SPECTRAL PROPERTIES OF BCG SIGNAL IN SITTING AND LYING POSITIONS IN NORMAL BLOOD PRESSURE AND HYPERTENSION

J. Alametsä, A. Saastamoinen, E. Huupponen and A. Värri

Digital Media Institute, Tampere University of Technology, Tampere, Finland

{jarmo.alametsa, antti.saastamoinen, eero.huupponen, alpo.varri}@tut.fi

Abstract: This paper presents spectral properties of ballistocardiographic (BCG) recordings made with a mobile physiological signal measurement station by using an EMFi (Electromachanical Film) sensor. Measurements were done in sitting and supine positions before and after physical exercise. The purpose is to describe the effect of an exercise into BCG signal in the situation, in which the measured person has a temporary mild hypertension. Some examples of measured BCG data from human body recorded in sitting position, in supine position and some extracted parameters in figurative form are also presented. The shape of the BCG complexes changed in time domain and frequency components of BCG changed when hypertension BCG was compared to normal blood pressure BCG.

Introduction

Ballistocardiography (BCG) [1] is one of the oldest non-invasive method for cardiac and respiration evaluation, where it reflects closely the strength of myocardial contraction revealing the condition of the heart. BCG is also the result of an intricate interplay between heart and dynamic circulatory system, which continuously adapts its parameters to changing homeostatic demands [2]. As the heart and the lungs are both located inside the thorax, respiratory movements have a direct effect on the operation of the heart via pressure changes inside the thorax. When the heart pumps blood first from the atrium via ventricles to the pulmonary arteries and ascending aorta, through aortic arch to the peripheral circulation, recoil of opposite direction is applied to the body and its force and direction is changing according to the cardiac cycle. The contracting heart forms ballistic recoil via blood flow to the aorta and pulmonary arteries and this pulse wave travels through the vascular system and diminishes gradually. The speed of the pulse wave is 4 – 5 m/s and the propagation speed is dependent of the elasticity of the arteries and the level of blood pressure.

The BCG waveforms (Fig. 1-3) have been divided into three groups, labelled with letters; Pre-ejection (FGH), ejection (IJK) and diastolic part of the heart cycle (LMN). Pre-ejection waves consist of venous return to the heart, atrial filling and contraction (H; head ward deflection). The foot ward pointing I reflects the rapid acceleration of blood in the ascending aorta and pulmonary arteries around the aortic arch and into the carotid arteries. The J-wave describes the acceleration of the blood in the descending and abdominal aorta and deceleration of blood in the ascending aorta. IJ amplitude reflects the force of contraction of the left ventricle and IJ velocity reflects contractility. The K, L waves reflect the deceleration and cessation of blood flow and the closing of aortic valve [1]. Diastolic waves (KL, MN) reflect the state of peripheral circulation. Also the influence of arterial wall stiffness and peripheral resistance has greater influence on the diastolic waves [3].

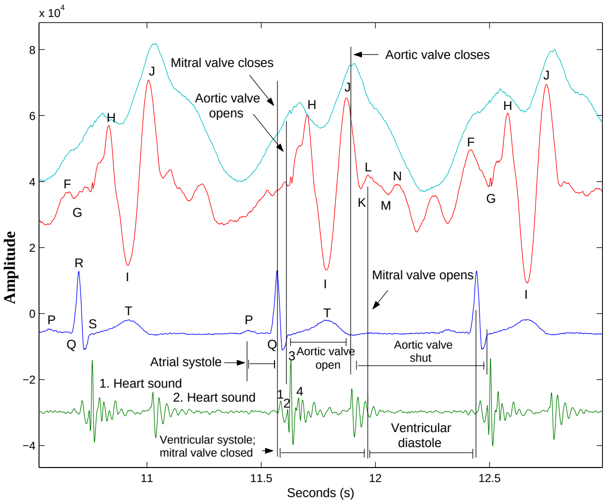

Figure 1: Signal recorded in sitting position. Signals from the bottom to top: PCG, ECG, signal from the EMFi sensors on a chair and from the back of the chair.

Two most important factors that have an influence on the BCG signal are posture and respiration. The posture of a measured person has a direct effect into the BCG signal because the hydrostatic pressure in blood vessels is altered by changes in posture. Hydrostatic pressure changes in turn have an influence on the capacity of veins and the distribution of blood around the whole cardiovascular system [3]. Venous return to the left heart is decreased in vertical posture causing a decrease in stroke volume and end-diastolic volume. Receptors of myocardium and blood vessels detect the end-diastolic volume change by increasing sympathetic activity, which causes a rise in heart rate and constriction of blood veins compensating the reduced stroke volume [3]. The effect of exercise into cardiac output and on stroke volume is different in supine and upright positions [3].

 ISSN: 1727-1983

During exercise cardiac output is increased by increasing stroke volume and heart rate. Moreover, the velocity of blood flow in veins is increased and blood flow distribution changes in according to the activity level of tissues. Systolic blood pressure changes in direct proportion to increased intensity of workout, while diastolic blood pressure changes very little if at all [3]. The way how stroke volume changes during exercise is highly dependent on age, sex and the endurance capacity of the individual person. The recovery after exercise, where heart rate, cardiac output and stroke volume return to their normal values, has been studied and there is an observation, that stroke volume decreases more slowly compared to cardiac output and heart rate [3].

Being not a homogenous mass, different body parts show separate resonant frequencies which produce phase differences in their relative accelerations. The natural frequencies of various body segments are within the frequency range of BCG exerting their influence on the shape of BCG [4]. Fourier analysis of the BCG has been used earlier to study different problems related to BCG, as for instance the elastic properties of blood vessels, frequency response and the effects of the dynamics of the human body on the BCG [2]. The frequency range of the BCG is from 0 to 40 Hz [5].

In this paper a Mobile Physiological Signal Measurement Station [6] has been used as a device which enables the recording of BCG with EMFi sensors. The main goal of this study is to present temporal spectral differences between normal blood pressure BCG signal and hypertension BCG signal. The effect of a posture on the BCG signal has been studied with some chair recordings where pieces of EMFi sensors were attached into the back of the chair and beneath the person sitting on a chair. Also some recordings with supine position are presented. Another objective is to describe changes of BCG signal caused by elevated blood pressure in order to study the possibility that hypertension could be estimated directly from ballistocardiographic signal.

Methods

The EMFi [7] is basically a thin biaxially oriented plastic film coated with electrically conductive layers, which are permanently polarized. Changes in the pressure acting on the film generate a charge on its electrically conductive surfaces and this charge can be measured as a current or voltage signal. It can convert mechanical energy to electrical and vice versa. Thus the EMFi acts as a sensitive movement sensor suitable for BCG recordings.

Signals from EMFi sensors were recorded with the Mobile Physiological Signal Measurement Station [6] into a notebook computer with a data acquisition card (Daqp16, recording software Quatech DaqEZ) and the recordings were made into ASCII format. In the Measurement Station an active Butterworth 8. degree low pass filter was used where the cut-off frequency was 256 Hz.

In chair recordings the EMFi sensor (42 cm x 36 cm) was beneath the person and in the back of the chair. In supine recordings one EMFi sensor (51 cm x 180 cm) was used in order to get BCG from the whole body.

Measurements

The BCG signals of one person in a sitting position and in a supine position were recorded before and after physical exercise (kickboxing, lasted about 1,5 h). One type of measurement was done: suppressed respiration in the beginning of the measurement and normal respiration after that. Each measurement lasted about 3 min and the used sampling frequency was 500 Hz. The measured person had a mild hypertension values (after consuming ammonium chloride day before the measurement) when the first measurement was made. After a physical exercise the blood pressure values dropped to normal values. The second measurement was done 1 hour after the exercise. Just before the BCG measurements the blood pressure and the pulse were measured with Omron M5-I blood Pressure Monitor Device.

In order to detect amplitudes of I and J slopes from the BCG signal, the signal was first band pass filtered (0.5 – 30 Hz FIR, 700 taps, time delay correction), down sampled into 100 Hz and the analysis was done with an analysis window of length of 0.8s, which moved with 0.4s steps. Two methods for detection were used. In the first one the index of the R spike from ECG was used for reference for I and J waves and the waves were detected by taking maximum from differentiated (5 points) ECG signal. In the second method the I slope was detected from the BGG signal with local minimum method and then the J slope was detected by using the index of I as a starting point. In both methods the interval of R or I waves were checked to be at an adequate distance from each other and possible double detections were removed.

The minimum method for the I wave detection was chosen in the second case because the time intervals from ECG peaks to BCG peaks vary in response to respiration [3] and also for the reason that the amplitude of the I wave has been found to be almost insensitive to peripheral resistance, distensibility of arteries and the radius of arteries [3]. I-J slope amplitudes and intervals were studied, because bad prognosis was given to patients, who had small I-J amplitudes, long I-J duration and poorly synchronised contractions in the literature [8]. Amplitude spectrum (length of FFT; 1024 taps) was taken from raw signal, cumulated (current spectrum value was added to amplitude scaled value) and normalised (divided by the number of spectra). In order to evaluate differences between spectra, coherence was counted from the hypertension BCG signal and the normal blood pressure signal in the frequency range of 0 – 20 Hz.

The suppressed part of respiration was chosen for the study because the effect of respiration was necessary to be excluded from the study in order to assess only the influence of the heart on the ballistocardiographic signal.

Results

EMFi sensors were able to produce good quality signals, as seen in figure 2 (hypertension case) and figure 3 (normal blood pressure case). After physical exercise blood pressure values dropped to normal values. I-J amplitudes increased (Tables 3 and 4) with normal blood pressure values compared to hypertension BCG values. In supine position and suppressed respiration, I-J amplitude almost doubled and in normal respiration part tripled compared to hypertension BCG value. In the sitting position changes are smaller, but with normal blood pressure the I-J amplitudes are higher than with hypertension BCG.

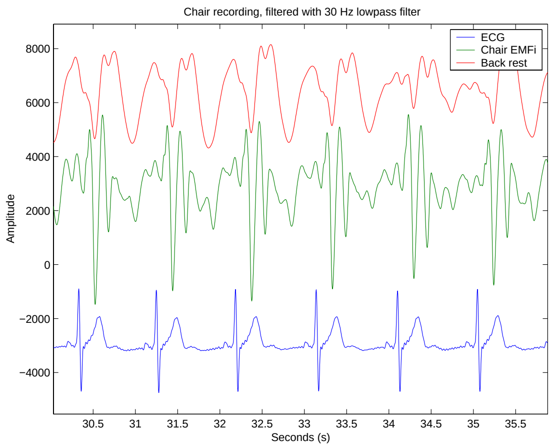

Figure 2: From top to down: EMFi sensor in the back of the chair, beneath the person and ECG in the hypertension (171/99, pulse 74). Suppressed respiration.

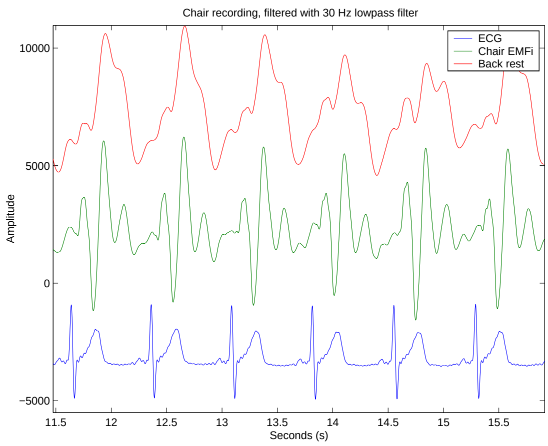

Figure 3: From top to down: EMFi sensor in the back of the chair, beneath the person and ECG in during of normal blood pressure (138/82, pulse 79) after exercise. Suppressed respiration. Differences compared to Fig. 2 can be seen especially in the chair BCG signal beneath the measured person.

Differences in amplitude spectrum compared to sitting and supine position are due to different orientation of ballistocardiographic forces. Also the physical size

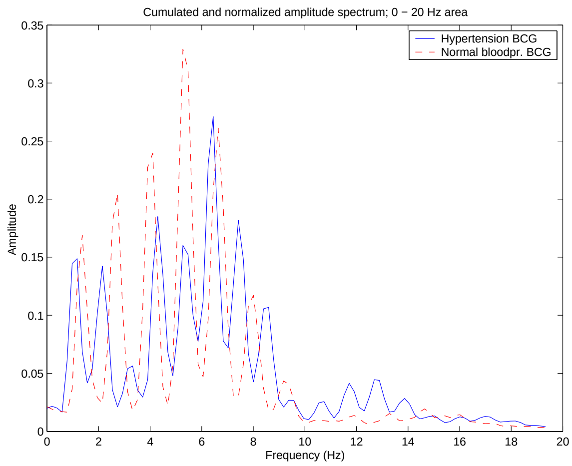

Figure 4: Amplitude spectrum of hypertension BCG is shown with solid line and normal blood pressure spectrum with dashed line. EMFi sensor was beneath the person in the chair. Suppressed respiration. The main components of the ballistocardiographic signal are in the frequency range of 2 – 10 Hz [9], but other frequencies may also have diagnostic value. Higher frequency components have emerged into hypertension BCG signal compared to normal blood pressure signal.

of the EMFi sensor in whole body supine measurement may have some minor influence into spectrum. One distinctive feature in amplitude spectrum is the emerging of high frequency components in the hypertension BCG case compared to normal blood pressure case. Similar changes can be seen in the chair BCG signal (Fig. 2), where visually more spike alike waves have been appeared compared to (Fig. 3). Median values of the coherence from hypertension BCG and normal blood pressure BCG (0 – 20 Hz) show only modest similarities of amplitude spectra between signals (Table 2).

Table 1: Blood pressure values before (mild hypertension) and after physical exercise.

	Hypertension	Normal Blood pressure
Sitting	171/99,pulse 74	138/82,pulse 79
Supine	149/85,pulse 68	139/84,pulse 78

Table 2: Median values of the coherence (0 – 20 Hz) between signals of hypertension BCG and normal blood pressure BCG.

	Suppressed respiration	Normal respiration
Sitting: Hypertension and normal BP	0.045	0.011
Supine: Hypertension and normal BP	0.049	0.014

Tables 3 and 4 show the results of the I-J amplitude measurements. Differences between values of (Table 3 and 4) can be explained by different starting points in slope detection. By using the index of R spike offered better detection of I and J slopes compared to used I

 ISSN: 1727-1983

slope detection with the minimum method. Poorer performance was seen especially in supine I-J detection where the detection of the I slope was more complex due to the different orientation of BCG forces compared to sitting position.

Table 3: Median values of I-J amplitudes from the part of suppressed respiration or normal respiration detected by using I slope as a reference point.

	Suppressed respiration	Normal respiration	Whole recording
Sitting: Hypertension	5778	2430	2582
Sitting: Normal BP	7258	4551	3195
Duration (s)	38	126	200
Supine: Hypertension	867	206	345
Supine: Normal BP	1723	920	973
Duration (s)	31	110	200

Table 4: Median values of I-J amplitudes from the part of suppressed respiration or normal respiration detected by using the index of R spike from ECG as reference point.

	Suppressed respiration	Normal respiration	Whole recording
Sitting: Hypertension	5957	2808	3478
Sitting: Normal BP	6774	2936	3841
Supine: Hypertension	933	329	366
Supine: Normal BP	1574	1003	1047

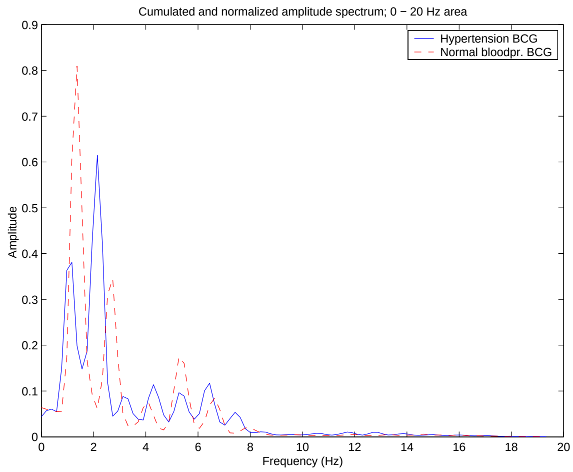

Figure 5: Amplitude spectrum of hypertension BCG in solid line and normal blood pressure spectrum with dashed line from the back of the chair. Suppressed respiration.

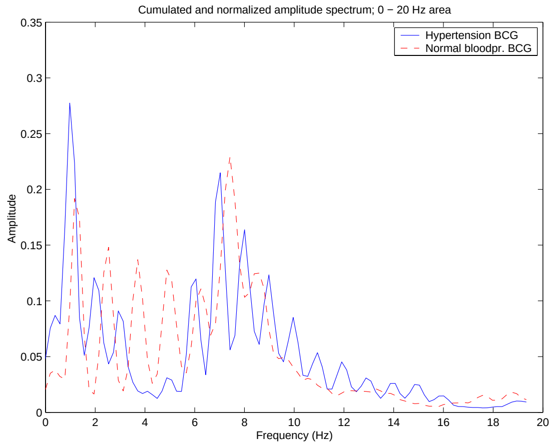

Figure 6: Amplitude spectrum of hypertension BCG in solid line and normal blood pressure spectrum with dashed line in supine position. Suppressed respiration. Slightly higher frequency components can be seen in the hypertension BCG signal compared to the normal blood pressure signal.

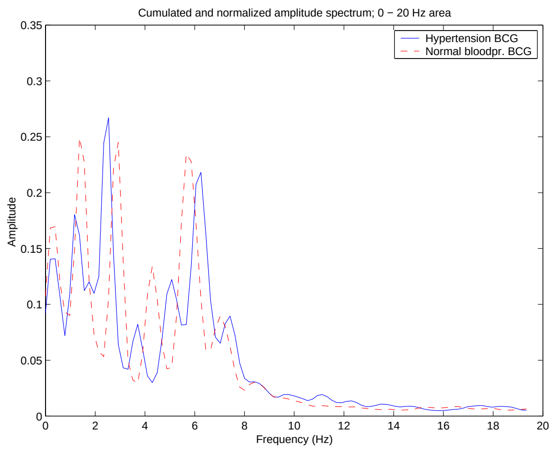

Figure 7: Amplitude spectrum of hypertension BCG in solid line and normal blood pressure spectrum with dashed line. EMFi sensor was beneath the person in the chair. Normal respiration of 3 min.

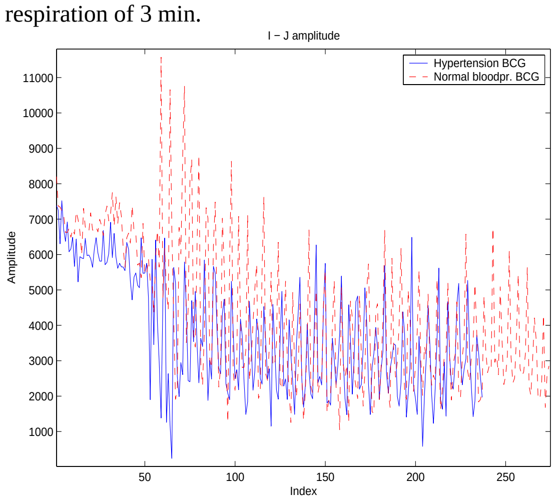

Figure 8: I-J amplitude in sitting position from buttocks including suppressed part of respiration (index up to 55) and normal respiration. Hypertension BCG in solid line and normal blood pressure with dashed line. More detected amplitudes can be seen in normal BP case.

ISSN: 1727-1983 © 2005 IFMBE

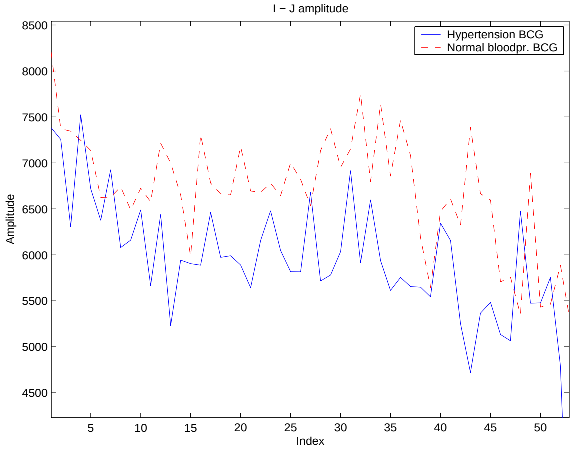

Figure 9: I-J amplitude from the suppressed part of respiration when the EMFi sensor was beneath the person in the chair. The BCG I-J complex of normal blood pressure amplitude increased compared to hypertension BCG I-J amplitude (Table 4).

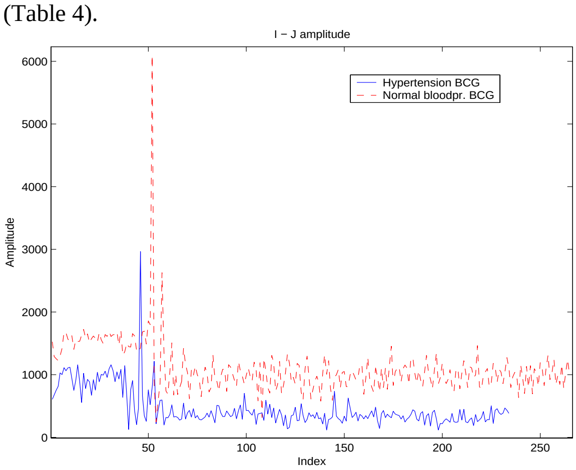

Figure 10: I-J amplitude from the supine position including suppressed part of respiration and normal respiration. Hypertension BCG (149/85, pulse 68) in solid line and normal blood pressure 139/84, pulse 78) with dashed line. Amplitudes with normal blood pressure are higher than in the hypertension case. More detected amplitudes can be seen in the normal BP case.

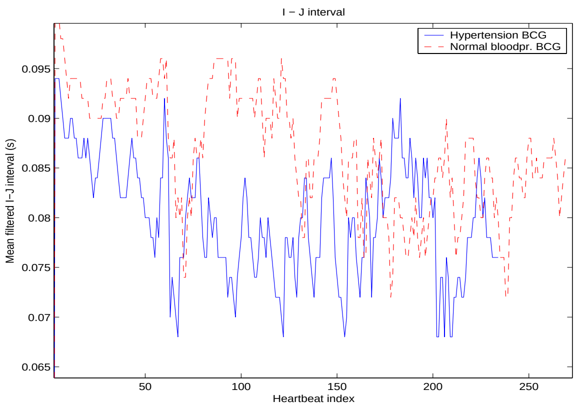

Figure 11: Mean filtered I-J intervals plotted against heartbeat index, sitting position. I-J intervals are larger in the normal BP case, seen in the suppressed respiration part (index up to 55) and just after that.

The effect of respiration into the amplitude spectrum of BCG signal from chair recording can be seen in figure 7 (0.5 Hz component). One distinctive feature is the almost total lack of 4 Hz component in the hypertension BCG signal (Fig. 6, 7). In Fig. 4 there are differences in the position of the 4 Hz spike compared to normal blood pressure values. Figures 8 to 10 present I-J amplitude plots in various conditions; figure 11 presents I-J time interval and figures 12 and 13 present the median heart rates during the experiments.

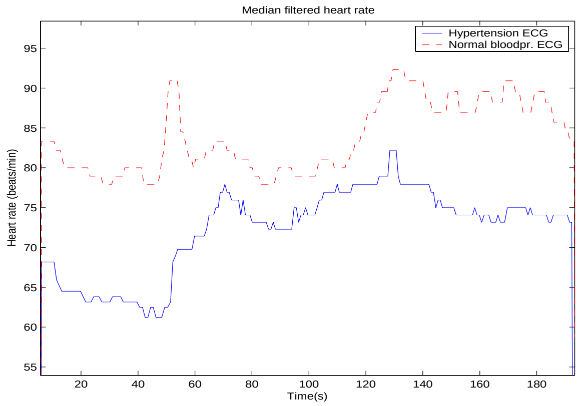

Figure 12: Median filtered heart rate (11 beats filtering) from the chair recording. The effect of suppressed respiration can be seen as lower levels of HR (index up to 55) and rising levels in recovery phase. The HR was calculated from R spikes of ECG.

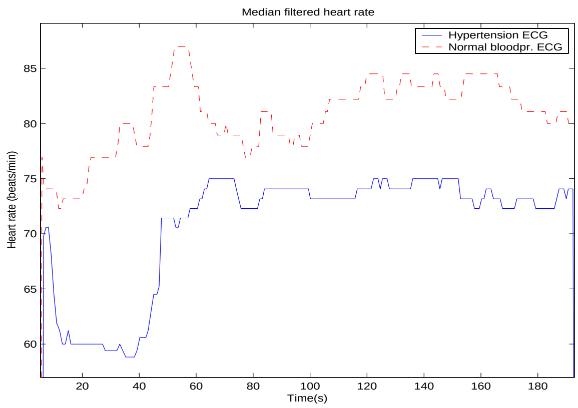

Figure 13: Median filtered heart rate (11 beats filtering) from the supine recording. The effect of suppressed respiration can be seen as lower levels of HR (index up to 50) and rising levels in recovery phase. The HR was calculated from R spikes of ECG.

Discussion

The positive influence of physical exercise into mild hypertension is apparent. Changes between hypertension BCG and normal blood pressure BCG can be seen in the shape of complexes of BCG signal and in frequency domain pictures. Elastic properties of blood vessels change when blood pressure rises and this has an influence on the ballistocardiographic waveforms. Usually, ballistocardiographic amplitude decreases while arterial pressure increases [1]. Previous studies have also confirmed the benefits of vigorous physical training providing a remarkable improvement in BCG waveforms. This can be seen as amplitude and waveform improvement especially in cases, in which BCG was abnormal in the beginning of the exercise [1].

Strong correlation has also been found between improvement of BCG and maximum oxygen uptake [1].

The normal amplitude growth of I slope during suppressed respiration compared to normal respiration can be explained by the fact that respiratory movements have a direct effect on the operation of the heart via pressure changes inside the thorax. Usually, the systolic complex (HIJK) increases during inspiration and decreases during expiration [10]. Inspiration and followed suppressed respiration resulted in increased pressure inside the thorax affecting to the fillings of heart chambers resulting strengthening of the systolic complex.

A marked linearity between abnormal BCG findings and the rise in blood pressure has been detected earlier. Also a marked correlation between coronary heart disease and BCG abnormalities had been found [11]. In an earlier work where the qualitative classification of waveform (Starr classification) and I-J amplitudes of ULF BGG were compared, both the Starr and ULF recordings showed a tendency for increasing abnormality in waveform which was associated with decreasing amplitude [12]. Our study shows, however, how different values of I-J amplitude can be obtained from the same person, depending on the situation in which the measurement was made. This makes it difficult to make conclusions of a person's health based on a single BCG measurement. It would have been interesting to see for how long the increase in the I-J amplitude would stay in the test subject but unfortunately it was not possible to make such study here.

The type of measurement in which suppressed respiration was in the beginning and normal respiration after that, was intended to be as a mild stress test for the body which possibly could give more information about the condition of the body regulatory system. The recovery from suppressed respiration showed some differences in I-J intervals with different BP levels (Fig. 12). Also in Fig. 13 and 14 the effect of recovery can be seen in the heart rate measurement.

Future studies include also the study of blood pressure changes into diastolic components of the BCG signal. Also the effect of the type of exercise into BP changes needs more study.

Because of small number of persons measured, these observations about the blood pressure influence on the BCG signal require more research in order to make more profound conclusions.

References

[1] WEISSLER A. M. (1974): 'The Ballistocardiographic waveforms', in 'Noninvasive Cardiology Monographs', (Grune & Stratton Inc. NY), pp. 55-61

[2] FRANKE E. K. (1973): 'A Look at the Fourier Spectrum of the Ballistocardiogram', *Bibl. Cardiol.*, **32**, pp. 109-114

[3] VÄHÄ-RAHKA T. (1997), 'Ballistocardiograms at rest and after exercise recorded with a new chair-type apparatus. A preliminary study', MSc Thesis, Helsinki University of Technology

[4] SOAMES R.W and ATHA J. (1982): 'Three-Dimensional ballistocardiographic responses to changes of posture', *Clin. Phys. Physiol. Meas.*, **3(3)**, pp. 169-177

[5] STRONG P. (1973): 'Biophysical Measurements', 1 st. Edition, 3 rd printing June 1973, 062-1247-00, p. 218

[6] ALAMETSÄ J., KOIVULUOMA M., VÄRRI A. (2001): 'Mobile Physiological Signal Measurement Station', Proc. of MEDICON 2001 –IX Mediterranean Conf. on Med. and Biol. Eng. and Comput. Pula, Croatia, June 2001, pp. 289 – 292

[7] KIRJAVAINEN K. (1987): 'Electromechanical film and procedure for manufacturing same. U.S. Patent no. 4654546'. Manufacturer of EMFi: Emfitech Ltd, Vaajakoski, Finland; http://www.emfit.com

[8] THEORELL T., BLUNK D., WOLF S. (1975): 'Ballistocardiographic indicators of prognosis in ischemic heart disease', *J. Lab. & Clin. Med.*, **86(1)**, pp. 46-56

[9] RITOLA J. (1997): 'Design and realization of a bathroom scale with ballistocardiographic heart rate measurements', MSc Thesis, Helsinki University of Technology, Department of Engineering Physics and Mathematics

[10] NOORDERGRAAF A., POLLACK G. (1966): 'Ballistocardiography and Cardiac Performance', Proc. of the 11th Annual Meeting of the Ballistocardiograph Research Society, Atlantic City, N.J April 30th, (Edited by Noordergraaf A. and Pollack G., Warren H. Green Inc. St. Louis, Missouri, USA), pp. 73-75

[11] NEDELJKOVIC S., DJORDJEVIC B., STOJANOVIC G. (1967): 'Ballistocardiographic findings in an Epidemiological Study of Cardiovascular Disease in Yugoslavia', Proc. 6th Europ. Congr. Ballistocardiography, London, *Bibl. Cardiol.*, **21**, pp.16-20

[12] SHERWIN R.W., HARRISON W.K., DAVIS F.W., BAKER B.M. (1969): 'Repoducibility of form Readings of Starr and Ultra Low Frequency Ballistocardiograms', *Bibl. Cardiol.*, **24**, pp. 51-56