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Numerical Modeling of Dynamics of Heart Rate and Arterial Pressure during Passive Orthostatic Test

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ABSTRACT

A model of human cardiovascular system is proposed to describe the main heart rhythm, influence of autonomous regulation on frequency and strength of heart contractions and resistance of arterial vessels; process of formation of arterial pressure during systolic and diastolic phases; influence of respiration; synchronization between loops of autonomous regulation. The proposed model is used to simulate the dynamics of heart rate and arterial pressure during passive transition from supine to upright position. Results of mathematical modeling are compared to original experimental data.

Cardiovascular system, autonomic regulation, baroreflex, mathematical model, arterial pressure

1. INTRODUCTION

Mathematical modeling is an important instrument for studying of important objects of real world. Mathematical models allows investigating the performance capabilities of electrical schemes. Complex models of atmosphere produce short-term weather forecasts and are used for studying of the climate. Architects use models of building to test their safety and resilience to naturel disasters.

Mathematical modeling is especially important for studying of biological objects, including humans. Direct physiological experiments on humans are strictly limited by the risks to the health of the patients, technical and ethical difficulties. Creation of mathematical models of different systems of human organism allows bypassing of these limitations. Model, proposed from the first principles, will be able to forecast behavior of the organism, its reaction to medical drugs and physiological tests. In addition, mathematical modeling allows registering of dynamical variables, which are inaccessible in direct experiments[1].

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However, biological objects are highly complex and development of mathematical models is tied with difficulties. One of the main problems is verification of the model, it can only be done through simulation of physiological tests and comparison with real data. Therefore, this study aims to propose mathematical model of CVS, which will reproduce qualitatively and quantitatively the dynamics of heartrate variability and arterial pressure during passive tilt test.

2. MODEL

Proposed mathematical model can simulate main hearth rhythm; influence of autonomous regulation on frequency and strength of heart contractions and resistance of arterial vessels; process of formation of arterial pressure during systolic and diastolic phases; influence of respiration; synchronization between loops of autonomous regulation[2-5]; Structure of the model is shown in figure 1.

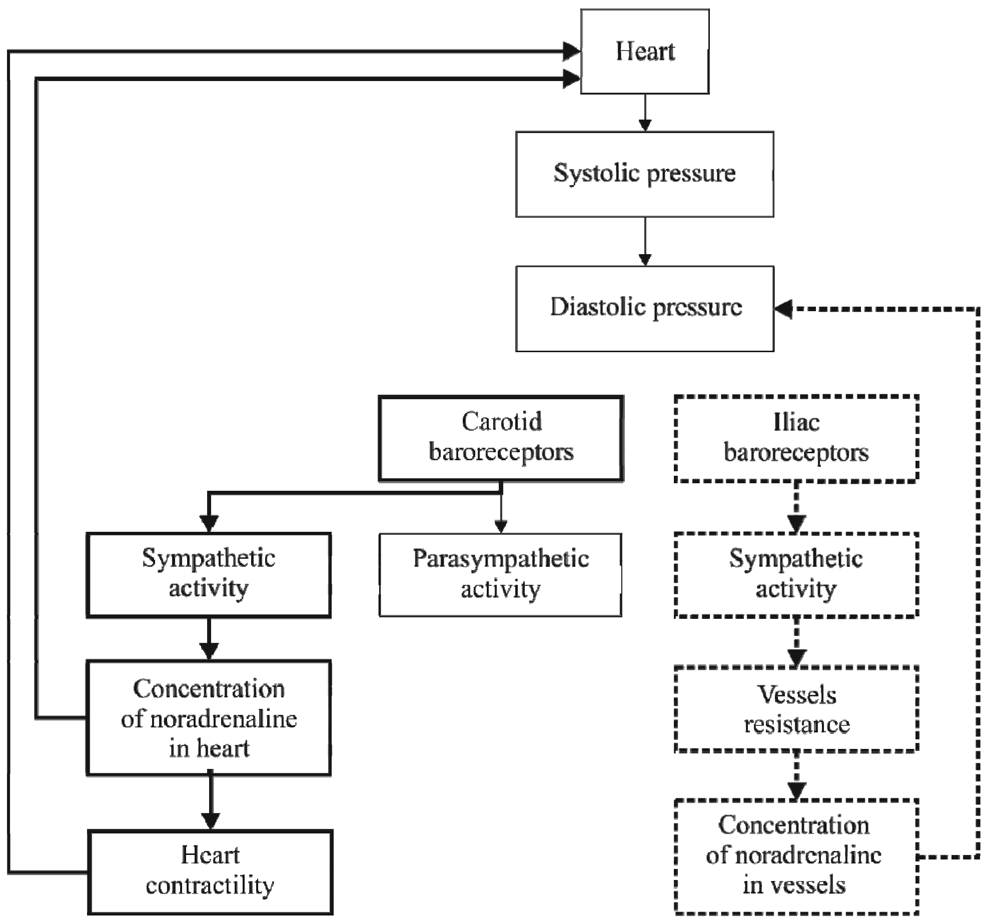

Figure 1. Block Diagram of the Model.

Heart is represented by sinoauricular node, its frequency is influenced by sympathetic and parasympathetic loops of autonomous regulation. Activation of sinoauricular node starts the systolic phase of cardiac cycle. During this phase arterial pressure rapidly increases. It also depend on diastolic pressure in the end of previous cycle; length of previous cycle; phase of respiration process; concentration of noradrenaline in cardiac muscle and walls of the vessels. To model the signal of respiration we use sinusoidal signal. Its period changes randomly after each respiratory cycle. Characteristic frequency of respiration in healthy subjects represents non-correlated stochastic process with Gaussian distribution, zero mean value and dispersion, which was estimated from real data.

Diastolic phase follows the systolic phase of rapid increase. In this phase, arterial pressure slowly decreases. Rate of decrease is defined by mechanical properties and tone of peripheral vessels. Tone of peripheral vessels is influenced by concentration of noradrenaline in walls of the vessels.

An important feature of proposed model is two loops of baroreceptors. Centers of autonomous control process their signals separately. Baroreceptors respond to the absolute value of arterial pressure and its change rate. It correlates with experimental results, obtained by Warner H.R. in [6]. Signals from the baroreceptors activate sections of nervous system, tied to carotid sinuses and iliac artery; and section of parasympathetic regulation that tied to the carotid baroreceptors[7,8]. Also respiration influence autonomous regulation. To model the system of the baroreflectory regulation we used accurate nonlinear equations[9] and dropped the simplified linear equations from[7,8].

3. Objects of investigation

To verify proposed model we compared its signals with experimental data from 20 subjects (males and females aged 20-40 years with average level of physical activity) without diagnosed CVS conditions.

All subjects were investigated in the afternoon fasting under spontaneous breathing. The signals were measured in a quiet, temperature-controlled room. All signals were sampled at 250 sps and digitized at 14 bits. The record of respiration was used to control evenness of breathing. All experimental signals were recorded using a standard electroencephalograph analyzer EEGA-21/26 ‘Encephalan-131-03’. Signals we filtered with band pass filter with cutoff frequencies of 0.05-100 Hz. 50 Hz noise from electricity mains was suppress with band-stop filter.

The head-up tilt test protocol includes the following stages: (1) In a preliminary stage lasting 10min, the subject was laying in a horizontal position without signal recording. (2) The signals were recorded within 10min in the horizontal position of subject’s body. (3) The subject were put passively in a vertical position with a tilt angle of about 80°. To exclude the transients the signals were not registered within 5min. The signals were recorded within 10min in the vertical position of subject’s body.

Proposed model was used to create statistical ensemble of signals of arterial pressure and ECG. The length of the signals was similar to the length of experimental signals. Model signals were generated with same parameters but with different realizations of noises. For each signal we dismissed the transient process of 3600 seconds.

4. RESULTS

Analysis of experimental data showed that passive transition from supine to upright position during tilt-test results in increase of heart rate by 20 beats per minute. Systolic blood pressure does not demonstrate the statistically significant change. Diastolic blood pressure rises at average on 5 mmHg. Proposed model quantitatively reproduced these changes.

Dynamics of systolic pressure, diastolic pressure and heart rate are rshown in figure 1. Median values and 1 and 3 quartiles of this indexes for experimental data and proposed model are shown in Table 1.

Index	Experiment	Model
HR supine	60(60, 71)	65 (65, 65)
SP supine	117 (110, 125)	116 (116, 116)
DP supine	70 (69, 75)	70 (70, 70)
HR upright	87 (78, 96)	79 (79, 79)
SP upright	115 (110, 120)	112 (112, 112)
DP upright	76 (70, 84)	73 (73, 73)

Table 1. Heart Rate (HR) Systolic Pressure (SP) and Diastolic Pressure (DP) in Supine and Upright Positions Averaged for Experimental and Model Data. Indexes are Provided in Following Format: Median Value (1 quartile, 3 quartile)

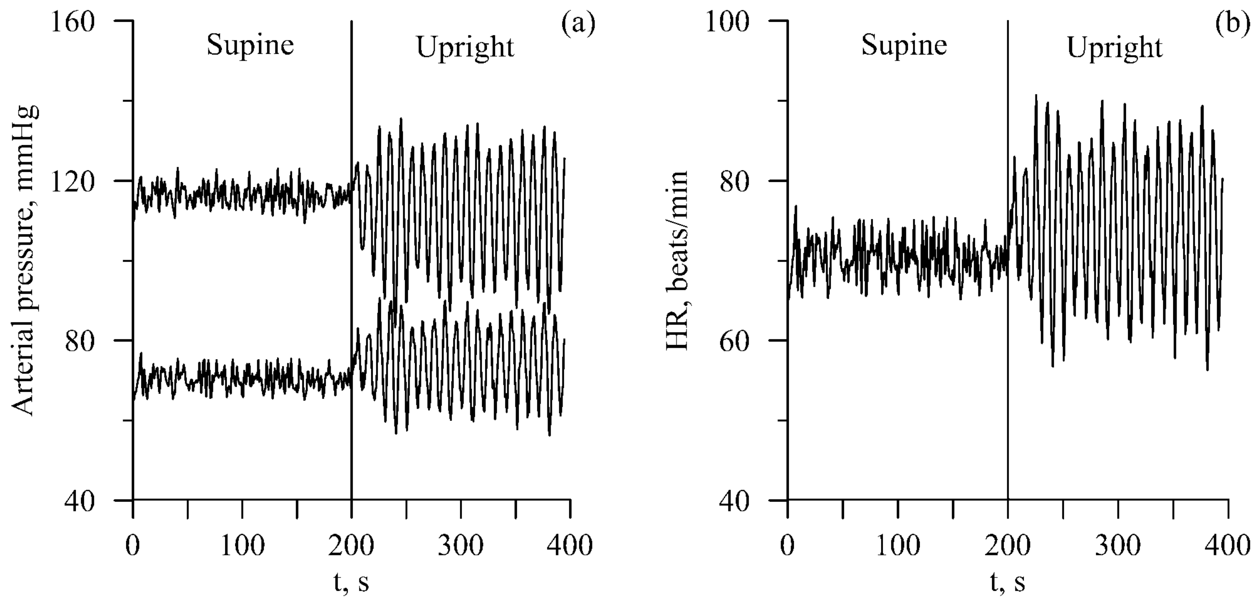

Figure 2. Model Signals of (a) – Systolic (top), Diastolic (bottom) Arterial Pressure and (b) – Heart Rate in Supine and Upright Positions.

5. CONCLUSION

We proposed a new model of vegetative regulation of human cardiovascular system. We introduced to the model two loops of baroreceptors that are described with accurate nonlinear equations. Structure of the model is based on result of physiological experiments, parameter have physiological meaning.

Proposed model was used to reproduce the dynamics of cardiovascular system during passive orthostatic test. During computer simulation, we reproduced the changes in arterial pressure and heart rate, that appear during transition from supine to upright position. Obtained results suggests that proposed model represents actual structure of human cardiovascular system and can be used for further study of this system and development of new methods of medical diagnostics.

6. ACKNOWLEDGMENTS

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