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Cardiac Sounds from a Wearable Device for Sternal Seismocardiography

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***Abstract*— Seismocardiography is the body-surface recording of vibrations produced by the beating heart. A high frequency (HF) accelerometric component of the seismocardiogram (SCG) is related to the heart sounds generated by the closure of atrio-ventricular and semilunar valves.**

This paper evaluates the feasibility of recording the SCG component associated to cardiac sounds by means of a wearable device originally designed for monitoring ECG, respiratory movements, body accelerations and posture in freely moving subjects. The method is based on the averaging of the HF component of the acceleration vector measured by the wearable system, and on the subsequent extraction of features from its envelope.

The method is applied on data recorded in healthy volunteers in different postures and during sleep. Results indicate that it is possible to reliably identify the time of occurrence of the first and second heart sound within the cardiac cycle. They also show significant differences in the HF component of SCG between supine and standing postures. Analyzing the HF SCG in a volunteer sleeping at high altitude (4554 m asl) substantial differences were also found among three body positions (lying supine or on the left or right side). These differences are likely to reflect changes in cardiac mechanics induced by different postures of the body.

I. Introduction

SEISMOCARDIOGRAPHY is a term introduced in the ‘60s to indicate the recording of body vibrations induced by the activity of the heart [1;2]. These vibrations are synchronous with the cardiac beat and include components of different origin. Body vibrations at relatively low frequencies include movements produced by the pulsatile ejection of blood volumes into the vessels [3]. This low-frequency component of the seismocardiogram (SCG) has been extensively studied with the name of ballistocardiogram mainly by Starr [4] and Noordergraaff [5] in the ‘50s and ‘60s. High frequency SCG components are generated inside the heart. They are related to the heart sounds produced by the closure of cardiac valves and by the flow of blood through or near the heart [6]. It has been reported that an accelerometer placed on the sternum is able to detect the infrasound component of the first heart sound (S1, associated to the closure of atrio-ventricular valves) and of the second heart sound (S2, associated to the closing of semilunar valves) [7].

In the last years, the interest in SCG recordings has been raised again thanks to the broad availability of small and cheap MEMS accelerometers. These sensors can be included in portable or even wearable systems allowing unobstrusive long-term monitoring of body accelerations in

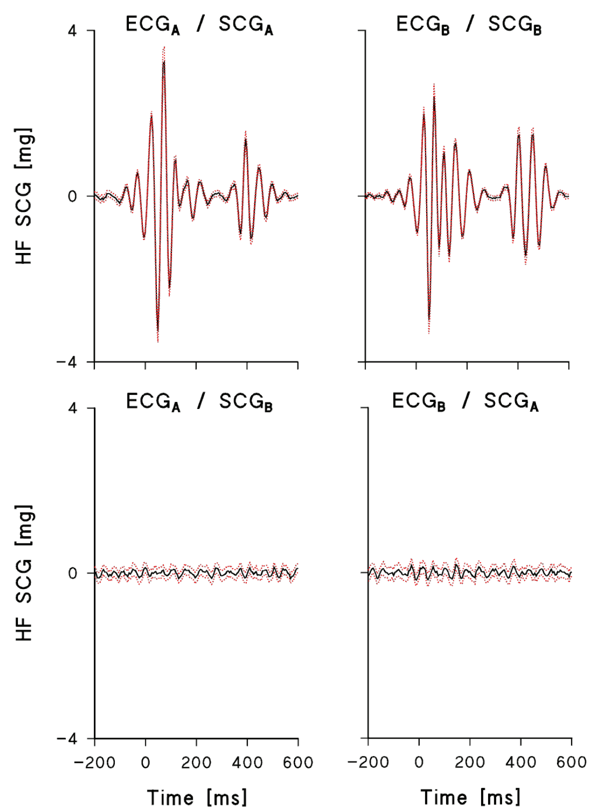

Fig. 1. Upper panels. High frequency accelerometric component of SCG estimated from 10-minute recordings in two subjects, *A* (left) and *B* (right), while resting supine; time 0 ms indicates the position of the R-peak; red dotted lines are 95% confidence limits. Two front waves with amplitude of few milli-*g* occur where the S1 and S2 components of the heart sounds are expected. Lower panels. Surrogate analysis performed by associating the SCG of subject B with the ECG of subject A and *vice-versa*.

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a wide range of conditions, including daily-life activities, sleep and exposure to extreme environments. In the past we showed that it is possible to detect specific components of the ballistocardiogram with wearable systems [8] by using textile ECG electrodes and an accelerometer placed on the clavicle. Subsequently we started to measure SCG components associated to the heart sounds by using a modified version of a smart garment we recently developed for the assessment of vital signs (the MagIC system) and that already integrate a MEMS tri-axial accelerometer in its electronic board [9]. Use of this wearable device largely facilitates the investigation of aspects of cardiac hemodynamics without interfering with the subject's activities, even for long time periods.

This paper describes the procedure for deriving the SCG component related to heart sounds by using the wearable device. It also illustrates examples of sternal seismocardiography in healthy volunteers during laboratory tests and during night sleep.

II. METHODS

A. Sensors and Signals Recording

The MagIC systems has been already described in details [9;10]. In short, it consists of a vest with embedded textile ECG electrodes and textile piezoresistive transducer for respiratory movements, connected to a compact electronic module. The latter includes a digital triaxial MEMS accelerometer (LIS3LV02DL, STMicroelectronics). The

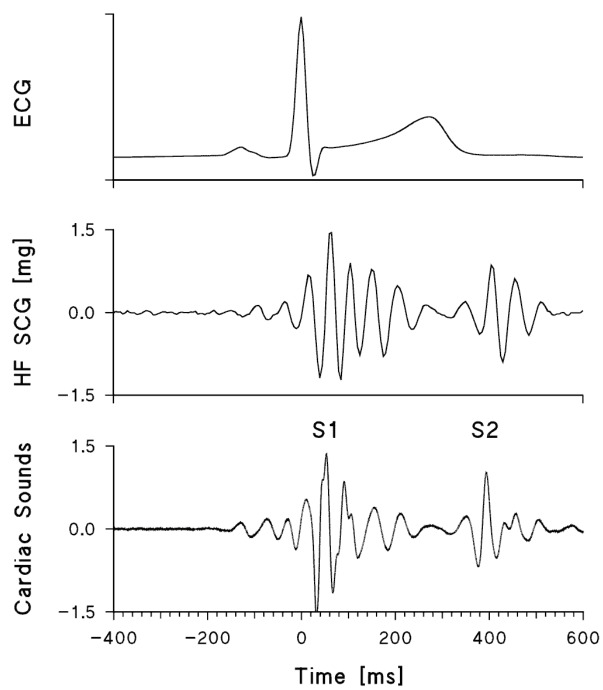

Fig. 2. ECG, high-frequency component of SCG and cardiac sounds in one supine volunteer: ensemble averaging from 10-minute recording; S1=first hear sound; S2= second heart sound.

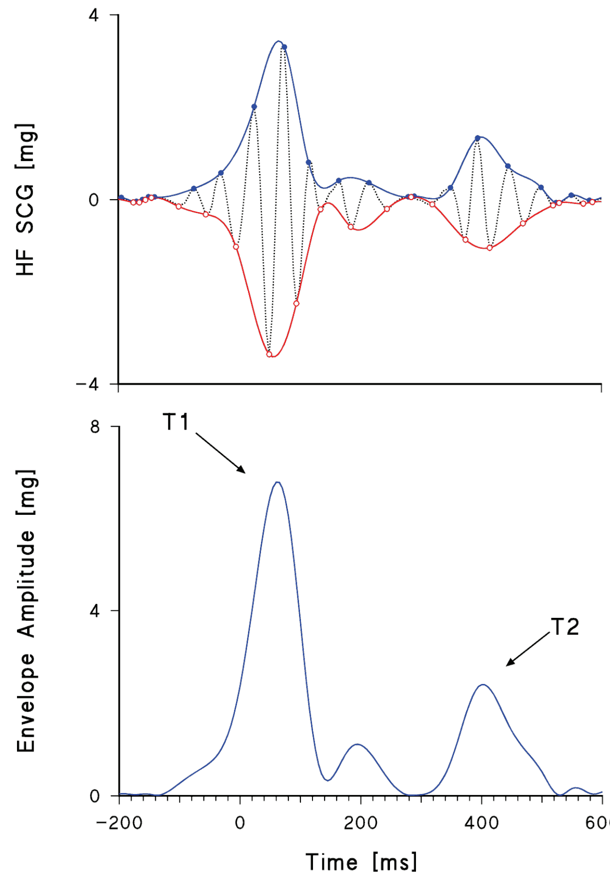

Fig. 3. Extraction of features from HF SCG. Upper panel: maxima (blue solid circles) and minima (red open circles) are identified and separately interpolated by cubic splines. Lower panel: difference between upper and lower splines is calculated; T1 and T2, i.e., time position of the components corresponding to S1 and S2, are identified.

module is located inside an elastic pocket of the vest at the sternum level. Further details on the modified version of the MagIC system for SCG recording can be found in [11].

The ECG is sampled at 200 Hz, the other signals (thorax movements and 3D accelerations) at 50 Hz. Signals are digitized on 12 bits and locally stored on a memory card.

B. Extraction of Heart Sounds Components

First, the R-peak is identified in the ECG by means of the detection algorithm described in [12]. A parabolic interpolation around the maximum of the QRS complex increases the time resolution of the detection of the R-peak position. Then the acceleration modulus, $|\boldsymbol{a}(k)|$, is calculated at each sample k from the three measured orthogonal components as

$$|\boldsymbol{a}(k)| = (a_x(k) + a_y(k) + a_z(k))^{1/2} \qquad (1)$$

The acceleration modulus is high-pass filtered by means of a zero-phase Chebyshev digital filter with cut-off frequency at 15 Hz. This filter separates the ballistocardiogram from the heart sounds component. Ensemble averaging

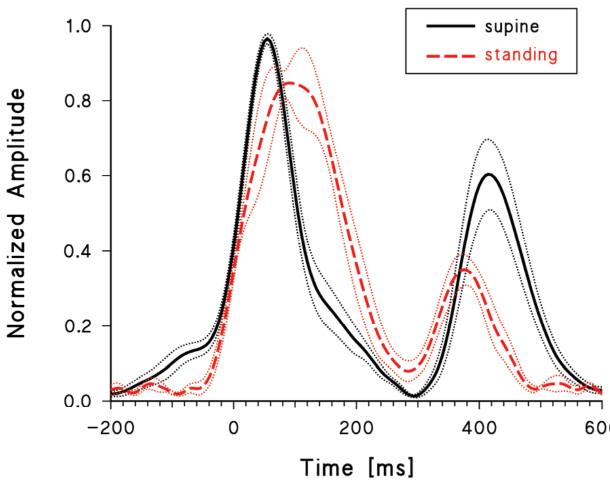

Fig. 4. Normalized amplitude of HF SCG envelope in supine and standing position: mean ±SEM in a group of 7 healthy volunteer.

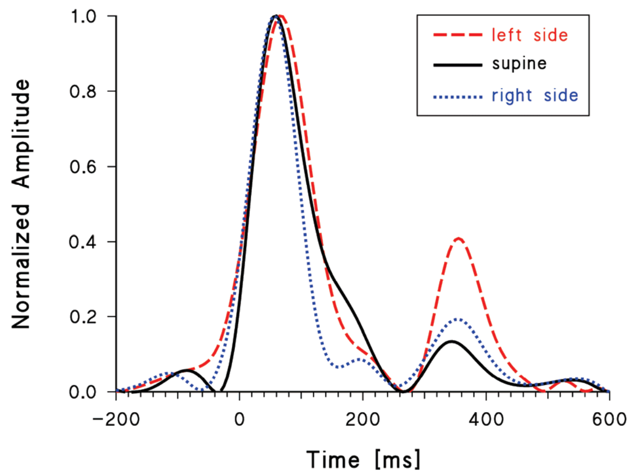

Fig. 5. Normalized amplitude of HF SCG envelope in one healthy subject sleeping supine and on his left or right side.

synchronous with the R-peak is then applied to reduce noise and to improve bit resolution by dithering.

Upper panels of fig.1 show examples of high-frequency (HF) SCG components detected in two subjects resting in supine position for ten minutes. Two wave packets likely associated with the S1 and S2 cardiac sounds can be observed. Surrogate analysis performed by swapping the SCGs (fig.1, lower panels) indicate that the detected waves are genuine physiological components of the SCG and are not due to noise.

To verify whether the two HF wave packets of SCG are actually associated to the S1 and S2 heart sounds, we simultaneously recorded ECG and accelerations by the MagIC device and heart sounds by a standard physiological sound microphone (TSD108 contact microphone, BIOPAC Systems, Inc.). The test was performed in a healthy volunteer lying supine for 10 minutes. Heart sounds were low-pass filtered at 5 kHz and sampled at 10 kHz. Ensemble averages are compared in fig.2. The figure shows a very good agreement between the time of occurrence of the first HF SCG front wave and S1, and between the time of occurrence of the second front wave and S2.

Then features are extracted from HF SCG by calculating the wave envelope. First maxima and minima are identified and separately interpolated by cubic splines (fig.3, upper panel). Then, the difference between upper and lower interpolating splines is calculated. The time position of the maxima of the two components corresponding to S1 and S2 heart sounds are identified and indicated as T1 and T2 respectively (fig.3, lower panel).

III. HF SCG and Posture

The occurrence of possible modifications in the HF component of SCG following changes of posture was tested by analyzing data collected both in laboratory experiments and during a sleep study.

A. Changing Posture from Supine to Standing

We recorded ECG, respiration and 3D accelerations with MagIC in a group of 7 healthy male volunteers (age range between 25 and 50 years; body mass index: 23.8 ±2.3 kg/m^2, M±SD). In each subject, recordings were performed for 10 minutes twice: first with the subject lying supine; then with the subject in standing position. The HF SCG envelope was calculated in each position. Envelope amplitudes were normalized to the unit so to facilitate the comparison of their shapes. The time of occurrence of first and second heart sounds, T1 and T2, were estimated.

Results (fig.4) show clear modifications of the shape of normalized amplitudes when changing posture from supine to standing. In particular, T1 increases significantly (p=0.006) from 56 (8) to 97 (27) ms, M (SD), while T2 tends to decreases (p=0.07) from 415 (23) to 354 (87) ms. These shifts in the T1 and T2 positions reduce significantly (p=0.002) the distance between the two peaks, from 359 (19) ms to 294 (26) ms.

B. Changing Body Position during Sleep

In the frame of a larger experiment aimed at evaluating the effects of high altitude during sleep, we recorded ECG, respiratory movements and 3D accelerations with the MagIC device for 8 hours in a different healthy volunteer (male, 41 yrs old, body mass index equal to 26.5 kg/m^2) while sleeping on the “Capanna Regina Margherita” hut on the top of Mount Rosa (4554 m absl). We identified the body position from the acceleration components on the three axes. We selected 3 periods of analysis each of ten minutes duration in which the subject was sleeping 1) supine; 2) on his left side; and 3) on his right side.

Normalized amplitudes of HF SCG envelopes calculated for the three body positions are shown in figure 5. The figure suggests the existence of differences during sleep associated to body position. In particular the relative amplitude of the second peak appears higher when the subject lies on his left side. Moreover, T1, that is equal to 60 ms when the subject lies on his back, decreases to 55 ms when he lies on his right side, while it increases to 65 ms when he lies on his left side.

IV. Conclusion

We showed that a wearable system like MagIC can be actually used to derive information on the component of SCG associated to the heart sounds. This opens the possibility to perform SCG studies in a wide range of conditions almost without interference with the subject's activity.

A significant contribution to the good performances we observed originates from the ECG-synchronous averaging procedure. This dramatically reduced noise at the frequency of heart sounds and improved the bit resolution of the sensor by dithering.

Measures of HF SCG in healthy volunteers who changed posture from supine to standing, revealed significant alterations. The reduced time interval between the instants of occurrence of the second and first heart sound, T2 and T1, could reflect the higher cardiac sympathetic tone which is known to characterize standing compared to the supine posture, and which is likely to have improved the cardiac contractility.

We also found substantial alterations associated with the body position in the heart sound component of SCG when we analyzed the overnight recording obtained in one volunteer sleeping at high altitude. Alterations in HF SCG may reflect changes in cardiac mechanic associated to the side where subjects lie when they sleep. Quantification of these changes might be of clinical importance, for instance in chronic heart failure patients, who report to feel more dyspnoeic when they sleep on their left side (position where they spend significantly less time of sleep) [13].

We also expect that correlations with other physiological signals recorded simultaneously by the MagIC device will enrich the analysis of the heart sounds component of SCG. For instance, ECG synchronous averaging separately in the inspiratory and expiratory phases of the breathing cycle may allow quantifying respiratory related SCG modulations. These might occur because of modulations in the filling of cardiac chambers during the breathing cycle. Correlations with levels of cardiac sympatho/vagal balance (easily derivable from spectral analysis of heart rate) may also reveal how the autonomic outflows influence those aspects of cardiac mechanics quantifiable by HF SCG. Therefore inclusion of additional information will help the interpretation of HF SCG changes in future physiological or clinical settings.

References

[1] R. M. Baevsky, A. D. Egorov, and L. A. Kazarian, "Seismocardiography.(Metodika seismokardiografii)," Kardiologiia, vol. 18, pp. 87-89, 1964.

[2] B. S. Bozhenko, "Seismocardiography -- a new method in the study of functional conditions of the heart," Terapevticheskiì arkhiv, vol. 33, pp. 55-64, 1961.

[3] B. Ngai, K. Tavakolian, A. Akhbardeh, A. P. Blaber, B. Kaminska, and A. Noordergraaf, "Comparative analysis of seismocardiogram waves with the ultra-low frequency ballistocardiogram," Conf. Proc. IEEE Eng Med Biol Soc., vol. 2009, pp. 2851-2854, 2009.

[4] I. Starr and F. C. Wood, "Twenty-Year Studies with the Ballistocardiograph: The Relation between the Amplitude of the First Record of "Healthy" Adults and Eventual Mortality and Morbidity from Heart Disease," Circulation, vol. 23, no. May, pp. 714-732, 1961.

[5] A. Noordergraaf, "Further Studies on a Theory of the Ballistocardiogram," Circulation, vol. 23, pp. 413-425, Mar.1961.

[6] Wikipedia, "Heart Sounds," 2011.

[7] D. M. Salerno and J. Zanetti, "Seismocardiography: A New Technique for Recording Cardiac Vibrations. Concept, Method, and Initial Observations," J Cardiovasc Technol, vol. 9, pp. 111-118, 1990.

[8] P. Castiglioni, A. Faini, G. Parati, and M. Di Rienzo, "Wearable seismocardiography," Conf. Proc. IEEE Eng Med Biol Soc., vol. 2007, pp. 3954-3957, 2007.

[9] M. Di Rienzo, P. Meriggi, F. Rizzo, P. Castiglioni, C. Lombardi, M. Ferratini, and G. Parati, "Textile technology for the vital signs monitoring in telemedicine and extreme environments," IEEE Trans Inf. Technol. Biomed, vol. 14, no. 3, pp. 711-717, May2010.

[10] M. Di Rienzo, P. Castiglioni, F. Rizzo, A. Faini, P. Mazzoleni, C. Lombardi, P. Meriggi, and G. Parati, "Linear and fractal heart rate dynamics during sleep at high altitude. Investigation with textile technology," Methods Inf. Med, vol. 49, no. 5, pp. 521-525, 2010.

[11] M. Di Rienzo, P. Meriggi, F. Rizzo, E. Vaini, A. Faini, G. Merati, G. Parati, and P. Castiglioni, "A Wearable System for the Seismocardiogram Assessment in Daily Life Conditions," Conf. Proc. IEEE Eng Med Biol Soc., 2011 (submitted).

[12] P. Castiglioni, G. Parati, A. Civijian, L. Quintin, and M. Di Rienzo, "Local scale exponents of blood pressure and heart rate variability by detrended fluctuation analysis: effects of posture, exercise, and aging," IEEE Trans Biomed Eng, vol. 56, no. 3, pp. 675-684, Mar.2009.

[13] R. C. Martin-Du Pan, R. Benoit, and L. Girardier, "The role of body position and gravity in the symptoms and treatment of various medical diseases," Swiss. Med Wkly., vol. 134, no. 37-38, pp. 543-551, Sept.2004.