Respiratory Rate Influence in the Resulting Magnitude of Pulse Photoplethysmogram Derived Respiration Signals

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Abstract

Parameters derived from the pulse photoplethysmographic (PPG) signal, such as pulse rate, amplitude, and width variability (PRV, PAV and PWV) have been previously proposed for deriving respiratory rate, obtaining less accurate estimates for higher respiratory rates (0.5-0.6 Hz). In this work we analyze the power of respiration related oscillations in PRV, PAV and PWV as a function of respiratory rate in controlled respiration experiments. PPG signals from 14 subjects breathing at constant rates from 0.2 to 0.6 Hz (with an increment of 0.1 Hz) during 2 minutes were analyzed. In addition, smartphone-camera-acquired-PPG signals from 10 subjects using three different devices (iPhone 4S, iPod 5 and Samsung Galaxy S3), during the same kind of experiments were also analyzed. Powers of PRV, PAV and PWV respiration-related oscillations were estimated by integrating their Welch periodograms at the respiratory band. When analyzing PRV and PWV, clear tendencies of power decrease as respiratory rate increases were observed, while less evident tendencies were observed when analyzing PAV.

1. Introduction

Obtaining accurate respiratory information from pulse photoplethysmographic (PPG) signal is a task of interest because its acquisition process remains very comfortable, economical and simple, requiring only a few optoelectronic components. Furthermore, other information which is relevant in clinical monitoring can be also obtained with no additional sensors such as pulse rate and its variability or, if PPG signal is being acquired by a pulse-oximeter, the arterial oxygen saturation.

Respiration modulates PPG signal through several effects [1], and several methods for deriving respiratory information from PPG signals have been proposed. These methods can be based on respiration-induced modulations in pulse rate, amplitude and width [2].

Pulse rate variability (PRV) is modulated by respiration as heart rate variability (HRV) is, through a phenomenon well known as respiratory sinus arrhythmia (RSA). PRV is not an exact surrogate of HRV [3] but they are highly correlated [4]. Respiration also modulates the pulse amplitude variability (PAV) through variations in stroke volume and in blood vessels stiffness [1], and in [2], it was also reported that pulse width variability (PWV) was modulated by respiration.

In [5], smartphone-camera-acquired-PPG (SCPPG) signals are used for deriving respiratory rate by using methods based on PRV, PAV and PWV, obtaining less accurate results for higher respiratory rates ($0.5 - 0.6$ Hz) than for lower rates ($0.2 - 0.4$ Hz). This may be because respiration-induced modulations on PRV, PAV and PWV probably have a less strong effect at higher respiratory rates as it is the case with RSA, which is known to decrease when the respiratory rate increases [6].

In this work we analyze the relative power of respiration-related oscillations in PRV, PAV and PWV as a function of respiratory rate in controlled respiration experiments.

2. Methods

2.1. Data and signal preprocessing

PPG signals: PPG and chest respiratory effort signals were simultaneously recorded with Medicom MTD Poly10 and Poly4 using a samplig rate of 250 Hz, from 14 healthy volunteers during controlled respiration experiments. A set of videos showing a moving bar were used for assist subjects to breath at constant respiratory rates, maintaining each one of the following rates during 2 minutes: 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 Hz. According to the chest respiratory effort signal, the subjects breathed at the requested respiratory rate with an error of 0.22 ± 1.05 mHz.

SCPPG signals: SCPPG signals were recorded from 10 healthy volunteers during controlled respiration experiments. Three smartphone devices were used: iPhone 4S, iPod 5, and Samsung Galaxy S3. The signals were obtained by a 50×50 pixel average of a region on the green video signal at each frame. The reason for using the green band is that it has been demonstrated to give a stronger cardiac pulse signal than the red or blue bands [7].

The sampling rate of SCPPG signals is variable due to internal processing load [8], and it depends on the measuring device. The SCPPG signals were interpolated to a constant sampling rate of 100 Hz.

Both PPG and SCPPG signals were low-pass filtered with a cut-off frequency of 35 Hz. Then, the apex (n_{A_i}), basal (n_{B_i}) and medium (n_{M_i}) points of the ith pulse were detected as described in [9], and its onset (n_{O_i}) and end (n_{E_i}) points were detected as described in [2].

2.2. Derived respiration signals

Three derived respiration (DR) signals were studied, based on pulse-to-pulse variations: the pulse rate, amplitude and width variabilities (PRV, PAV and PWV).

Inverse interval function was used for studying PRV, taking n_{M_i}:

$$d^u_{\mathrm{PRV}}(n) = \sum_i \frac{1}{n_{\mathrm{M}_i} - n_{\mathrm{M}_{i-1}}} \delta\left(n - n_{\mathrm{A}_i}\right) \tag{1}$$

where the superscript u denotes that the signal is unevenly sampled as pulses occur non-uniformly in time.

For studying PAV, the amplitude of each pulse was measured with respect to the baseline:

$$d^u_{\mathrm{PAV}}(n) = \sum_i \left[x\left(n_{\mathrm{A}_i}\right) - x\left(n_{\mathrm{B}_i}\right)\right] \delta\left(n - n_{\mathrm{A}_i}\right) \tag{2}$$

where $x(n)$ denotes the PPG signal.

For studying PWV, the width of each pulse was measured as the time between its onset and its end:

$$d^u_{\mathrm{PWV}}(n) = \sum_i \left[n_{\mathrm{E}_i} - n_{\mathrm{O}_i}\right] \delta\left(n - n_{\mathrm{A}_i}\right). \tag{3}$$

Figure 1 illustrates these three PPG-DR signals.

Then, a median-absolute-deviation outlier rejection rule was applied, and subsequently, a $f_s = 4$-Hz evenly version of each signal was obtained by cubic spline interpolation. These versions of the signals are denoted without the superscript u in this paper, e.g., $d_{\mathrm{PWV}}(n)$ denotes the outlier-rejected-evenly-sampled version of $d^u_{\mathrm{PWV}}(n)$. Further details of this process are given in [2].

2.3. Estimation of power of oscillations

Power of oscillations in DR signals at the respiratory band was estimated by an algorithm based on power

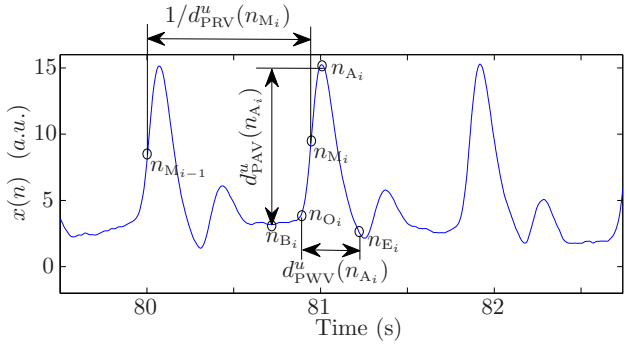

Figure 1. PPG derived respiration signals.

spectrum density (PSD). PSD, denoted $S_d(f)$ ($d \in \{\mathrm{PRV,PAV,PWV}\}$), was estimated from each fragment corresponding to each subject and each respiratory rate by the Welch periodogram using a 96-samples-length (24 seconds) Hamming window with an overlap of 50%.

Subsequently, the principal frequency of the oscillations at the respiratory band is estimated as:

$$\hat{f}_d = \arg\max\left\{S_d(f)\right\}, \quad f \in \Omega_{\mathrm{R}} \tag{4}$$

$$\Omega_{\mathrm{R}} = [f_{\mathrm{R}} - 0.05\mathrm{Hz}, \quad f_{\mathrm{R}} + 0.05\mathrm{Hz}] \tag{5}$$

where f_{R} denotes the respiratory rate at which subject is requested to breath.

Then, the power of the oscillations at the respiratory band was estimated as:

$$\mathcal{P}_d = \frac{f_s}{N_{\mathrm{FFT}}} \sum_{f=\hat{f}_d-0.025\mathrm{Hz}}^{\hat{f}_d+0.025\mathrm{Hz}} S_d(f) \tag{6}$$

where N_{FFT} denotes the number of points of $S_d(f)$.

3. Results

Table 1 shows inter-subject medians and interquartile ranges (IQR) of obtained $\mathcal{P}_{\mathrm{PRV}}$, $\mathcal{P}_{\mathrm{PAV}}$ and $\mathcal{P}_{\mathrm{PWV}}$, for each device and each respiratory rate. These powers are also illustrated in Fig. 2.

Note that the PRV, PAV, and PWV are sampled only at pulse occurrence, so respiratory rate cannot be tracked if it is higher than half the mean pulse rate due to aliasing problems. For this reason, registers with a respiratory rate higher than half the mean pulse rate where discarded from this study. This problem mainly affected to respiratory rates of 0.5 and 0.6 Hz which require a minimum mean pulse rate of 60 and 72 pulses per minute, respectively. The number of discarded registers for each device and rate (#/rate) were: photoplethysmograph (1/0.5 Hz; 7/0.6 Hz), iPhone 4S (3/0.6 Hz), iPod 5 (2/0.5 Hz; 7/0.6 Hz), and Galaxy S3: (1/0.5 Hz; 3/0.6 Hz).

Table 1. Inter-subject medians and IQR of obtained $\mathcal{P}_{\text{PRV}}$, $\mathcal{P}_{\text{PAV}}$ and $\mathcal{P}_{\text{PWV}}$, for each device and each respiratory rate.

	Respiratory rate	$\mathcal{P}_{\text{PRV}}$ (s^{-2})		$\mathcal{P}_{\text{PAV}}$ $(a.u.^2)$		$\mathcal{P}_{\text{PWV}}$ (s^2)	
		Median	IQR	Median	IQR	Median	IQR
Photoplethysmograph	0.2 Hz	3.95E-05	2.46E-05	3.95E-04	3.09E-04	6.12E-06	1.40E-05
	0.3 Hz	1.19E-05	1.47E-05	3.13E-04	1.04E-03	2.84E-06	4.80E-06
	0.4 Hz	5.40E-06	3.66E-06	1.79E-04	1.55E-03	1.84E-06	4.02E-06
	0.5 Hz	3.41E-06	7.47E-06	1.52E-04	9.34E-04	1.17E-06	2.67E-06
	0.6 Hz	2.99E-06	2.77E-06	1.78E-04	1.71E-03	4.63E-07	3.41E-07
Iphone 4S	0.2 Hz	7.63E-06	8.61E-06	4.24E-04	1.05E-03	1.61E-06	2.48E-06
	0.3 Hz	2.29E-06	5.74E-06	2.28E-04	3.86E-04	5.56E-07	1.14E-06
	0.4 Hz	1.23E-06	2.44E-06	1.00E-04	3.97E-04	4.16E-07	6.63E-07
	0.5 Hz	1.27E-06	4.20E-06	1.11E-04	2.87E-04	2.73E-07	4.73E-07
	0.6 Hz	6.87E-07	9.48E-06	1.66E-04	4.10E-04	1.64E-07	1.39E-06
Ipod 5	0.2 Hz	6.93E-06	8.01E-06	2.27E-05	3.40E-04	4.59E-06	3.76E-06
	0.3 Hz	1.87E-06	5.97E-06	5.08E-05	2.29E-04	5.14E-07	7.88E-07
	0.4 Hz	1.96E-06	1.17E-06	2.82E-05	1.93E-04	5.34E-07	2.52E-07
	0.5 Hz	1.14E-06	6.58E-06	1.85E-05	2.57E-04	3.66E-07	2.75E-07
	0.6 Hz	3.07E-06	7.00E-06	5.53E-06	2.03E-05	2.00E-07	6.57E-07
Galaxy S3	0.2 Hz	2.19E-05	8.73E-05	1.57E+02	7.54E+02	3.68E-06	1.17E-05
	0.3 Hz	9.99E-06	6.22E-05	1.13E+01	6.20E+01	2.31E-06	2.69E-06
	0.4 Hz	2.88E-06	2.59E-05	1.24E+02	4.69E+02	1.12E-06	9.93E-07
	0.5 Hz	1.87E-06	4.29E-06	1.12E+02	1.53E+02	5.86E-07	8.27E-07
	0.6 Hz	3.81E-06	1.38E-05	4.05E+01	9.19E+01	3.12E-07	5.74E-07

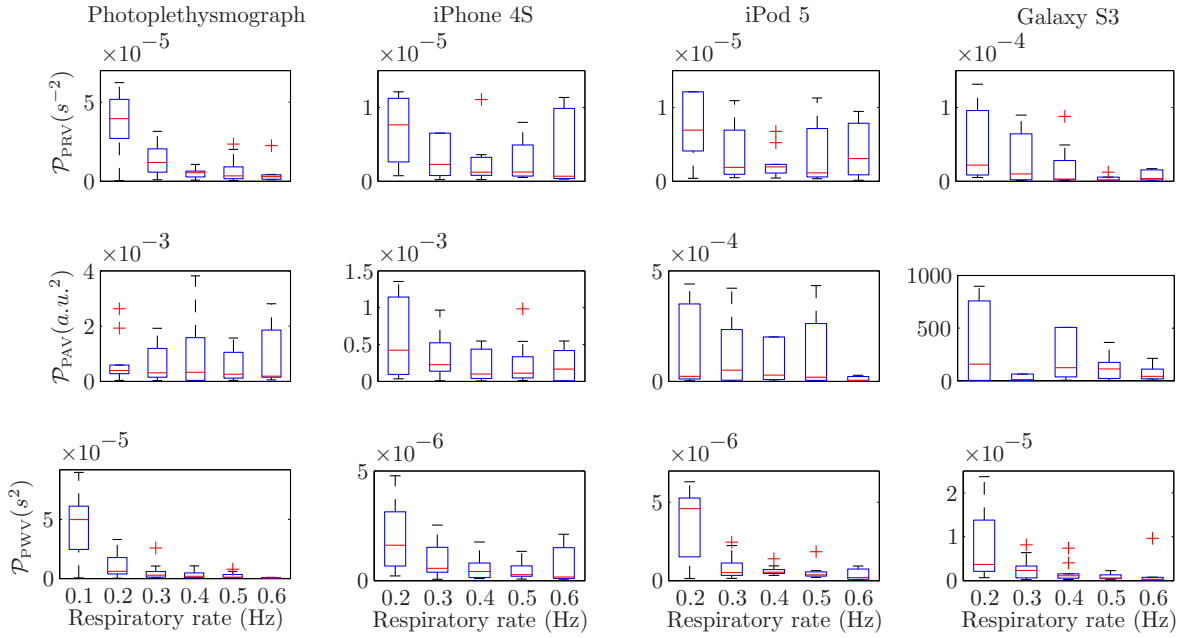

Figure 2. Boxplots of obtained $\mathcal{P}_{\text{PRV}}$, $\mathcal{P}_{\text{PAV}}$ and $\mathcal{P}_{\text{PWV}}$, for each device and each respiratory rate.

The Friedman statistical test was used in order to study whether there are significant differences (p-value < 0.05) for different respiratory rates for each device. Significant differences were found for the following groups:

- Photoplethysmograph: 0.2-0.5Hz, 0.2-0.6Hz and 0.3-0.6Hz for PRV; 0.2-0.6Hz for PWV.
- iPhone 4S: 0.2-0.4Hz for PRV; 0.2-0.4Hz and 0.2-0.5Hz for PWV.
- Galaxy S3: 0.2-0.6Hz for PWV.

4. Discussion and conclusions

An analysis of the influence of respiratory rate in the power of known respiration-related oscillations in PRV, PAV and PWV has been presented.

Significant differences according to the Friedman statistical test were found in the powers $\mathcal{P}_{\text{PRV}}$, $\mathcal{P}_{\text{PAV}}$ and $\mathcal{P}_{\text{PWV}}$ for some groups, in all cases between groups differing in at least 0.2 Hz of respiratory rate. When analyzing PRV and

PWV, clear tendencies of power decrease as respiratory rate increases were observed, while less evident tendencies were observed when analyzing PAV. Estimated PSD of PAV signals showed other non-respiration-related oscillations, which act as noise from the point of view of the study of respiration-related oscillations and make longer the IQR of $\mathcal{P}_{\text{PAV}}$. However, a median decrease tendency when respiratory rate increases can be still observed.

These results suggest that the power of respiration-related oscillations in PRV, PAV and in PWV decreases when respiratory rate increases. A possible reason for this observation is that the autonomic nervous system response which generates the respiration-related modulations in PRV, PAV and PWV may act as a physiological low-pass filter, and other mechanical effects may also interfere in PAV and PWV.

Registers associated to respiratory rates of 0.1 Hz were recorded with the photoplethysmograph but not with the smartphone devices. However, they were not studied in this work. The reason for this exclusion is that non-respiration-related oscillations with comparable power to respiration-related oscillations were observed in the traditional HRV low-frequency (LF) band ($0.04 - 0.15$ Hz) for PRV and PAV, associated to sympathetic activity. Obtained distribution of $\mathcal{P}_{\text{PWV}}$ (not so affected by LF oscillations [2]) for $f_{\text{R}} = 0.1$ Hz showed a median of 4.99E-05 and an IQR of 3.67E-05, following the expected behavior (See Fig. 2).

Aliasing problems affect specially to respiratory rates of 0.6 Hz. The number of registers which were not discarded by the aliasing criterion at this rate is low (7 for the photoplethysmograph and the iPhone 4S, 6 for the Galaxy S3 and only 3 for the iPod 5), so strong conclusions should not be extracted from registers at 0.6 Hz.

One limitation of this study which affect only to the SCPPG signals is the absence of a reference respiratory signal, so it cannot be determined how accurate is the subject breathing at the requested respiratory rate. However, the photoplethysmograph dataset with similar acquisition protocol but including a reference respiratory signal, showed that subjects breathed at requested respiratory rate with an error of 0.22 ± 1.05 mHz, accurate enough to get their respiration inside Ω_{R} (100 mHz around requested respiratory rate, see eq. 5).

Another limitation of this study is the absence of a measure of the tidal volume. Tidal volume may also have effect on the power of the respiration-related oscillations in PRV, PAV and PWV as it does in RSA [6]. Furthermore, it is natural to decrease the tidal volume when forcing to increase the respiratory rate during rest conditions. In this way, when a decrease of $\mathcal{P}_{\text{PRV}}$, $\mathcal{P}_{\text{PAV}}$ or $\mathcal{P}_{\text{PWV}}$ is observed, it cannot be determined how much of this decrease is due to a decrease of tidal volume, and how much is due to an increase of respiratory rate.

This observation derived in this study should be taken into consideration when PPG derived respiration studies are carried out.

Acknowledgements

This work was supported in part by the US Army Medical Research and Materiel Command (USAMRMC) under Grant No. W81XWH-12-1-0541, by Universidad de Zaragoza under fellowship PIFUZ-2011-TEC-A-003, by Ministerio de Economía y Competitividad (MINECO), FEDER; under projects TEC2013-42140-R, TEC2010-21703-C03-02 and FIS-PI12/00514, by CIBER de Bioingeniería, Biomateriales y Nanomedicina through Instituto de Salud Carlos III, and by Grupo Consolidado BSICoS (T96) from DGA and European Social Fund (EU).

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