Phase and frequency locking in the model of cardiovascular system baroreflectory regulation

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ABSTRACT

We proposed the model of cardiovascular system which describes the sinus rhythm, autonomic regulation of heart and arterial vessels, baroreflex, arterial pressure and respiration process. The model included a self-oscillating loop of regulation of mean arterial pressure. It was shown that suggested model more accurately simulated the spectral and statistical characteristics of heart rate variability signal in comparison with the model proposed earlier by Seidel and Herzel.

Keywords: dynamical modeling, autonomic regulation, cardiovascular system, nonlinear dynamics

1. INTRODUCTION

The complex internal structure and rich dynamics of living systems make its investigation difficult because an obtainment of experimental data of such systems is often difficult or impossible. In such circumstances, the use of dynamic modeling can greatly assist in the investigations. Modeling allows one to predict the behavior of the system in time and in case of the control parameters changing. Sometimes it is possible to estimate the values of parameters and dynamic variables that are not accessible for direct measurement.[1]

Recently, there are known few mathematical models of the cardiovascular system (CVS) taking into account its autonomic regulation.[2,3] In particularly, the Seidel and Herzel model is described in details.[4] However, these models include circuit baroreflex regulation of mean arterial pressure (MAP) in the form of a linear equation and are not able to demonstrate sustained self-oscillations experimentally observed at a frequency of about 0.1 Hz.[5] But the results previously obtained by us[6–10] and by other researchers[11–14] show the self-oscillatory nature of this contour. Moreover, the autonomic nonlinear model of MAP regulation circuit was proposed in the experiment of Malpas and Ringwood.[15] The authors have shown that this model is able to demonstrate the stable self-sustained oscillations with characteristic frequency of about 0.1 Hz.

In this paper, we considered results of Malpas and Ringwood in model generation and propose the model of the CVS taking into account the sinus rhythm, autonomic regulation of heart and arterial vessels, the self-oscillatory contour of the baroreflex MAP control, the formation of arterial blood pressure (AP) and the respiration process. The features of the proposed model are investigated by comparing the results of spectral and statistical analysis of the experimental data with the model heart rate variability (HRV) and the well-known model proposed by Seidel and Herzel in.[4]

2. THE MODEL

The proposed model has the same structure as a model proposed by Seidel and Herzel.[4] The structure of the model is shown in Figure 1.

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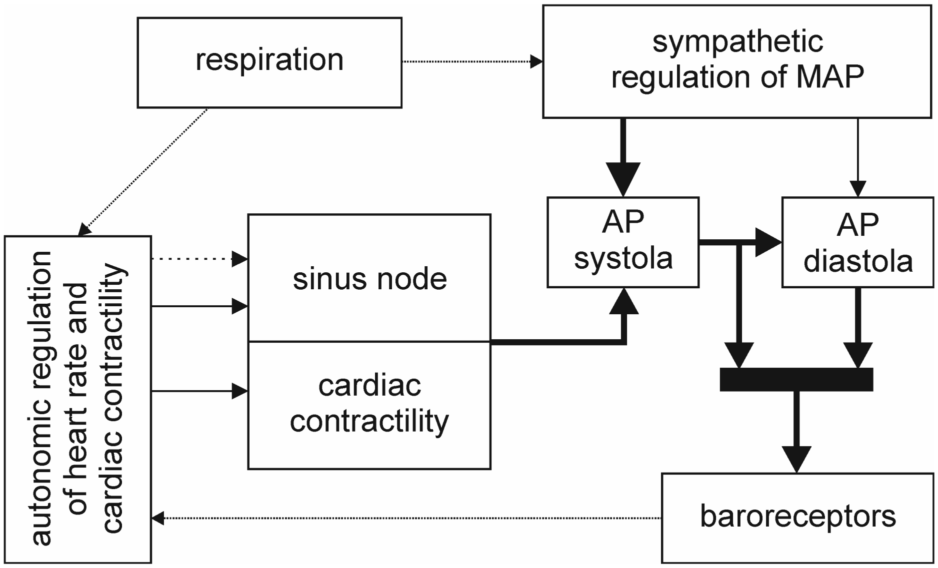

Figure 1. Block diagram of the model. The bold lines correspond to blood pressure, thin lines sympathetic activity, dashed parasympathetic.

Our model includes the periodic activity of sinus node, the activity of sympathetic and parasympathetic divisions and the baroreflex regulation of arterial pressure.

Seidel and Herzel proposed a model of the blood vessels tone regulation in the form:

$$\dot{c}_{vNa} = \frac{c_{vNa}}{\tau_{vNa}} + k^S_{c_{vNa}} v_s(t - \theta_{vNa}) \tag{1}$$

where c_{vNa} is a vascular concentration of sympathetic transmitter, $\tau_{vNa} = 2s$ is a time constant, v_s is an activity of sympathetic division, $\theta_{vNa} = 1.65s$ - is a time delay, $k^S_{c_{vNa}} = 1.2$ (see eq.12 in[4]). But this linear equation exhibits only damped oscillations. In accordance to Ringwood and Malpas[15] and Burgess[5] we refuse the linear conception and apply the model of baroreflex loop control in the form:

$$\dot{m} = \frac{1}{\varepsilon}(-m + G(m(t - \theta)) + k_r R(t)) \tag{2}$$

where $\varepsilon = 2s$ is a time constant, $\theta = 3.6s$ is a delay time, G is a sigmoid nonlinear function, $R(t)$ is a respiration signal, k_r is a coefficient of coupling strength. The equation 2 describes self-oscillating system with delay. The main period of this system is about 10 s that corresponds to experimental observations and modern physiological concepts.

The next step is the consideration of the effect of 2 on blood pressure in the diastolic phase:

$$\dot{p} = -\frac{p}{\tau_v(t)} \tag{3}$$

where $\tau_v(t)$ is a relaxation time:

$$\tau_v = \tau_v^{(0)} - \bar{\tau}_v \left(c_{vNa} + (\hat{c}_{vNa} - c_{vNa}) \frac{c_{vNa}^{n_{vNa}}}{\hat{c}_{vNa}^{n_{vNa}} + c_{vNa}^{n_{vNa}}} \right) \tag{4}$$

where $\tau_v^{(0)}$, $\hat{c}_{vNa}$ and are the parameters (see eq. 11, 14 in[4]). Equation 3 describes the windkessel effect. The parameter τ_v depends on the tone of arterial vessels.

We replaced the expression 4 using the following expression:

$$\tau_v = \tau_0 \left(1 + k_m G(m(t - \theta_\varepsilon))\right) \tag{5}$$

where $\tau_0 = 1.5s$ is a time constant which depends on the inertial properties of aorta and arterial vessels[16], $\theta_\varepsilon = 3.24s$ is a the time lag of the signal propagation in the efferent nerves in the loop of baroreflex regulation of vasomotor tone of arteries, the coefficient $k_m = 0.015$.

The final step is the account of a mean arterial pressure modulation in the expression of the systolic blood pressure. We added the term $k_s m(t)$ in the equation 13 in[4] :

$$p = d_{i-1} + S_i \frac{t - t_i}{\tau_{sys}} \exp\left(1 - \frac{t - t_i}{\tau_{sys}}\right) + k_s m(t) \tag{6}$$

where d_{i-1} is a diastolic pressure (blood pressure at contraction onset), t_i is a time of last contraction onset, τ_{sys} and $k_s = 3.0$ are the parameters.

3. METHODOLOGY

Spectral analysis of HRV is widely used in researches and medical diagnostics. We used the method of spectral estimation proposed by Welch.[17] Spectral analysis was performed on the time series with duration of 10 minutes. The analysis was carried out in the time window of 1 minute duration, the window shift was 20 seconds. The Hamming window was used for the analysis.[18]

To quantify the activity of the autonomic nervous system special quantitative indices and statistical analysis of HRV signal are widely used. These indices are based on the evaluation of power spectral density of the frequency bands (so called LF, HF bands etc.), as well as on an assessment of the probability density of the signal HRV. In this paper, we calculated some of these indices based on the methodological recommendations given in the article.[19] For comparison of the models the indices were calculated from the time series obtained using the models whose length is equal to the duration of the experimental record.

4. DATA

To study the performance of the models, numerical indices are calculated from their time series as well as from the experimental signal. Here, we analyzed the experimental ECG recorded in I limb lead. The signals were registered in the supine position in two hours after a meal. The recording time was 10 minutes. The signal was recorded with a healthy 23 years old man. All experimental signals were recorded using standard instrument with a sampling frequency of 250 Hz and 14-bit quantization. The bandwidth of the analog channel was 0.05-100 Hz. To suppress a power-supply noise we used a notch filter. The HRV signal was obtained from the ECG signal.

5. RESULTS

Time series of HRV signal of the suggested model is compared with time series of the model of Seidel and Herzel and experimental data in the Fig. 2a. Also we made a comparison between time series of AP obtained using our model and the model of Seidel and Herzel (Fig. 2b). In the result our model demonstrated systolic to diastolic pressure ratio equal to 145/70. This value is closer to typical for healthy subjects at rest than value obtained using the model of Seidel and Herzel – 200/110.

In the Figure 3a a typical Fourier power spectrum of HRV signal for healthy subject is presented. The power spectra of HRV signals generated by suggested model and the model of Seidel and Herzel are shown in the Figure 3b.

The component at frequency of about 0.1 Hz reflected the activity of the sympathetic part of autonomic regulation of the CVS is appeared in the HRV signal spectrum of the suggested model in contrast to the model of Seidel and Herzel (Fig. 2b).

The statistical and spectral indices calculated using models data and experimental signal are presented in Table 3. The values of indices calculated for the suggested model are closer to typical experimental values than the values of indices calculated for the model of Seidel and Herzel.

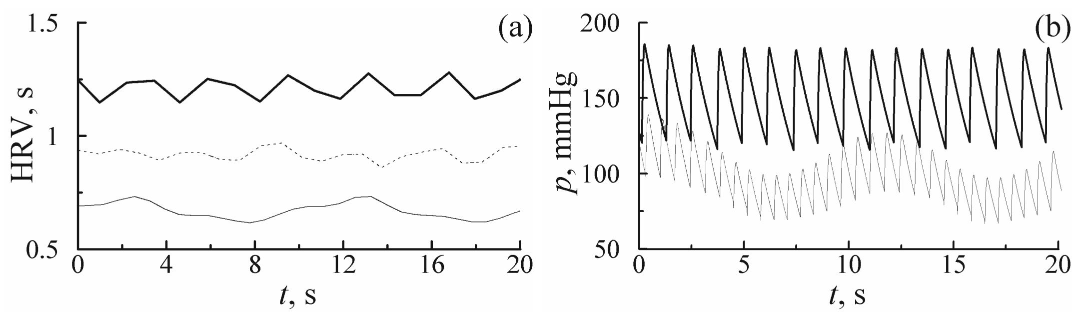

Figure 2. Time series of (a) — HRV and (b) – AP. Suggested model — thin line, the model of Seidel and Herzel – bold line, experimental data – dashed line.

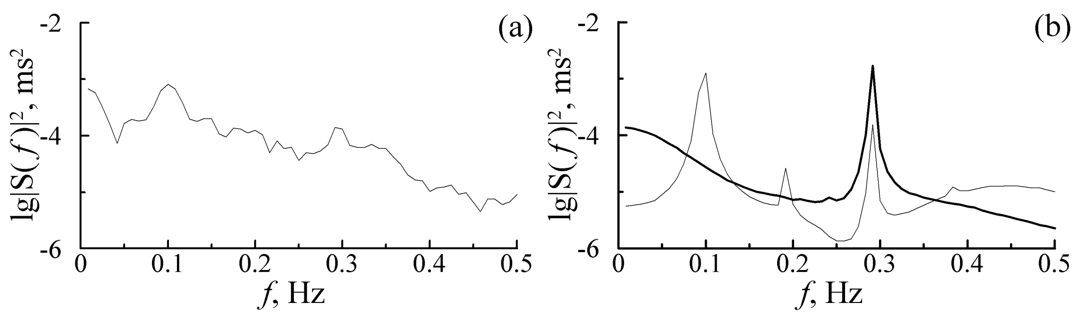

Figure 3. Power spectra of (a) — the experimental HRV signal, (b) – suggested model – thin line and the model of Seidel and Herzel — bold line.

Table 1. Spectral and statistical indices.

Indices	**Our model**	**Model of Seidel and Herzel**	**Experimental results**
HR	89.9	50.6	80.5
SDNN	35.8	82.0	47.5
RMSSD	18.9	98.3	24.0
LF	605	0.17	707
HF	66.9	972	139
LF/HF	9.02	0.0002	5.09
LFpc	90.0	0.02	57.7
HFpc	9.94	99.8	11.3

6. CONCLUSION

The model of the human CVS which includes the self-oscillatory circuit of baroreflex vasomotor tone regulation was proposed. The time series of this model, the model of Seidel and Herzel and the experimental data were compared during spectral and statistical analysis.

It has been shown that the presence of the self-oscillating circuit allows our model to reproduce a characteristic peak in the power spectrum of the HRV signal at a frequency of about 0.1 Hz.

In addition the model better reproduces the spectral and statistical indices of HRV signal and the typical value of the ratio of systolic and diastolic blood pressure.

7. ACKNOWLEDGEMENTS

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