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Local Ballistocardiographic Spectrum Studies from Signals Obtained from Limbs and Carotid Artery with an EMFi Sensor Induced with a Tilt Table*

Jarmo Alametsä, Ari Palomäki, and Jari Viik

Abstract— **The purpose of this work is to study the effect of a tilt table test procedure on ballistocardiographic (BCG) signal by using Electromechanical Film (EMFi) strip sensors. The ECG, BCG, carotid pulse (CP) from the neck near the carotid artery and ankle pulse signals were recorded from 7 persons. The spectral components of the recordings during the tilt table test were studied concentrating mainly on heart induced pulsatile signals propagating along the artery to the periphery.**

The properties of BCG pulse signal changed due to the tilt test in spectral domain. Blood pressure (BP) values and shape of the pulse changed due to the tilt test. According to this study, local BCG measurements with EMFi sensor strips combined with a tilt test can be used as a very simple non-invasive method in hemodynamic studies.

I. Introduction

Ballistocardiography (BCG) is a non-invasive method for cardiac and respiratory evaluation and it reflects closely the strength of myocardial contraction revealing the condition of the heart [1]. It is a record of the movements of the body caused by shifts in the centre of the mass of blood, and to a lesser extent, of the heart, caused by cardiac contraction [1]. When the heart pumps blood from atrium via ventricles to the ascending aorta, recoil of opposite direction is applied to the body and its force and direction is changed according to the cardiac cycle [1]. Fourier analysis has been used earlier in BCG analysis when the elastic properties of the blood vessels and the dynamics of the human body on the BCG have been studied [2, 3]. The Fourier spectrum of the BCG has a relationship to the 'BCG impedance' and defined as;

$F(n\omega_H)\cdot Z_B(n\omega_H) = B(n\omega_H)$, where

$\omega_H = 2\pi\cdot(cardiac\,cycle/s)$,

$B(n\omega_H)$ = Complex fourier spectrum of the BCG,

$F(n\omega_H)$ = Complex fourier spectrum of the flow (or pressure) pulse and

$Z_B(n\omega_H)$ = Complex BCG impedance, (n=1, 2, 3,…) [2].

In this paper a newer version of the Mobile Physiological Signal Measurement Station [4] has been used for recording of BCG and carotid pulse signals with EMFi sensors. The main goal of this study is to evaluate spectral differences in measured signals induced by the tilt table test.

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J. Alametsä and J. Viik are with the Tampere University of Technology, Department of Electronics and Communications Engineering, Tampere, Finland (e-mails: jarmo.alametsa@tut.fi and jari.viik@tut.fi)

A. Palomäki is with the Kanta-Häme Central Hospital, Hämeenlinna, Finland (e-mail: ari.palomaki@khshp.fi).

II. Methods

A tilt table test is often used to identify patients who have a vasodepressor and/or cardioinhibitory response as a cause of syncope. Patients are positioned on a tilt table in the supine position and are tilted upright to a maximum of 60 to 80 degrees for 20 minutes or more [5].

Patients with symptoms of dizziness or lightheadedness, with or without a loss of consciousness (fainting), suspected to be associated with a drop in blood pressure or positional tachycardia have been usually tested. With healthy persons the rapid change in orientation causes minor effects to the blood pressure (BP). The sensitivity of the regulative system varies with different people and large fluctuations in BP may occur with vasomotoric labile persons. Usually orthostatic test has been done in order to test the state of the autonomic nervous system [6].

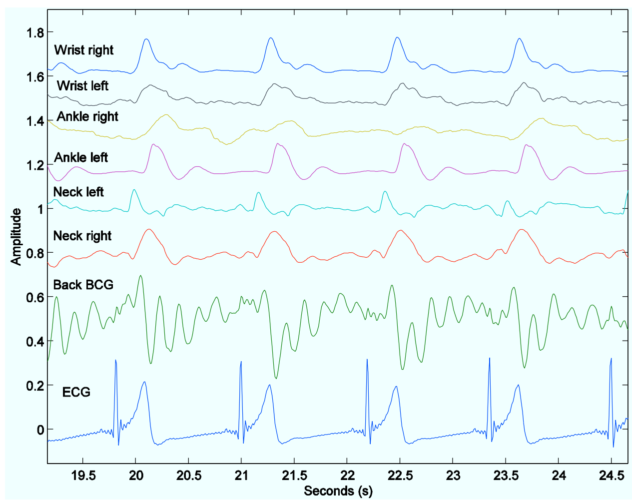

Figure 1. Signals recorded in the supine position and case 2. Signals from the bottom to top: ECG, BCG signal from the large EMFi sensor on a tilt table, signals from the left and right carotid artery and from the limbs recorded with EMFi sensor strips.

The EMFi [7] sensor is 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 a voltage signal. It can convert mechanical energy to electrical energy and vice versa. Thus the EMFi acts as a sensitive movement sensor suitable for BCG recordings.

Signals from the EMFi sensors were recorded with the newer version of the Mobile Physiological Signal Measurement Station [4] into a notebook computer with a data acquisition card (Daqcard 6036E) and the recordings were transcribed to ASCII format. In the Mobile Physiological Signal Measurement Station an active Butterworth 8. degree low

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pass filter was used, having the 250 Hz cut-off frequency. The Fourier analysis of the BCG pulse signals was used to evaluate the state and operation of the heart and the elastic properties of the blood vessels due to hemodynamic changes induced by the body position. The length of the analyzed recordings was about 3 min. Ballistic amplitude spectrum was calculated from a raw signal with a 1024 point fast Fourier transform (FFT). Spectrum was amplitude scaled with a symmetric Hanning window, culumated (added to a preceding spectral value), normalized (cumulated spectrum divided by the number of spectral components) and finally the area of the spectrum was scaled to 1 (0 – 20 Hz area).

III. Measurements and study population

The recordings were made with a tilt table. Two EMFi sensor strips (10 x 2 cm) were attached to the neck near carotid arteries and similar EMFi sensor strips were attached to the wrists and ankles (dorsalis pedis pulse) in order to study spectral properties of the measured pulse signals.

Each of the measurements lasted about 3 min and the sampling frequency used was 500 Hz. Although ECG was measured, it was only used to calculate HR. Just before the BCG measurements the blood pressure (BP) and the pulse were measured with an Omron M5-I blood pressure monitor device. The BCG pulse signal measurements were done before and after the tilting procedure. The measuring was, in each case, as follows: during the first 2-3 measurements the subject was in supine position, then the same measurement was carried out in vertical position (70°) and again, in supine position. Two of the measured persons were considered as young control group (presumably healthy, physically active men; cases 2 and 4) and the rest of measured persons were considered as middle-aged men (over 37 years). Cases 6 and 7 were regular smokers and case 6 had hangover during measurements. Case 1 engaged in regular physical activity (2-3 times in one week), as well as cases 2 and 4. Cases 3 and 7 had a moderate physical activity. The measurements were made in Kanta-Häme Central Hospital, Hämeenlinna.

IV. Results

In the following spectrum figures, the traces from the EMFi sensor strips on the person's neck or limbs during tilt procedure are presented. Heart rate (HR) calculated from ECG (Table 1) increased in upright position with cases 2 - 5, and 7. The increase in HR was large in cases 3 and 7 during upright tilt position. HR stayed very stable with case 1 during the whole tilt test. Possibly due to the increasing HR in the upright position, the frequencies of the peaks moved to higher frequencies. This was seen in cases 3, 6 and 7. In contrast to other cases, case 3 had spectral spikes below 1 Hz area obtained from the pulse signal from the left ankle (Fig. 6) induced by the orientation from supine to vertical and back to supine position.

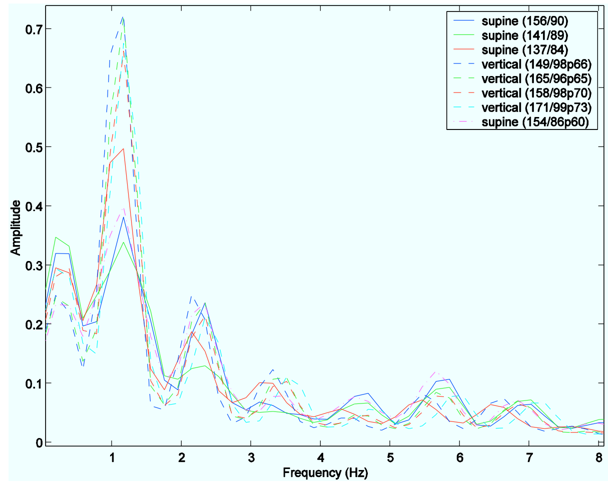

Figure 2. Spectrum from case 1 with the small strip EMFi sensor on the right side of the neck. BP and HR in the picture legend are from the Omron device. The lowest frequency spectrum spike denotes the breathing frequency 12 breaths/min. Vertical position induced higher spectral spikes in 1 Hz.

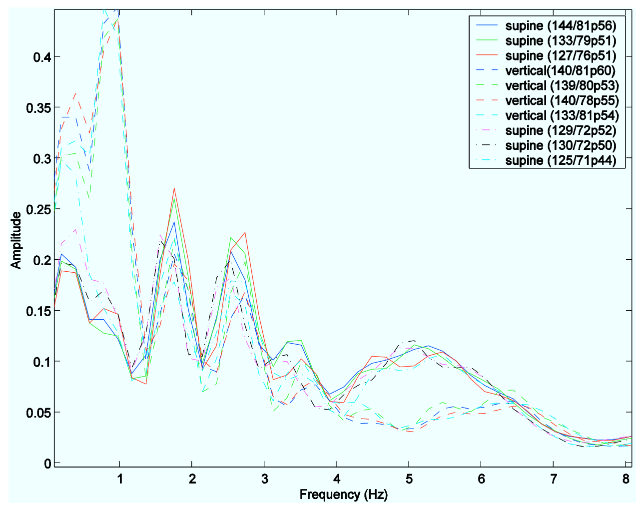

Figure 3. Spectrum from case 2 from the left side of the neck.

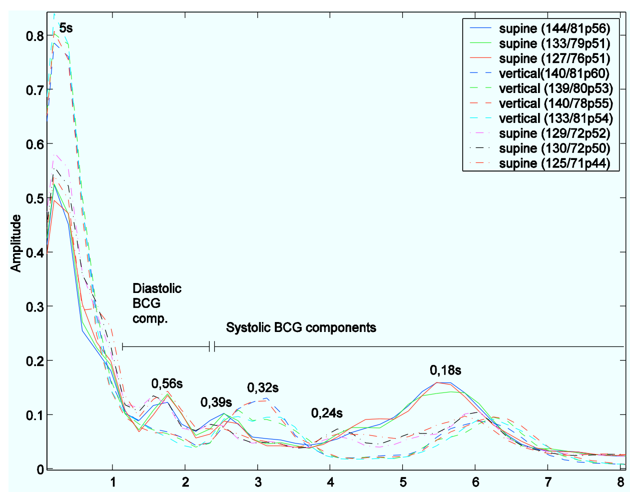

Figure 4. Spectrum from case 2 with a large EMFi sensor beneath. Local spectral traces from the neck (Fig. 3) have similarities with the whole body recoil forces recorded during the tilt test. The division into systolic and diastolic portions of the frequency area was based on the inverse of the frequency value giving time domain values seen at the top of the main spectral spikes. Normal time for maximum ejection is 0.12s following reduced ejection at 0.14s [8].

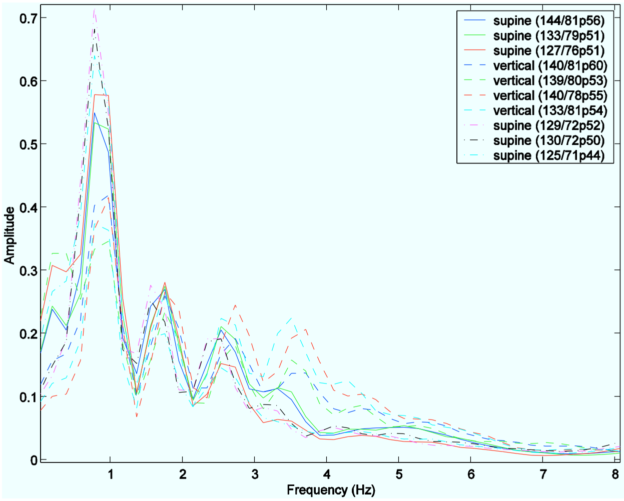

Figure 5. Spectrum from case 2 from the left wrist. Tilt test induced minor changes into the spectrum into lower frequencies.

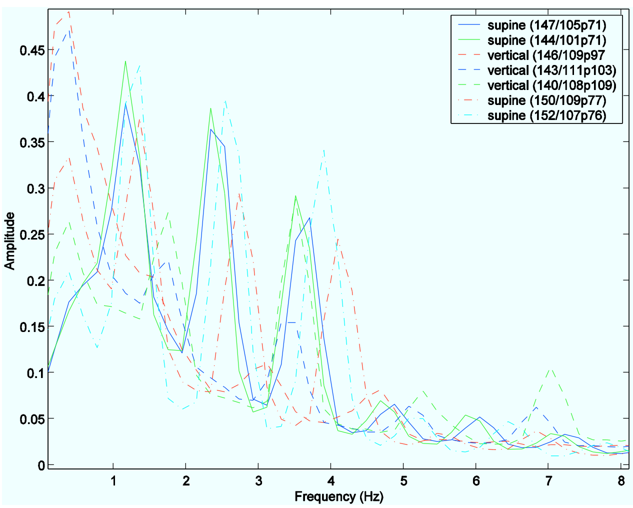

Figure 6. Spectrum from case 3 from the left ankle. In vertical position BP increased considerably (Table 1). Moving back to supine position made spectral spikes to appear in higher frequencies. In contrast to other cases with ankle spectrum, vertical and back to supine positions induced highest frequency spikes located below 1 Hz frequencies.

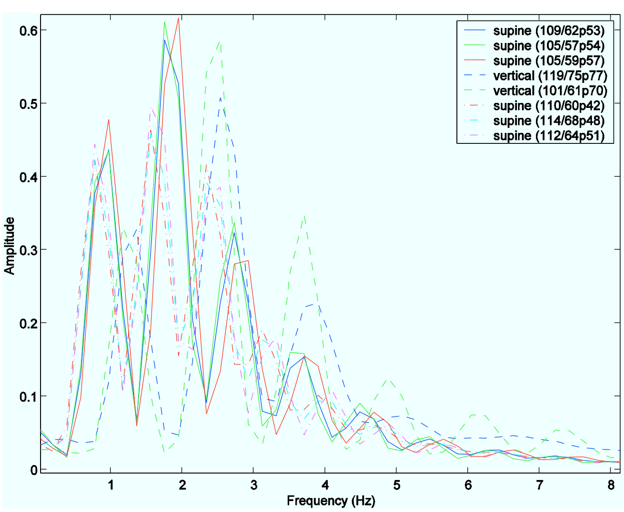

Figure 7. Spectrum from case 4 from the left ankle. Vertical position induced minor changes into spectral spikes but increased their amplitude.

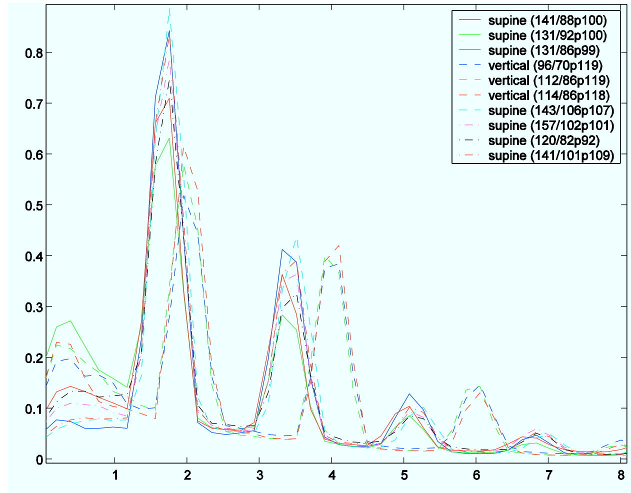

Figure 8. Spectrum from case 6 (age 53 years) from the left ankle. In vertical position the spectral spikes moved to higher frequencies.

V. Discussion

In this study, a tilt test was used to produce BP and HR changes. It may also provoke elasticity changes of the aorta. These changes were seen in spectral domain, as well as in HR values. The spectral properties of the local BCG originated pulsatile signals clearly changed due to the tilt test. The frequency of the HR (about 1 Hz), belongs to the BCG frequency area. The frequency of the BCG ranges from 0 to 40 Hz, but the important frequency components of the BCG are in the area of 1 – 15 Hz [9, 10]. The frequency of the oscillations due to blood's movement during systole are connected to the ratio of oscillating masses and the elasticity of the cardiac wall. This influences also to the intensity of the first heart sound being proportional to the rate of change in the pressure in the ventricle [11].

In vertical position heart contracted faster, possibly linked to frequency shift of the BCG pulse signals to higher frequencies. In young control group (case 2) the HR increase was very moderate in upright position and very modest changes were seen in spectral figures due to the tilt test. Another younger person (case 4) showed elevated HR values in upright position and only amplitude rise of the spetral spikes in some complexes. Those cases, which reacted more to the upright position in HR (and during return to supine position), seemed to have more fluctuation also in spectral traces. As the pulse signal measured from ankle is more defined in time domain, so does the spectral trace in frequency domain in most of the studied cases (except case 3) having lesser components below 1 Hz. Although the same alike frequency spikes were found from wrist and neck spectrum figures, more components were found below 1 Hz resembling more detailed pulse signals in time domain found in the neck and wrist signals. Aorta is the most compliant artery in the cardiovascular system (peripheral arteries are more muscular and less compliant) and changes its compliance can be seen also in time domain traces.

During the tilt test strong fluctuation was seen in the BCG signal due to the change of body position from supine

Table 1. Mean heart rate values calculated from the ECG:s R-R waves from the different positions during the tilt test. In some recordings (Case 3) ECG electrodes got off from the chest due to rapid movement during tilting procedure. With cases 1, 4 and 5 all the recordings were not performed.

			Supine			Vertical			Supine		
Case	Age	BMI	rec 1	rec 2	rec 3	rec 4	rec 5	rec 6	rec 7	rec 8	rec 9
1	44	32	70	70	66	66	69	69	69	na	na
2	26	26	51	53	53	54	54	53	50	49	52
3	50	22	73	85	na	98	101	na	83	78	na
4	27	22	55	54	57	78	74	na	48	49	49
5	42	33	78	77	83	81	85	85	92	78	na
6	53	31	98	98	98	115	114	115	99	98	97
7	37	27	74	75	74	86	90	91	72	71	72

to vertical and back to supine position. This complicates the accurate detection of the BCG signal components in the time domain. For that reason, the study of the spectral properties induced by the change in hemodynamic due to the tilt test might be a better alternative.

Differences in the BCG pulse spectral waveforms between different subjects can be explained by the different physiological and anatomical causes; as the BP values differ with different people, so does the contraction ability of the heart and the elasticity of the veins. Also the level of physical fitness and the age of a person have their own influence on the measured signals.

In a previous study, the linearity between abnormal BCG findings, the rise in blood pressure and blood cholesterol level was noticed [12]. From the same recordings we have previously studied BCG signal in spectral and time domain recorded from a big EMFi sensor (180 x 60 cm) beneath the measured person [13] in order to get vascular impedance (Z_B) from the whole body noninvasively [14]. As older methods required invasive meassurements when defining vascular impedance, EMFi sensor offers clear advantages offering also local measurements.

VI. Conclusion

The presented novel method of measuring local BCG pulse wave changes with EMFi sensors combined with a tilt test may offer new method for noninvasive evaluation the state of the cardiovascular system via hemodynamic changes induced by the body position.

By examining the state of cardiovascular system, the extent of progression of calcification and atherosclerosis may be revealed.

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