LINEAR FEEDBACK ANALYSIS OF CARDIOVASCULAR SYSTEM USING SEISMOCARDIOGRAM

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Abstrakt Článek popisuje metodu analýzy vztahů mezi veličinami popisujícími řízení srdeční činnosti (reprezentované posloupností intervalů mezi jednotlivými srdečními stahy) a mechanickou odezvou srdce charakterizovanou posloupností hodnot systolických sil generovaných srdcem v jednotlivých srdečních cyklech. Obě posloupnosti byly určeny ze seismokardiografického signálu zaznamenaného ze zdravých osob za dvou různých experimentálních podmínek. Pro výpočty byla použita metodika lineární zpětnovazební analýzy baroreflexu, původně vyvinutá a popsaná v [1], [2] a [3]. Odlišný charakter získaných výsledků je vysvětlován rozdíly mezi frekvenčními vlastnostmi zaznamenaných posloupností systolických sil a hodnot systolických tlaků v jednotlivých srdečních cyklech.

Summary The paper deals with an analysis of relationship between heart rate described by a sequence of cardiac interbeat intervals and mechanical activity of heart represented by a sequence of systolic forces. Both the quantities were determined from seismocardiograms recorded from healthy subjects under two different experimental conditions. The method of the linear feedback baroreflex approach originally developed in [1], [2] and [3] was applied for the analysis. Different character of obtained results in comparison to those described in [1], [2] or [3], is explained by differences between frequency properties of the recorded sequences of the systolic forces and values of systolic blood pressure.

1. INTRODUCTION

Quality of cardiovascular function and control is usually evaluated by means of so called baroreflex sensitivity defined in various ways, but most often as a ratio of Fourier transforms of sequences of RR intervals R(ω) and systolic blood pressures P(ω). If it is the case, the baroreflex sensitivity equation is

$$BRS(\omega) = \frac{R(\omega)}{P(\omega)} \qquad (1)$$

It is either evaluated for the whole frequency range from 0 Hz to about 0.5 Hz, its part, or at the particular frequency (e.g. 0.1 Hz). The eq. (1) represents frequency characteristic of a linear open loop system with information about the blood pressure at its input and values of RR interval at output. In fact, the cardiovascular control system contains complicated feed backs that are realised in cardiovascular system (CVS) at local level, and/or in neural system at global level.

In [1], [2] and [3], we designed and described an alternative approach for explaining the relationship between electrical control of heart (represented by a sequence of RR intervals) and the mechanical response of the cardiovascular system (described by the sequence of the systolic blood pressure values) by means of linear feedback model of the cardiovascular system control (Fig.1). In the block diagram, the block F_s in direct branch represents properties of the cardiovascular system and the block F_b properties of its neural control. Typical shapes of transfer function modules for patients with normal findings are shown in Fig. 2, where the system F_s transmits the signal components typically rather at lower frequencies and in turn maximum of a normal function $|F_b(\omega)|$ usually lies in interval between 0.1 and 0.3 Hz.

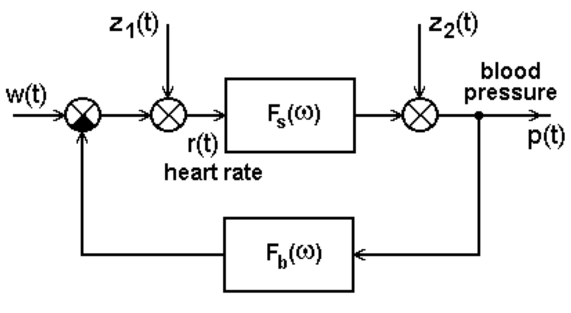


Fig.1. Block diagram of the linear feedback model of cardiovascular control mechanisms.

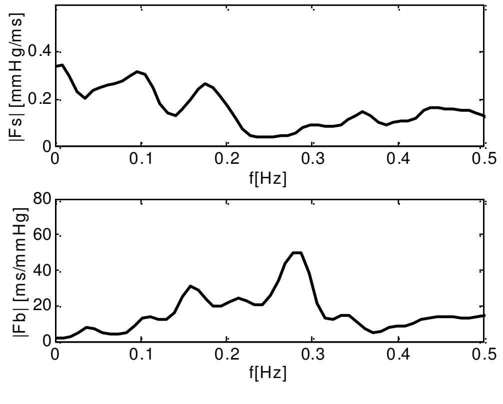


Fig.2. Modules of the typical transfer functions $F_s(\omega)$ and $F_b(\omega)$ (normal person).

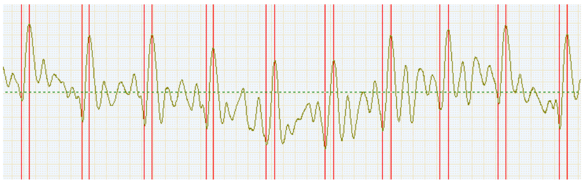


Fig.3. Example of seismocardiographic signal with reference points (minimum and maximum value) in every heart cycle.

Unfortunately, continuous measurement of blood pressure curve sometimes predetermines conditions of an examination and can limit the character of measuring. That is why the approach was rather modified to use information provided by a seismocardiogram.

2. METHODS

Seismocardiogram (SCG) (e.g. [4], [5], Fig.3 and 4) is a record of cardiac vibrations as they affect the entire body. It provides a convenient and relatively reliable measure of left ventricular systolic and diastolic performance both at rest and immediately after exercise. It is shown that the seismocardiogram contains clearly defined points associated with the cardiac cycle that are correlated to various phenomena as the mitral valve closure, aortic valve opening, onset of rapid ejection, aortic valve closure, mitral valve opening that can be recognized in simultaneously recorded M-mode and Doppler echocardiograms. In the absence of heart disease, the seismocardiogram recorded at a rest state remains stable over a period of at least three months. There is a recognizable normal seismocardiogram that is altered by chronic left ventricular dysfunction, including myocardial infarction and dilated cardiomyopathy. The seismocardiogram can be used to measure instantaneous heart rate and systolic force developed by heart ventricles. The interbeat intervals are determined as time between two successive J waves in the seismocardiographic signals and the beat systolic force is proportional to value usually calculated as [5]

$$F_s = \frac{\Delta_{FHI} + \Delta_{FIJ} + \Delta_{FJK}}{3} \qquad (2)$$

where Δ_{FHI} is a difference between values of the signal at the top of H wave and minimum of I wave, Δ_{FIJ} is a difference between extremes of I and J waves, and finally, Δ_{FJK} is a difference between extremes of J and K waves.

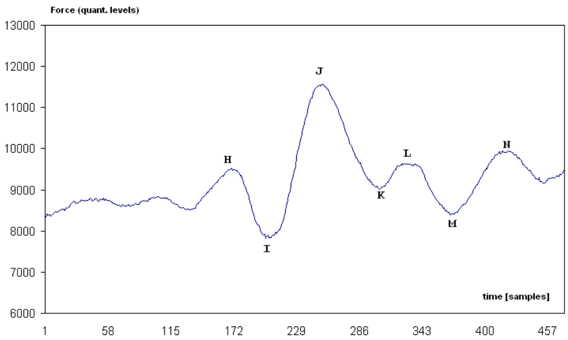


Fig.4. Seismocardiographic signal of one cardiac cycle with characteristic waves.

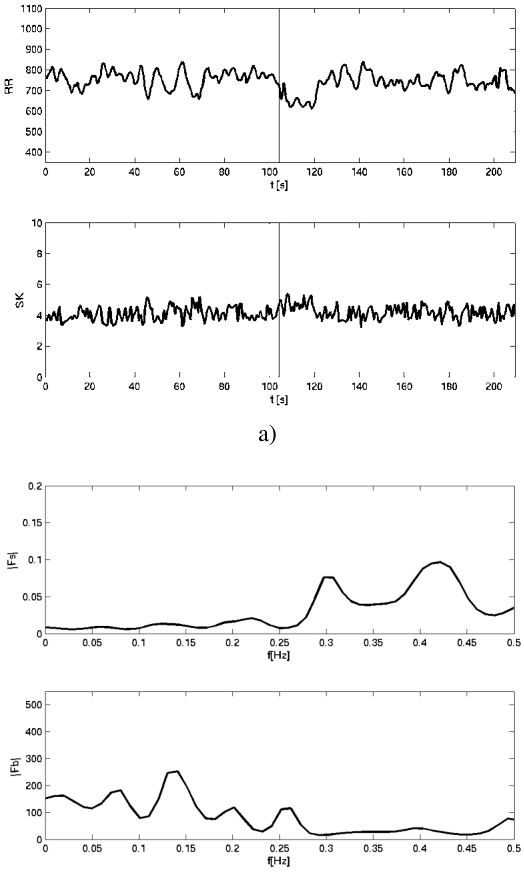
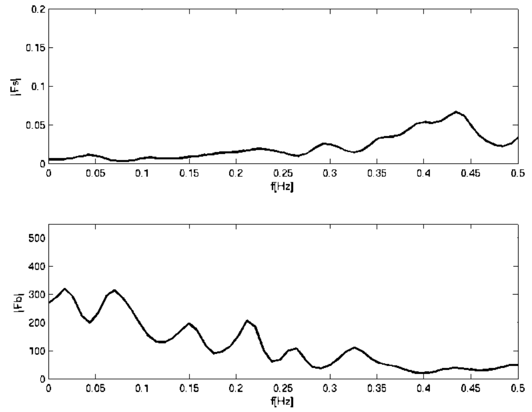


Fig.5. Results of the rubber ring experiment - a) time sequences of the interbeat intervals (RR) and systolic forces (SK), the vertical line separates the rest and active

The pilot study data were measured from 4 healthy males, age from 27 to 35 years, under two different experimental set-ups. First, seismocardiogram was recorded in sitting rest position for about 3 minutes. Then an intensive grasp at rubber rings in both hands for 10 seconds followed. Final phase of the experiment was again a rest of about 3 minutes. Second experiment started with a 3 minutes long rest followed by sinking both hands of the examined person into cold water (cca 8 °C) for about 1.5 minute. The experiment ended by rest of about 3 minutes as in the previous case.

Sequences of interbeat intervals and values of systolic forces were determined from the recorded seismocardiograms (Fig.5 and Fig.6). The values of the parameters were linearly interpolated, regularly resampled by a sampling frequency of 4 Hz and module frequency responses of the subsystems F_s

a)



b)

Fig.6 Results of cold water experiment - a) time sequences of the interbeat intervals (RR) and systolic forces (SK), the vertical line separates the rest and active part of the experiment; b) computed frequency responses of the partial subsystems F_s and F_b of the linear model.

and F_b were computed according to the following formulas [1], [2]

$$F_s(\omega) = \frac{F_0(\omega)}{R_0(\omega)}, \tag{3}$$

$$F_b(\omega) = \frac{R_2(\omega) - R_0(\omega)}{F_0(\omega) - F_2(\omega)}. \tag{4}$$

where $R_0(\omega)$ and $F_0(\omega)$ are Fourier transforms of sequences of the interbeat intervals and systolic forces measured at rest (about 2 minutes) and $R_2(\omega)$ and $F_2(\omega)$ are transforms of the sequences measured during and after the external stimulation. Frequency transforms of both measured sequences have been estimated by the unconditioned least square parametric method [6] that despite some of its short-comings proved to be the most robust method relatively independent on content of various disturbing phenomena influencing the patient examinations. Meaning of both the subsystems stays the same as in case when values the systolic blood pressure were used, that is F_s describes properties of the cardiovascular system and F_b more or less properties of its control by central nervous system.

3. RESULTS AND DISCUSSION

Typical signals recorded during the described experiments are displayed in Fig.5a and Fig.6a. It can be seen that both the maneuvers evoked relatively well visible response of heart rate. The systolic force response was usually not so well recognizable as that of heart rate.

The computed frequency characteristics of both the partial systems F_s and F_b (Fig.1) are presented in Fig.5b and Fig.6b. Typically, the system F_s in the direct branch of the model transmits better frequency components from the higher half of the frequency band. The cut-off frequencies differ for the different examined persons, from 0.25 Hz to about 0.4 Hz. However, it can be said that the cut-off frequencies were approximately the same for each person examined under both the experimental conditions. On the contrary, the subsystem F_b in the feedback transmits better components of lower frequencies. It seems that the cut-off frequency of the F_b low pass filter is approximately the same as that of the high pass system F_s. Again, it is valid that the cut-off frequency can differ for examined persons but it is equivalent for each person and both the experimental conditions.

If the described shapes of the frequency responses are compared with the results of our previous feedback baroreflex analysis published in [1], [2] and [3] (see also Fig.2) we can find important discrepancies. While the frequency response of the F_s system in [1], [2] or [3] more amplifies lower frequency components for healthy subjects, the character of this frequency response described here is quite reverse. This fact cannot result from rather plain response of systolic force to the stimuli, because the characteristics of the system F_s are calculated from sequences recorded during rest phase of the experiments. Further, because the sequence of interbeat intervals is used in both the cases we can presume that the different shape of the response $F_s(\omega)$ depends on a spectrum of the systolic force signal which should contain accentuated higher frequency components than the signal derived from values of systolic blood pressure. The question is if these higher frequency components follow from the physiology of heart activity or if they are a consequence of some additional parasitic process running in heart or body or if it is caused by errors in measuring. This question cannot be probably answered now, yet.

Another problem is in a different shape of the $F_b(\omega)$. In [1] $F_b(\omega)$ for healthy people was described as a frequency response of pass band system with the pass band from about 0.1 to 0.4 Hz. It means that in comparison with results published before there is rather small difference between amplitudes of very low frequency components of systolic forces at rest and after the stimulation. If it is true, than it would be necessary to look for another experimental arrangement under which a response to the change of the examined person state would have differed from the rest signal at very low frequencies much more than under the condition described here.

4. CONCLUSIONS

The method of the linear feed back baroreflex analysis was applied for analysis of electro-mechanical response of heart. The difference between obtained and expected shapes of the frequency responses of both the subsystems F_s and F_b used in the model can be explained by different properties of the systolic force signal both at rest and after the external stimulation.

Acknowledgement

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