Ballistocardiogram Amplitude Modulation Induced by Respiration: a Wavelet Approach

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Abstract

Ballistocardiography is recognized as a reliable method for non-invasive assessment of cardiovascular functions. In this work, a wavelet approach was used on the y-axis ballistocardiogram (BCG) to evaluate the respiratory sinus arrhythmia (RSA) phenomenon using a new parameter: the ballistocardiogram amplitude modulation induced by respiration (BAMR). Ea_{max}, local maximum energy of BCG_y, was quantified for each cardiac cycle. Then a time series of Ea_{max} was created and analyzed using continuous wavelet transform to provide BAMR values. The ECG was used to compute the RSA amplitude as reference. Data were collected on four subjects participating to an imposed controlled breathing protocol with four different breathing sequences. RSA amplitudes and BAMR present significant changes ($p < 0.05$) for low breathing rate (0.10 Hz) compared to high breathing rate (0.25 Hz) and a within-subject correlation was observed. This study suggests that BAMR could be used as a relevant alternative to RSA amplitude for HRV investigation.

1. Introduction

Heart rate variability (HRV) has been used extensively to investigate cardiorespiratory interactions, sleep stages, autonomic nervous system and also to identify cardiovascular diseases [1–5]. HRV analyses are usually performed by spectral analyses of RR-interval (RRI) time series, obtained from the ECG, which typically show three components: a very low-frequency (VLF) [0.003-0.04 Hz], a low-frequency (LF) [0.04-0.15 Hz] and a high-frequency (HF) component [0.15-0.45 Hz] [4]. The latter reflects the respiratory sinus arrhythmia (RSA), which corresponds to heart rate oscillations at the breathing frequency [6].

Imposed controlled breathing (ICB) protocols are often used to investigate cardiorespiratory interactions and cardiovascular reactivity [7–9]. Indeed, stepwise controlled breathings allow to separate precisely LF and HF oscillations from each other allowing a reliable estimation of RSA [8, 10]. Furthermore, the magnitude and phase of the transfer function of cardiorespiratory interactions can be quantified [11]. Different breathing sequences are then imposed in order to obtain a detailed profile of the cardiorespiratory interaction over a wide frequency spectrum.

Thanks to technology improvements of last few years, especially on MEMS, HRV is being investigated using another non-invasive and cheaper method: ballistocardiography. A ballistocardiogram (BCG) represents the global acceleration of a human body recorded using accelerometers. Due to its simple design, BCG can be obtained using sensors placed on a chair, a bed, a weighing scale or directly on the subject. For that purpose, ballistocardiography is used for cardiovascular changes monitoring as HRV, cardiac contractility investigation and also breathing rate detection [12–15]. However, for a suitable monitoring technique, BCG events should be robustly and precisely estimated for each heart beats (time domain methods), which is not always possible [12, 16]. Therefore, time-frequency domain methods are commonly used for HRV investigations, especially, the continuous wavelet transform (CWT) widely used due to its flexible time-frequency resolution. CWT is considered as a reference for non-stationary biomedical signals analysis [17] and is already used to investigate BCG signals [13, 18].

In this work, a wavelet approach is presented to investigate the influence of respiration on BCG_y signals during short stepwise ICB protocols. The maximum energy peak of each cardiac cycles is determined by CWT and used to construct a time series of beat-by-beat maximum energy. A second wavelet analysis is performed to extract the ballistocardiogram amplitude modulation induced by respiration (BAMR). BAMR is then compared with RSA amplitudes also obtained by CWT.

2. Ballistocardiography

Ballistocardiography investigates the global motion of the body due to the mechanical activity of the heart and the blood circulation. In this study, we investigated the y-axis of the BCG signal, which is the main component representing accelerations associated to the feet-to-head axis [12]. Figure 1 shows typical BCG waves within a cardiac cycle and their nomenclatures. The J-wave, or a_{max}, representing the maximum amplitude of the BCG$_y$, was already proved related to heart rate, pre-ejection period or even stroke volume estimation [12–14].

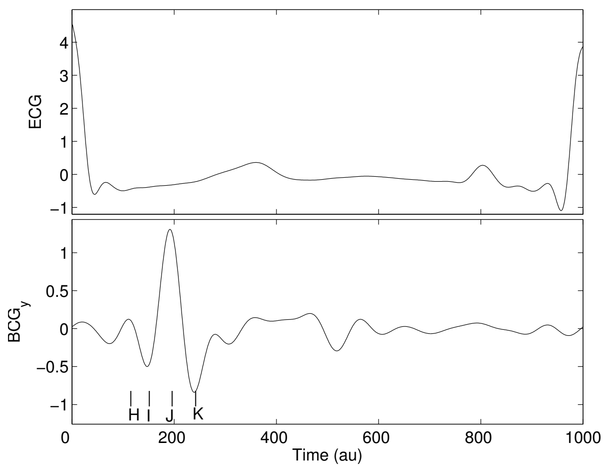

Figure 1. Ensemble average of 50 heart beats for a typical subject. Classical waves of the BCG$_y$ are presented. The J-wave or a_{max} is the maximum of the BCG$_y$ curve.

3. Methods

3.1. Human data and protocol

Data were collected on 4 subjects (age: 41 +/- 12 years; weight: 58 +/- 16 kg; height: 166 +/- 10 cm) during the baselines of the ESA-61th parabolic flight campaign. Subjects participated to a supine ICB protocol with 4 groups of 10 breathing cycles at 4, 6, 8 and 10 s as respiratory period (Tresp).

ECG, BCG, impedance cardiogram (ICG) and respiration were continuously recorded at 1 kHz using the Cardiovector device [19]. R-peaks were automatically detected in the ECG to generate RRI time series [12]. Spectral analyses of BCG$_y$ and RRI were performed by the CWT method using the Matlab software (The MathWorks, Inc., USA). BAMR and RSA amplitudes were then estimated for each breathing steps.

3.2. CWT theory

CWT is recognized for its flexible time-frequency resolution. In this study, we used a Morlet wavelet function considered as an optimal solution for time-frequency analysis [17]. In the frequency domain, the Morlet wavelet is defined as:

$$\hat{\Psi}_0(s\omega) = \pi^{-1/4} H(\omega) e^{-(s\omega-\omega_0)^2/2} \tag{1}$$

where

$$H(\omega) = \begin{cases} 1 & ,\forall\omega > 0 \\ 0 & ,otherwise \end{cases} \tag{2}$$

ω_0 is the central wavelet frequency and s the wavelet scale. Those parameters determine the time-frequency resolution. Indeed, a high value implies a high frequency resolution but a low time resolution and vice-versa [3]. Furthermore, ω_0 should satisfy the admissibility condition for a wavelet: $\omega_0 \geq 6$ [20]. In this study, to optimize the time resolution due to short consecutive stepwise breathings steps, a low wavelet frequency ($\omega_0 = 6$) was used. The scale is defined as:

$$s_j = s_0 2^{j\delta j}, \qquad j = 0, 1, ..., J \tag{3}$$

where s_0 is the smallest scale chosen, δj is the scale resolution and J determines the largest scale. Using a Morlet wavelet with $\omega_0 = 6$, the relationship between scale and frequency is expressed by $f = 1/1.03s$. In this study, the scale-related parameters were chosen as: $s_0 = 1.9$, $\delta j = 0.125$ and $J = 50$, allowing HRV analysis ranging from 0.007 Hz up to 0.5 Hz recommended by [4]. To perform the time-frequency analysis on the BCG$_y$ component, the frequency band [1-30 Hz] was investigated. For that purpose, we used the following scale-related parameters: $s_0 = 0.030$, $\delta j = 0.05$ and $J = 100$.

The instantaneous amplitude of signal's energy is computed by taking the square root of the wavelet coefficients, represented by the following relationship [21]:

$$W_n(s) = \sum_{k=0}^{N-1} \hat{x}_k \hat{\Psi}^*(s\omega_k) e^{i\omega_k n\delta t} \tag{4}$$

where δt is the sampling period, $\hat{x}_k$ the discrete Fourier transform of the signal and ω_k the angular frequency.

3.3. RSA-BAMR determination

RSA amplitudes were estimated for each subjects using the CWT method applied on RRI time series, resampled at 8 Hz. Figure 2 presents the RSA amplitude computation for one subject performing the ICB protocol.

To estimate the BAMR parameter, the maximum energy of BCG$_y$, Ea_{max}, was localized for each cardiac cycle. For that purpose, the CWT method was applied on

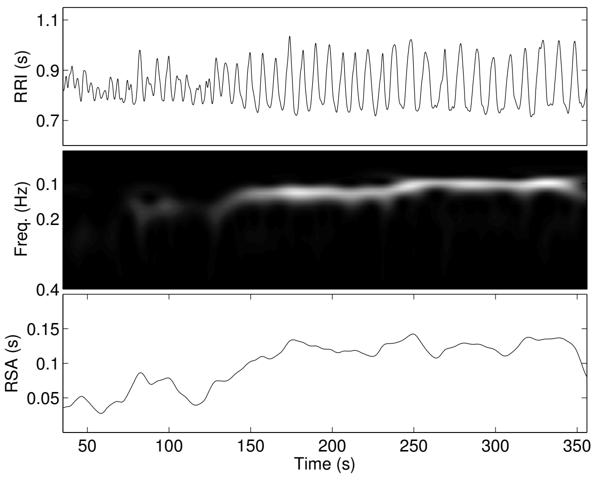

Figure 2. RSA amplitude estimate using CWT during an ICB protocol. From top to bottom: 1) RRI time series 2) Scalogram obtained using CWT on RRI 3) Instantaneous amplitude of RSA.

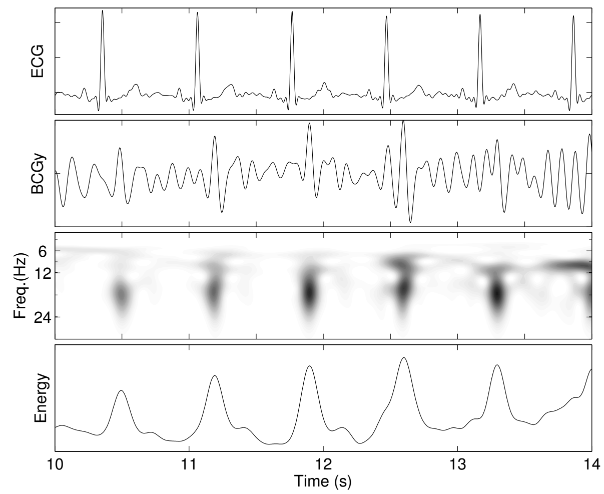

Figure 3. Estimation of the maximum energy of BCG_y, Ea_{max}, for each cardiac cycle. From top to bottom: 1) ECG 2) BCG_y 3) Scalogram obtained using CWT on BCG_y. 4) Instantaneous amplitude of the energy contained in the BCG_y component. Each local maximum (black spot) corresponds to an Ea_{max} value.

the BCG_y and the instantaneous amplitude of the signal was computed (Figure 3). A time series of each local energy maximum, Ea_{max}, was created and resampled at 8 Hz. Ea_{max} time series was then investigated again by the CWT method in the same frequency range as HRV (i.e. from 0.007 Hz to 0.5 Hz). Finally, the instantaneous amplitude was computed and corresponds to the BAMR estimate.

4. Results

RSA amplitudes and BAMR values were estimated for each subjects (n=4) for all breathing frequencies. Mean values were then computed. Figure 4 presents the results of both parameters in function of the breathing period. As expected [9], the RSA increases with the breathing period. Significant RSA amplitude changes ($p < 0.05$) were observed for the last two breathing periods (Tresp=8,10 s). Similarly, BAMR increases with the breathing period and statistically significant changes ($p < 0.05$) are observed for the highest breathing period (Tresp=10 s). By contrast, a_{max} decreases with Tresp ($p < 0.05$) while RRI remains constant during the ICB protocol. For each subjects, a linear regression was performed between RSA and BAMR and a high correlation was obtained. Mean R^2 was then computed: $R^2 = 0.8466 \pm 0.1073$.

5. Conclusion

Ballistocardiography has already been proved as an innovative and reliable alternative to ECG for HRV or cardiac contractility investigations [13–15]. However, most studies used time intervals analysis such as J-J intervals, as an alternative to classical HRV analysis.

In this study, we proposed another alternative by investigating energy amplitude variations using a wavelet approach to quantify the BAMR especially during stepwise ICB protocols. A Morlet mother wavelet function with a low central wavelet frequency (ω_0=6) was used to optimize the time-frequency resolution. This CWT method presents the advantage of not requiring BCG events determination and allows robust beat-by-beat investigations. Our results demonstrate a significant increase with the breathing period for the BAMR parameter similar to the RSA dependence and a high correlation was observed within-subjects. However, due to the high subjects variability, the correlation was not confirmed between subjects. Despite the fact that data were collected on a low numbers of subjects (n=4), significant results are encouraging for further researches.

Our results suggest that BAMR can be a reliable replacement to RSA amplitude, extracted from RRI time series. As suggested by literature, we recommend the use of ballistocardiography as a relevant alternative to ECG for HRV investigation, especially in new cheaper non-invasive technologies. Furthermore, the CWT method could be implemented into small wearable devices for smart monitoring.

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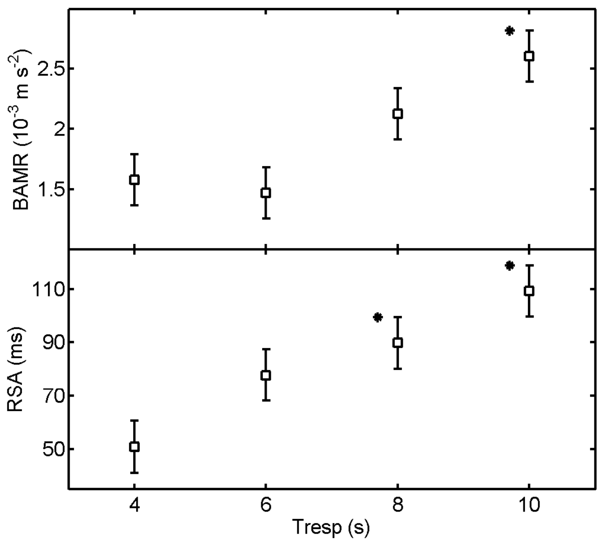

Figure 4. BAMR and RSA versus the breathing period (Tresp). Mean values are presented ± standard deviation. (*) indicates significant changes ($p < 0.05$) compared to Tresp=4s.

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