Models of Reactions of Human Heart as Nonlinear Dynamic System to Cosmic and Geophysical Factors

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The paper analyzes theoretical models of the adaptive modes of generation and stability of human heart as a nonlinear point source. The analysis encompasses only ECG time-domain dynamics. To solve the general problem of the study of the adaptive changes of the cardiosignal under the action of external periodic force and parametric noise, a new dynamic model is proposed, which incorporates two control physical parameters: power of signal generation and coefficient of diffuse signal scattering. For the entire set of parameters, the examined modeled nonlinear system demonstrated a number of various performance modes ranging from steady-state periodic and quasi-periodic states to chaos. The model showed that variations in cosmic, geophysical, and weather conditions in the frequency range of 0.1-0.9 Hz produce the greatest biotropic influence.

Key Words: *heart; dynamic systems; geophysical factors*

By the present time, numerous mechanisms of the biotropic effects of natural fields were proposed [1,2]. Our aim was to examine the work of the heart as a nonlinear dynamic system and to reveal the peculiarities of its stability and performance under the action of an external driving force.

In the study of the effects of such large-scale environmental phenomena as variations of cosmic and geophysical factors, the size of the heart can be neglected. Therefore, it is considered here as a point source of self-excited oscillations with a variable amplitude measured by ECG. Such formulation of the problem helps to avoid analysis of the causes, sources, and peculiarities of generation of the oscillations; it also neglects the processes of spatial propagation of the excitation signal across the cardiac tissue. These features are discussed in details elsewhere [3]. Thus, in this work we analyzed only the regularities of dynamic changes of oscillation amplitude in the time domain and searched for the control parameters in the phase space and peculiarities of their changes under the action of external force of various types. In a health individual, the amplitude variations of cardiac signals are not strictly periodic, but quasi-periodic [4-7,11,12]. The differences from a strictly periodic process manifest in phase variations and in changes of ECG shape. It is difficult to explain this behavior of the system within the framework of a single model. The chaotic component of ECG variations can be explained, specifically, by the interaction between the cardiovascular and respiratory systems. This approach is elaborated previously [9], where the peculiarities of oscillation spectrum of cardiovascular system are simulated on the basis of interaction of two stochastic oscillators individually responsible for the cardiovascular and respiratory systems. The results adequately describe the internal rearrangement of the dynamic system due to the endogenous factors and transition of the system

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to chaotic oscillations. However, the questions on system behavior under the external force remained open.

The satellite (on-line) dynamic models are very useful tools for the analysis and filtration the cardiograms. One of the examples of application of such models is given in [8]. Other examples are the interpolation models [5], which were employed to automatically analyze the telemedical data obtained with “Geliomed” system. A specific feature of these models is the fact that the signal shape and its variations are determined by the choice of model functions presented as the sums of delta-like sources, whose centers coincide with the certain moments of ECG phase (maxima and minima of PQRST complex). The mathematical procedure can efficiently automate the problem of comparative ECG analysis by transferring it from the time domain (time, amplitude) to the phase space (amplitude and the rate of its changes) neglecting the physical and biological specificity of the observed phenomena. The regularities of cardiac signal as a point source with no account for an external force are described previously [10]. In the paper, the researchers were mainly interested in the conditions of transition from regular to chaotic oscillations and in assessment of the order and the chaos measure in the examined systems [10]. They presented the functional dependence as a sum of several dozen polynomials with the adjustment coefficients calculated from the rough data of experimental cardiograms.

Application of the models [5,7-12] to the real data of Geliomed monitoring showed that in order to comprehensively describe the environmental effects on the cardiac activity, the original dynamic equations should be further simplified, while the model should be constructed not from mathematical, but from physical principles describing the examined phenomena.

MATERIALS AND METHODS

The papers [1,4,6] discuss the structure and the primary results of a large-scale geliomedical telemonitoring “Geliomed”. In 2006-2008, simultaneous geliomedical monitoring was carried out in Moscow, St. Petersburg, Kiev, Simferopol, and Yakutsk. It yielded a comprehensive WEB database composed of more than 20,000 measurements reflecting the temporal and spatial dynamics of the first lead ECG variations. To perform synchronous biophysical monitoring, a special WEB-based technique was developed knows as “Geliomed” (http://geliomed.immsp.riev.ua) [1]. The measurements were carried on the same group of examinees in fall and spring (September, October, November, February, March, and April). This choice of time was determined by the semiannual maxima of geomagnetic activity. In all monitored groups, the every-day recordings were performed in four states: at rest, after a standard psychological test, after the Ruffier (squatting) test, and after 10-min postload rest. The data obtained were compared with the Wolf numbers (W), which are the indices characterizing perturbation of the geomagnetic field, and with the parameters of the space rays taken from IZMIRAN database.

RESULTS

In this study, we started from analysis of the ideal self-oscillating generator modeling the action of a healthy heart. We assumed that in the most members of population, the work of a healthy organism and its organs is optimally tuned during the evolutionary adaptation, while any disease is an individual deviation from the norm. Numerical simulation and reconstruction of individual monitoring data yielded by “Geliomed” project showed that without external driving force, the phase space demonstrated in most cases (8:2) superposition of two topologically different phase states: the more or less regular basic state and excited and rather chaotic state, while the minor cases were characterized by a mono portrait of cardiocycles. The incidence of these two modes of the phase depended on the load type. Inclusion of additional load (20 squats for 30 sec) resulted in transition of the examined biological system to the basic monostate, while the reverse transition was caused by a single magnetic storm, which increased the number of more chaotic states in the phase space. At the first look, any external force should exert unidirectional effect during a non-specific reaction. However, the experimental data favors the opposite view. Being paradoxical from the biological and medical viewpoints, this phenomenon needs theoretical explanation.

To reveal the degree of generalization of the above physiological phenomenon and peculiarities of its manifestations, we analytically simulated the dynamics of the modes of action of the heart and its adaptation to a weak external force. To roughly describe the signal generation and to reveal the most general properties of the examined biological system, we introduced only two control parameters of the opposite directivity: *1*) *D*, which is proportional to the power of impulse generation and responsible for the forces maintaining this generation (in reality, it can be related to an increase of the power of cardiac beats or to elevation in the blood flow rate), and *2*) *K*, which is proportional to power dissipation caused by diffusion and describes the generalized forces counteracting the generation processes (for example, increase in permeability of myocardium due to the destructive alterations or elevation of blood clotting).

As a model dynamic system, we used the following nonlinear model of the parametric generation of cardiac contractions:

$$\dot{B}=D\times f_1\times A-K\times B;\ f_1=(^1/_2\sin^2\omega t-^4/_5),$$
$$\dot{A}=(1-H)\times f_2\times B-K\times A-A^3;\ f_2=\sin^2 t \qquad \textbf{(1)}$$
$$\dot{H}=-K_2H-K(1+H)\times(A^2+B^2),$$

where A and B are the amplitudes of cardiac signal and its first derivative; f_1 and f_2 simulate the periodic external force with the frequency ω and variable H describes saturation of generation. Here we introduced additional variable H to simulate fine adjustment of the system to the load. This variable takes into account possible dynamic saturation of the oscillation amplitude under the external load. Thus, the third equation is introduced here to close the system and to limit the amplitude of generation with due account for correspondence of the developed model to the observed experimental data.

Solution of these equations for different values of D and K made it possible to plot the following diagram (Fig. 1). We revealed several stable generation modes, whose phase portrait coincided with those observed in experiments. These modes were separated by areas of chaotic and unstable solutions. Thus, solution of the system (**1**) naturally postulates existence of several modes of cardiac generation (which corresponds to real clinical observations) and disruption of the system with transition to the area of chaotic oscillations provoked by certain unfavorable combinations of the control parameters.

Another peculiar feature of the solutions of system (**1**) is existence of generation thresholds in respect to the control parameters D and K – both the upper and low ones (Fig. 1). Such a behavior is an inherent feature of any nonlinear system (examples are the optical quantum generators, solar magnetic dynamo, and the economic processes of market saturation). In biological systems, the existence of generation threshold is postulated in many papers on adaptation response. However, presently there are only few theoretical models, where existence of generation threshold directly results from nonlinear dynamic equations, so possibility to determine the regions of these thresholds is undisputable advantage of the model (**1**).

Supplementing the system (**1**) with external periodic forces at the frequencies multiple to N (natural number from 1 to 10) and to 1/N basic harmonic revealed the differences in the effects of the long and short periods of external oscillations on the examined system. The effect of the forces with long periods was greater. Figure 2 shows the original signal, its phase portrait, and the power spectrum. The effects of amplitude modulation of original signal at the frequencies 3 and $^1/_3$ are shown in Fig. 2, *b*, *c*, respectively. When the external force had a long period, the amplitude modulation depth was as large as a half of initial amplitude. In contrast, during the action of a short-period force, the modulation depth stabilized at merely few percents of the initial amplitude value. The area with the greatest values of D and K was more resistant to the external influences. Since the large-scale medical monitoring is characterized by significance of no better than 5%,

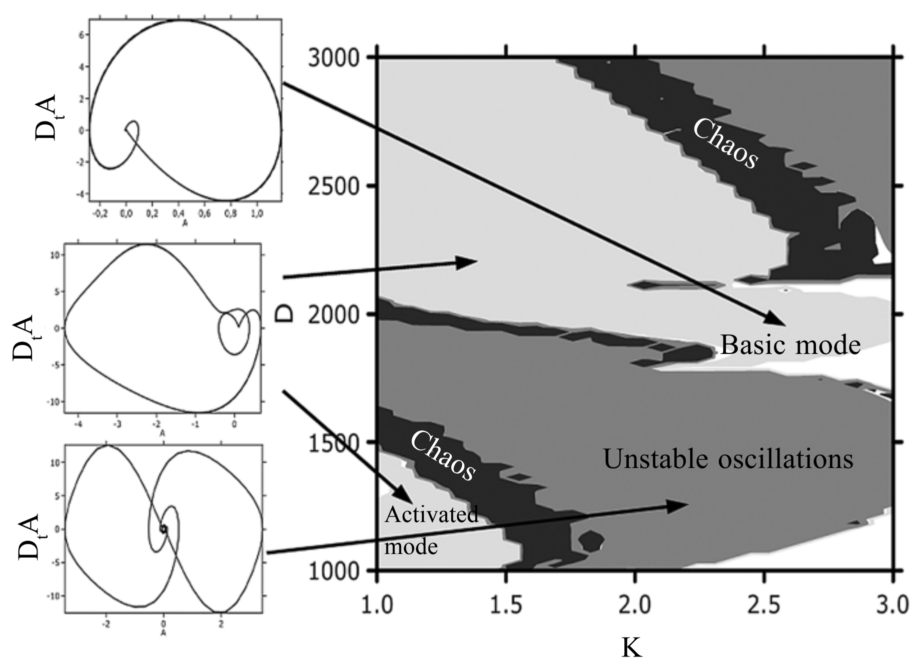

Fig. 1. Parametric diagram of generation modes and domains of stable oscillations.

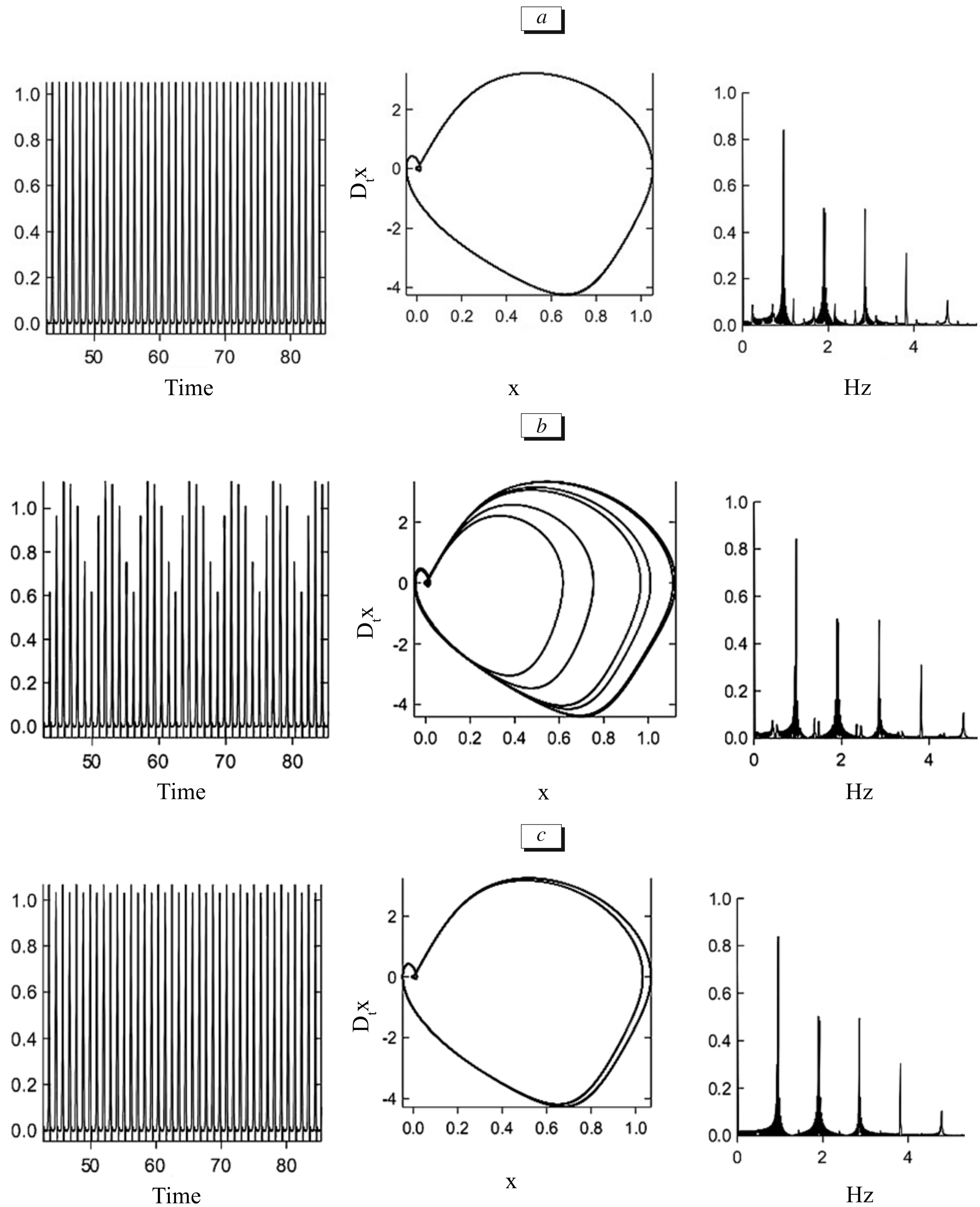

Fig. 2. Original signal, its phase portrait, and power spectrum (*a*), amplitude modulation (*b*), and stabilization of the amplitude modulation (*c*), phase portrait, and the power spectrum of the original signal under the action of an external periodic force. *b*) F=0.1sin(t/3); *c*) F=0.1sin(3t).

the area of efficiency of the external forces should be searched for within the range of 0.1-0.9 Hz.

Thus, theoretical analysis of nonlinear model aimed add describing the dynamics of cardiac signals during the action of various types of external forces showed that physical load is a factor augmenting internal noisiness of the system and leading to changes of its internal control parameters. By contrast, magnetic storm can be considered as an external driving force, which modulates the amplitude of oscillations and tunes their frequency.

Therefore, to develop maximally generalized model of adaptation dynamics of the cardiac signal amplitude, which can reflect the physical nature of the underlying phenomena, we intently simplified the dynamic equations by the use of only two control parameters: generation power and counteracting diffuse dissipation of oscillation energy. This structure of the dynamic system yielded the analytical solutions of equations (*1*), which described a number of nonlinear properties of cardiac activity: *1*) existence of the upper and lower parametric thresholds of generation of oscillations; *2*) existence of several modes of generation, whose phase portraits coincide with the experimental observations; and *3*) existence of various modes of system behavior under the effect of external force from periodic and quasi-periodic stable oscillations to chaotic fibrillations resulting from internal rearrangement of the control parameters.

It was shown that the periodic external force with the period longer than the time needed to change the phase of cardiac oscillations exerted the greatest effect on the heart. The physical load is the factor that elevates the internal noisiness of the system and changes the intrinsic control parameters. Magnetic storm can be viewed as an external driving force, which tunes the frequency of oscillations and modulates their amplitude.

It is hypothesized that variations of space, geophysical, and meteorological factors possess the greatest biotropic effects in the frequency range of 0.1-0.9 Hz.

REFERENCES

1. V. V. Vishnevskii, M. V. Ragulskaya, and S. N. Samsonov, *Tekhnol. Zhiv. Sist.*, No. 4, 61-66 (2007).
2. B. M. Vladimirskii and N. A. Temuryants, *Effect of Solar Activity on Biosphere and Geliosphere* [in Russian], Moscow (2000).
3. A. Yu. Loskutov and A. S. Mikhailov, *Principles of Complex Systems Theory* [in Russian], Moscow (2007).
4. V. N. Obridko, M. V. Ragulskaya, D. G. Strelkov, *et al.*, *Tekhnol. Zhiv. Sist.*, Nos. 2-3, 38-46 (2008).
5. L. S. Fainzil'berg, *Information Technologies of Complex-Shape Signal Processing: Theory and Practice* [in Russian], Kiev (2008).
6. S. M. Chibisov, V. V. Vishnevskii, and M. V. Ragulskaya, *Byull. Eksp. Biol. Med.,* **145**, No. 6, 714-718 (2008).
7. A. Babloyantz and A. Destexhe, *Biol. Cybern.*, **58**, No. 3, 203-211 (1988).
8. G. D. Clifford and P. E. McSharry, in: *Fluctuations and Noise in Biological, Biophysical, and Biomedical Systems*, Eds. D. Abbott, *et al.*, SPIE International Society for Optical Engineering: Bellingham (2004), pp. 290-301.
9. A. Duggento, D. G. Luchinsky, V. N. Smelyanskiy, *et al., Phys. Rev. E.*, **77**, No. 6, 061106 (2008).
10. N. Janson, A. N. Pavlov, and V. S. Anischenko, *J. Bifur. Chaos*, **8**, 825-833 (1998).
11. N. Wessel, J. Kurths, W. Ditto, and R. Bauernschmitt, *Chaos,* **17,** No. 1, 015101 (2007).
12. N. Wessel, H. Malberg, R. Bauernschmitt, and J. Kurths, *J. Bifur. Chaos*, **17**, 3325-3371 (2007).