Investigation of ECG amplitude-phase coupling mechanisms

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Introduction

The paper studies system effects in human organism, which reflect in electrocardiographic (ECG) data. The reliable and informative interpretation of ECG information is the basis for establishing and predicting the level of organism functional state (OFS) for a single person. In general despite the successes in diagnostics and treatment of heart deceases, specialists could not reach the level that provides system understanding of physiological mechanisms in the human organism that would be enough for accurate external regulation and control of the heart activity. Only the highest qualification and professional intuition of the cardiologist allow defining reliably determine the current OFS basing on typical results of the morphological analysis of small time group of cardiocycles.

The transformation of a quantitative analysis of ECG time-form signal to a system qualitative OFS criterion is key aspect of ECG-diagnostics. Consequently the interpretation of the ECG becomes the urgent task of information system analysis. ECG is discovered to contain informative system features in RR-interval dispersion and amplitude dispersion. In this paper authors adhered the principle of frequency coding in physiology and biophysics [1, 2], which allows coupling of the external stimulus amplitude and phase with the frequency and duration of discharges of the communication generator potential. It is known that in terms of physiological control and regulation the intersystem interconnection between the external environment and the human organism is accomplished only by rhythms. This principle is fit also for organism intersystem, for example: baroreceptors transform the pressure levels of the pulse wave into the discharge frequency [2]. In this sense, the system endogenous rhythm of the human body adopts a heart rhythm in the form of a sequence of cardiac cycles, or RR-intervals [1-3].

The electrocardiogram does not contain the direct information about the result contractile heart function, which provides a volumetric blood output. However, the maximum electrical action potential of each cardiac cycle (R-peak) indicates the strength of the electrical effect on the ventricular myocardium, predetermining the intensity of their contraction, and, consequently, the amount of blood ejection into both circulation circles. Thus, the absence of a direct connection between the rhythmic (phase) and energy (amplitude) processes explains the generally accepted representation of the ECG information in orthogonal coordinates, but it does not deny the mechanism of their coupling.

Earlier, the mechanisms and visualization of ECG amplitude-phase coupling in healthy persons using statistical methods of processing and combined analysis of digital series of R-grams and RR-intervals were discussed in the previous studies [4-6]. The previous results indicated the presence of complex and nonlinear amplitude-phase communication mechanisms in the heart activity. With the growth of the ECG averaging intervals, the effects of cause-effect relationships between the ECG-components were discovered, including the processes up to the harmonic functional connection - at the intervals of averaging Δn = 300-400 cardiocycles, that equivalent to 5-6 minutes of registration.

Further [7] it was found that, separately, the ECG amplitude and phase components in healthy young people in a state of rest and in the form of finite series follow the normal distribution law. The linear form of the distribution of statistical and information parameters of these digital series on a single diagram "standard deviation (σ) - information entropy (I*)" and on a semi logarithmic scale also indicated a normal distribution law fitting for all group and serial ECG-registrations. Nevertheless the structural and informational features of R-peak amplitudes have not sufficiently been studied in healthy and sick persons as for RR-intervals.

The purpose of the study is a research the amplitude-phase coupling form in the electrocardiographic information.

Materials and Methods

The experimental database consisted of 503 twenty-minute ECG-records of 117 conditionally healthy persons (CHP): students aged 18-20 years, without symptoms and indications of cardiovascular system diseases. Registrations were carried out using the second thoracic lead (Nehb lead) in group and serial forms during rest period with a 5-minute subject adaptation to the registration conditions. Recorded ECGs were converted into digital rows of R-grams and RR-intervals.

412 group ECGs were recorded from 117 people in spring period (March-May), the other 91 serial ECGs were recorded from 2 young men in autumn period, (30 ECGs for CHP #1 and 61 ECGs for CHP #2).

The group of conditionally healthy young persons was proposed to be a statistical ensemble on the basis of the following features: age, day schedule (same course), rest state, registration time (13:00-16:00). These features allowed carrying out statistical averaging procedures for the ensemble of the parameters of ECG, assuming the ergodic hypothesis.

The method of structural and topological analysis of ECG interval data applying the standard deviation (σ) and the information-related entropy (I^*) diagram was used in the processing, analysis and modeling of RR- and R-data rows, where

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})}{n}}, \quad (1)$$

$$I^* = \frac{1}{n \cdot \ln 2} \ln \frac{n!}{\prod_{i=1}^{k} n_i!}, \quad (2)$$

x_i – sampled value of RR- or R-data row, $\bar{x}$ - mean value of the row, n – number of data samples, n_i – number of data samples in the histogram tier, k – number of tiers in the data structure.

It must be noted that the important criterion for the calculation of information entropy of two different digital series was the identity of the combinatorial conditions [8]. To fulfill this criterion, the digital row of RR-intervals (hereinafter RR-series) was represented with a sampling rate of 1 ms, and the digital series of R-peak amplitudes (hereinafter R-series) - with a sampling rate of 3.9 μV.

For comparing the experimental data and refine the results of the analysis, additionally authors have chosen for analysis 14 twenty-minutes ECG of sick people (myocardial infraction).

Information Coupling Model. The structural diagrams ($\log\sigma(I^*)$ form) of the data R-series and RR-series were combined in a one particular diagram as follows: the 0X axis with the scale of information entropy measurement is general, the 0Y1 and 0Y2 axes with the standard deviation measurement logarithmic scales are separate. Fig. 1 shows the combined diagram, where each ECG-record is represented by two points (I^*_{RR}, σ_{RR}) and (I^*_R, σ_R) connected with a straight infocommunication link (ICL).

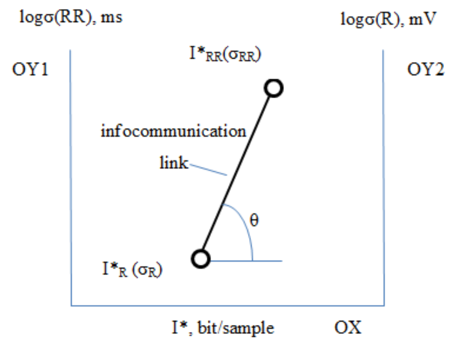

Figure 1: Formation of infocommunication links

Authors denoted this link as direct interpolation line. The ICL depends on the amplitude and phase parameters, that was resulted in the value of the angle θ of infocommunication link. ICL could be characterized by coupling angle in the following way – acute θ refers to $I^*_{RR}>I^*_R$ state, right θ refers to $I^*_{RR}>I^*_R$ state, and obtuse θ refers to $I^*_{RR}<I^*_R$ state.

Results

It is known that RR-series of CHP in rest state tend to build up a normal distribution of RR-intervals [7]. The analysis of R-series structure was carried out and it was shown that R-amplitudes had the same tendency to a normal distribution building up, as shown at fig. 2. Both series are fitted to a linear trend with $R^2>0.98$.

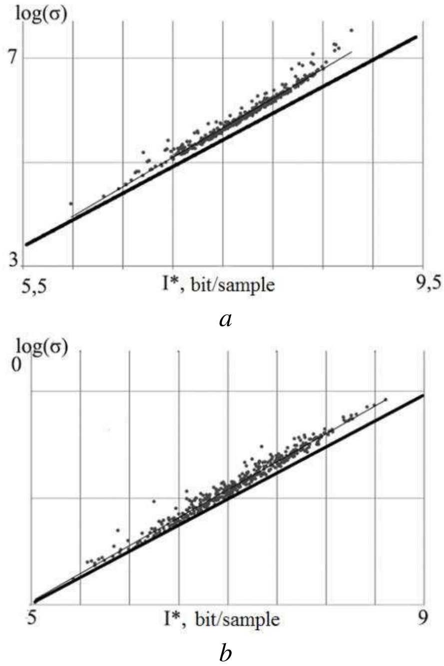

Figure 2: Comparison of RR-series (a, dots with trend line) R-series (b, dots with trend line) with normal distribution (bold lines)

The fig. 2 shows the following: a) a deviate between experimental data trend and linear theoretically data for I^* is determined by experimental data amount limitation, b) the maximum of deviate between experimental data trend and linear theoretically data for I^* corresponds to high mean values of RR and R, which is caused by reducing of the experimental data amount in a 20-minutes registration.

Consequently each group of RR and R points represents a statistical ensemble that is fitted to the normal distribution law. In common the deviation from trend parallelism determines numerically the different level of normalization.

All group R- and RR-series data were placed to the same structural diagram and linked with ICLs, see fig.3a. The distribution of the θ in group ECG-data of young healthy persons was discovered to be fit to lognormal, see fig. 3b.

As it is shown on fig.3 in the large group the statistical regularities are distinguished in the distribution of the angles θ of their orientations relative to the common horizontal axis 0X. In this case, the number of ICLs with an acute angle (θ<90°) prevails over the number of links with an obtuse angle (θ>90°). The most probable value of θ calculated from the group data was 76°. A stable and apparently non-chaotic ICL distribution at fig. 3b causes the parametric diagram of R-series and RR-series to have features of a reliable information-statistical model interface surface.

The statistic comparison of acute and abuse θ in different groups is shown at fig.4.

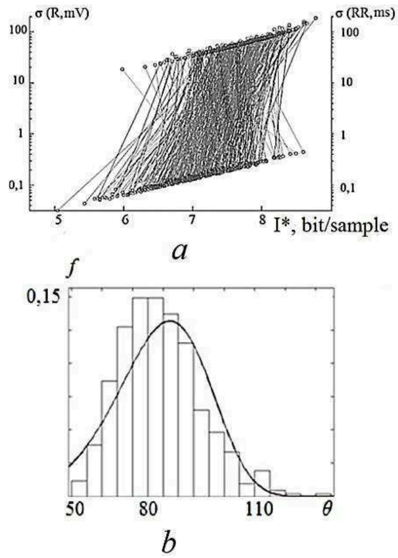

Figure 3: Results of ICL in group ECG-data: *a* – the group ICLs, *b* – the θ distribution

The calculated range of the coupling angle for CHP was 52°-132°, for sick persons the angle range was 80° – 150°.

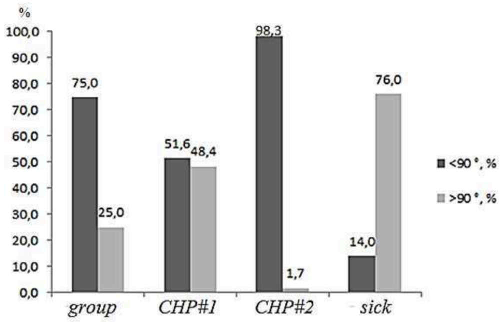

Figure 4: Coupling angle comparison in different groups

Fig. 4 reveals the group and individual features. For group CHP data were characterized by prevalence of acute coupling angles, in contrast the sick person data were characterized by prevalence of obtuse coupling angles. Serial CHP data provide two different individual cases. To continue the analysis of θ-statistics and to confirm the fulfillment of the ergodic hypothesis authors highlight the ICL region in the form of a trapezium at the fig. 3a and overlay data of two serial registrations of CHP #1 and CHP#2 and data of 14 registrations of sick people at the fig.4.

Figure 5 reveals individual differences more clearly: for CHP#1 coupling angle in general deviates near 90°, and for CHP#2 the acute angles prevail. It is needed to be noted that the serial ICLs positioned in the trapezoid region in the same manner like group ICLs. A similar procedure for combining ECG-data of sick people with the ICL area of the group CHP data resulted in a specific way.

R-series data of sick persons with slight deviation coincides on the lower base of the trapezoid, but the RR-series data mostly located beyond the limits of the ICL of the group data.

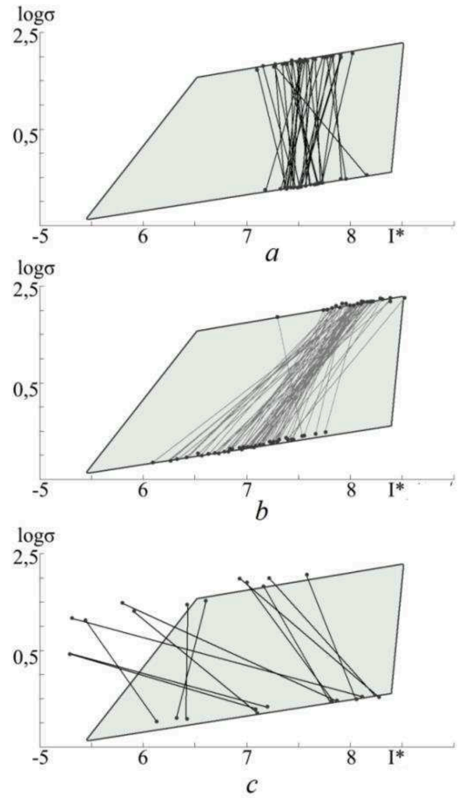

Figure 5: ICL imagery comparison, *a* – CHP#1 data, *b* – CHP#2 data, *c* – sick people data

The difference of R- and RR-data from normal distribution trends for sick people is statistically significant and could be explained by the influence of determinant processes, which have changed the structure of the signal from normal to another distribution. It is provided by various pathophysiological processes in the organism and continuous intensive therapy, which aimed at bringing the OFS of the clinical patient to the physiologically normal OFS.

The effectiveness of condition severity compensation and intensive therapy in practice depends upon the qualification of the resuscitator. A successful compensation could give the effect of moving the sick person ICL to the CHP area of the group data. In the proposed method of ECG analysis, the clinical patients should probably be called "conditionally ill patients".

Discussion

Two key features in the distribution along the slope of the ICLs were noted on the ICL-diagrams in conditionally-healthy persons:

1. Prevalence of acute ICL angles for healthy persons (θ<90°);
2. The asymmetric distribution of the ICL angles θ in the range of 0°-180° with the shift of the most probable value to θp = 76°.

The distribution of ICLs at figures 3 and 5 allows visualizing a surface of the ICL-diagram. If single ICL moves from left – low I^*_R values area - to the right – higher I^*_R

values area it is a way of possible "scanning" of all the diagram area. Herewith the ICL data points run on "rails" of R- and RR- structural data. The R-data point of ICL runs faster than RR-data point that makes the θ angle of ICL continual growing. This way of "scanning" lasts until the area of ICL concentration. Then the RR-data point of ICL changes the direction of running but R-data point of ICL keeps the direction to I^*_R growth.

In the area of direction and speed change the "folding" and "surface twist" occurred. These two functional procedures should not be underestimating. The "twisting" effect of ICLs was visualized through the shifting of ICLs with θ>90° to the second plain, that parallel to the diagram plain. Taking into consideration the fact that ICLs originates the solid surface of the diagram, where every ICL orientation (0° – 180°) is allowed, the "folding" and "surface twist" procedures have produced the twisted 3D lineate surface (ICLS), see fig.6. The color of the surface is referred to ICL angle distribution, the maximum ICL representation is colored with black.

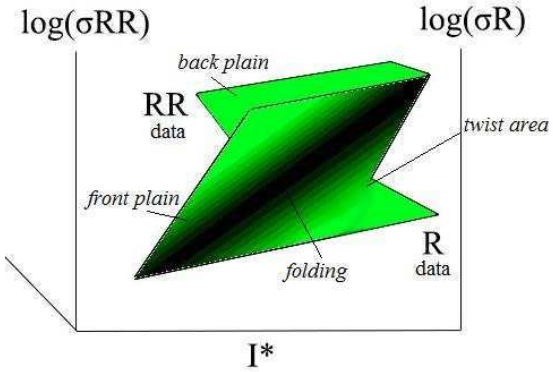

Figure 6: Topological imagery of the information-statistical model of the amplitude-phase coupling of ECG-data

The ICLS is forming the topological image of the information-statistic model of the ECG amplitude-phase coupling in the $log\sigma(I^*)$ diagram and it also has a physiological meaning:

1. The interval of I^*_R scattering is greater in 1.5 times than such interval for I^*_{RR}, see fig.3a, that indicates the greater structural variability of R-amplitudes in the amplitude-phase relations.
2. The acute ICL angle prevalence determines the preferable link of low I^*_R values with higher I^*_{RR} values, that points the strong subjection to R-stimulus with a determined reaction. Taking into account the frequency coding principle the phase component is susceptible to external rhythmic influence and amplitude component is determined by internal factors, such as amplitude of discharge frequency and conduction of generator potential. So the causal-resultative links in amplitude-phase relations are provided by system factors. The phase component, implemented by RR-intervals, is the instrument for external and central nervous system control, and the amplitude component, implemented by R-amplitudes, is a kind of a reader mechanism for internal and autonomic nervous system regulation.
3. The simultaneous slow growth of I^*_{RR} values and their constancy during ICL angle growth for CHP is suggested to be the balanced OFS.
4. The simultaneous decrease of I^*_{RR} and ICL angle growth for CHP indicate the reversible OFS decline because of the parallel projection of $log\sigma(I^*_{RR})$ functional link.
5. The prevalent deflection of ICL for sick persons from the suggested model could be explained as a new imagery of ICLS in the new parallel second plain.

Conclusions

It was concluded that amplitude and phase components in the form of R-series and RR-series respectively in the rest condition in healthy persons tend to normalization. But such processes of normalization were revealed to be coupled.

As a result of the study of topological imagery of the ECG amplitude-phase coupling we can make a conclusion that the surface of the infocommunication links between structural data of R- and the RR-series is not a statistical abstraction. The imagery contains physiological authentic and universal information. In the coupling model development, the authors made no assumptions, indicating its simplified or complicated interpretation.

Application of the topological imagery of ECG amplitude-phase coupling will allow developing new methods and possibilities of diagnostic systems for organism functional state characterization in both healthy and sick subjects.

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