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On Time Interval Measurements Using BCG

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Abstract— **Time intervals measured between the electrocardiogram (ECG), the photoplethysmogram (PPG) or the impedance plethysmogram (IPG), have long been used to noninvasively assess cardiovascular function. Recently, the ballistocardiogram (BCG) has been proposed as an alternative physiological signal to be used in time interval measurements for the same purpose. In this work, we study the behavior of the RJ interval, defined as the time between the R wave of the electrocardiogram (ECG) and the J wave of the BCG, under fast pressure changes induced by paced respiration and tracked by a beat-to-beat blood pressure (SBP and DBP) waveform monitor. The aim of this work is to gain a deeper understanding of these newly proposed time intervals and to further assess their usefulness to determine cardiovascular performance.**

I. Introduction

Measuring time intervals between physiological waves has been widely used for many years as a non-invasive alternative to assess many aspects of cardiovascular function [1-6]. Nowadays, two of these intervals are the pulse arrival time (PAT), defined as the time between typically the R wave of the electrocardiogram (ECG) and a fiducial point of an arterial pulse waveform [2], and the pulse transit time (PTT), which has also been used sometimes as an alternative name for PAT [6], but which is usually defined as the time delay between two arterial pulse waveforms simultaneously detected at different points of the body. The main difference between the two intervals is that the first includes the pre-ejection period (PEP) whereas the second depends only on the propagation time along the major blood vessels. The arterial pulse waveform, traditionally obtained by applanation tonometers and Doppler ultrasound devices, is nowadays commonly obtained in an easier manner also from the photoplethysmogram (PPG) [7] or the impedance plethysmogram (IPG) [8]. Impedance methods are being also successfully employed to obtain the whole-body impedance cardiogram (ICG) [9], which is currently a routine method to estimate PEP.

Recently, the ballistocardiogram (BCG) has been proposed as an alternative physiological signal to measure time intervals and estimate from them several cardiovascular parameters. The BCG has been traditionally attributed to the body reaction to the forces exerted by cardiac contraction and blood acceleration in the major blood vessels [10]. Although in its first era of development and use in 1940 to 1960, the BCG was usually obtained using cumbersome floating platforms [10], nowadays it offers an interesting option for non-invasive cardiovascular monitoring at home because it can be obtained from electronic weighting scales [11,12] and other simple methods [13]. The most widely measured time interval based on the BCG is the RJ interval, defined as the time between the R wave of the electrocardiogram (ECG) and the J wave of the ballistocardiogram (Fig. 1). The RJ interval has been found to correlate with both systolic blood pressure (SBP) [14] and PEP variations [15] caused by Valsalva maneuvers. This fact cannot be considered surprising as PEP has been reported to play a prominent role in causing SBP changes [16, 17]. On the other hand, it should be taken into account that Valsalva maneuver, which implies exhaling against a closed glottis, causes a cascade of changes in most of the major cardiovascular parameters [18], and, in the time scale in which the measured changes occur, from 50 s to 100 s, it is difficult to clearly ascertain which parameter or combination of them are actually inducing RJ changes. One further issue is that the origin of the BCG, and specially that of its J wave, despite the modeling efforts performed during the first BCG era [10], is still considered controversial [19], and consequently, there is not, up to day, a fully-accepted explanation able to account for the cause of RJ interval dynamics either.

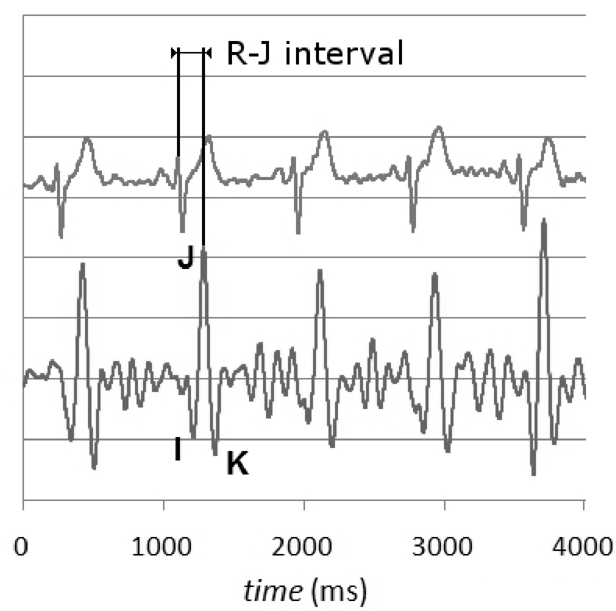

Figure 1. The RJ interval is defined from the ECG (top signal) and the BCG (bottom signal).

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In order to further elucidate these questions, we propose in this work to study RJ changes under paced respiration. Paced respiration is an alternative hemodynamic maneuver, which causes blood pressure changes related to the respiratory sinus dysrythmia [20 - 22], and has the advantage of being much easier to perform than Valsalva maneuver. Furthermore, pressure changes caused by paced respiration are much faster than those in Valsalva's, thus allowing to better distinguish which cardiovascular parameters evolve simultaneously to the RJ interval and which ones start evolving at different times, hence being mediated by different factors.

II. Materials and Methods

A. System design and data processing

The BCG signal was obtained from four strain gauges of a bathroom scale connected in a Wheatstone bridge. The signal obtained was band-pass filtered (first-order) between 0.5 Hz and 25 Hz and amplified by 15,000. The ECG signal was sensed at the wrists by using dual ground dry electrodes [23] mounted in bracelets. This configuration provided signals with an acceptable level of 50/60 Hz and EMG interference, and dry electrodes are more comfortable and less expensive than wet electrodes. The signal was filtered between 0.5 Hz (first-order) and 40 Hz (first-order) and amplified by 1000. The blood pressure waveform was obtained from a finger arterial pressure monitor (Nexfin® from BMEYE BV) that obtains beat-to beat aortic pressure waveforms using the volume-clamp method.

The three systems were connected to a 12 bit data acquisition system (μDAQ Lite®, Eagle Technology) and the signals were sampled at 1 kHz and sent to a PC. All data were processed offline with Matlab®. The QRS complexes on the ECG were detected with a simplified Pan-Tompkins algorithm [24], and the peaks in BCG waves were detected by windowed peak detection, as were the systolic and diastolic levels in the blood pressure waveform.

B. Procedure

Two test subjects were asked to perform paced respiration by synchronizing its respiration with an on-screen bar graph in order to produce the hemodynamic changes. The most relevant data from both subjects are shown on Table 1. Subject 1 has been practicing sport (cycling) on a regular basis for more than 25 years.

TABLE I. DATA FOR THE TEST SUBJECTS

Subject	***Age***	***Height***	***Weight***
S1	47 years	173 cm	75 kg
S2	28 years	189 cm	72 kg

In order to record the evolution of the visible parameters in a beat-to-beat scale, the paced respiration was set at 0.1 Hz, which is in the lower range of regular respiration rates. Hemodynamic effects of respiration at higher rates could be masked by the sampling effect of normal heartbeat rate (1-2 Hz). ECG, BCG and blood pressure waveform were recorded during this process for 90 s for each test subject.

III. Results and Discussion

Fig. 2 shows the systolic (SBP) and diastolic (DBP) pressure changes caused by paced respiration in subject 1 together with their related RJ interval variations. As it can be seen from the figure, SBP changes are much higher than those in DBP for this subject. On the other hand, it can be observed that RJ minima are somewhat synchronous to SBP maxima, thus suggesting an inverse SBP vs. RJ relationship as the one obtained in previous studies based on the Valsalva maneuver [14].

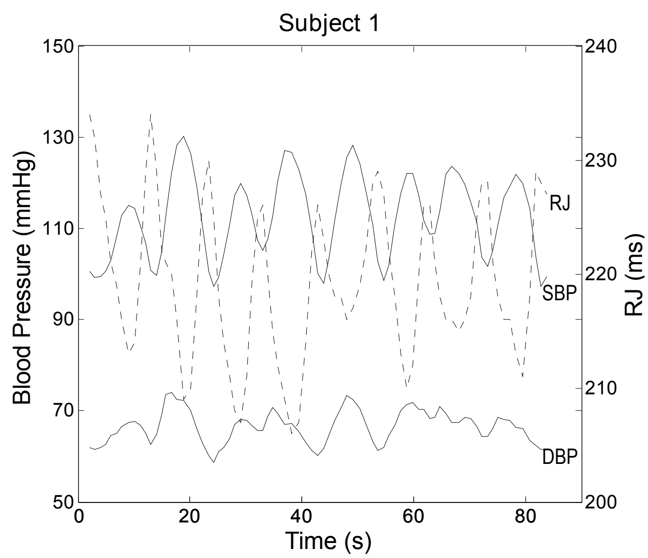

Figure 2. Changes in systolic blood pressure (top solid line), diastolic blood pressure (bottom solid line) and RJ interval (dotted line) during paced respiration in subject 1.

Fig. 3 shows the pressure pattern obtained for paced respiration for subject 2. In this case, in addition to SBP changes, there are large DBP changes that follow the respiration rate but that occur at a different moment of the respiration cycle with respect to SBP changes. For this subject, it can be observed that variations in the RJ interval tends more to display a trend inverse to that of DBP maxima and that the changes are not longer synchronous with SBP, hence showing a very different behavior from that observed in Valsalva maneuvers [14]. This divergence between cardiovascular parameters, which involves only some heartbeats, can be noticed because paced respiration causes fast enough pressure changes to clearly distinguish the different time occurrence of each parameter. This cannot be observed during a Valsalva maneuver because these short time differences are masked by the wider pressure changes at the longer time scales measured. Actually, changes in time intervals caused by respiration are often considered as "high-frequency noise" in most works that deal with these longer scale changes, induced by maneuvers or by drug administration [14-16].

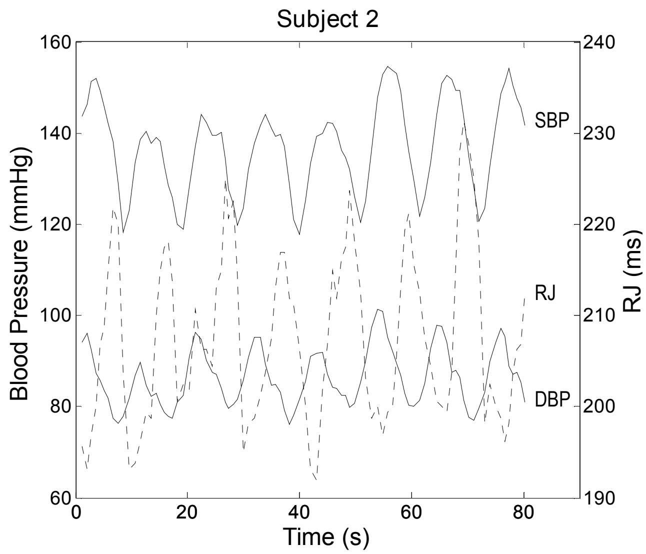

Figure 3. Systolic blood pressure (top solid line), diastolic blood pressure (bottom solid line) and RJ interval (dotted line) changes measured during paced respiration in subject 2.

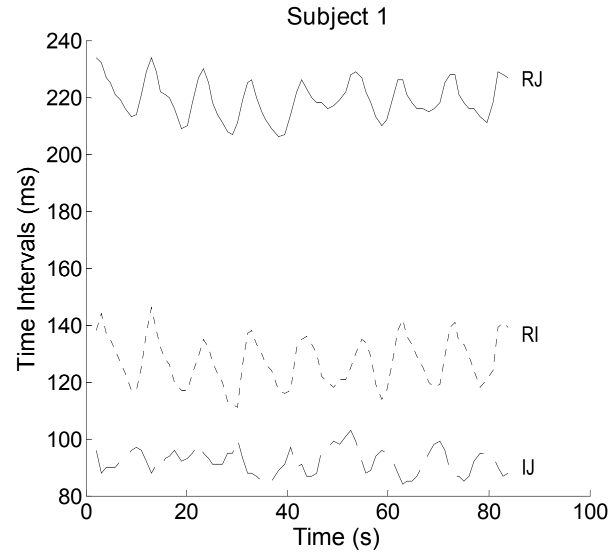

Figure 4. Changes in the RJ interval (solid line), RI interval (dotted line) and IJ interval (bottom dashed line) during paced respiration in subject 1.

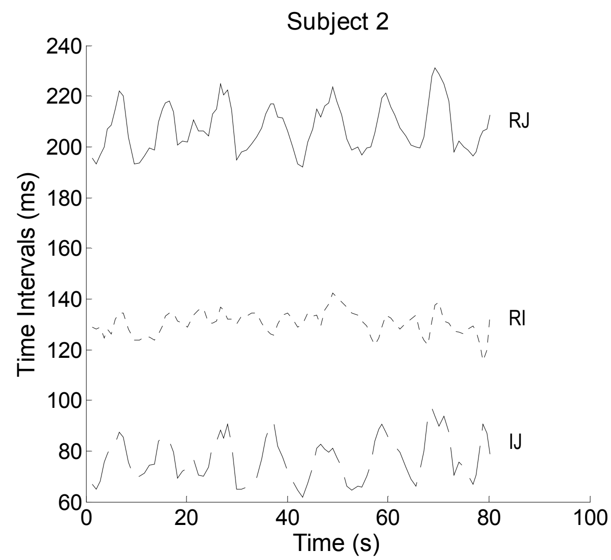

Figure 5. Changes in the RJ interval (solid line), RI interval (dotted line) and IJ interval (bottom dashed line) during paced respiration in subject 2.

In order to further elucidate the reasons from the different behavior observed between these two subjects, we have decomposed the measured RJ intervals into two main components. On the one hand, the interval between the R wave of the ECG and the I wave of the BCG (see Fig. 1), which we name RI interval, and on the other hand, the time interval between the I wave and the J wave, called the IJ interval. Fig. 4 shows the changes of these three intervals for subject 1 and Fig. 5 for subject 2. For subject 1, the changes in the RJ interval are mainly caused by RI interval changes, whereas the IJ changes, which are smaller and not synchronous to RI changes play a minor role in the final RJ output. For subject 2 the opposite happens: RJ changes are mainly caused by IJ changes, which are much greater than those for subject 1 and greater than the RI changes. Table II shows the correlation coefficient *r* between the RJ interval and both SBP and DBP values and RI and IJ intervals for the two subjects (obtained with *p*-values, for the significance of the fitting, $\ll 0.005$, except for RJ vs. IJ in subject 1, for which there is not a significant correlation). Correlations confirm the visual observations from the figures: for subject 1, RJ interval changes mainly with SBP, whereas for subject 2 the correlation is higher with DBP changes. On the other hand, RJ interval for subject 1 is correlated to RI interval and absolutely uncorrelated to IJ interval, whereas for subject 2, the highest correlation of RJ interval is that of IJ interval.

These results show that RJ interval seems to comprise two independent dynamics, one that depends on RI interval, which occurs in subject 1 more synchronously with SBP changes, and a second one, which is more evident in the subject with strong DBP variations, and that mainly affects the IJ part of the RJ values.

The I wave is the first major peak in the BCG and it is commonly attributed [10] mainly to the acceleration of blood in the ascending aorta. On the other hand, J peak was traditionally attributed mostly to acceleration of blood in the descending abdominal aorta and in the upper part of the legs. According to this, it is expected that J peak occurrence will be more influenced by the pulse propagation velocity in the aorta than the ocurrence of the I peak. This fact could help to understand the observed behavior of the measured BCG intervals, as pulse velocity is known [16] to be more dependent on mean pressure, and therefore more on DBP than on SBP. Because of this, IJ interval would be expected to mainly capture wave propagation and DBP related effects, while RI interval should account mainly for ejection (PEP related) SBP changes.

The main goal of this work has been to contribute to gain a deeper understanding of BCG time intervals by showing that RJ changes can have a richer dynamics than previously expected, caused independently by RI or by IJ changes.

Obviously, a larger number of subjects and experiments will be required in the future to futher confirm the hypothesized relationships between time intervals and blood pressure and their agreement with existing or newly proposed BCG models.

TABLE II. MAIN CORRELATION COEFFICIENTS BETWEEN ECG-BCG TIME INTERVALS

r	**Subject 1**	**Subject 2**
RJ vs. SBP	-0.77	-0.26
RJ vs. DBP	-0.53	-0.64
RJ vs. RI	0.64	0.44
RJ vs. IJ	0.05	0.84

IV. CONCLUSION

Fast pressure changes induced by paced respiration and the decomposition of the RJ interval in its RI and IJ components may offer complimentary information for a better understanding of RJ dynamics than that available only from maneuvers, such as Valsalva's, which involve larger time scales. Preliminary results obtained in two subjects that displayed different trends in RJ intervals and blood pressure, together with clearly different RI and IJ dynamics, suggest that ECG-BCG and intra-BCG time intervals could have a higher diagnostic potential than previously expected because they could be related to both heart dynamics and blood vessel performance. Because of all that, time intervals based on the BCG seem to be a very promising tool for monitoring trends in cardiovascular parameters, both in medical and non-medical environments, which deserve, and will surely receive, an increasing and renewed attention in the nearest future.

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