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Interaction between Respiration and Low-Frequency Cardiovascular Rhythms

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***Abstract*—**The interaction between respiration and low-frequency rhythms of the cardiovascular system is studied. The obtained results count in favor of the hypothesis that low-frequency rhythms in blood pressure and R-R intervals are generated in different central neural structures involved in the autonomic control of the cardiovascular system.

***Keywords*—**Cardiovascular system, R-R intervals, blood pressure, synchronization.

I. Introduction

HUMAN cardiovascular system (CVS) is one of the most important physiological systems whose operation is governed by several rhythmic processes interacting with each other [1,2]. The most significant among them are the main heart rhythm, respiration and the process of low-frequency (LF) regulation of blood pressure and heart rate with a fundamental frequency of about 0.1 Hz [3]. The origin of these low-frequency oscillations is still a subject of controversy. According to one hypothesis, the 0.1-Hz oscillations in heart rate and blood pressure are largely an index of baroreflex gain. On another hypothesis these oscillations have a central origin and represent an intrinsic property of autonomous neural network. Interaction between these main rhythms has been an active area of research. It has been found that this interaction leads to the frequency modulation of the heart rate known as respiratory sinus arrhythmia (RSA) [4–7] and Mayer wave sinus arrhythmia (MWSA). Characteristic temporal periods of RSA and MWSA are determined by the periods of respiration and self-sustained blood pressure oscillations (Mayer wave), respectively.

Recently, it has been found that the rhythmic processes in the CVS can be synchronized between themselves. The most intensively studied synchronization is that between the heartbeat and respiration. This cardiorespiratory synchronization has been demonstrated by various groups of researches for the cases of spontaneous respiration and paced respiration [8-12]. Synchronization between the respiration and the process of LF regulation of heart rate has been reported in Refs. [11, 13] for various regimes of breathing. Interaction between the rhythms of CVS including the case of their synchronization has been investigated also in the models.

In this paper we study synchronization between the respiration and the processes of heart rate and blood pressure regulation with the basic frequency close to 0.1 Hz. Synchronization between the rhythms is investigated under paced respiration with varying frequency.

Arguments are adduced in favor of the concept that oscillations of heart rate and blood pressure with a frequency of about 0.1 Hz have a central origin. Moreover, these oscillations may be considered as different processes that exhibit a comparatively high synchronization between themselves in healthy subjects ensuring a high adaptability of the cardiovascular system.

II. Data and their Processing

In this paper we use a method for detecting synchronization of a self-sustained oscillator by external driving with linearly varying frequency [13]. The principal point of this approach is a variation of the frequency of external signal. Method was applied to the investigation of synchronization between respiration and low-frequency rhythms of the cardiovascular system with a frequency of about 0.1 Hz. The frequency of respiration was linearly varied in the range from 0.05 to 0.2 Hz. Thus, the experiment with the frequencies of respiration close to the basic frequency of the LF heart rate and blood pressure oscillations exhibits a frequency locking phenomenon typical for a classical self-sustained oscillator under external forcing [14].

We studied 3 healthy subjects. The signals of electrocardiogram (ECG) and blood pressure on the middle finger of the subject's hand were simultaneously recorded in a supine resting condition under spontaneous breathing. All signals were sampled at 250 Hz and digitized at 16 bits for off-line analysis with a personal computer. The duration of each record was 18 minutes.

Fig. 1 shows short segments of a typical experimental record. Extracting from the ECG signal a sequence of R-R

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intervals, i.e., a series of time intervals between the two successive *R* peaks, we obtain information about the heart rate variability (HRV). To obtain equidistant time series from not equidistant sequence of R-R intervals we approximate it with cubic splines and resample with a frequency of 4 Hz.

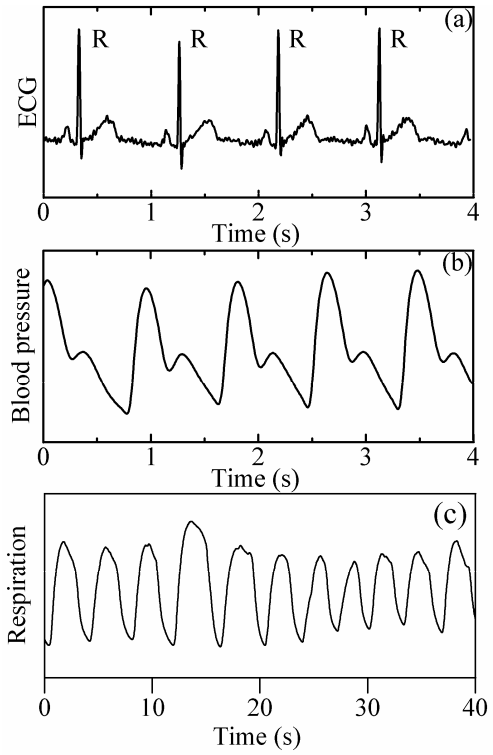

Fig. 1. Segments of an ECG signal (a), blood pressure signal (b), and respiration (c). All signals are given in arbitrary units.

Spectral analysis of R-R intervals reveals different frequency domains of HRV. Generally the Fourier power spectrum of R-R intervals exhibits well-distinguished characteristic peaks at frequencies f_r and f_{vh} associated with the respiratory and LF fluctuations of heart rate, respectively [Fig. 2(a)].

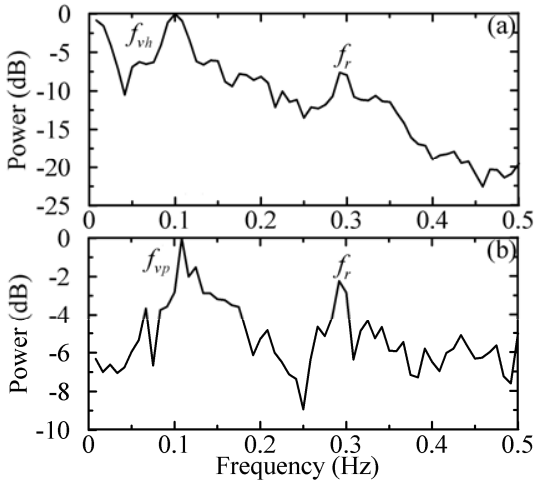

Fig. 2. Typical Fourier power spectra of R-R intervals (a) and blood pressure signal (b).

Besides high-frequency range, 0.15–0.4 Hz, and LF range, 0.04–0.15 Hz, containing the peaks f_r and f_{vh}, respectively, a very low frequency range, <0.04 Hz, is defined in the HRV power spectrum. A power spectrum of blood pressure signal also exhibits peaks at frequencies f_r and f_{vp} associated with the respiratory and LF oscillations of blood pressure, respectively [Fig. 2(b)]. In this paper we consider only oscillations relating to the LF range of power spectra.

To extract the LF (slow) component of HRV associated with a process of heart rate regulation with a frequency of about 0.1 Hz let us filter the sequence of R-R intervals removing the high-frequency oscillations (>0.15 Hz) associated predominantly with respiration, and very low frequency oscillations (<0.05 Hz). Similarly, we extract the LF component of blood pressure signal by using the same filtration with the bandpass 0.05–0.15 Hz.

III. Analysis of Interactions within the CVS

The analysis of synchronization between 0.1-Hz oscillations of blood pressure and heart rate is based on the assumption that they are generated in different central neural structures involved in the autonomic regulation of the CVS. Several facts count in favor of this hypothesis. Firstly, the concept of a central origin of the LF cardiovascular oscillations is supported by animal studies. In vagotomized and sinoaortic denervated cats an activity of medullary neurons involved in the regulation of cardiovascular function contains distinct LF oscillatory component, which is correlated with blood pressure variability [15]. Secondly, the results of experiments where the LF oscillations were present only in one of the signals, either blood pressure or R-R intervals, point to the presence of at least two different centers responsible for generation of oscillations with a frequency of about 0.1 Hz. For example, elimination of HRV in supine humans by using a fixed-rate cardiac pacing with electrical stimuli did not alter LF arterial pressure oscillations [16]. On the other hand, implantation of a left ventricular assist device in patients with severe heart failure restore the LF oscillations in R-R intervals of the native heart, even in the absence of any LF oscillations in blood pressure [17]. After such implantation the native heart remains innervated and continues to be regulated by the autonomic nervous system while interactions between R-R intervals and blood pressure are absent.

Another argument in favor of the hypothesis of the presence of two interacting self-sustained oscillators with basic frequencies close to 0.1 Hz is different response of the LF heart rate and blood pressure oscillations to external stimulation. Oscillatory lower body negative pressure at 0.1 Hz increases both LF blood pressure and R-R interval oscillations. However, cross-spectral coherence between these increased oscillations becomes highly variable, both among subjects and across stimulus level [18]. Furthermore, the frequencies of the LF cardiovascular rhythms can be locked by a signal of stimulation in the form of neck suction with the

frequency continuously increasing from 0.02 Hz up to 0.20 Hz [19]. Note that R-R intervals exhibit a wider range of frequency locking by external stimulation than blood pressure.

We observed a similar effect studying synchronization between the respiration and the LF cardiovascular rhythms in healthy subjects under breathing with the frequency continuously increasing from 0.05 Hz to 0.20 Hz within 18 minutes. Fig. 3(a) shows a typical dependence of the frequency of heart rate slow oscillations f_{vh} on the frequency of respiration f_r. In Fig. 3(b) a dependence of the frequency of blood pressure slow oscillations f_{vp} on the respiratory frequency is displayed.

The frequencies f_r, f_{vp}, and f_{vh} are defined as the frequencies at which the main peaks are observed in the power spectra of the signal of respiration and the filtered signals of blood pressure and R-R intervals, respectively. The power spectra of these three signals are computed in a moving window.

The presence of 1:1 frequency locking is clearly seen within the interval 0.068–0.142 Hz in Fig. 3(a) and within the interval 0.071–0.113 Hz in Fig. 3(b). Thus, the experiment with the frequencies of respiration close to the basic frequency of the LF heart rate and blood pressure oscillations exhibits a frequency locking phenomenon typical for a classical self-sustained oscillator under external forcing. Different width of synchronization band for the considered rhythmic processes is consistent with the hypothesis that different self-sustained oscillators generate these rhythms.

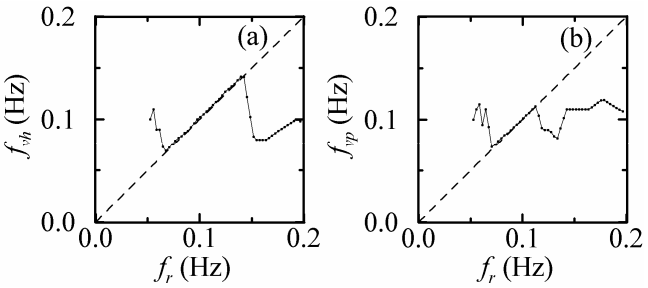

Fig. 3. (a) Dependence of the frequency of heart rate LF oscillations on the frequency of respiration for one of the healthy subjects. (b) Dependence of the frequency of blood pressure LF oscillations on the frequency of respiration for the same subject.

IV. Conclusion

We have investigated interaction between the breathing and the oscillatory processes with a frequency of about 0.1 Hz observed in the human heart rate and blood pressure. Our results count in favor of the conclusion that these oscillations are generated in different central neural structures involved in the autonomic control of the CVS. Optimal adjustment between the LF cardiovascular rhythms resulting in their comparatively high synchronization ensures a high adaptability of the CVS that is necessary for global healthy behavior of the organism.

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