EXTRACTION OF FUNCTIONAL STATE PATTERNS BASED ON AMPLITUDE-PHASE COUPLING OF ECG

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Abstract. The present study is dedicated to the investigation of slow-waves in heart rate activity of healthy persons. Approaches to the description of the cardiovascular functional states using the dynamic characteristics of the amplitude-phase coupling mechanisms of the electrocardiographic signal are described. Amplitude-phase coupling based pattern extracting was carried out. Suggested informative features and patterns of regulatory systems will allow the analysis of the diagnostic procedure results with reference to the central mechanisms of regulation and control.

Keywords: heart rate, ECG, amplitude-phase coupling, physiological pattern.

List of Abbreviations

ECG – electrocardiogram; RR-interval – interval between two R-peaks; RRs – smooth RR-intervals, R-gram – a row of R-peak amplitudes, Rs – smooth R-gram, mV – millivolts, ms – milliseconds, OFS – organism functional state, CVS – cardiovascular system, AHS – apparently healthy person, ANS – autonomic nervous system, HRV – heart rate variability

Introduction

Small reversing deviations of the organism functional state (OFS) in phase transitions between the “health standard” to the prenosological and further to the premorbid states are referred to understudied sections of human physiology. Correct use of the initial concept of “health standard” is practicable if the examined physiological process is stationary over time, which is practically possible under conditions of systemic OFS (Schmidt & Thews, 2005, Vinogradova, 1986, Baevsky & Berseneva, 2008, Kuznetsov 2011, 2013).

The human body as a semi-open dynamic system within its subsystem hierarchy utilizes indirect "soft" mechanisms for controlling the phase transitions of subsystems from one functioning to another one with the preservation of systemacity. The structures of each successively lower level of the hierarchy are continuously involved into the dynamic operation of event variant enumerating with a mandatory and reliable resulting choice. The continuous operation presupposes the presence of regulatory and operational biorhythms, and the small deviations from normal OFS require the presence of control rhythms. With the determination of a hierarchical system algorithm chain (past and present) it becomes possible to forecast the dynamics of dependent biorhythm indicators basing on control biorhythm data.

In medical practice, symptomatic diagnostics and corresponding management decisions have a significant lag of a few phases from the functional deviation. In this case the effectiveness of the prognosis and medical diagnostic process is reduced. Diagnostics of highly hierarchical biorhythms requires advanced system approaches, including modeling of physiological biorhythm synchronization and desynchronization, and in particular, in the heart rate (Ashoff, 1984). Despite of the modern arsenal of mathematical and technical methods, the professional intuition of a physician still plays a huge role in the diagnostic process. It is extremely important to provide the medical support system with all possible data, which is not duplicating information on the functional state of the patient’s cardiovascular system (CVS).

Normally, the operation of CVS is under the control of the sympathetic part of the autonomic nervous system (ANS) with a wide interface for internal and external stimuli. The stimuli provide a set of influence factors and corresponding reactions. The ANS activity reflects in the variability of both the heart rhythm and the amplitudes of R-peaks of the QRS-complex (Schmidt & Thews, 2005). It is supposed that the research of interconnections or coupling of RR-intervals and the corresponding R-peak amplitudes R of ECG will allow studding the formation of the cardiac signal electrical structure in the current functional state of the CVS.

According to the principle of frequency coding, the amplitude of the perceived external influences of various nature is transformed into the frequency of the electric generator potential, and the external influence duration is transformed into the generator potential duration (Kostuyk, 1988). Consequently, the dynamics of the external stimuli intensity could be studied by heart rate variations. Heart rate variability (HRV) is a universal operative response of the whole organism to any impact of the external and internal environment while maintaining the balance of the effects of the sympathetic and parasympathetic parts (Schmidt & Thews, 2005, Kostuyk, 1988, Heart rate variability standards, 1996, Kuznetsov, 2010). However, the question about the generator potential amplitude remains open, and, in particular, the dynamics of the plateau level of the action potential is outstanding. The system correlations of the amplitude and phase components remain little studied (Kuznetsov, 2010-2011). In fields of preventive and evidence-based medicine a variety of analysis methods has been proposed for ECG-signal and rhythmograms (Kuznetsov, 2010). Nevertheless techniques for a digital series of R-amplitudes that represent, outlined further as the R-grams (Kuznetsov, 2011), representing the QRS-dynamics, are small in numbers (Kuznetsov, 2010-2011). One of the priorities of HRV research is the analysis of slow (long) waves of the first and second orders (Baevsky & Berseneva, 2008, Heart rate variability standards, 1996) in the range from 0 to 0.015 Hz. However, the same range is could be registered at R-grams of the ECG (Kuznetsov, 2012). Taking into account various biophysical myocardium processes characterized by a chronoinotropic effect, the Frank – Starling law, and others, it is concluded that there are special processes that determine the coupling of the R-wave amplitude and the cardiocycle phase in form of the RR-duration. It could be expected that a new research perspective on the dynamic relationship between energy and rhythm will make it possible to re-evaluate the OFS level.

The purpose of the present study is to introduce the method of amplitude-phase coupling of the electrocardiogram (ECG) components for solving the problems of finding physiological OFS patterns in apparently healthy subjects.

Methods

In terms of second order slow wave studying, the authors proposed dependency graphs of the systolic potential of the ECG and the RR-interval duration of young apparently healthy subjects (AHS). For orthogonal coupling of long-wavelength ECG components, the “moving averages” method (Kuznetsov, 2010–2013) convenient for R-grams and rhythmograms with high-frequency component filtering, was applied. The accepted width of the scan window ($n = 400$ samples) corresponds to the recommended standard 5-minute ECG-registration (Heart rate variability standards, 1996). Smooth parametric diagrams (RRs and Rs) was obtained using a moving average with a shift of 1 count represent the dynamics of the corresponding rhythmogram and R-gram processes in the very low (VLF) and ultra-low (ULF) frequency ranges (Heart rate variability standards, 1996, Kuznetsov, 2010). It allows to visualize the amplitude-phase ECG coupling with a diagram named as “regulatory curve” (Kuznetsov, 2010–2013) (Fig. 1).

A Lissajous figure with a sign of cross-correlation function was obtained by means of orthogonal process composition in a unified coordinate system. The image allows the highlighting the time shift between the amplitude and phase components of a single ECG-signal. If the slow wave captures the entire signal, the regulative curve will appear in the shape of a circle.

The curve closure determines the slow wave period. With a relative delay between amplitude and phase ECG components, the curve is deformed, taking the shape of ellipse with an information slope indicating a phase shift (Permiakov et al, 2018).

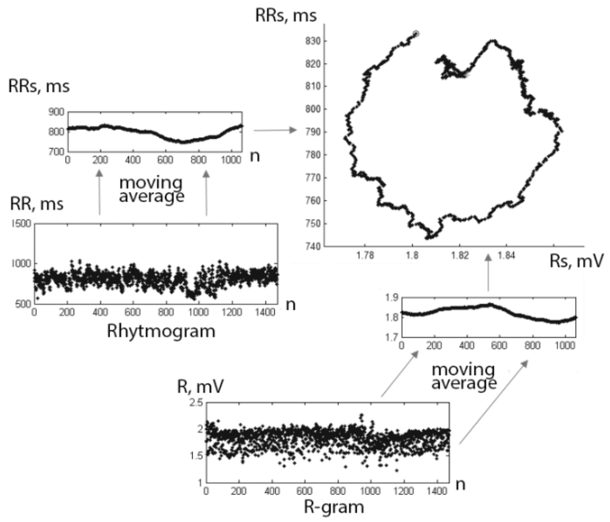


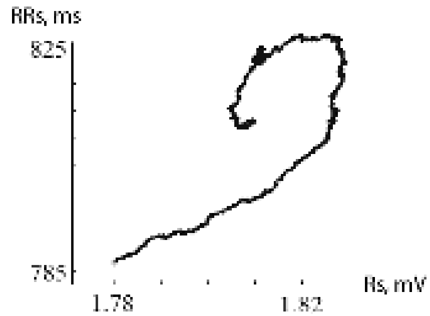
Fig. 1. The formation of the RRs(Rs) dependency graph RR-interval rows had discretization period of 1 msec, R-amplitude raw had quantization interval of 3,6 uV. Moving average window = 400 dots. Dots represent discrete values of RR-intervals and R-amplitudes. Smooth data rows are visualized by solid lines after moving average processing. The combination of smooth data rows is reflected as RRs(Rs) graph. The RRs(Rs) graph

Over the period of 2008-2018 on the basis of Vladimir State University named after Alexander and Nikolay Stoletovs more than 1000 registrations of apparently healthy 2-year students were carried out. Recording was carried out in a rest condition and sitting position. The registrations were of two types: group and serial. For present the study, 504 twenty-minute ECG recordings were selected from 117 AHS (413 group recordings and two serial registrations of 30 and 61 ECG-recordings). Based on the results of calculating the RRs(Rs) graphs a primary classification was proposed (Fig. 2).

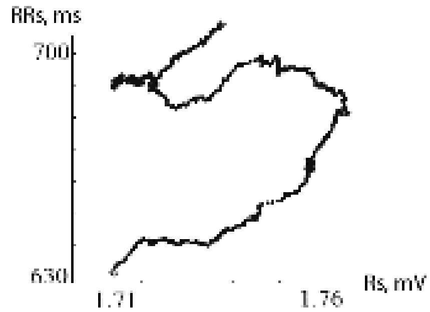
The variety of patterns in the regulatory curves of healthy subjects indicates the prevalence of individual coupling characteristics. The proposed classification should be considered conditional, since the class of curves without the formation of stable cyclic elements involves the certain difficulty for analysis (Fig. 2 c).

Curves belonging to the first two classes with observable closed or semi-closed cycles represented approximately 60% of the total number of group recordings and about 80% in each of the recording series.

According to group ECG recordings, a influencing slow wave was detected on most diagrams in the form of one complete or, more often, incomplete fluctuation with an individual situational period depending on subject. Generally, the allocated cycles were closed by 70% (σ = 15.9%). To determine the duration of incomplete cycles, the interpolation method of the elliptic element was applied.



A



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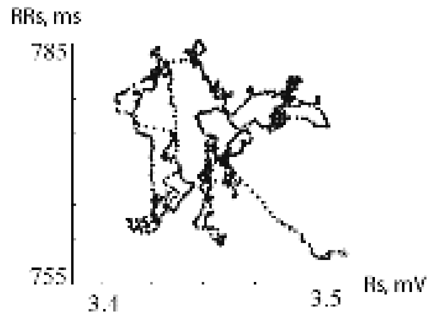

C

Fig. 2. Regulatory curves of three different apparently healthy persons. Duration of the registration was 20 minutes each. Moving average window = 400 dots. Dots represent discrete values of smooth RR-intervals and R-amplitudes. Dot closeness is related to smooth characteristic alteration that is revealed at Fig. 2 A) and Fig. 2 B). Non-stationary state at Fig. 3 C) allows outlier-type of dot appearance

The distribution of cycle durations had a log-normal distribution form of with a mode of 517 sec and an average value of 813.9 sec (σ = = 312.5 sec, variational range = 1582 sec). Attempts of parametric prediction of the cyclic structures formation using statistical, spectral, and variational parameters of HRV were made utilizing multidimensional data analysis methods and classification trees. The accuracy of the different model classification for the “cycle formation – absence of cycle formation” criterion did not exceed 40%.

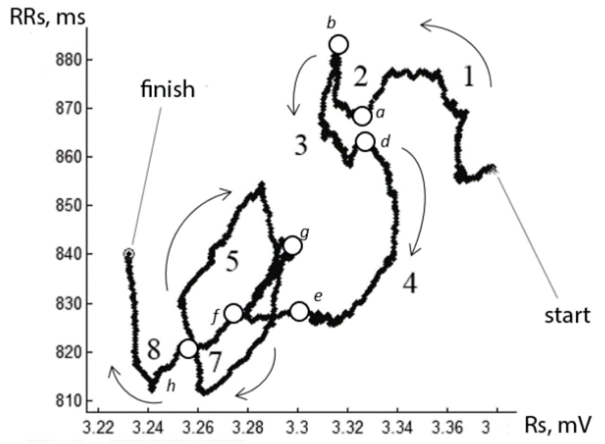

Fig. 3. Significant episodes were marked with letters. Arrows describe the regulatory curve progress. For visual analysis time stamps of the regulatory curve start and finish were added

For the functional pattern analysis of amplitude-phase coupling, it is necessary to identify the parameters that are significant for each regulatory curve. As an analysis flow demonstration, one of the representative serial registrations of an AHS, belonging to the class of curves with closed or semi-closed cycles and swirl changes (Fig. 3), was chosen.

Discussion

In scope of the analyzed ECG-recording (Fig. 3), 7 cyclic stages were detected. Each stage lasted from 4.5 minutes to 7.6 minutes (Table 1). In the second half of the recording semiclosed cycles brought monotonic relaxation of the RR intervals in narrow ranges of amplitude regulation (0.04-0.05 mV). Three swirl change events were detected in the first third of recording.

The primary swirl direction of cycles was clockwise. Thus, during using HRV methods throughout the entire recording with the standard registration window, it is a high chance to select for the analysis an unsteady recording section (Fig. 4), which contains transitions between cycles or a swirl changes. Such events will negatively affect the interpretation of the results with a standard methodology.

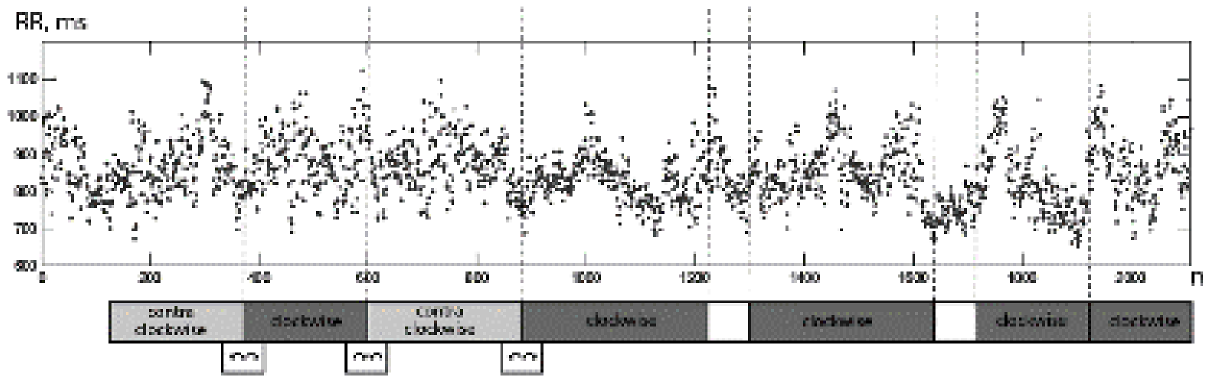

Fig. 4. Double arrow sign belongs to the episode of regulator curve swirl alteration. Dots represents RR-intervals without interpolation. Contraclockwise, Clockwise – highlight the specific regions with stable regulatory curve swirl direction with the relative vertical marker reference to rhythmogram

Table 1

Stage analysis of the AHS regulatory curve

Stage	t, sec	Description
1	338	From the registration beginning the contraclockwise cycle with the RR value rising and amplitude regulation in range of 0.04 mV is setting up. Swirl change appeared at point *a*
2	302	After swirl change event the second semiclosed cycle was setting up. The cycle is limited with maximum average RR-value of 885 ms at point *b*. Then the new event of swirl change appeared.
3	389	Semiclosed cycle of 3d stage repeats the shape of second stage cycle elements with observing shift and duration. At d point swirl change occurred with the further new cycle start
4	449	At this stage more prolonged cycle was started. Within amplitude regulation the smooth average RR-value descending of 30 ms was occurred. Semiclosed cycled came to the end at the lowest point *e* with the further plain period of constant RR = 829 ms. The duration of the plain period is 58 sec
5	456	At *e* point closed clockwise cycle was started with the amplitude regulation of 0.05 mV and mean heart rate value alteration of 32 ms. The cycle was ended at point *f*. Next step is a passing to point g within 40 seconds.
6	272	At *g* point new semiclosed cycle was started with amplitude-phase delay comparable to stage 5. Swirl direction was clockwise, the cycle was ended after passing the lowest point of lowest minimal mean RR-value of 811 ms with amplitude regulation in range of 0.05 mV.
7	298	At *h* point new clockwise cycled was started similar to stage 6 by all the parameters besides amplitude regulation range, that is shifted to 0.03 mV

Results

1. The delay and the coupling mode of the amplitude and phase ECG components form the patterns of regulatory mechanisms and soft control. Their changes correspond to an optimal condition search mode for the CVS functioning.

2. Analysis of the regulatory curve allows the current OFS level to be described by a set of functional patterns:

• Formation of a sustainable cycle. Constant temporal shift in the range of slow waves. Steady predicted condition.

• The swirl direction of the curve, which represents a graph dependence of smoothed rhythm grams and R-grams, determines the binary pattern of the ECG component relationship.

• The clockwise swirl direction represents the control mode of the heart functioning, the energy component of the ECG is coupled to phase component. The mechanisms of heart regulation are adjusted according to environmental information.

• The contraclockwise swirl direction of the cycle means the control mode of the heart functioning, where the phase component of the ECG is coupled to energy component. The mechanisms of heart regulation are adjusted according to information from the internal environment.

• A swirl direction change corresponds to inhibition of the regulation of one of the coupling processes relative to the coupled one, with the purpose to change the roles of the functional relationship between them.

• A constant swirl direction change without a stable cycle formation corresponds to the conditions of an unsteady adaptation mode of the CVS with an increase in the functional reserves consumption.

An approach for highlighting new informative signs based on the study of patterns of amplitude-phase conjugation of an ECG signal in healthy subjects was proposed. It is advanced for the diagnostic process and automation of diagnostic process applying the parameters of cycle duration, swirl direction and event of swirl change. Development of algorithms for automatic analysis of regulatory curves will allow diagnostic system extension for assessing the treatment quality of patients under intensive care conditions.

The program of further research will include the development of algorithms for automatic regulatory curve analysis in the monitoring mode, the study of fractal properties, as well as the study of the specifics of amplitude-phase ECG coupling depending on the psychological status of the subject.

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