Algorithms for Real-time Detection of Motion Artifacts and Accurate Estimation of Respiratory Rates using Pulse Oximeter

Nandakumar Selvaraj and Ki H. Chon
Department of Biomedical Engineering, Worcester Polytechnic Institute, Worcester, Massachusetts, USA

1. INTRODUCTION

A tremendous research interest prevails for the real-time monitoring of multi-physiological activities using noninvasive Photoplethysmography (PPG) waveforms. However, motion artifact is a serious obstacle in realizing this quest. We present the application of two novel nonparametric spectral approaches recently developed in our Laboratory in PPG data for robust detection of motion artifacts and accurate estimation of respiratory rate using PPG signals.

2. MOTION ARTIFACT DETECTION

The motion artifact has been recognized as the intrinsic weakness of PPG signal that limit the practical implementation, and as a serious obstacle to reliable use of PPG for real-time and continuous monitoring applications. The motion artifacts are more likely in clinical situations where the patient is awake due to voluntary or involuntary movements. Our present objective is to develop a robust computational technique that can be used to accurately detect the motion artifacts.

Hypothesis: A second order nonlinear phase coupling exists between the fundamental heart rate (HR) frequency and its first harmonic for noise-free PPG signal, but it is absent for a noise-corrupted PPG signal. We propose to use the bispectral analysis combined with a surrogate data (BWS) approach, which we have recently developed [1], to quantitatively determine the statistical significance of the quadratic phase coupling (QPC) in PPG signals.

Experiment: In laboratory-controlled settings, PPG signals were acquired from a reflection type finger PPG transducer (TSD200, 860nm) at 100 Hz in five healthy volunteers under upright sitting posture with and without motion artifacts, induced by left-right movements for predetermined time intervals that specified the presence of noise from 10 to 50 % with respect to the total duration each PPG segment. A representative PPG data that illustrates the induced left-right movement for 10- 50 % of noise within each min of data length (Fig. 1).

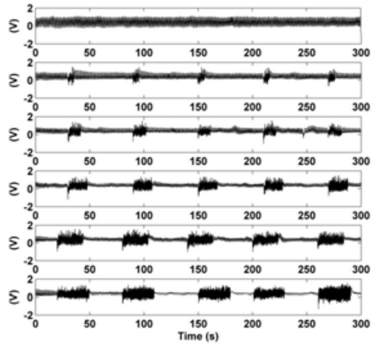

Fig. 1. Representative finger PPG signal recorded during protocol that simulated 10 %-50% of noise induced by the left-right movements.

BWS technique: The BWS method is a combination of bispectral estimation followed by testing the significance of QPC against surrogate data realizations [1]. The direct method of calculating the bispectrum of a signal is to take the average of triple products of the Fourier Transform over K segments:

$$BS(f_1,f_2)=\frac{1}{k}\sum_{k=1}^{k}X_k(f_1)X_k(f_2)X_k^*(f_1+f_2)$$

Realizations of 50 surrogate bispectral data from the original PPG data were generated. Any bispectral peaks estimated from original PPG data that are above the 95% statistical threshold value (mean+2*SD) of surrogate bispectra are considered to have significant QPC.

The presence or absence of QPC between the HR and its first harmonic, and its coupling strength has been evaluated for each 1 min PPG segment.

Results: Fig. 2 shows the presence of phase coupling at the frequencies associated with HR and its first harmonic in noise-free PPG signal (3rd row, left panel), meanwhile the phase coupling is absent with the PPG signal corrupted with motion artifacts induced by left-right movement (3rd row, right panel). Note that the power spectral density (PSD) suppresses phase relations; thus, it cannot be used for detection of phase coupling (2nd row). When we analyzed 750 PPG segments of 1 min data from 5 volunteers, BWS method allows the detection of motion artifact with specificity of 94 % and sensitivity of 86 % (Table 1). When we used a threshold value for QPC strength at 0.07, the sensitivity increased to 95 % but with a decrease in specificity to 85 % as a trade off.

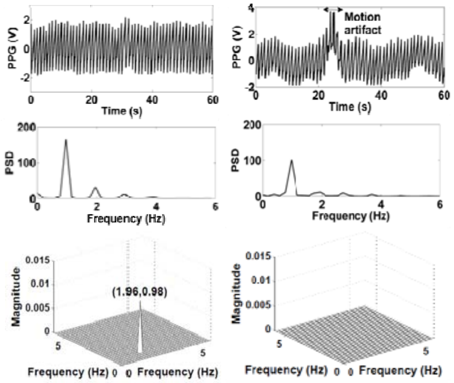

Fig. 2. Finger-PPG signal, its PSD and the identified statistically significant phase coupled peak are given for representative of clean (left panel) and with motion artifact induced by left-to-right movement for 6 s (right panel).

	Sensitivity (TP/(TP+FN)*100)						**Specificity (TN/(TN+FP)*100)**
	10% noise	20% noise	30% noise	40% noise	50% noise	Overall noise	
No QPC_{Th}	64.0	72.0	87.2	95.2	97.6	**85.9**	**93.6**
QPC_{Th} =0.07	72.8	96.8	98.4	100	100	**94.7**	**84.8**

Table. 1. The sensitivity and specificity values obtained from 125 clean and 625 corrupted PPG segments with left-right movements. QPC_{Th}: Threshold value for the strength of QPC.

From the false negatives, we observed a weak phase coupled peak between HR and its first harmonic frequency indicating the motion artifacts in these segments are not significant and do not disrupt the oscillatory dynamics of PPG signals. This is an optimal scenario where we want to preserve these data since they are usable rather than discarding them as unusable data.

3. RESPIRATORY RATE DETECTION

Respiratory rate detection is important in many clinical uses including detecting sleep apnea, sudden infant death syndrome and chronic obstructive pulmonary disease. Capnograph, the current standard practice, is an expensive device and requires significant maintenance. In addition, it requires a mask or nasal cannula, and is therefore obtrusive to the patient and cumbersome to use. Extraction of respiratory rates from pulse oximeter in addition to SpO2 and heart rate is very appealing from both economic and patient comfort perspectives. The PPG signal contains not only the heart beat but also the respiratory signal, and the respiration is known to modulate amplitude and frequency of PPG signal. This phenomenon is similar to respiratory sinus arrhythmia modulating HR.

Hypothesis: The amplitude (AM) and frequency (FM) modulations associated with HR band frequencies of PPG signal have a measurable periodicity which may provide an estimate of respiration rate.

Experiment: Finger PPG data were collected from 15 healthy subjects in the upright and supine positions using MP506 pulse oximeter (Nellcor Oximax, Boulder, CO). The subjects were instructed to breathe at a constant rate according to a timed-beeping sound. The PPG data were collected at a rate of 200 Hz for breathing frequencies ranging from 0.2 to 0.6 Hz at an increment of 0.1 Hz. A true breathing signal was also acquired using Respitrace system.

Variable complex demodulation (VFCDM) technique: Detection of AM and FM modulations of PPG signal using conventional methods such as PSD is difficult since they are highly time-varying and often subtle which requires a high resolution time-frequency spectral (TFS) method such as VFCDM. Our recently developed VFCDM algorithm provides one of the highest possible time-frequency resolutions and most accurate amplitude estimates as compared to other TFS methods [2]. The application of VFCDM for respiratory rate extraction from PPG signal has been presently attempted.

The VFCDM method involves two-step procedure. At first, the fixed frequency complex demodulation (FFCDM) technique identifies the signal's dominant frequencies, shifts each dominant frequency to a center frequency, and applies low-pass filter (LPF) to each of the center frequencies. The LPF has a cutoff frequency less than that of the original center frequency and is applied to each dominant frequency. This generates a series of band-limited signals.

The instantaneous amplitude, phase and frequency information is obtained for each band-limited signal using the Hilbert transform and are combined to generate a TFS. Thus, the VFCDM is designed to select only the dominant frequencies and produces a high resolution TFS. For complete details of VFCDM algorithm, refer [2].

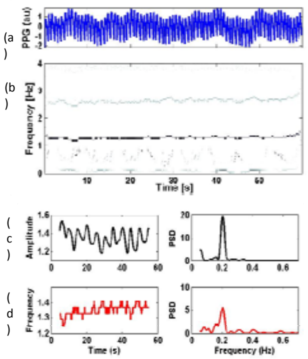

Fig. 3. (a) Representative PPG signal recorded at metronome breathing rate of 12 breaths/min. (b) Estimated TFS using VFCDM with prominent frequency oscillations seen near HR (1.3 Hz). The extracted (c) AM and (d) FM sequences of HR band of TFS are shown along with their corresponding PSDs where the highest peak is obtained at 0.2 Hz, which is same as the breathing frequency.

Respiratory rate Extraction: The largest amplitude at each time point within the HR band (~ 1 Hz in Fig. 3b) of TFS of VFCDM can be extracted as AM sequence, and the corresponding instantaneous frequency for the largest amplitude constitute the FM sequence. By taking the PSD of AM and FM sequences of HR band (since they are relatively stationary, see left panels of Fig. 3c-d), the respiratory frequency can be determined as the frequency corresponding to the maximum peak of PSD.

In addition, we used Morlet wavelet with a half-length of five samples at the coarsest scale to estimate the scalogram of the PPG signal. The procedure to extract respiratory rates is identical to the VFCDM. Burg algorithm [3], an AR modeling approach has also been used to extract respiration rate.

Results: VFCDM method is the most accurate (i.e. smallest median error) to extract the respiratory rate from PPG signal for widely varying breathing rates and with the fastest computational time than CWT and auto regressive (AR) based methods for both supine and upright positions as shown in Fig. 4.

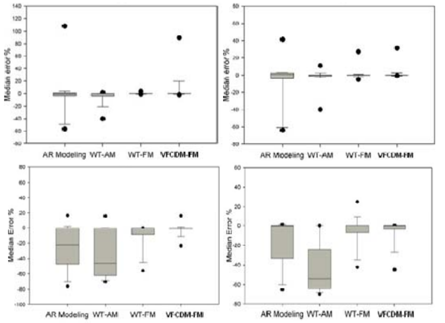

Fig. 4. The accuracy (median error) of respiratory rate detection as a function of true breathing rate is given for supine (left panel) and upright (right panel) positions using AR modeling, AM/FM based CWT and FM based VFCDM methods from 15 healthy subjects. The top and bottom panels correspond to the metronome breathing frequencies of range (LF: 0.2-0.3 Hz) and (HF: 0.4-0.6Hz), respectively. Among the four methods, VFCDM-FM is the most accurate method for respiratory rate detection using PPG signals.

4. CONCLUSION

We presented two unique signal processing approaches and demonstrated their potential applications. Integration of such algorithms into the existing pulse oximeter device can be used for simultaneous measurement of respiration, HR and SpO_2. It has the potential to be of great benefit in acute hospital settings, reducing morbidity and mortality as well as the ever-increasing cost of healthcare since these vital signs can all be derived from a single pulse oximeter.

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