35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Comparative analysis of two systems for unobtrusive heart signal acquisition and characterization

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Abstract — **In this paper we describe and compared method of heart rate estimation from cardiac signal acquired with EMFIT, FMCW Doppler radar and Finapres based technology, in the same context, and briefly investigated their similarities and differences. Study of processing of acquired cardiac signal for accurate peak detection using Wavelet Transform is also described. The results suggest good reliability of the two implemented unobtrusive systems for heart rate estimation.**

I. INTRODUCTION

By monitoring cardiac functions important information can be obtained on the body's physiological adaptation and the intensity of effort as well as on health and wellness, medical condition and emergency situations. New development of sensors and electronic techniques made quantifying the movements generated by the beating heart very easy in domestic furniture such as chair [1-4], bed [5] or weighting scale [6,7], overcoming disadvantages of heavy and inconvenient methods used in hospitals, in the first half of the 20th century. Moreover, in recent years, small and cheap accelerometers based on MEMS technology, became part of a new class of wearable systems for long term monitoring of seismocardiography - sometimes referred to as sternal acceleration ballistocardiogram [8] - in a wider range of conditions, including sleep [9] and daily life activities [10]. Furthermore, in order to minimize disruption of the subjects' activities, particularly where prolonged monitoring is needed, various approaches based on radar technology were described in the literature for cardiac function monitoring. Additional benefits of radar technology for vital signs monitoring include the versatile ability to function at a distance of monitored person, through clothing, and for some type of radar technology also the capacity to acquired vital signals through the walls [11-14]. Meanwhile, testing reliability of the implemented unobtrusive system for physiological parameters and motor activity measurement, represent an important challenge considering the variety of hardware and software for unobtrusive monitoring, the particular interaction between the monitored person and the measurement system, but also the personalized response provided by the systems for different users. In the paper is presented a comparative study of two unobtrusive systems for heart rate acquisition. We studied and compared cardiac signal acquired with EMFIT, Frequency Modulated Continuous Wave Doppler Radar (FMCW Doppler radar) and Finapres based system. With this comparative study we aimed to underscore the information associated with the acquired signs provided by the two unobtrusive heart rate monitor as well as the performance on heart rate estimation of the implemented systems by our research team.

Kind support for this work was provided by Instituto de Telecomunicações and Fundação para a Ciência e Tecnologia project PTDC/DTP-DES/1661/2012.

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II. METHOD OF MEASUREMENT

In this paper we compare the heart rate (HR) obtained from EMFIT based ballistocardiography (BCG) and from FMCW Doppler radar technology with heart rate values obtained from electrocardiogram (ECG). We also analyze the accuracy of heart rate estimation by the two unobtrusive devices by comparing with cardiovascular signs detected by Finometer Midi device (Finapres Medical Systems, Amsterdam, The Netherlands) which give information on blood pressure, electrocardiogram and cardiac output. We used the Finometer Midi device to visualize and analyze the relation between electrical and mechanical heart dynamics during heart signal recording by for methods and technologies (ECG, EMFIT, Doppler radar, continuous blood pressure) as well as to underscore the relation between radar signal and stroke volume. We hypothesize that radar based device can be used as unobtrusive method for estimation of heart rate as well as relative stroke volume changes in resting condition. As the main physiological determinants of mean blood pressure (MBP) are cardiac output (CO) and arterial resistance (R) we used the blood pressure signal recorded in sitting position and stationary psychological state (R constant) in order to estimate the correlation between stroke volume (SV) and cardiac signal detected by radar sensor. Stroke volume, the volume of blood pumped from one ventricle of the heart with each beat, can be estimated on healthy person in resting condition as:

$$SV = \frac{MBP}{HR \cdot R} \qquad (1)$$

Recently published evidence based on echochardiography and cardiovascular magnetic resonance data as well as by mathematical modelling [16] suggests that stroke volume can be estimate as sum of the displaced volume as a result of longitudinal shortening and the volume from epicardial displacement.

$$SV = (EVd - MV) - (EVs - MV) \quad (2)$$

where EVd is external volume at end-diastole, EVs is external volume at end- systole and MV is muscle volume. Therefore:

$$SV = EVd - EVs \quad (3)$$

In comparison with EMFIT based device that acquire shock waves propagating from the beating heart, the microwave Doppler radar give information on the position of heart wall during cardiac cycles. As external volume of heart is changing by a combination of longitudinal and circumferential shortening when heart ejects its stroke volume during systole, the echo signal acquired by radar device during approximation and retraction of heart from chest wall may reflect dynamic changes in stroke volume.
The architecture of the designed and implemented system for unobtrusive cardiac activity monitors characterization are following presented.

A. *EMFIT based system*

The BCG measurement is done using a normal office chair with 30 x 29 cm size EMFi-sensor films (manufactured by EMFIT Ltd) fitted under the upholstery on the seat. EMFIT sensor it is expressed by an elastic electret film consisting of three layers of polyester film with aluminum electrodes. The sensor presents highly sensitivity to applied dynamic forces (S_q=25 pC/N for normal force) the force variation being expressed by charge variation that is captured using a charge amplifier scheme based on FET-input operational amplifier. The sensor capacitance is about 22 pF/cm2 and in the present case for a L-type Emfit sensor is about 17.4 nF. Changes in EMFi sensor caused by applied dynamic forces (such as cardiac ballistic forces) conduct to charge variations that are converted in voltage, by using and appropriate BCG conditioning circuit (BCGcc) [3]. Details on the characterization of the acquired waves by EMFIT based system is described in [4].

B. *FMCW Doppler Radar*

A second considered system, by the authors, for his feature that allow the non-mechanical contact, is based on the FMCW Doppler radar that delivers a signal which amplitude is modulated by the small cardiac motion. Doppler radar and FM radar remote sensing has shown promise for heart rate monitoring, with proof of concept demonstrated for various applications [11-14]. We use FMCW Doppler radar, 24GHz IVS-162 DRS, in order to implement a robust, inexpensive, contactless and harmless tool for real-time monitoring of the cardiac and respiratory rates [15].

C. *Architecture of the Measurement System*

To simultaneously acquire cardiac signal from the considered unobtrusive sensing system and reference system, automated measurement system was implemented. The experiments were conducted on six healthy subjects ranging in age from 28 to 45 years old. The subjects were seated on the normal office chair at a 30 cm distance from radar device. We recorded the cardiac signal on healthy volunteers during 5 minutes, sitting at rest. The sensing system was characterized by two cardiac activity reference channels (RefCh1, RefCh2) expressed by continuous blood pressure measurement (BP) and electrocardiogram (ECG) channels, and the channels under test (Ch1UT, Ch2UT) - the ballistocardiography (BCG sensor module) and radar sensing channels (R-BCG sensor module) (Fig.1). The BP and ECG signals are delivered by Finometer in digital form through RS232 communication interface and in analog form as outputs of digital-to-analog converter module of the system.

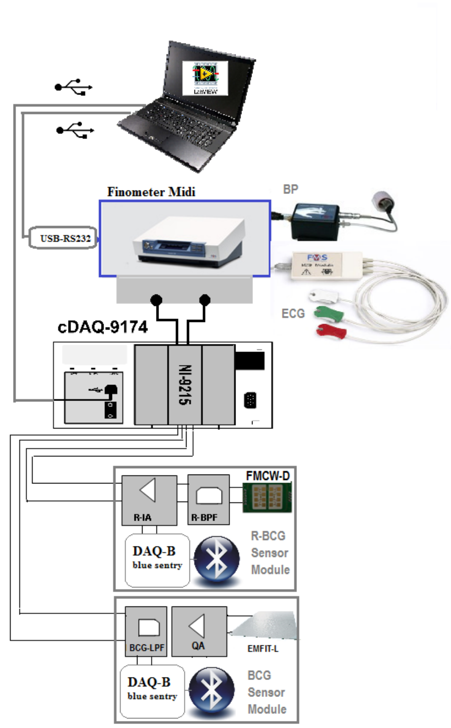

Fig. 1. Block diagram of the measurement system for unobtrusive cardiac sensing channels characterization (R-BCG: radar signal, FMCW-D: frequency modulated continuous wave Doppler radar, DAQ-B – acquisition module with Bluetooth communication capability, NI-9215 – analog input module)

Simultaneous acquisition of RefChi and ChiUT signal channels is performed using 4channels, 16-bits simultaneous analog input module NI-9215 “plug-in” cDAQ-9174 that is USB connected to a computer. During the tests the acquisition module with Bluetooth communication capability (DAQ-B) is switched off. The BCG and R-BCG signals are simultaneously acquired by two analog input channels of NI-9215 that is programmed for 0.5kS/s acquisition rate. A set of active filters are designed for BCG and R-BCG conditioning circuits. In the BCG case a 2^{nd} order Butterworth active low-pass filter characterized by f_c=15 Hz is used while in the R-BCG case a 4^{th} Butterworth band pass filter characterized by f_{c1}=0.9Hz and f_{c2}=15Hz is used. Using a set of instrumentation amplifiers INA114 appropriate amplifications of filtered BCG and R-BCG signals are imposed.
The software for automatic characterization of the BCG and R-BCG measurement channels includes the data acquisition

component, the data processing, data storage and data communication component. The processing steps associated with HR extraction from ECG signal are: i) low pass filtering (IIR 5^{th} order low pass filter, fc=40Hz), ii) differentiation, iii) Hilbert transform (HT) processing. After the above mentioned steps the signal is applied to the curve fitting-based peak detection (LabVIEW *peak detector.vi*) function that is configured imposing the number of signal consecutive samples $n_{fitting,}$ used in the quadratic least squares fit, where $n_{fitting}$=[3;10]. The threshold value, *th*, applied to the peak detection function was calculated based on RMS value of Hilbert transform samples $X_h(k)=H(x_{tw}(n))$ where t_w represents a time window (windows of 4s to 30s width were tested). To diminish the errors on HR estimation an additional algorithm for non-cardiac induced peaks removal was implemented taking into account the time distance between the successive detected peaks. The HR extraction from BP signal was realized after signal normalization by peak detection with LabVIEW *peak detector.vi* function. Taking into account the shape characteristics of BCG signal, beat-to beat interval extraction was performed using *Multiresolution Analysis* based on Discret Wavelet Transform (DWT) and Complex Wavelet Transform (CWT) with Morlet mother wavelet. The *WA Multiresolution Analysis* LabVIEW function was configured imposing the decomposition level from 5 to 10. The Wavelet coefficient resulted by signal decomposition with different mother wavelets such as Doubechies (db02, db04, db06), Coiflet (coif4, coif5), Biorthogonal (bior1_5, bior1_3) were studied. The approximation signal (Ai) within selected frequency band of DWT decomposition is applied to the LabVIEW *peak detector.vi.* Good results on BCG peaks localization were obtained for 7^{th} level of decomposition and db06 mother wavelets. The peak detector setting were $n_{fitting}$=50 and *th*=0. In order to increase the BCG peak detection accuracy alternative processing was performed by combining BCG power signal and CWT algorithm expressed by the *WA Analytic Wavelet Transform* LabVIEW function. The main steps of the algorithm for peak detection procedure based on CWT are: i) mean value removing: $V1_{BCG}=V_{BCG}-mean(V_{BCG})$ calculation; ii) energy calculation, $E_{BCG}=V1_{BCG}^2$; iii) normalization based on statistical profile of the $V1_{BCG,}$, iv) analytic Wavelet Transform calculation and Wavelet coefficients magnitude selection, v) application of peak detection function to reconstructed signal from selected coefficients values within frequency band of interest (0.8-1.2 Hz, mainly 10^{th} scale selection). The same algorithms applied to BCG signal were used to detect heart beat intervals from FMCW Doppler radar signal.

III. Results and discussions

Simultaneously acquisition of the BP, ECG, BCG and R-BCG signals was performed (Fig. 2). Fig. 3 presents BCG energy scallogram (Fig.3.a) and a M=4 selected scale, that is used as the input of peak detection function with configuration settings: *width=20*, *threshold=0.5*. Taking into account that radar signals are more affected by motion artifacts in comparison with signal from EMFIT based device, the results obtained on HR estimation using CWT algorithm was characterized by high errors (greater than 2 beats for 120s recording times). By using the *Multiresolution Analysis* the heart rate estimation in FMCW radar device was improved using selected Wavelet coefficients of R-BCG signal at 7^{th} level of DWT decomposition when bior1_3 mother Wavelets was used.

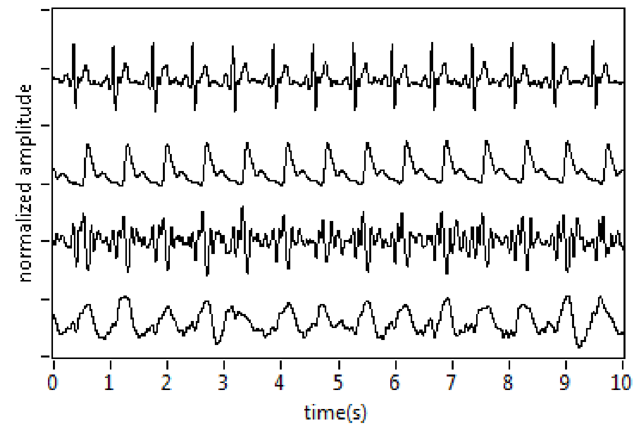

Fig. 2. ECG, BP, BCG and R-BCG signals obtained with implemented measurement system.

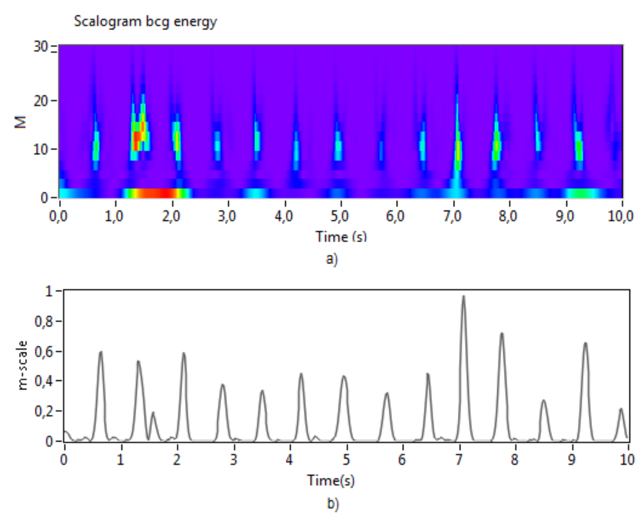

Fig. 3. BCG energy CWT scallogram and selected decomposition scale for HR detection

Performance of HR estimation was additionally tested by visual estimation of HR for 300s interval recording of each signal and comparison with HR derived from automated LabVIEW processing of BP, ECG, BCG and R-BCG signs.
The Fig. 4 presents the Bland-Altman obtained for 300s recording time signals from one volunteer.
An average 0 beat differences can be observed when heart rate is estimated visually in ECG and BCG signals during cardiac signal recording of 300s. Automated detection of heart rate from BCG loose 4±2 beats from an average 400 beats recorded during 300s showing a good accuracy on estimation of heart rate using the implemented EMFi based balllistocardiogram. *Multiresolution Analysis* was also tested but proves to be less accurate comparing with the CWT scallogram. However, the results have underscore *Multiresolution Analysis* as more appropriate for processing

of R-BCG for HR estimation. The Bland Althman plot of HR estimation based on *Multiresolution Analysis* applied to the R-BCG obtained from one volunteer, for 300s recording time and 10s processing time window is shown in Fig. 5.

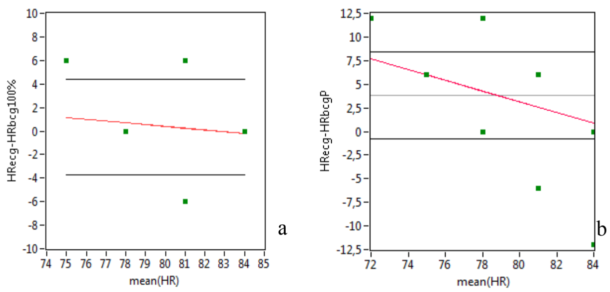

Fig. 4. Bland-Altman plots for heart rate estimation. Differences between visual (a) and automated (b) detection of heart rate from ECG and BCG (HRecg, HRbcg)

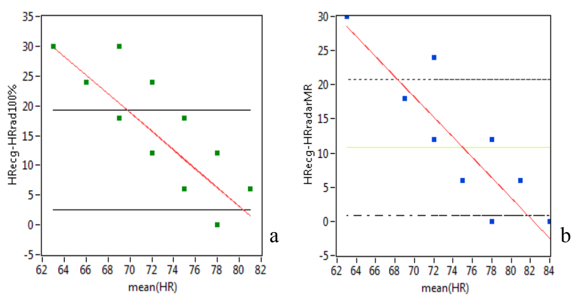

Fig. 5. Bland-Altman plots for heart rate estimation. Differences between visual (a) and automated (b) detection of heart rate from ECG and radar device (HRecg, HRrad)

The plot describes the obtained distribution related with beats lost by small movement of the body and not related to the implemented algorithm for HR estimation using radar device for 300s. The calculated stroke volume by using blood pressure signal obtained by Finometer midi correlates (r=0.77) with radar signal amplitude recorded during 30s when no motion and no high variation in respiratory rhythm was registered. An important problem that we encountered during heart rate estimation using FMCW Doppler radar was the difficulty to reproduce the same position of sensor as the HR estimation could be affected by a slight change of angle or depth of measurement. Generally, by positioning the sensor at the heart level a good estimation of HR is obtained.

IV. Conclusion

In this work we have outlined methods for signal acquisition and processing of two unobtrusive system for heart rate estimation - the EMFIT and FMCW Doppler radar systems. We studied and compared these signals in the same context and briefly investigated their accuracy on heart rate estimation. The results suggest good reliability of the two implemented system for heart rate estimation as well as potential use of combined information from the two devices for inexpensive, robust and accurate in home monitoring of cardiac functions.

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