping and lining the variable pulsograms up, is also 5-minute standard. Another way of lining up the variable pulsograms confines in definition of modal meaning of cardiointerval for the first and then using ranges for 50 ms to form histogram to both sides from the mode. Variable pulsogram can be also presented by "plane" graphic of density of allocation (look pic.3).

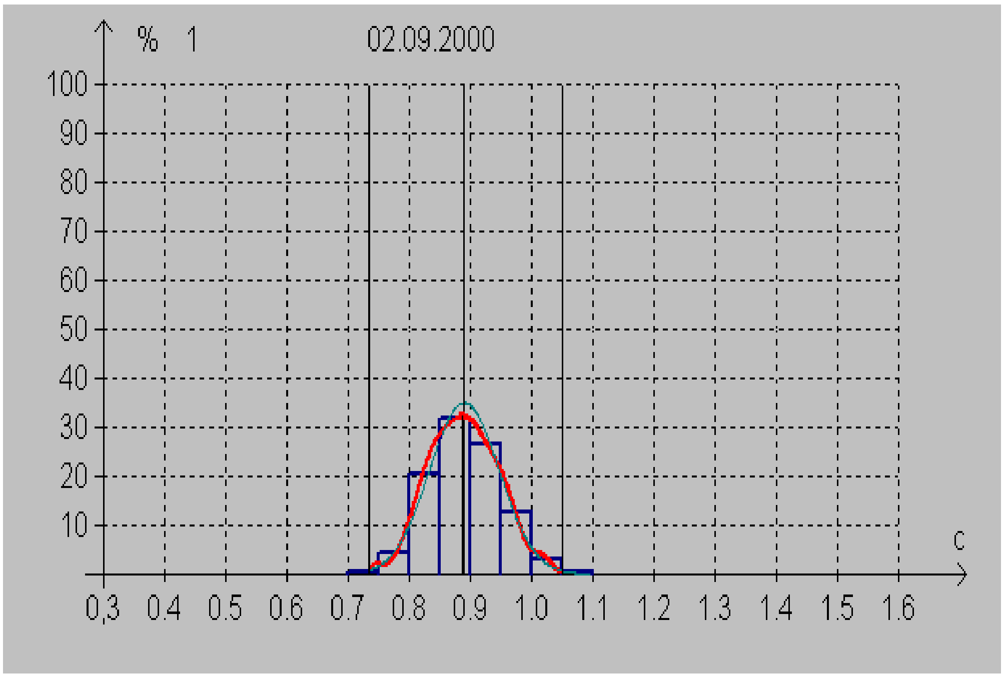
According to the data of variable pulsometry widely diffused in Russia index of tension of regulatory systems or stress index is calculated.

Ин=AMo/2Mo*MxDMn

West European and American researchers use approximation of curved line of cardiointervals' allocation as a triangle and count a so-called triangular index – the integral of density of allocation (common number of cardiointervals), referred to the maximum of allocation density (AMo). This exponent is designated as TINN (triangular interpolation of NN intervals).

Moreover, the lining up of histograms is used by differential meanings of adjoining cardiointervals with the approximation of their exponential curved line and with the counting of logarithmic coefficient and other way of approximation





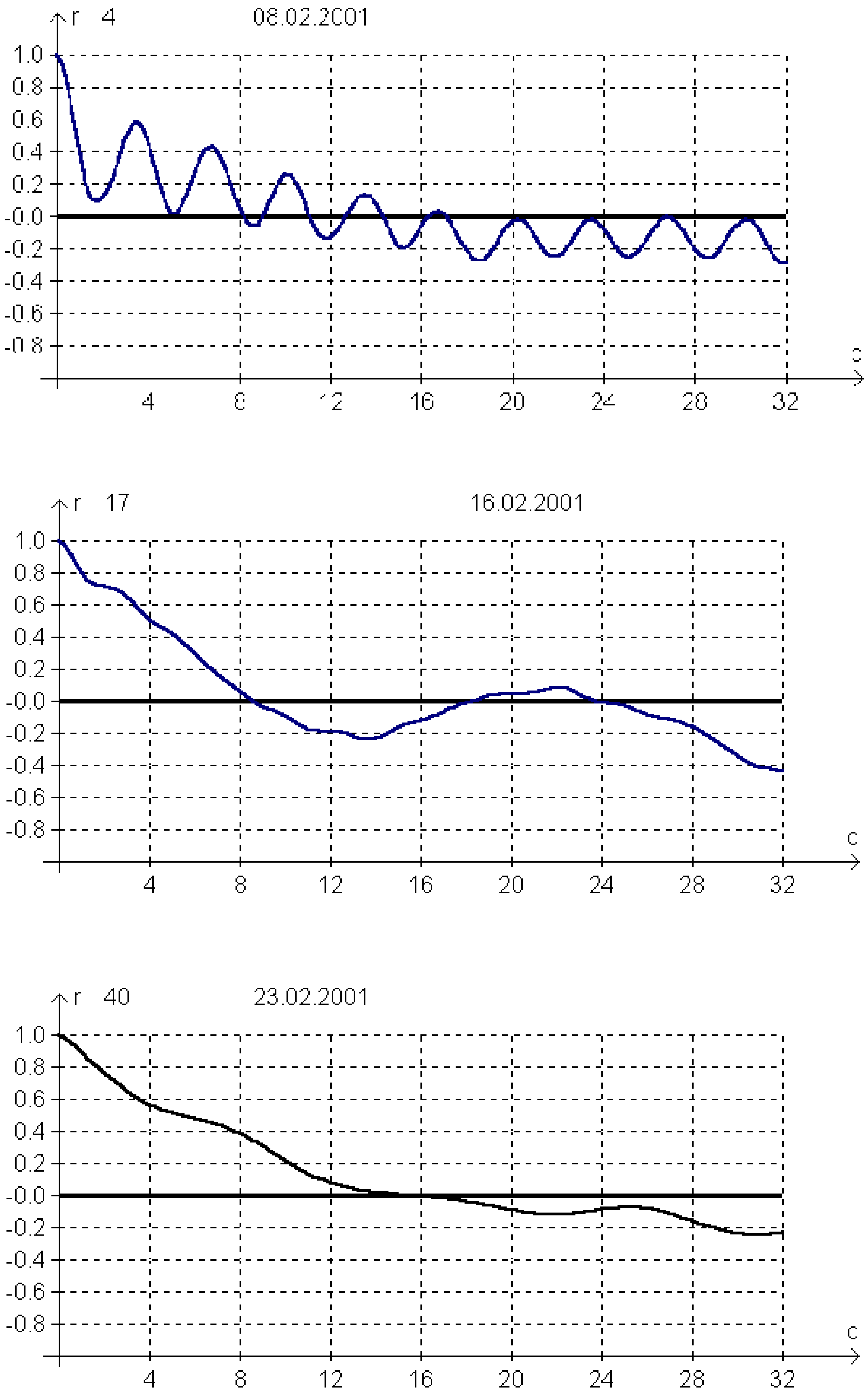
Pic.3. Models of variative pulsograms by tachycardia and normocardia (histogram and diagram of allocation intensity)

5.3. Autocorrelating analysis.

Discount and lining up of autocorrelating function of cardiointervals' dynamic row is directed at the studying of internal structure of their row as of casual process. Autocorrelating function is a graphic of dynamics of correlation coefficients received at the case of successive deviation of analyzing dynamic row for one number relatively to its own row.

After the first dislocation for one value the correlation coefficient is such less than one as more breathing waves are expressed (pic.4). If slowly waved components dominate in investigated selection, then correlation coefficient will be insignificantly lower than one after the first dislocation. Next dislocations lead to gradual extenuation of correlation coefficients. Autocorrelogram let us try on hidden periodicity of CR.

C1 is the meaning of correlation coefficient after the first dislocation and C0 is number dislocation, which result to the meaning of correlation coefficient becoming negative, are recommended to be used as amounting meanings of autocorrelogram.



Pic.4. Models of autocorrelograms with expressed breathable waves (at the top), with the prevalence of slow (in the middle) and the slowest waves (at the bottom)

5.4. Correlating rhythmography-scatterography.

The essence of correlating rhythmography method is in graphic rendering of successive pairs of cardiointervals (last and next) in by-measured coordinate plain. During this quantity R-Rn is put on the axle of abscissa, and quantity R-Rn+1 is on the axle of ordinates. The graphic and region of points received by such way (Puankare's or Lorence's spots) is called correlating rhythmogram or scatterogram. This way of estimation of HRV concerns to the methods of nonlinear analysis and it is mostly useful for the cases when rare an sudden breaches (ectopical systoles and/ or "prolapse" of separate heart systoles) are met at the background of monotone of the rhythm.

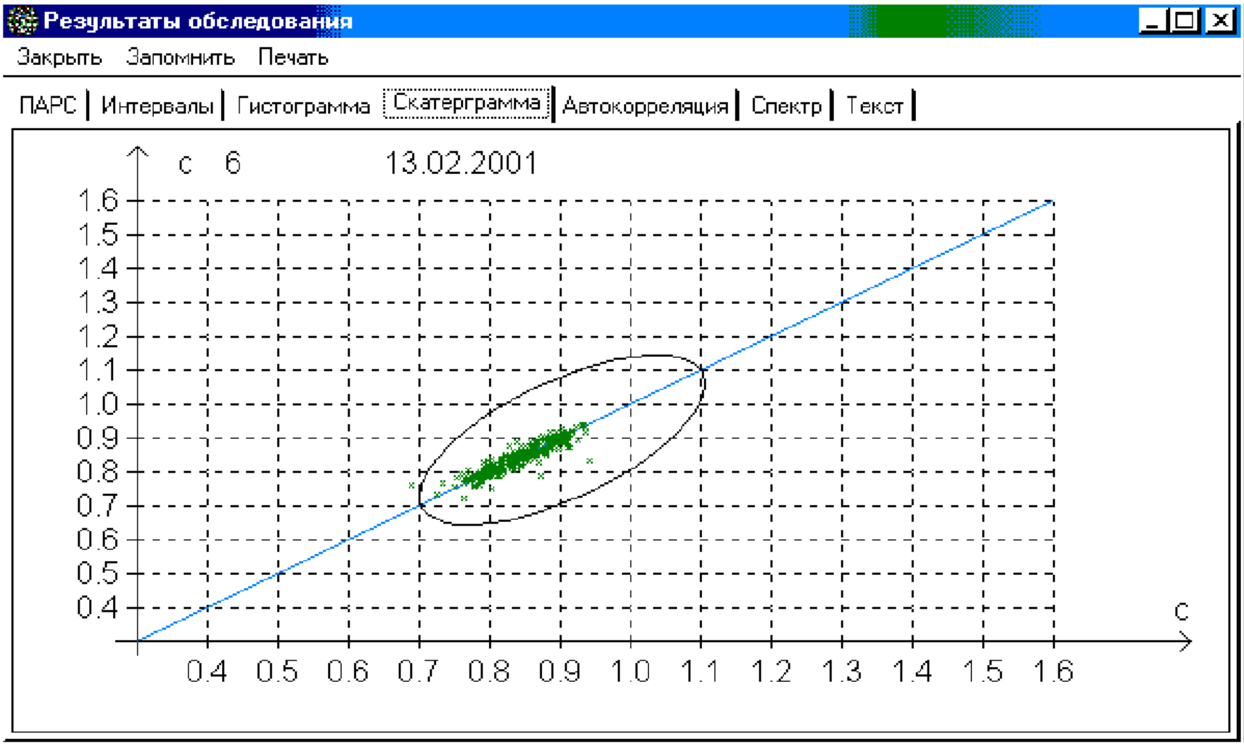
When lining up scatterogram a join of points whose centre is situated at the bisector is organizing. The distance from the centre to the beginning of coordinate axles suit to the linger of heart cycle (Mo) most waiting for. The value of deviation of the point from bisector to the left shows, how is this heart circle shorter than the previous one, to the right from bisector, how it is longer than the previous one. The following indicators of scatterogrm are supposed to be calculated:

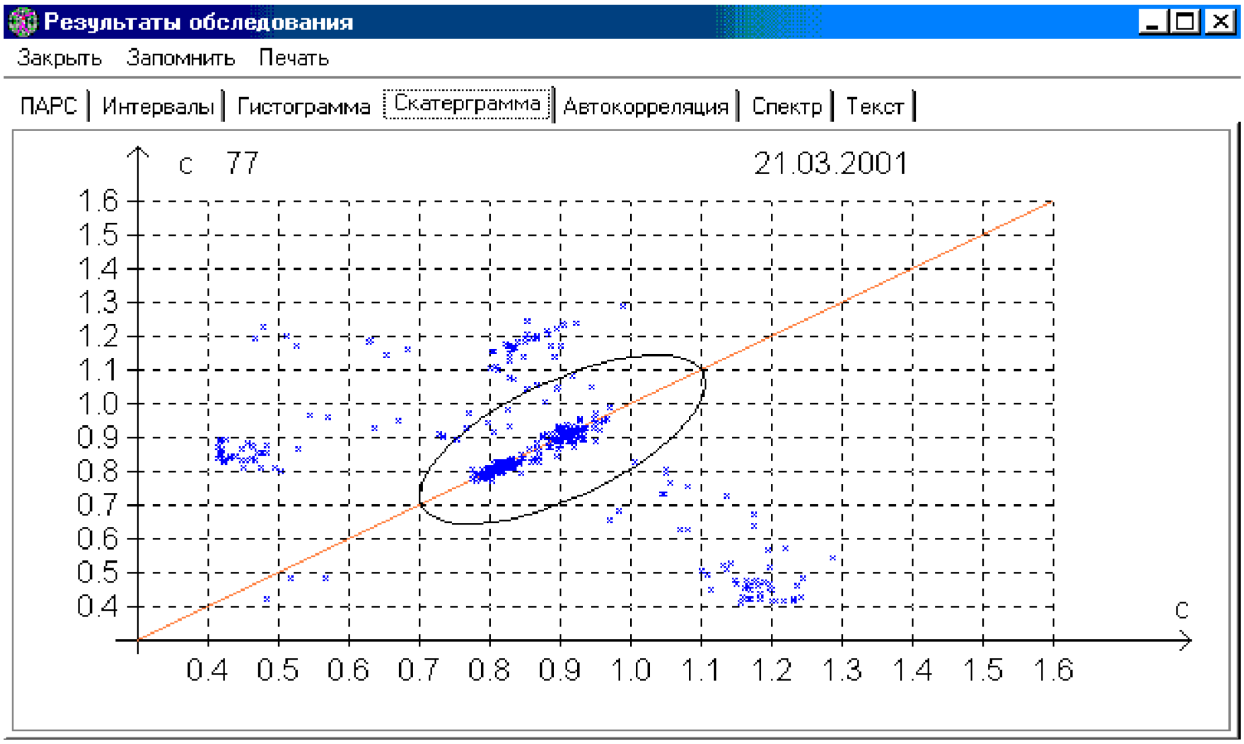
a. Length of the main "eddy" (without extrasystole and artifacts) corresponds with variation range. With its physiological sense this indicator does not differ from SDNN, i.e. it reflects the summary effect of HRV regulation, but indicates maximum amplitude of fluctuations of R-R intervals duration;
b. Width of scatterogram (perpendicular to the long axis drawn across its middle –w);
c. Scatterogram area is to be calculated according to the ellipse area formula:

$S=(\pi \cdot L \cdot w)/4$.

Normal shape of scatterogram is represented by ellipse starched along bisector. This very arrangement of ellipse means that some non-respiratory arrhythmia value is added to the respiratory one. The round shape of scatterogram means the absence of arrhythmia non-respiratory components. Narrow oval (pic.5) corresponds to the predominance of non-respiratory components in general rhythm variability that is determined by the "eddy" length (scatterogram length).

The oval length correlated well with HF magnitude and correlated with LF (see below). In case of arrhythmias, when statistic and spectral analysis methods for heart rate variability estimation are not very informative or not acceptable, it would be necessary to use correlation rhythmogram estimation.





Pic.5. Models of correlative rhythmogram (CRG). Normal CRG (at the top), with a patient with arrhythmia (at the bottom).

5.5. Spectral methods of HRV analysis.

Spectral methods of HRV analysis are widespread nowadays. Analysis of spectral density of oscillations rate gives information on power allocation depending on the oscillations frequency. Spectral analysis application allows making quantitative evaluation of different frequency constituents of the cardiac rhythm oscillations and represents graphic correlations of different CR components that reflect activity of definite regulatory mechanism links.

There are parametric and non-parametric of spectral analysis. Former includes autoregressional analysis, latter includes Fure's quick transformation (FQT) and periodogram analysis. Both groups of methods provide comparative results. Parametric and, in particular, autoregressional methods requires correspondence of an analyzed object with the definite models. General for all classical methods of spectral analysis is the problem of Windowing application. Its main role is reducing shift value in periodogram spectral evaluations. There are definite differences in spectral estimation of data using periodogram method with even window (256 values of RR) and application of different inter segment shift of levels and of different number of indication per segment.

Enhance of clearance in case of inter segment shift increase indication per segment causes appearance of many additional peaks in the spectrum and increase of peaks amplitude in the right half of spectrum. In application of spectral analysis of HRV volume of analyzed selection has important meaning. In brief records (5 minutes) there are three main components outlined. These components correspond to respiratory waves range and slow waves of 1-st and 2-d degree (pic.6).

In western literature the corresponding spectral components were called **“High Frequency” (HF), “Low Frequency” (LF)** and **“Very Low Frequency” (VLF).**

Frequency ranges of each of three above-mentioned spectral components are discussional. According to Euro-American recommendations (1996) the following frequency ranges are offered:

HFR (respiratory waves) – **0.4-0.15 Htz (2.5-6.5)**;

LF range (slow waves of the 1-st degree) – **0.15-0.04 Htz (6.5-25);**

VLF range (slow waves of the 2-d degree) – **0.04-0.003 Htz (25-333).**

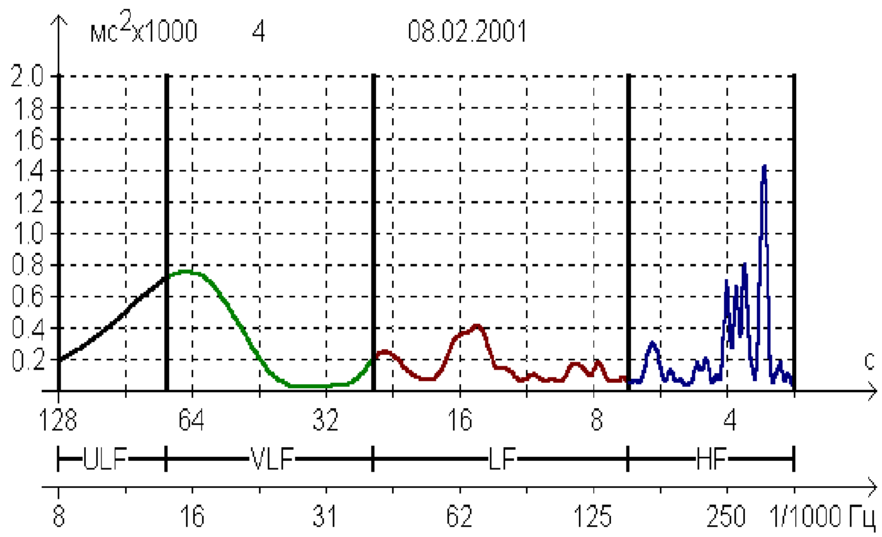
In case of long term record analysis **“Ultra Low Frequency” (ULF) (more than 0.003 Htz)** component is also singled out.

Experience of the Russian investigations and their results that have been carried out by many foreign authors, show that these recommendations should be corrected. It’s mostly relevant to VLF range. This is the following corrected scheme of frequency ranges for spectral analysis of HRV:

Names of spectrum components	**Frequency range, Htz**	**Period, seconds**
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	**Less than 0,015**	**More than 66,0**

The offered limitation for VLF range to 0.015 Htz is explained by the fact that making analysis of 5-minute long records we, in fact, can accurately identify only oscillations with a period that is 3-4 times less than signals registration period (about 1 minute). That is why all oscillations with the period more than one minute are offered to be referred to as of ULF range and to single out corresponding sub-ranges in it.

As for the spectral analysis the absolute summary power of a range, average power of a range, maximum harmonics value and relative value (in percent of Total Power – TP) are usually calculated for each component. So TP is the sum of range power HF, LF and VLF. According to the spectral analysis data (CR analysis) the following indicators are calculated: Index of centralization **(IC=(HF+LF)/VLF)** and Index of vagosympathetic interaction **LF/HF**.



Pic.6. Typical HRV spectrogram by using the method of Fure's quick transformation (FQT).

5.6. Other methods of HRV analysis.

Digital filtration. Methods of digital filtration are appointed for fast analysis of brief parts of ECG (less than 5 minutes) and they allow making quantitative evaluation of HRV periodical components. For instance, this is sliding averaging on the definite number of consecutive cardiointervals. For identifying of the slow waves of the 1-st degree averaging on 5 or 9 cardiointervals is applied.

Nonlinear dynamics methods. Many influences on HRV including neurohumoral mechanisms of higher vegetative centers cause nonlinear character of changes of CR for the description of what application of special methods is needed. To this problem has been recently paid much attention abroad as well as in our country. For the description of nonlinear properties of variability section of Puankare, chest spectral analysis, attracter's graphics, singular decomposition, Lapunov's exponent, Kolmogorov's entropy were applied. All these methods are recently only of investigation interest and their practical application is limited. Along with this it is necessary to mention method of functional state estimation based on the chaos' theory used in "Neurosoft", "Vita-Rhythm" device. In2001 the special symposium under the name "Theoretical and Applied Aspects of Nonlinear Chaos and Fractal's Dynamics in Physiology and Medicine" in Novokuznezk was held.

6. Reproductiveness and comparativeness of data.

Constantly acting regulatory mechanisms provide adequate adaptation responses of an organism caused by continuous environmental changes. It means that the functional state of different regulation links is constantly changing and it is impossible to obtain identical results after repeated HRV investigations.

That is why reproductiveness of data can not be equal to 100% (completely the same). High reproductiveness means only qualitative but not quantitative correspondence of two compared records (registrations) obtained from one and the same person even after rather small period of time. Discussing the problem of reproductiveness of HRV analysis data one must consider high sensitivity of the vegetative nervous system for external and internal influences, typical peculiarities of patient and his health.

In a number of cases (initial stages of some diseases, non-stability of vegetative regulation) high reproductiveness should not be expected at all. Daily changes in vegetative regulations must also be considered. For the high data (of HRV analysis) reproductiveness obtaining it is recommended to keep to registration's method described in chapter 4.2.

Comparativeness of registrations and HRV analysis results means that it is possible to compare data obtained in different clinics and establishments with the help various equipment and programs. Without the possibility of such comparison it is impossible for methods of HRV analysis to develop in future. It is a question of comparing main (key) indicators of statistical and spectral analysis.

Clinic physiological interpretation of these indicators and creating new evaluation algorithms based on them ought to be the subject of further scientific investigations. However, if the min indicators of HRV are essentially different depending on the types of applied devices and programs, it will be of no progress in HRV analysis.

Present recommendations for application of different ECG systems for HRV analysis envisage using of special testing system that must include set of control files, special test-program and special standard ECG database. All firmware complexes manufactured in Russia must pass testing procedure to determine the accordance to the accustomed HRV analysis standards.

As a standard test-system it is recommended to use "HRV-test" complex that includes set of real and generated signals (ECG) and also the results of data processing by standard analysis program (for HRV).

Three levels of testing are studied:

1. Testing of the system that fulfils the functions of identifying of R-cogs, R-R intervals duration, measuring, formation of normalized cardiointervals row and calculating of key indicators of HRV.
2. Testing of the system that has only functions of making normal range of cardiointervals and calculating key (standard) indicators of HRV.
3. Testing of the system that is only for calculating key (standard) indicators of HRV.

Adjusting of such levels of testing it is necessary for making standards of not only complete firmware complexes but also of special programs products designed for HRV analysis included into serial produced devices as well as designed for dealing with database or separately gathered R-R intervals files autonomously.

The list of recommended set of HRV indicators is given in 1-st supplement and formulas for calculating them are given in the 2-d one.

7. Evaluation of HRV analysis results.

Clinical interpretation (and physiological) of results obtained is of the paramount importance for investigators and clinicians who use HRV analysis. However, nowadays there is no consentaneous opinion concerning HRV analysis results interpretation. But there are definite clinical physiological evaluations that are already more or less alike in the major part of publications. For some indicators there are original but yet disputed interpretations that need more details.

In the present chapter the materials on HRV analysis results evaluation are given only the main indicators that are used in Russia more often are listed; their clinical physiological interpretation based on the traditional viewpoint concerning vegetative regulation of heart, sympathetic and parasympathetic influence, and role of subcortical cardio-vascular centre and higher physiological control centre in it.

Much attention is paid to the complex evaluation of the organism functional conditions according to RSAI (Regulatory System Activity Indicator).

An important role belongs to the comparing of the obtained during results evaluation data with standard indicators.

Standard considered to be some complex of statistical data obtained while examination of deliberately selected group of healthy people needs to be clarified as the HRV analysis application.

As it is not a question of relatively stable parameters evaluation but of rather changeable parameters of vegetative regulation so it would be more correct to regard standard being the functional optimum.

Here it is to be pointed out that individual organism optimum does not always coincide with average statistical standard for common adaptation reactions take place differently depending on the conditions that surround the examined person and depending on his personal functional reserves. Notion of the physiological standard has been made out in space medicine. It indicates at reservation of sufficient level of organism' functional abilities. So that the homeostasis of the main systems of the organism is provided with minimum of regulatory mechanisms stress. So the value of the biggest part of indicators of HRV must not exceed definite levels corresponding to the definite age, sexual, professional and regional group. This point is mostly fulfilled by application of complex HRV analysis results evaluation (see below). There is also a notion of clinical standard that characterizes indicators values in visually healthy persons. However, as it is known, nosologic approach is based on the evaluation changes, mainly on structural, metabolic and energic metabolic levels of organization of living system, and it also takes into account the state of regulatory systems. Thus, norm problem with reference to an estimation of HRV requires the further profound development.

It is necessary to point, that the materials of the given unit carry only recommendatory character. They can be especially useful for the beginning experts for the correct use of a method and understanding of its opportunities.

7.1. Indicators of the statistical analysis (temporarily analysis)

Average square-law deviation (ASD, SD). The calculation of ASD is the simplest procedure of the HRV statistical analysis. The meanings of ASD are expressed in milliseconds (ms). The normal meanings of ASD are within the limits of 40 - 80 ms. However these meanings have age-sexual features, which should be taken into account at an estimation of results of research.

The increase or decrease of ASD can be connected both with an independent circle of regulation, and with central (both with sympathetical and with parasympathetical influences on a rhythm of heart). At the analysis of short records, as a rule, increase of ASD points to intensifying of an independent regulation, that is the body height of influence of respiration on a rhythm of heart, that is observed in dream more often.

The decrease of ASD is connected with intensifying of a sympathetic regulation, which inhibits the activity of an independent circle. The sharp drop of ASD is caused by considerable strain of regulation systems, when highest levels of control are included in the process of regulation that conducts to almost complete inhibition of activity of an independent circle. The information on physiological sense similar to ASD can be received from a parameter of cooperative capacity of a spectrum - TP. This parameter differs by that it characterizes only periodic processes in a rhythm of heart and does not contain a so-called fractional part of process, that is nonlinear and acyclic components.

RMSSD is a parameter of activity of a parasympathetical link of vegetative regulation. This parameter is calculated on dynamic series of differences of meanings of consecutive couples of cardiointervals and does not contain slow-wave components of CR. It represents activity of an independent contour of a regulation. The higher is the meaning of RMSSD, the more active is the part parasympathetic regulation. In norm meanings of this parameter are within the limits of 20-50 ms. The similar information can be received from a parameter pNN50, which expresses in persentage the number of differential meanings more than 50 ms.

The index of pressure of control systems (IP) characterizes activity of mechanisms sympathetic of a regulation, state of the central circle of a regulation. This parameter is calculated on the basis of the analysis of the diagram of cardiointerval distribution - variational pulsegramm. The activation of the central circle, intensifying of sypmathical regulation during mental or phisical exercises is shown by stabilization of a rhythm, decrease of disorder of the length of cardiointervals, by increasing of quantity of intervals with the same duration (the increas of AMo). The form of histograms changes, there is their narrowing with simultaneous raise in height.

Quantitatively it can be expressed by the ratio of height of a histogram to its width (see above). This parameter has received the name of an index of a control systems pressure (IP). In norm IP changes within the limits of 80-150 standard units. This parameter is extremely sensitive to intensifying of sympathetic nervous system tone. The small load (physical or emotional) enlarges IP in 1.5-2 times. At considerable loads it grows at 5-10 times. Patients with a constant tension of circle systems have IP in rest equal to 400-600 standard units. IP in rest of patients with attacks of a stenocardia and myocardial infarction reaches 1000 - 1500 units.

7.2. Parameters of a spectral analysis (frequency analysis)

Capacity of high-frequency component of a spectrum (respiratory waves). Activity of sympathetical department of vegetative nervous system, as one of components of vegetative balance, can be estimated on a degree of activity inhibition of an independent circle of a regulation, for which parasympathetic section is responsible.

Vagus activity is a basic amounting of HF component. It is well reflected by a parameter of capacity of CR respiratory waves in absolute digits and as relative quantity (in % from cooperative capacity of a spectrum).

Usually respiratory amounting (HF) makes 15-25 % of cooperative capacity of a spectrum. The drop of this share to 8-10 of % specifies shift of vegetative balance to the side of prevalence of a sympathetic department. If the quantity does not fall below 2-3 % than it is possible to speak about sharp prevalence of sympathetic activity. In this case parameters RMSSD and pNN50 also decrease essentially.

Capacity of allow-frequency amounting of spectrum (slow waves 1st order or vasculomotor waves). This parameter (LF) characterizes a condition of a sympathetic department of vegetative nervous system, in particular, systems of a regulation vascular tone. In norm the sensitive receptors of a sinocarotid zone perceive changes of arterial pressure value and afferent nervous impulsation acts in vasculomotor centre of an oblong brain. Afferent synthesis (processing and analysis of the acting information) is carried out here and the signals of management goes into a vascular system (afferent nervous impulsation). This process of the vascular tonus control with a feedback on lubricous muscular fibre of vessels is carried out by vasculomotor centre constantly. The time necessary for vasculomotor centre to operate receptions, to processe and transfer of the information changes from 7 up to 20 sec.; usually it is equal to 10 -12 sec. Therefore in a rhythm of heart it is possible to find out waves with frequency close to 0,1 Htz (10), which have received the name vasculomotor. For the first time these waves were observed by Mayer with the co-authors (1931) and therefore they are sometimes referred to as Mayer waves. The capacity of slow waves of 1-st order determines activity of vasculomotor centre.

The transition from a position "laying" in positions "standing" conducts to substantial growth of capacity in this range of fluctuations CR. The activity of vasculomotor centre falls with age and the persons of elderly age have this effect practically absent (see pic. 7). Instead of slow waves of 1-st order, the capacity of slow waves of 2d order is enlarged. It means, that the process of a AD regulation is carried out at participation of nonspecific mechanisms by activization of the sympathetic department of a vegetative system. Usually in norm the percentage share of vasculomotor waves in a "laying" position is from15 till 35-40%.

It is necessary to mention also a parameter of dominant frequency in a range of vasculomotor waves. Usually it is within the limits of 10-12 sec. Its increase to 13-14 sec can specify the drop of activity of vasculomotor centre or on retardation of baro-reflector regulation.

Capacity of a "very" low-frequency amounting of a spectrum (slow waves of 2d order). Spectral amounting of a cardiac rhythm in a range 0.05 – 0.015 Htz (20 - 70 sec.), in opinion of many foreign authors, characterizes activity of a sympathetic department of vegetative nervous system. However in this case it is about more complex influences from the side of above-segmental level of regulation, as the VLF amplitude is closely connected with psychoemotional state and functional condition of a cortex of a brain. It is shown, that VLF reflects cerebral ergotropic influence on below levels and allows to judge a functional condition of a brain at a psychogenic and organic pathology of a brain (N.B.Haspekowa, 1996).

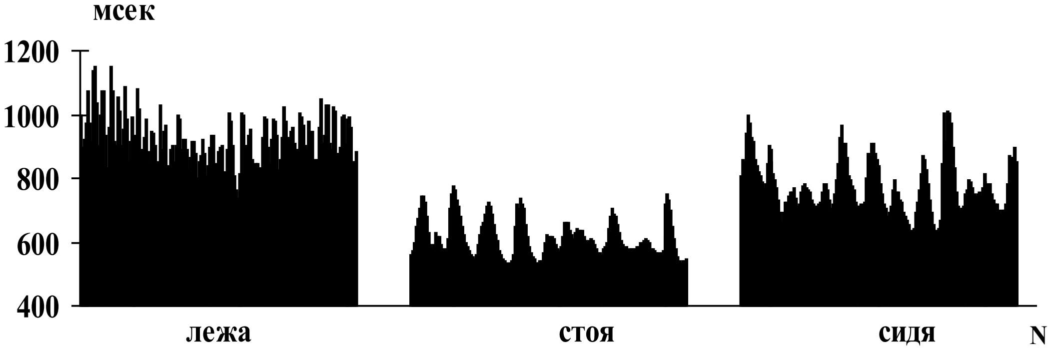
The purposeful researches hold by A.N.Fleishmann (1999) have shown the important meaning of the HRV and VLF - range analysis. In the classification of BCP spectral components, offered by him, the ratio of HF, LF and VLF amplitudes is taken into account, and 6 classes of spectrograms (see pic. 8) are surveyed. It is also shown by A.N.Fleishmann that the capacity of VLF-fluctuations of HRV is sensitive indicator of management of metabolic processes and well reflects deficit energy states. As this approach has no foreign analogues it is expediently to present its more detailed description.

In a pic. 9 the circuit of an estimation of deficit energy states with use of a series of functional tests (account in mind and hyperventilation) is submitted. High in comparison with norm VLF level can possibly be treated as hyperadaptiv state, the reduced VLF level specifies on энергодефицитное state.

Despite of conditional and in many respects still disputable character of such interpreting of VLF changes it can be useful for research of both healthy people, and patients with various states connected with infringement of metabolic and power processes in an organism.

The mobilization of energetic and metabolic reserves at functional influences can be reflected by changes of capacity of a spectrum in VLF - range. At increasing of VLF in reply to a load it is possible to speak about hyperadaptive reaction, at its drop - about afterload deficit energy.

Thus, VLF characterizes influence of the highest vegetative centres on cardiovascular subcortical centre, it reflects a condition of neurohumoral and metabolic levels of a regulation. VLF can be used as a reliable marker of blood circulation connection degree between autonomous (segmental) and supersegmental regulation levels, including hypophysis-hypothalamus and cortical levels. To be normal VLF=15-30% of total spectrum power.



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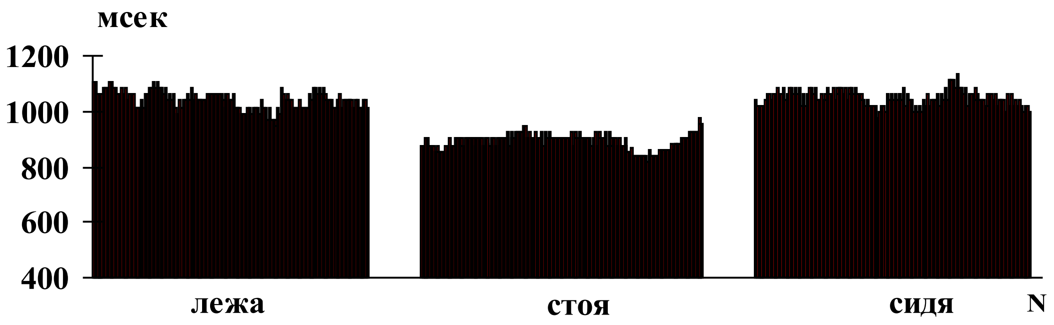

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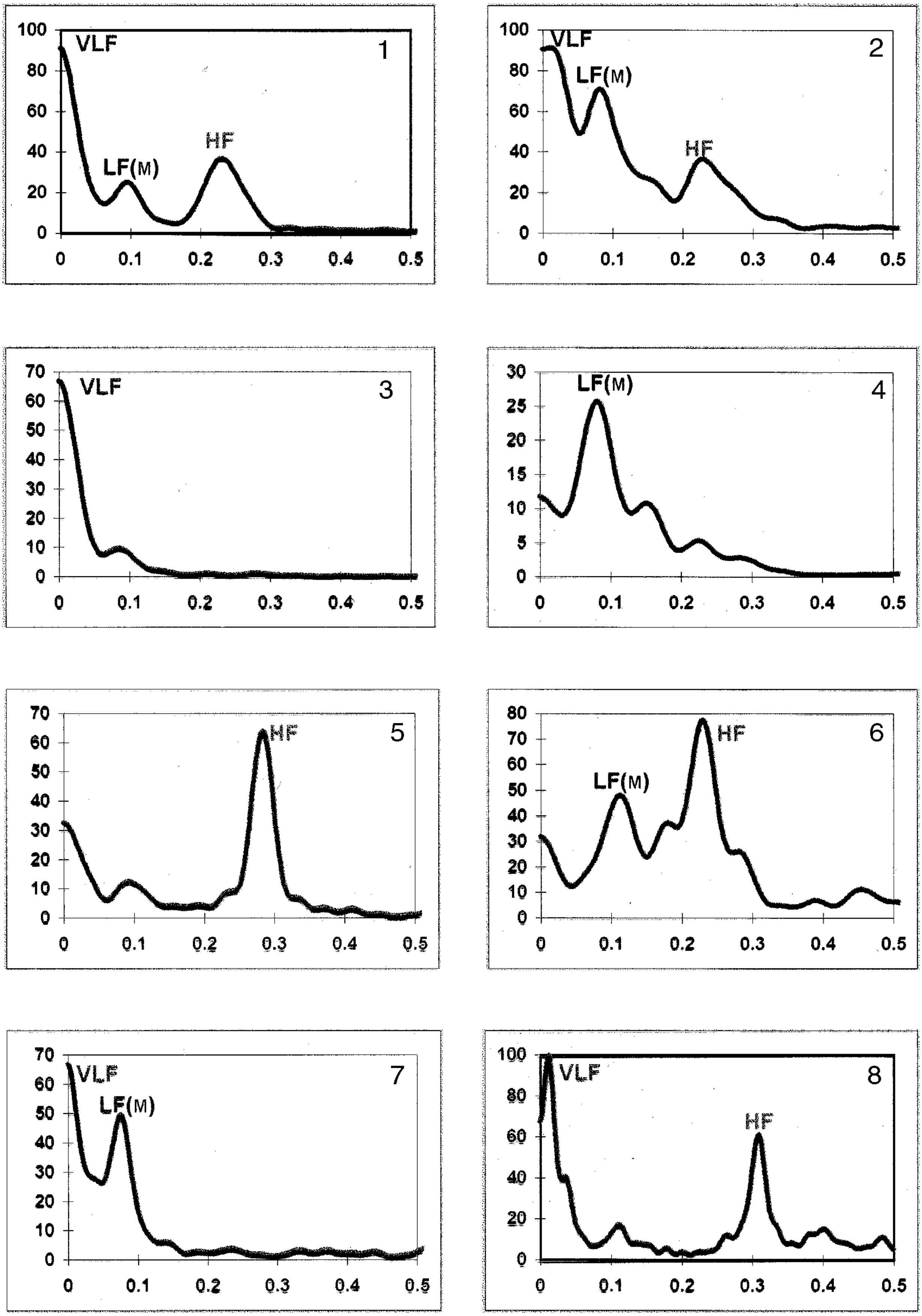
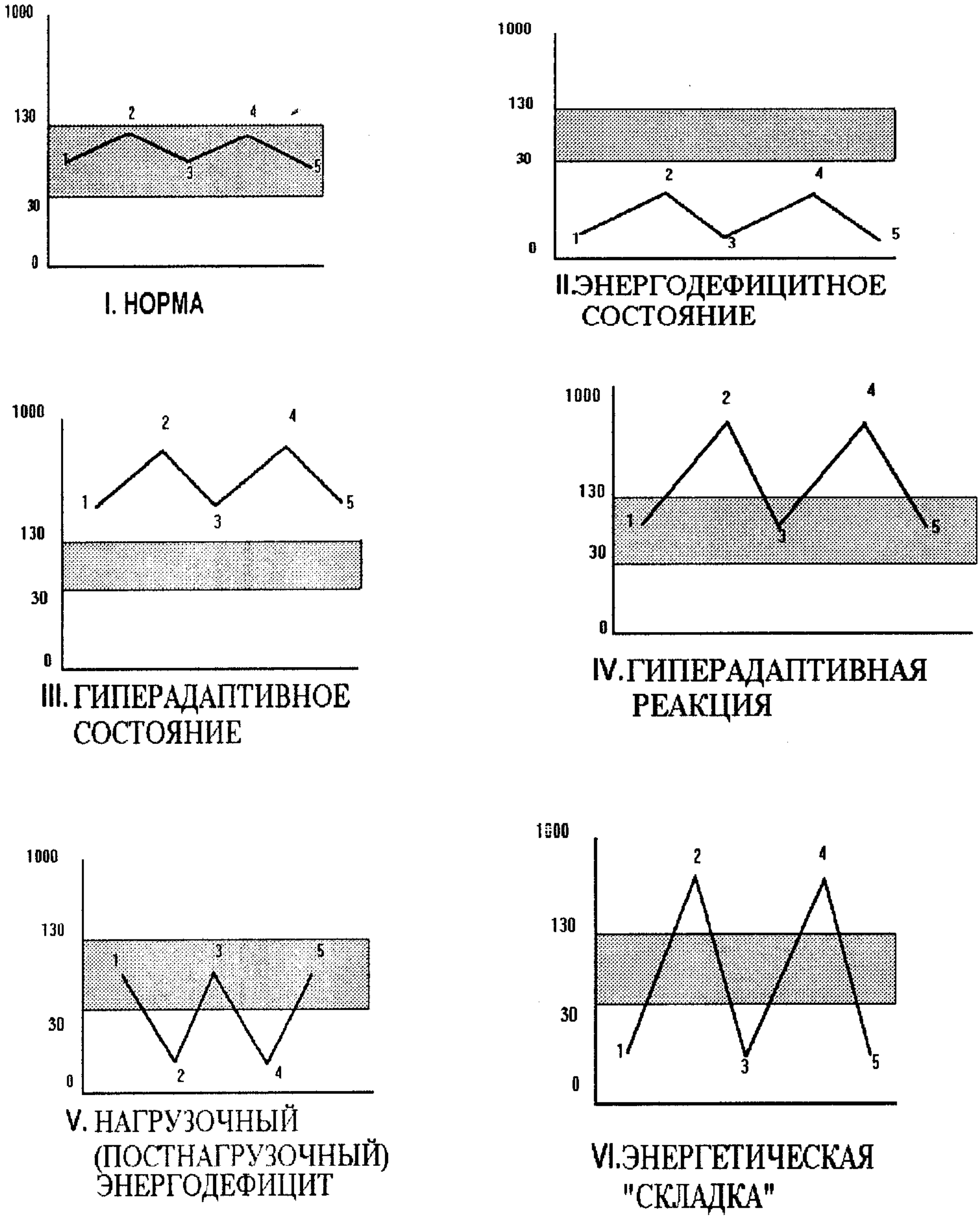
Pic.7. Cardiointervalogram by active orthostasis test with young (at the top) and old (at the bottom) patients.



Pic.8. Kinds of spectrum characteristics of cardiac rhythm (by A.N.Fleishmann, 1999).



Classification of energo-changed states on the basis of dynamics of SPM spectrums MCG on the load.
(1 – background; 2 – count in wit; 3 – recovering 1; 4 – hyperventilation; 5 – recovering 2)

Pic 9. Scheme of evaluation of deficit energy states (by A.N.Fleishmann, 1999).

7.3Functional condition integrated assessment

Integrated assessment of heart rhythm variability contemplates functional condition (not diseases!) diagnostics. Vegetative balance changes in the form of sympathetic section activation rates as nonspecific adaptation reaction component in response to different stressful influences.

One of the ways of such reactions estimation is the regulatory systems activity index (RSAI) computation. It is calculated in numbers with special algorithm that takes account of statistic figures, histogram ones and cardiointervals spectrum analysis data.

RSAI allows to differentiate regulatory systems different tension degrees and appreciate organism adaptation abilities (R. M. Baevsky, 1979). RSAI calculation is realized by a program that accounts next five criterions:

A. Regulation total effect by pulse frequency (PF) figures.
B. Total regulatory mechanisms activity by standard deviation – SD (or by total spectrum power - SP)
C. Vegetative balance by a complex of figures: RMSSD, HF, IC.
D. Activity of vasomotor centre, that regulates vascular tone, by the first-order slow waves (LF) spectrum power
E. Cardiovascular subcortical nerve centre or supersgmental regulation levels activity by the second-order slow waves (VLF) spectrum power.

RSAI value evaluates in 10 to 10. Basing RSAI values analysis next functional states may be diagnosed:

1. Optimal (working) regulatory systems exertion condition, necessary for the active organism and environment balance support (RSAI in norm=1-2).
2. Moderate regulatory systems exertion condition, when for the adaptation to the environment conditions organism requires additional functional reserves. Such conditions arises in the processes of the adaptation to a work activity, under emotional stresses or under negative ecological factors influence (RSAI=3-4)
3. Marked regulatory systems exertion condition, that relates to active defensives mobilization, including sympathetic-adrenal and hypophysis-adrenal systems activity rise (RSAI=4-6)
4. Regulatory systems overstrain condition, for which it is typical protective-adaptation mechanism insufficiency, their failure to provide adequate organism reaction to environmental impact. Here excess regulatory systems activation doesn't fortified by existent functional reserves (RSAI=6-7)
5. Regulatory systems exhaustion (asthenisation) condition, where management mechanisms activity decreases (regulation mechanisms insuf-

ficiency) and internals of pathology appear. At this point specific changes distinctly prevail on nonspecific (RSAI=7-8).

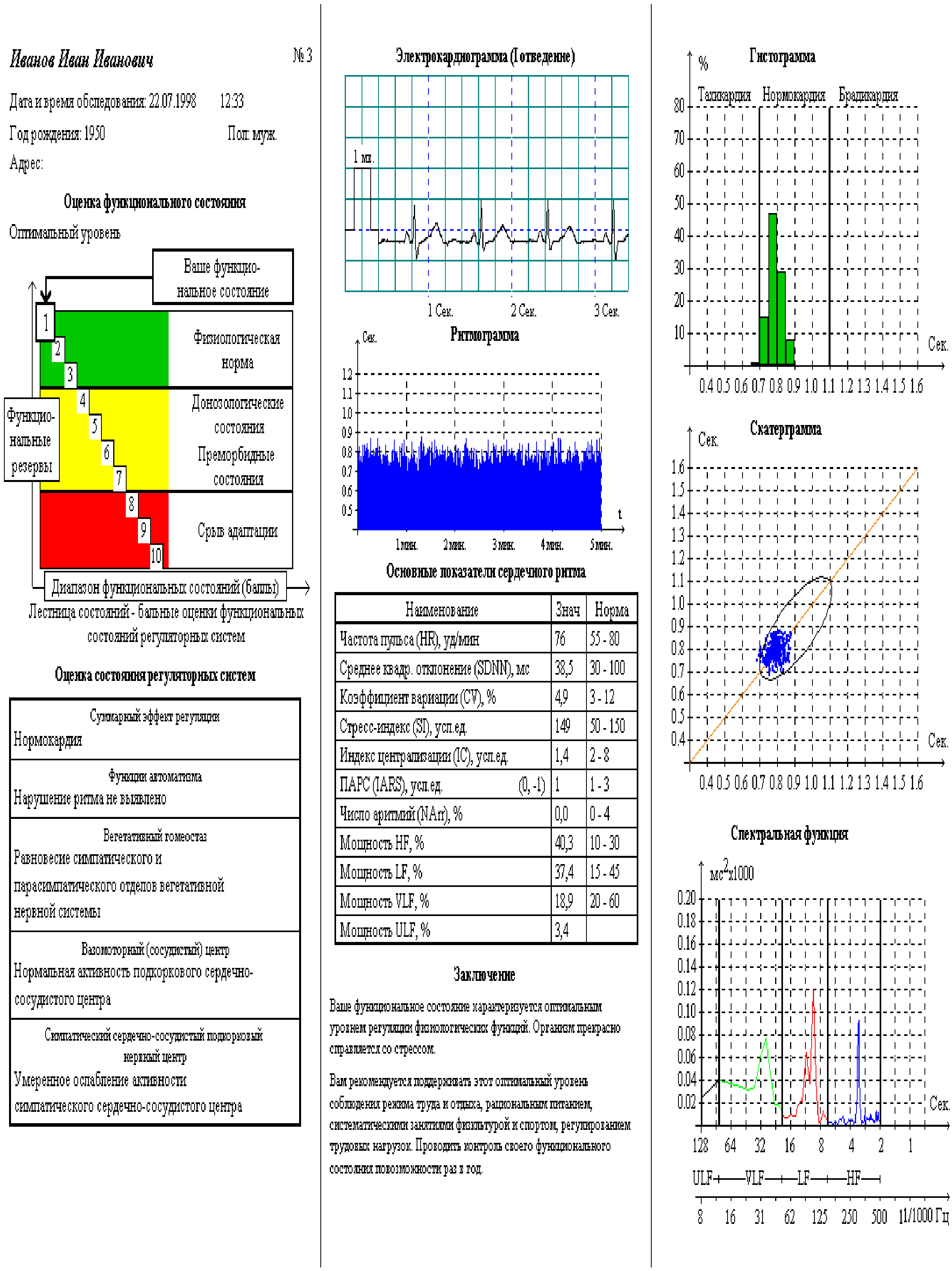
6. Regulatory systems "brake" condition (adaptation failure), when specific pathological changes dominate and adaptation self-regulating mechanisms partly or fully violated (RSAI=8-10)

When RSAI value is estimated, one can conditionally distinguish three functional conditions zones, for clearness represented like the "traffic lights": GREEN means that everything is in norm, and doesn't call for any special actions by prophylactic and treatment. YELLOW – indicates prophylactic and treatment actions necessity. Finally, RED shows, whether at first diagnostics and then the treatment of possible diseases is required.

The isolation of the green, yellow and red zones of health makes it possible to characterize the functional state of man from the point of view of the risk of the development of disease. For each step of the "stairs of states" the "diagnosis" of functional state is provided according to the degree of the manifestation of the regulatory systems voltage. Furthermore, there is a possibility to refer the examined patient to the one of 4 functional states according to the classification accepted in prenosological diagnostics (R.M.Bayevskiy, A.P.Beresneva, 1997):

- The normal state or the state of satisfactory adaptation (IARS=1-3),
- The state of functional stress (IARS=4-5),
- The state of overstress or the state of unsatisfactory adaptation (IARS=6-7),
- The state of the exhaustion of regulator systems or the disruption of adaptation (IARS=8-10)

Developed by IVNMT "Ramena" the complex "Varikard" not only makes it possible to calculate IARS and to evaluate functional state, but also forms the individual conclusions (see Picture 10). It is necessary to note that IARS does not have analogs in foreign studies. The disquality of IARS is that it makes its possible to obtain only the discrete estimations of functional states, which is insufficient during the dynamic control. For guaranteeing the continuous scale of estimations mathematical models can be used as quantitative dependences between the collection of numerical signs (values of HRV indices) and the functional states of organism (Bayevskiy R.M., Semenov YU.N., Chernikov A.G., 2000).



Иванов Иван Иванович №3

Дата и время обследования: 22.07.1998 12:33

Год рождения: 1950 Пол: муж.

Адрес:

Оценка функционального состояния

Оптимальный уровень

Лестница состояний - бальные оценки функциональных состояний регуляторных систем

Оценка состояния регуляторных систем

Суммарный эффект регуляции Нормокардия
Функция автоматизма Нарушение ритма не выявлено
Вегетативный гомеостаз Равновесие симпатического и парасимпатического отделов вегетативной нервной системы
Вазомоторный (сосудистый) центр Нормальная активность подкоркового сердечно-сосудистого центра
Симпатический сердечно-сосудистый подкорковый нервный центр Умеренное ослабление активности симпатического сердечно-сосудистого центра

Электрокардиограмма (I отведение)

Ритмограмма

Основные показатели сердечного ритма

Наименование	Знач	Норма
Частота пульса (HR), уд/мин	76	55 - 80
Среднее квадр. отклонение (SDNN), мс	38,5	30 - 100
Коэффициент вариации (CV), %	4,9	3 - 12
Стресс-индекс (SI), усл.ед.	149	50 - 150
Индекс централизации (IC), усл.ед.	1,4	2 - 8
ПАРС (IARS), усл.ед. (0, -1)	1	1 - 3
Число аритмий (NArr), %	0,0	0 - 4
Мощность HF, %	40,3	10 - 30
Мощность LF, %	37,4	15 - 45
Мощность VLF, %	18,9	20 - 60
Мощность ULF, %	3,4	

Заключение

Ваше функциональное состояние характеризуется оптимальным уровнем регуляции физиологических функций. Организм прекрасно справляется со стрессом.

Вам рекомендуется поддерживать этот оптимальный уровень соблюдением режима труда и отдыха, рациональным питанием, систематическими занятиями физкультурой и спортом, регулированием трудовых нагрузок. Проводить контроль своего функционального состояния по возможности раз в год.

Гистограмма

Скатерграмма

Спектральная функция

Pic.10. Sample of complex conclusion according to the results of HRV analysis (firmware complex “Varikard”).

7.4. The evaluation of HRV analysis results in functional trials conducting

The HRV analysis estimation in functional load trials conducting requires a special attention. The development of separate medical instructions for each functional trial is necessary. The most complete information about the HRV analysis in different functional trials conducting is contained in V.M.Mikhaylov monograph (2000). Some general recommendations regarding the interpretation of HRV indices in the functional trials consist of the following:

1. The functional state of organism estimation (vegetative balance, the degree of the stress of regulatory systems etc.) has the greatest value in the initial period (background) prior to the beginning of functional action. The interpretation of data in the different stages of functional trial must be carried out, first of all, via comparison with the initial state.

2. In all functional trials there is a transient process between the initial state and the new functional state, which is formed in the process of conducting the trial. This transitional process has different nature and different duration in different functional trials. The isolation of transitional process from the common record and its estimation by special methods is one of the important problems of functional testing. The most valuable information about the state of regulator mechanisms is frequently contained in the transitional process. The methods of the transitional processes analysis are not included in the given systematic recommendations.

3. Under the effect of functional action the new functional state is formed, and it is not steady.

This fact must be considered especially, while analyzing the dynamics of HRV indices, which reflect the subtle interconnections between different links of regulator mechanism. Therefore it is necessary to separate different stages of functional trial for the estimation.

4. At least two stages of the functional trial should be distinguished: the stage (or period) of direct effect of the corresponding factor on the organism and the stage (or period) of restoration. There is a transitional process between the end of action and the beginning of restoration also, which requires recognition, isolation and special estimation.

5. During the HRV indices estimation in the different stages of functional trial it is recommended to evaluate not only their average values, but also dynamics of changes, and the synchronization of these changes.

CONCLUSION. BASIC TRENDS IN FURTHER DEVELOPMENT OF THE HRV ANALYSIS METHODS

On present stage of the practical use of HRV analysis methods in the applied physiology and clinical medicine the approaches to the physiological and clinical interpretation of above represented data make it possible to effectively solve many problems of diagnostic and prognostic profile, evaluation of functional states, control of the effectiveness of therapeutic and prophylactic actions, etc. However, the possibilities of this methodology are far from exhaustion and its development continues. The brief enumeration of some trends in further development of the HRV analysis methods, which are developed mainly in Russia Is given below. Their number includes:

- Study of the slow waves of 2nd order (VLF) and ultra-slow-wave components of the heart rate spectrum (ULF) - oscillations at frequencies below 0,01 Hz (100 s), including the minute and hour waves (ultraDian rhythms).
- Development of the methodology of variation pulsimetry, including differential chronocardiography and new approaches to the statistical analysis of the heart rate variability (Fedorov V.F., Smirnov A.V., 2000).
- Use of heart rate variability for evaluating the level of stress, degree of the tension of regulator systems (Computer electrocardiography, M., 1999).

- Study of the heart rate variability in children and adolescents, including the influence of school loads and the age-sexual aspects (Bezrukich M.M., 1981, Shlyk N.I., 1991).
- Use of methods of the heart rate variability analysis in aerospace biomedicine, in medicine of extreme actions and in different fields of applied physiology (Grigoryev A.I., Bayevskiy R.M., 2001).
- Development of the clinical directions of the use of the method: A) in the surgery - the control of anesthesia, b) in neurology - the differential estimation of morphological and functional damages, c) in oncology - attempt at the estimation of the degree of metabolic disturbances (Computer electrocardiography, 1999, Fleishmann A.N.1999).
- Development of the new principles of heart rate variability analysis use in the cardiological clinic - the estimation of pathologic process gravity, the prognostication of outcomes and effectiveness in the treatment, the estimation of gravity and risk with arrhythmias (Dovgalevskiy P. 0., O.K.Rybak 1996, Ivanov G.G., etc.1999, Minakov E.V., etc.1998, Mironov V.A., 1998, Yavelov I.S., etc., 1997, Smetnev A.S., etc., 1995).

In conclusion it should be again emphasized that in the given systematic recommendations only the aspects of the use of the so-called “short-term” records of heart rate (from several minutes to several hours) were examined. Research methodology and analysis principles of such records differ essentially from methods of approach of higher complexity in case of working with 24-hour HRV records which can be obtained due to Holter’s monitoring. Undoubtedly, day observe data let us evaluate mechanisms of neuroendocrine regulation condition more deeply and our native researchers have achieved a great success in this field (G.V.Rabykina, A.V.Sobolev, 1998; V.M.Makarov, 1999).

However, 24-hours analysis is much more valuable and difficult, HRV day records analysis is not worked out enough, particularly it concerns to the transitional processes. Short records incontestable advantages are wider range of method using, simplicity of apparatus and software, possibility of fast results obtaining. All this determines wide perspective prevalence of HRV analysis methods in applied physiology, prophylactic medicine and clinical practice.

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Supplement 1

List of main indices of heart rate variability

№	Abbreviation	Names of Indices	Physiological Interpretation
1	PF	Pulse frequency	Middle level of functional systemcirculation
2	SDNN	Standard deviation of full solid cardiointervals	Total effect of vegetative regulation circulation
3	RMSSD	Square root from sum of difference of logical row of cardiointervals	Activity of parasympathetic chain of vegetative regulation
4	pNN50	Number of pairs of cardiointervals with difference more than 50 ms in percentage to the total numbers of them in massive	Index of prevalence level of parasympathetic chain regulation over sympathetic (relative value)
5	CV	Coefficient variation of full solid of cardiointervals	Standard index of regulation total effect
6	MxDMn	Difference between max and min values of cardiointervals	Maximal amplitude of regulator influences
7	Mo	Mode	More presumable level of cardiovascular function system
8	AMo	Amplitude mode	Nominal index of activity of sympathetic chain regulation
9	SI	Stress index (index of regulatory systems tension)	Level of tension of regulatory systems (level of activity prevalence of central mechanisms regulation above autonomic)
10	CC1	Value of first coefficient of function autocorrelation	Level of activity of autonomic circle regulation
11	CC0	Amount of shifts of function autocorrelation before obtaining coefficient correlation value less than 0	Level of activity of central circle regulation
12	TP	Total power of HRV spectrum in ms^2	Total absolute level of regulatory systems activity
13	HF, (%)	Power spectrum of high frequency component of variability in percentage from total power waves	Relative level of activity of parasympathetic chain regulation
14	LF, (%)	Power spectrum of low frequency component of variability in percentage from to-	Relative level of activity of vasomotor centre

		tal power waves	
15	VLF, (%)	Power spectrum of very low frequency component of variability in percentage from total power waves	Relative level of activity of sympathetic chain regulation
16	HFav	Middle power value spectrum of high frequency component HRV in ms^2	Middle absolute level of activity of parasympathetic chain vegetative regulation
17	LFav	Middle power value spectrum of low frequency component HRV in ms^2	Middle absolute level of activity of vasomotor centre
18	VLFav	Middle power value spectrum of very low frequency component HRV in ms^2	Middle level of activity of sympathetic chain vegetative regulation (mostly above segmental sections)
19	(LF/HF)av	Difference of middle values of low and high frequency component HRV	Relative activity of subcortical sympathetic nervous centre
20	IC	Index o centralization	Level of centralization of cardiac rhythm managing (prevalence of activity of central circle regulation above autonomic)

The above-presented list of indices does not delete of using other methods of analysis and development.

Supplement 2.

Accounting formulas for calculation of main indices of heart rate variability.

There are three forms of data presentation of HRV mathematical analysis:

1. dynamic row of NN intervals – Nni, i=1,2….n;
2. data calculated on the basis of difference between NN-intervals;
3. new row of discrete values x_i, i=1,2….N. The scheme of a new row is based on the state, that HRV is set by unceasing function from time – x(t), defined out of number of elementary actions, i.e. moments of appearance of R-notches. Function values in these moments are equal to values corresponding to NN-intervals. Function values in gaps of time between appearance of R-notches are calculated by the method of splin cubical interpolation. Row is built by method of quantum function x(t) with step 250 ms.

Statistic methods.

The calculation of basic parameters of variability must include the following indices:

HR is calculated as quantity of NN-intervals in record, sharing at duration of their record:

$$HR = 60 \cdot 1000 \cdot \frac{n}{\sum_{i=1}^{n} NN_i(мс)} \text{ (in 1min);} \quad (1)$$

Middle value:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \ (ms), \qquad (2)$$

Where x_i is a value of i-quantum element of function x(t), i=1,2,...,N;

Dispersion is meant to its selectional (empirical) value and calculated by formula:

$$D = \frac{1}{(N-1)}\sum_{i=1}^{N} (x_i - \bar{x})^2 \ (ms^2); \qquad (3)$$

Middle solid deviation (SDNN) or σ is defined as a share root out of dispersion:

$$\sigma = \sqrt{D} \ (ms); \qquad (4)$$

variation coefficient (CV) is inter-changed of its empirical characteristics and counted as relation (in percents) of average root deviation to appropriate mathematical waiting

$$CV = \frac{\sigma}{\bar{x}} \cdot 100\%$$

(5)

RMSSD – root mean sum successful deviation counted as

$$RMSSD = \sqrt{\frac{1}{(n-1)} \cdot \sum_{i=1}^{n-1} \left(NN_i - NN_{i+1}\right)^2} \qquad (ms)$$

(6)

PNN50 – relation (in per cents) of NN-intervals, difference of those $(x_i–x_{i-1})$> 50 ms, to total number of NN-intervals.

1. **Geometric methods**

Geometric methods are based on drawing graphic of function of density of variability distribution x(t). Graphic drown on next algorithm:

1. The scheme of histogram with 50ms stepping from 0.3 to 1.7 s. Thus we get 28 ranges of function. We get ordinates of histogram ranges by relation of x_i elements quantity which come in range of total N-elements quantity and have measure of 1/50 (ms)
2. The scheme of the 2nd histogram quantity of ranges (classes) in which we get with Shtrurges's rule:

$$Nclass = Int(1 + 1.44\ln(N))$$

(7)

where N is total number of elements x_i, and int is a whole part selection function.

3. Variation amplitude (-Δx) estimated (MxDmn in first approach) by empirical formula:

$$\Delta x = 0.025 + 5.83y$$

(8)

4. In each class of 2nd diagram counted the number of discrete x_i indices. On graphic for each class plotted a dot with abscise equal to average value of all x_i, and ordinate equal to quantity of discrete x_i indices in this class. If there is no data in this class dot is absent.

5. Ordinates of dots in 2nd histogram multiplied on normalization coefficient:

$$h = \frac{1}{N} \cdot \frac{50}{\left(\frac{\Delta x}{NClass}\right)} \quad \text{(ms)}$$

(9)

and connected with smooth curve by spline interpolation method. The 2nd graphic has the same measurement as the 1st one.

In function of variability density distribution graphic we can get to know next indices:

Moda amplitude (Amo) correlates with the level of maximum of function of variability density distribution and the value of argument at maximum point – with moda (Mo). Then in function of variability density distribution in 2% level from Amo founded minimal (x_{min}) and maximal (x_{max}) function values.

Variational sweep (MxMDn) – is difference between minimal and maximal values of R-R intervals dynamical row:

$$MxDMn = x_{max} - x_{min}$$

(10)

the relation of minimal and maximal values of R-R intervals

$$MxRMn = \frac{x_{max}}{x_{min}}$$

(11)

stress-index (index of regulatory systems tension - SI) counted by division moda amplitude to double multiplicative of moda and sweep

$$SI = \frac{Amo \cdot 100\%}{2 \cdot Mo(s) \cdot MxDMn(s)}$$

(12)

Autocorrelaive analisys

Correlation coefficient after 1st shift (CC1):

CC1=$r_{0,1}$, where $r_{0,1}$ is correlation coefficient which counted by the calculation of autocorellatonal function with shift value – 1 second. Autocorrelaive function is built on values of correlation coefficient row betweeen source dynamical row x_i and new rows, which we got by subsequent shifting by one mesure.Correlative cofficient is counted by formula:

$$r_{0,k} = \frac{m \cdot \sum_{i=1}^{m} \left(x_i \cdot x_{i+k}\right) - \sum_{i=1}^{m} x_i \cdot \sum_{i=1}^{m} x_{i+k}}{\sqrt{\left[m \cdot \sum_{i=1}^{m} \left(x_i\right)^2 - \left(\sum_{i=1}^{m} x_i\right)^2\right] \cdot \left[m \cdot \sum_{i=k+1}^{m+k} \left(x_i\right)^2 - \left(\sum_{i=k+1}^{m+k} x_i\right)^2\right]}}$$

, k=0,…,m-1

(13)

where k is shift step number, m is shift steps quantity (m=128 when step Δt=250 ms).

number of shifts to first zero level of correlative cooefficients (CC0):

$$CC0 = k \cdot \frac{\Delta t}{1000}, r_{0,k} = 0$$

(14)

Spectral analysis

For spectral analysis of dynamic rows of cardiointervals proposed using of non-parametrical methods, based on using of straight Fourie transformation of function x(f) in frequent distribution (specter). In realisation of this algorithm on PC usually use discrete Fourie transformation and particularly fast Fourie transformation, using next 2 formulas:

$$X_l = \sum_{k=0}^{N-1} x_k \cdot e^{-jl\Delta\omega k\Delta t}\Delta t, l = 0, 1, .., N-1 \quad (15)$$

$$x_k = \frac{1}{2\pi}\left(\sum_{l=0}^{N-1} X_l \cdot e^{-jl\Delta\omega k\Delta t}\Delta\omega\right), k = 0, 1, .., N-1 \quad (16)$$

$$x_k = x(k\Delta t)$$

Here

$$X_l = X(l\Delta\omega)$$

N is a number of counting out, Δt is time interval between the ones, Δω is spectrum stem in the frequency domain, that calculates by the formula:

$$\Delta\omega = \frac{2\pi}{T} \quad (17)$$

, and T – analyzing signal time interval, a so-called **record length or main order:**

$$T = (N-1)\cdot\Delta t \quad (18)$$

Spectrum (15) is dissymmetrical (two-sided) relative to its central point l=(N-1)/2, that is: $X_l = X_{N-1}$, that's why for its graphic representation and following investigation it's enough first (N-1)/2 amplitudes (one-sided) spectrum. When switching to the one-sided spectrum from the two-sided one its amplitudes should be normalized by multiplication on 2 (power spectrum is normalized by multiplication on 2)

The upper bound of analyzing spectral band is determined by the numeralization frequency of signal $f_s=1/\Delta t$ and equal $f_s/2$, and the lower bound is equal frequency resolution1/T. Value 1/T is also called the main circular frequency. Spectrum analysis results frequency range from 1/T to f/2 is called spectral band width.

For getting well smoothed (interpolated) spectrum by brief signal realization and for the spectral peak frequency evaluation accuracy increasing the basic temporary consequence supplement with nulls is executed. It results in appearance of m=n/N intermediate values in the spectrum, where n – number of nulls added; N – basic signal values number in temporary realization. However it is possible to increase frequency resolution only due to analyzing signal section duration increasing, but certainly not due to supplement with nulls.

In general case for the (15) execution it is necessary to calculate N^2 product of $x_k F_N^m$, where $F_N^m=(e^{-jl\Delta\omega k\Delta t})^m$ – multiplication factor (m=kl).

SPF is calculated by a number of discrete values x_i, I=1,2,…,N, with obtained function x(t) quantification method by the next algorithm:

1. The five-minutes record division into three segments;
2. Function x(t) centering in each segment with regard to the average value (constant component elimination) and simultaneous weighing of it (fon Hann window application) according to formula:

;

(19)

, where x_i, $\hat{x}_i$ are basic and centralized-weighed signals amplitudes, $\bar{x}$ is average value, calculated according to formula (2), and W – fon Hann window, that in time domain is described like squared cosine function:

$$W_i = 0.5\cdot\left[1+\cos\left[2\pi\cdot\left(\frac{i-\frac{N-1}{2}}{N-1}\right)\right]\right],\ i = 0, 1, 2, .., N-1$$

(20)

3. Value series x_i, I=1,2,…,N supplement in every segment with nulls to the nearest number “two in power”. In compliance with agreements (ch. 2) a three-minute segment consists of 720 readings, what should be supplied with nulls up to 1024 readings.
4. Fourier conversion of the value series, i=1,2,..,N in every segment according to formula (15) using fast Fourier transform.
5. Spectrum X_i amplitudes normalization by multiplication by $\sqrt{2}$.
6. SPF computation according to formula:

$$P_l = \frac{N}{2}\cdot\left(X_l\right)^2 \quad 0, 1, .., \frac{\ }{2} \quad (ms^2)$$.

(21)

7. SPF segments linear averaging-out

Value $P_i(\omega)$ is also called power falling on frequency $\Delta\omega$ unit on the frequency ω. Total power is equal sum of powers falling on all units of frequencies $\Delta\omega$.

On a diagram power is showed in frequency k/T values that changes from 1/T to 1/(2 Δt). In Russia the agreement of inverse scale on horizontal axis use without periodogram modification. At that abscissas are measured in run length.

Spectral analysis indexes calculation is kept in four frequency ranges Δf_{HF}, Δf_{LF}, Δf_{VLF}, and Δf_{ULF};

high-frequency rippling HF in range:
0.4-1.5 hertz (2-6.6 sec)
low-frequency rippling LF in range:
0.15-0.04 hertz (7-25 sec)
very low frequency rippling VLF in range:
0.04-0.015 hertz (25-66 sec)
ultralow-frequency rippling ULF in range:
0.015-0.003 hertz (66-333 sec)

Next values are to be calculated by the spectrum evaluations: ***HF, LF, VLF, ULF*** – spectrum powers in frequency ranges Δf_{HF}, Δf_{LF}, Δf_{VLF}, and Δf_{ULF} correspondingly.

In every of frequency ranges Δf_{HF}, Δf_{LF}, Δf_{VLF}, and Δf_{ULF} harmonics powers spectrum evaluations maximal values (HFmx, LFmx, VLFmx, and ULFmx) are to be found.

Spectrum HF power (total power in the frequency range Δf_{HF}) is calculated according to formula:

$$HF = \sum_{j=L_{HFl}}^{L_{HFr}} P_J \quad ,(ms^2) \qquad (22)$$

, where L_{HFr} and L_{HFl} are numbers of spectrum evaluations corresponding to range Δf_{HF} scope.

Powers of spectra LF, VLF, ULF (in frequency ranges Δf_{LF}, Δf_{VLF}, and Δf_{ULF}) are calculated in much the same way.

Total spectrum power:
TP=HF+LF+VLF+ULF;

HFt,LFt, VLFt, ULFt – spectrum peaks maximal (dominating) periods values in corresponding frequency ranges;

Average spectrum power in frequency range Δf_{HF}:

$$HF_{av} = \frac{HF}{\left(L_{HFr} - L_{HFl}\right)}$$

(25)

Average spectrum power in frequency range Δf_{LF}:

$$LF_{av} = \frac{LF}{(L_{LFr} - L_{LFl})} \quad (26)$$

Average spectrum power in frequency range Δf_{VLF}:

$$VLF_{av} = \frac{VLF}{(L_{VLFr} - L_{VLFl})} \quad (27)$$

Average spectrum power in frequency range Δf_{ULF}:

$$ULF_{av} = \frac{ULF}{(L_{ULFr} - L_{ULFl})} \quad (28)$$

Spectrum power in frequency range Δf_{HF} percentage wise to all range:

$$HF\% = \frac{HF}{TP} \cdot 100\% \quad (29)$$

Spectrum power in frequency range Δf_{LF} percentage wise to all range:

$$LF\% = \frac{LF}{TP} \cdot 100\%$$

(30)

Spectrum power in frequency range Δf_{VLF} percentage wise to all range:

$$VLF\% = \frac{VLF}{TP} \cdot 100\%$$

(31)

Spectrum power in frequency range Δf_{ULF} percentage wise to all range:

$$ULF\% = \frac{ULF}{TP} \cdot 100\%$$

(32)

Centralization index

(33)