

# Blood Pressure and Heart Rate Variabilities Estimation Using Ballistocardiography

Eduardo Pinheiro<sup>†</sup>, Octavian Postolache<sup>†</sup>, Pedro Girão<sup>†</sup>

<sup>†</sup> Instituto de Telecomunicações, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

Phone: +351-218418454, Fax: +351-218418472, e-mail: eduardo.pinheiro@lx.it.pt, opostolache@lx.it.pt, p.girao@lx.it.pt

**Abstract**— In this work a blood pressure and heart rate variability estimation system is presented. Instead of merely using beat-to-beat time interval extracted from the electrocardiogram (ECG), it is also used finger photoplethysmography (PPG) and ballistocardiography (BCG) information to have three independent estimates of the heart rate variability. Since pulse arrival and transit times can be extracted considering the acquired physiological waves, its correlation to blood pressure (BP) enables to obtain an estimation of BP variability for a particular subject, both from PPG and BCG. Given that BCG is extremely susceptible to movement artefacts, the system also infers context-related information as BCG detects subject's motion and posture.

## I. INTRODUCTION

The ECG is a generalized method to evaluate the condition of a patient's heart, from both the heart rate and ECG-wave analysis [1-2]. For heart rate variability (HRV) evaluation purposes, the heart rate can be extracted from any biological signal dependent on the cardiac cycle, such as a photoplethysmogram or a ballistocardiogram, providing that reasonable accuracy in event detection is guaranteed. Adding PPG and BCG experimental information brings supplementary advantages to the clinical evaluation, since Pulse Arrival Time (PAT) – the time-delay between the R-peak of the ECG wave and the blood arrival at the peripheral measurement point – and Pulse Transit Time (PTT) – purely vascular component of the PAT – may be measured [3-4].

In most BCG measurements, the sensing device is a pressure sensor, usually placed in a chair's back or seat [5-7], which records the body's vibrations, and thus, besides sensing the person's movement, it also assesses the pressure oscillations due to heart activity [5-7]. Since the sensing device can be embedded unremarkably in the patient's chair, the validation of the BCG as a legitimate alternative to ECG would decrease patient's involuntary psychophysiological responses to measurement-related stressors, such as the placement of the ECG electrodes, and his inability to relax when said so, removing important bias sources of cardiologic assessment tests [6-8].

The two main alternatives to measure PPG are finger and earlobe photoplethysmography. In this work, it is shown that the integration of chair seat BCG and finger PPG measurement capabilities allows the measurement of heart rate and pulse transit time with minimal invasiveness. ECG acquisition circuitry was also developed, using a three chest electrodes scheme, to perform the validation tests.

Acquiring these three biological signals, heart rate variability can be estimated using three different estimates, and blood pressure variability (BPV) using two types of

signals for pulse arrival time calculations. The estimated variabilities based on the proposed methods are significant markers of the autonomic cardiovascular regulation [1,6-8].

Being applied in diverse contexts, there are several bibliographic references that consider heart rate variability both as a diagnostic and outcome estimator of neurological pathologies, due to the alterations induced by these cardiac maladies in the autonomic function and thus in the HRV [1,6,9-10]. Heart rate variability and blood pressure variability are referred to as being capable of foretelling cardiovascular risks [10], hence precise measurement of these parameters is required to avoid false diagnosis.

Both PAT and PTT have indistinguishably been employed in studies to evaluate their correlation with blood pressure with confirmatory results [4,11-15,17]. In these medical studies, and in system implementations, the pulse times were computed mostly using the R-peak of the ECG and the maximum peak of the PPG, or checking both the minimum and the maximum peaks of the PPG. The PPG maximum peak was the reference for the measurements in this work.

Using a sampling frequency of 1.5 kHz, and implementing notch filters instead of low-pass filters to remove the power line noise, the time measurements will not affect the correlation of pulse arrival time with blood pressure variability [1-2,16] and so continuous cuff-less estimation of BPV is achieved. Another special attribute of the developed implementation is the ability to extract patient's movement information from BCG measurements. In this case the signal suffers heavy deformations, while PPG and ECG only have small distortions, thus allowing HRV and BPV real-time tracking while marking the moments when there was user movement, in order to facilitate offline HRV and BPV enhancement by neglecting data acquired while moving.

The work presents the design and implementation of a low cost portable BCG, ECG, PPG and PAT measurement system, with BPV and HRV analysis capabilities.

## II. SYSTEM DESCRIPTION

The ballistocardiogram, electrocardiogram and photoplethysmogram measurement system includes a set of sensors with dedicated conditioning circuits, a multifunction data acquisition board (DAQ) PCMCIA compatible, and a laptop PC implementing the data processing algorithms needed to accurately evaluate heart rate and investigate heart rate and blood pressure variabilities.

To acquire the BCG an electromechanical film (EMFi) sensor was embedded in the seat of a normal office chair, while the ECG was acquired using three chest leads, and the PPG by evaluating index finger absorption of red radiation, see Fig. 1.

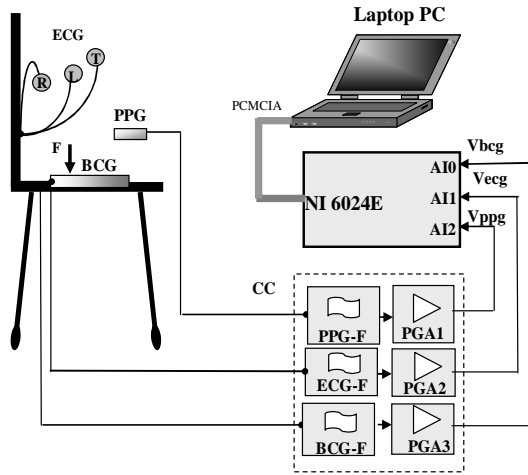


Fig. 1. BCG, ECG and PPG measurement system (PGA<sub>i</sub> – programmable gain amplifiers, BCG-F – BCG signal filter, PPG-F – plethysmography filter, ECG-F- ECG filter).

### A. Ballistocardiogram

The BCG transducer is based on an EMFi sensor which is composed of exterior homogeneous surface layers having in its interior a number of thin polypropylene layers with air voids [19]. When pressure is applied on the surface of the film, the charges resident in the polypropylene-void interface rearrange themselves, generating a charge on the sensor's electrodes proportional to the pressure exerted [19].

A voltage BCG signal is obtained connecting the EMFi output to a charge amplifier scheme that uses OPA2604, a low-noise (at 10Hz, 25 nVHz<sup>-1/2</sup>), high input impedance (10<sup>12</sup> Ω || 10 pF) operational amplifier. After the charge amplifier, an active 2<sup>nd</sup> order 40 Hz low-pass Butterworth filter to increase the signal-to-noise ratio [2], before the digitalization using the analogue input AI0 of the DAQ.

Further BCG digital low-pass filtering allowed obtaining a clear signal with the most important waves (I and J) well demarcated, see Fig. 2.

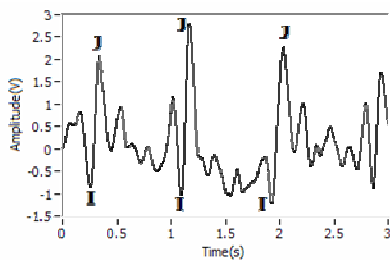


Fig. 2. The evolution of BCG signal for 3 seconds with I-valley and J-peak marked.

Using LabVIEW peak detection functions it was built an adaptive peak detector with proven results [4,18] to determine the I valley position in the BCG signal. The HR estimates were the II intervals determined by this processing, and its variation associated with the HRV estimation.

### B. Electrocardiogram

Three leads ECG acquisition circuitry was designed and implemented in laboratory [4,18]. It includes amplification and filtering stages built with high input impedance instrumentation and operational amplifiers, removing slow motion interferences and baseline wandering, as well as the EMG interference, limiting the signal to a band of 0.05-150 Hz. The enhanced signal is applied to AI1 analogue input of the multifunction board, acquired at a 1.5 kS/s sampling rate. An additional notch digital filter ( $f_c=50\text{Hz}$ ) was designed and implemented in LabVIEW in order to minimize the power line interference.

To determine time stamp position of the QRS complex, the referenced adaptive peak detector was used. The RR time distance was used to calculate the heart rate.

### C. Photoplethysmogram

It was developed a finger PPG sensor using controlled red light emission and a light transducer (TSL257) of high responsiveness in this part of the visible spectrum, with improved signal quality regarding the application in [4], where good results were also obtained. This signal is also acquired by the DAQ board previously described (AI2), and passes through a digital notch filter to diminish power line traces.

The same peak detector was used to identify the maximum peaks of the PPG waveform. The heart rate and the HRV are calculated based on beat-to-beat analysis.

Fig. 3 shows the evolution of BCG, ECG and PPG signals during 4 seconds.

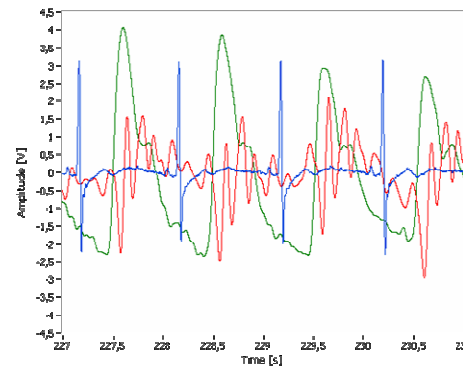


Fig. 3. Evolution of the three signals during 4 seconds.

### D. Pulse Arrival Time

The delay between the ECG and PPG peaks is usually named pulse arrival time, but may also be referred to as pulse wave transit time, pulse wave delay or inversely pulse wave velocity [11-15]. Several studies [4,11-15,17] account for the existence of a significant relation between pulse arrival time and blood pressure, so the measurement of this parameter increases the knowledge on the patient's cardiovascular status. In this application, PAT was calculated as the time

difference between ECG and PPG maximum peaks, and when using BCG-PPG relation, the I-valley was the reference.

This parameter's correct evaluation is strongly dependent on the peak detection accuracy. The choice of the sampling frequency is also important and for accurate description of the acquired signal a sampling rate of about 1.5 kHz is usually used.

PAT allows BPV estimation from PAT variability, and also to estimate the systolic BP from a simple function (1), which needs individual calibration to tune the parameters  $\alpha$ ,  $W$  and  $\beta$  [3,17].

$$SPB = \alpha \frac{W}{PAT} + \beta \quad (1)$$

### III. RESULTS AND DISCUSSION

Five young volunteers  $24.7 \pm 2.4$  years old and weighting  $74.2 \pm 11.8$  kg (mean  $\pm$  standard deviation), without known cardiac abnormalities, tested the system. After a 10 minutes period seated to relax, the subjects underwent the data recording process, being told to be still for the whole duration of the test. The PPG sensor was placed on the left index finger, the ECG electrodes in a triangular disposition on the chest, and the BCG sensor in the chair seat. The test consisted of a continuous 10 minutes recording of the BCG, ECG and PPG signals of each person.

#### A. Heart Rate Estimation

Considering the average of the three estimatives as reference, the root mean square deviations ( $\epsilon_{HR}$ ) of the measurements were computed using (2), generating the results presented in Table I.

$$\epsilon_{HRi} = \sqrt{\frac{1}{n} \sum (HR_i - HR_{ref})^2} \quad (2)$$

Table I. Heart rate results

	ECG	PPG	BCG
	$\epsilon_{HR}$ [bpm]	$\epsilon_{HR}$ [bpm]	$\epsilon_{HR}$ [bpm]
<b>Average</b>	0.4236	0.5448	0.6381
<b>Best</b>	0.3137	0.4557	0.3836

This test shows that BCG is a more unreliable source to extract the heart rate, when compared to ECG and PPG, since the root mean square deviation of its results exceeds the values obtained with the other methods. Despite this important first observation, it is also noticeable that the best BCG result outcomes the PPG best result. Moreover, the average root mean square deviation of BCG is 50.64% larger than the ECG  $\epsilon_{HR}$ , and 17.12% larger than the PPG  $\epsilon_{HR}$ , denoting poorer results than both, but of the same order of magnitude of the PPG, which has a comparable performance.

These are somewhat expected conclusions, considering that BCG is a signal extremely sensitive to movement artefacts, and much more likely to be disturbed. Even though  $\epsilon_{HR}$  BCG results are the worst, they are based on 10 minutes recordings when a minimum of 550 beats are accumulated. Hence the

instantaneous estimates from BCG are actually not bad, and the only setback in its use is the prospect of having to reject some cycles due to movement noise.

#### B. Heart Rate Variability Estimation

The recordings from the subjects were processed, extracting the evolution of the time between beats and the power spectral density of the HRV. The correlation coefficients,  $\rho$ , for heart rate variation are shown in Table II.

Table II. Heart rate variation correlation coefficient

	$\rho_{ECG \leftrightarrow PPG}$	$\rho_{ECG \leftrightarrow BCG}$	$\rho_{PPG \leftrightarrow BCG}$
<b>Average</b>	0.9938	0.9914	0.9873
<b>Best</b>	0.9967	0.9947	0.9901

The results attest the similarity of the heart rate estimates. ECG and PPG have the most related estimates, but BCG also has a very high relation with the other two signals.

The power spectral density of the HRV estimate obtained from the three signals is close, as it is seen in Fig. 4, which was expected, since the correlation between the estimations was very strong.

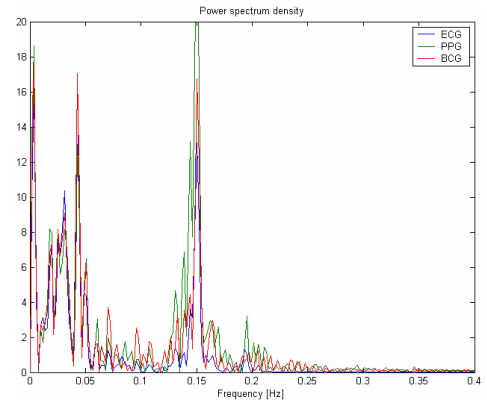


Fig. 4. HRV power spectral density for one of the subjects.

#### C. Pulse Arrival Time Estimation

The correlation coefficients,  $\rho$ , for different PAT estimatives are shown in Table III.

Table III. PAT estimations correlation coefficient

	$\rho_{E-P \leftrightarrow B-P}$	$\rho_{E-P \leftrightarrow E-B}$	$\rho_{E-B \leftrightarrow B-P}$
<b>Average</b>	0.8321	0.3730	0.1846
<b>Best</b>	0.9212	0.5392	0.5128

It can be seen that PAT estimation via ECG-PPG is correlated to the estimation via BCG-PPG, while ECG-BCG is not a valid method for PAT estimation. Moreover, given that ECG-BCG exhibits even lower correlation with BCG-PPG, which measures PTT, then it is clear that PAT is less dependent on pre ejection period than on pulse transit time.

#### IV. CONCLUSIONS

The designed system permits the BCG, ECG and PPG signals monitoring. The heart rate estimations produced from the signals recorded from a healthy group of subjects, showed that all the signals present good results in heart rate and HRV estimation, since the signal conditioning and data processing algorithms have already been proven exact, and the results confirm correlation between the signals and similar h estimates. The data gathered showed that ECG, but also PPG, provide the most accurate results, what is not unexpected, given that ECG has in the QRS complex a sharp event, while the regularity of PPG also allows good detection of events, characteristics that in BCG are diminished, making it a more complicated signal to process. Despite that, heart rate variability estimates from these signals are very similar, so all of them are usable to compute HRV.

The performed measurements conduct to pulse arrival time accurate estimation, which is known to be a good estimator for blood pressure variability. The use of ECG is recommendable, but BCG proved to be a valid and unobtrusive alternative. If BCG is not used to compute PAT it can be used for movement detection, enhancing the quality of both blood pressure and heart rate variabilities estimation.

#### REFERENCES

- [1] Task force of the European society of cardiology and the North American society of pacing and electrophysiology, "Heart rate variability - standards of measurement, physiological interpretation, and clinical use", *Circulation*, vol. 93, iss. 5, 1996, pp. 1043-1065.
- [2] P. Strong, *Biophysical measurements*, Beaverton, Or.: Tektronix, 1970, pp. 218.
- [3] J. Muehlsleff, J. Espina, M. Alonso, X. Aubert and T. Falck, "Wearable Body Sensor Network for Continuous Context-Related Pulse Arrival Time Monitoring", *Proc. 6<sup>th</sup> IASTED Biomed. Eng. Int. Conf.*, Innsbruck, Austria, February 2008, pp. 378-383.
- [4] E. Pinheiro and O. Postolache, "Heart Rate Variability Virtual Sensor Application in Blood Pressure Assessment System", *Proc. 6<sup>th</sup> IASTED Biomed. Eng. Conf.*, Innsbruck, Austria, February 2008, pp. 79-82.
- [5] T. Koivistoinen, S. Junnila, A. Varri and T. Koobi, "A new method for measuring the ballistocardiogram using EMFi sensors in a normal chair", *Proc. of the IEEE EMBS 26<sup>th</sup> Annual Conference*, San Francisco, USA, September 2004, pp. 2026-2029.
- [6] O. Postolache, G. Postolache and P. Girão, "New Device for Assessment of Autonomous Nervous System Functioning in Psychophysiology", *Proc. IEEE Int. Workshop on Med. Meas. and Applications 2007*, Warsaw, Poland, May 2007, pp. 1-5.
- [7] O. Postolache, P.S. Girão and G. Postolache, "New Approach on Cardiac Autonomic Control Estimation Based on BCG Processing", *Proc. of Canadian Conf. El. Eng.*, Vancouver, Canada, April 2007, pp. 876-879.
- [8] G. Berntson, J. Cacciopo, K. Quigley and V. Fabro, "Autonomic space and psychophysiological response", *Psychophysiology*, vol. 31, iss. 1, pp. 44-61, 1994.
- [9] G. Parati, J. P. Saul, M. D. Rienzo, and G. Mancina, "Spectral analysis of blood pressure and heart rate variability in evaluating cardiovascular regulation: a critical appraisal", *Hypertension*, vol. 25, pp. 1267-1286, 1995.
- [10] S. L. Dawson, B. N. Manktelow, T. G. Robinson, R. B. Panerai and J. F. Potter, "Which parameters of beat-to-beat blood pressure and variability best predict early outcome after acute ischemic stroke?", *Stroke*, vol. 31, 2000, pp. 463-468.
- [11] T. Ma and Y. T. Zhang, "A Correlation Study on the Variabilities in Pulse Transit Time, Blood Pressure, and Heart Rate Recorded Simultaneously from Healthy Subjects", *Proc. of the IEEE EMBS 27<sup>th</sup> Annual Conference*, Shanghai, September 2005, pp. 996-999.
- [12] W. Chen, T. Kobayashi, S. Ichikawa, Y. Takeuchi and T. Togawa, "Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration", *Med. Biol. Eng. Comput.*, vol. 38, no.5, pp. 569-574, September 2000.
- [13] Y. Sugo, R. Tanaka, T. Soma, H. Kasuya, T. Sasaki, T. Sekiguchi, H. Hosaka and R. Ochiai, "Comparison of the relationship between blood pressure and pulse wave transit times at different sites", *Proc. of the 1<sup>st</sup> Joint BMES/EMBS Conference Serving Humanity, Advancing Technology*, Atlanta, 1999, pp. 222.
- [14] A. Steptoe, H. Smuylan, and B. Gribbin, "Pulse Wave Velocity and Blood Pressure Change: Calibration and Applications", *Psychophysiology*, vol. 13, no.5, pp. 488-493, 1976.
- [15] B. Gribbin, A. Steptoe, and P. Sleight, "Pulse Wave Velocity as a Measure of Blood Pressure Change", *Psychophysiology*, vol. 13, no.1, pp. 86-90, 1976.
- [16] M. Merri, D. Farden, J. Mottley and E. Titlebaum, "Sampling frequency of the electrocardiogram for spectral analysis of the heart rate variability", *IEEE Trans. Biomed. Eng.*, vol. 37, no. 1, pp. 99-106, 1990.
- [17] J. Espina, T. Falck, J. Muehlsteff and X. Aubert, "Wireless Body Sensor Network for Continuous Cuffless Blood Pressure Monitoring", *Proc. 3<sup>rd</sup> IEEE EMBS International Summer School and Symposium on Medical Devices and Biosensors*, Boston, USA, September 2006, pp. 11-15.
- [18] E. Pinheiro, O. Postolache and J. M. Dias Pereira, "A Practical Approach Concerning Heart Rate Variability Measurement and Arrhythmia Detection Based on Virtual Instrumentation", *Proc. 6<sup>th</sup> Conf. on Telecommunications ConfTele*, Peniche, Portugal, May 2007, pp. 209-212.
- [19] J. Lekkala and M. Paajanen, "EMFi - New Electret Material for Sensors and Actuators", *Proc. 10<sup>th</sup> IEEE International Symposium on Electrets*, Delphi, Greece, September 1999, pp. 743-746.