

A preliminary study of respiratory variations in the photoplethysmogram during lower body negative pressure

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ABSTRACT

Previous studies have shown that the photoplethysmogram (PPG) may be a useful tool for the noninvasive detection of hypovolemia. The focus has been on determining if frequency analysis of the respiratory induced variations of the PPG can be used as an indicator of blood volume. In this preliminary study, we evaluate these frequency analysis techniques for two subjects undergoing Lower Body Negative Pressure (LBNP) induced hypovolemia. Using Matlab®-based software the power of the respiratory component and heart rate component were calculated using the periodogram method for spectral estimation. Consistent with other studies our algorithms were able to automatically detect changes in the respiratory variations. We found a significant increase in the respiratory variations in the PPG during simulated hypovolemia. By taking the ratio of the respiratory power to the heart rate power we consistently detected hypovolemia in subjects corresponding to sequestration of approximately 2 liters of blood (LBNP >70 mm Hg). The increase in this ratio occurred before significant change in blood pressure or tachycardia were observed.

1. Introduction

Early detection of hypovolemia is of critical importance for patient care. Standard noninvasive indicators of hypovolemia such as heart rate and blood pressure often do not give enough lead time before rapid decline and cardiovascular collapse onsets.

Almost twenty years ago, a clinician noticed changes in the pulse oximeter waveform while blood volume decreased during surgery (Partridge 1987). These findings were largely ignored and unexplored until the mid to late 1990's when several research groups began to investigate the possibility of using the pulse oximeter



Figure 1. Subject in the LBNP chamber at the Institute for Surgical Research, Brooks Army Medical Center, San Antonio, Texas.

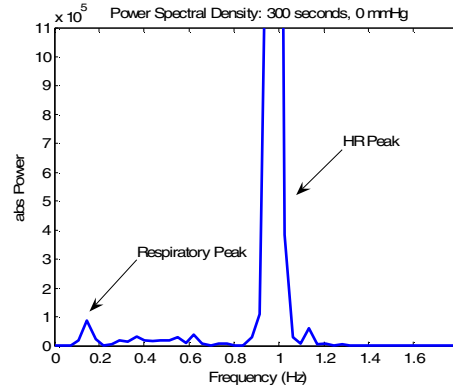
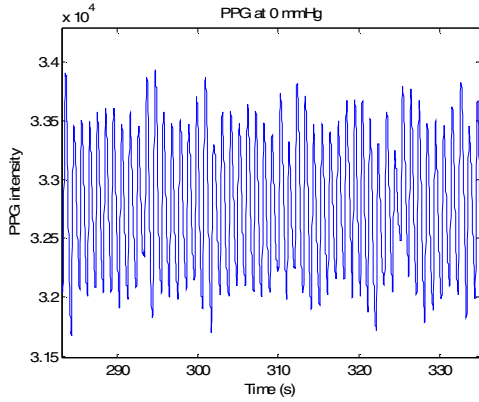
waveform for noninvasive blood volume and respiratory rate assessment.

Recent studies have shown that the photoplethysmogram (PPG) can be used to detect blood loss in mechanically ventilated, sedated patients (Shamir, Eidelman et al. 1999; Shelley, Stout et al. 1999; Cooke, Ryan et al. 2004; Cannesson, Besnard et al. 2005) and in healthy subjects with paced or spontaneous breathing (Nilsson, Johansson et al. 2003; Gesquiere, Awad et al. 2004; Jablonka, Awad et al. 2004). These studies showed that the respiratory induced variations in the PPG increase as blood volume is lost.

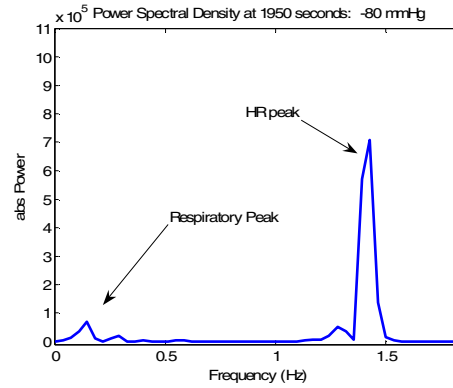
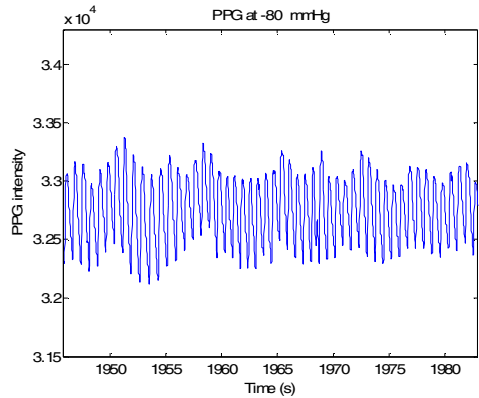
In this preliminary study, we analyzed the PPG in two subjects undergoing lower body negative pressure (LBNP). The LBNP device (see Figure 1) safely simulates hypovolemia by sequestering blood into the lower extremities by applying a negative pressure around the legs and abdomen (Cooke, Ryan et al. 2004). This device can simulate severe hemorrhage (approximately 1 liter of blood volume at 40 mm Hg and 2 liters of blood volume at 80 mm Hg).

The effects of LBNP conditions on the PPG have not previously been studied. This study uses

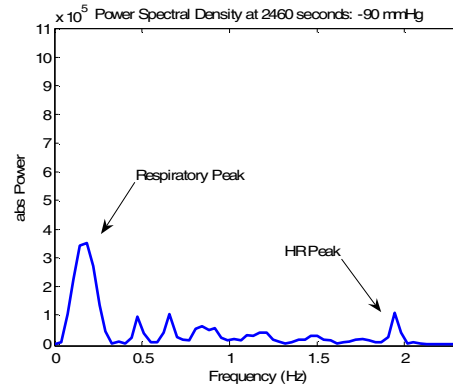
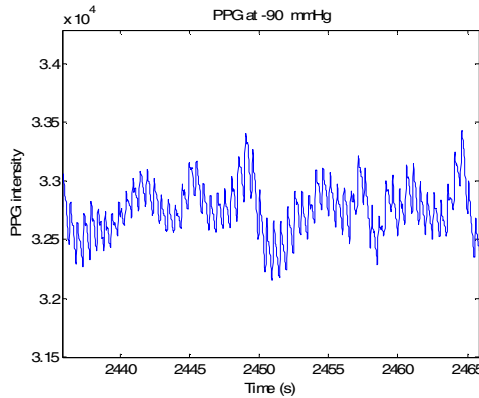
LBNP = 0



LBNP = 80



LBNP = 90



frequency analysis techniques that have previously been shown to be indicators of blood loss to analyze the PPG data to show an increase in the respiratory induced variations of the PPG and a simultaneous decrease in the power of the heart rate signal.

2. Methods and Materials

With IRB approval and informed consent, two healthy, male individuals participated in the study. Two FDA approved Nonin® pulse oximeters were placed on the subjects' forehead and

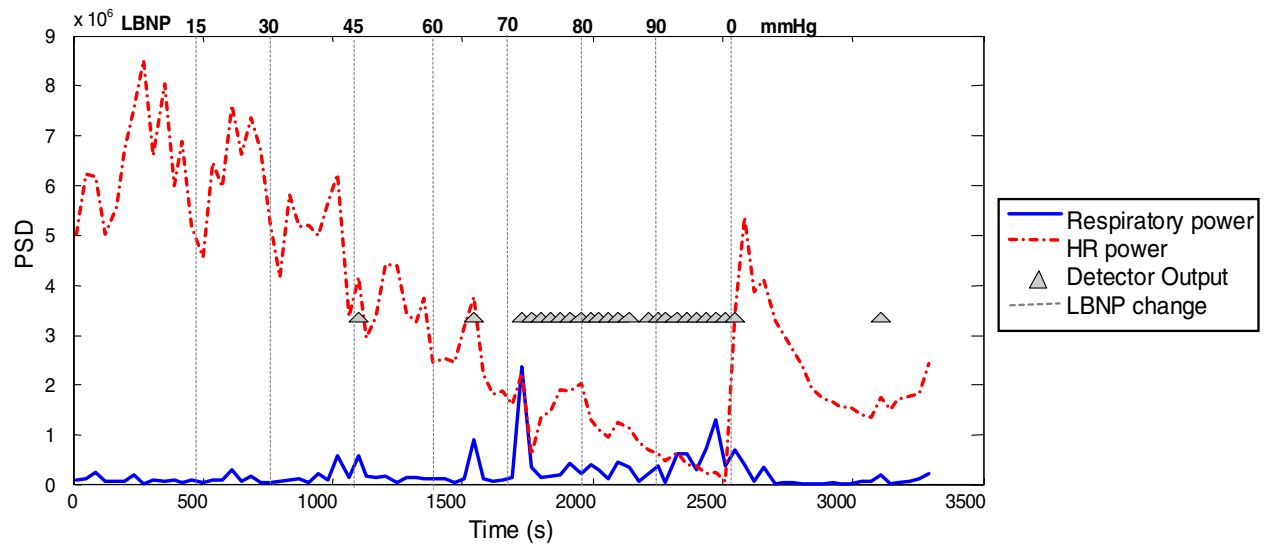


Figure 3. Total power for the heart rate component (red) and respiratory component (blue) during Trial 1 of the LBPN experiment. The triangles mark where the ratio of the respiratory power to the heart rate power is greater than 0.1. The heart rate power decreases and the respiratory power increases as the LBPN decreases pressure, sequestering more blood into the lower extremities.

finger. Each sensor was connected to a Nonin OEM III interface module which generated data packets at 75 Hz of filtered 16-bit PPG data. The PPG signal was pre-processed by the OEM III module with high pass and notch filters. A serial RS232 interface allows a personal computer to record data.

A Java-based program was developed to simultaneously log data from multiple sensors. The annotated data was saved in text files for later analysis.

2.1 Experimental Protocol

Three trials were performed using LBPN chamber at ISR, Brooks Army Medical Center. Because there were several research groups involved in the study each trial had a slightly different protocol. In the first trial there were 3 minutes at LBPN = 15, 30, 45 and 60 mm Hg. In the second trial there were 3 minutes at LBPN = 15, 30, 45, 60, 70, 80 and 90 mm Hg. In the third trial the pressure was reduced to LBPN = 80 mm Hg in 60 seconds and then held there for nine minutes. In this trial, an impedance threshold device (ITD) was used for three minutes during the 80 mm Hg phase.

2.2 Data Analysis

Using Matlab® programming language, we developed signal processing software to analyze the PPG. Our method used a sliding window of

2048 samples, with a 700 sample increment (approximately 27 seconds worth of PPG data with 17 seconds of overlapping data). The power spectral density was estimated using the periodogram¹ method with a Hamming window (length 2048). The respiratory peak power (P_{resp}) and frequency (f_{resp}) was found by taking the maximum power between 0.07 and 0.3 Hz. A normal respiratory rate of 12 breaths per minute lies in this frequency range. The total power of the respiratory component (P_{resp_total}) was calculated by integrating the power in the band

$$0.07 \text{ Hz} < f < f_{resp} + 0.05 \text{ Hz}.$$

The heart rate peak power and frequency was found by taking the maximum power (P_{hr}) at the heart rate frequency (f_{hr}) as determined by our feature extractor algorithm (Linder, Wendelken et al. 2006). This technique was used to find the peak heart rate because there was occasionally some high power noise around 1 Hz in later stages of the trial that did not appear to be related to the actual heart rate signal. The total power in the heart rate band (P_{hr_total}) was calculated by integrating the power from the band

$$f_{hr} - 0.2 \text{ Hz} < f < f_{hr} + 0.2 \text{ Hz}.$$

¹

<http://www.mathworks.com/access/helpdesk/help/toolbox/signal/periodogram.html>

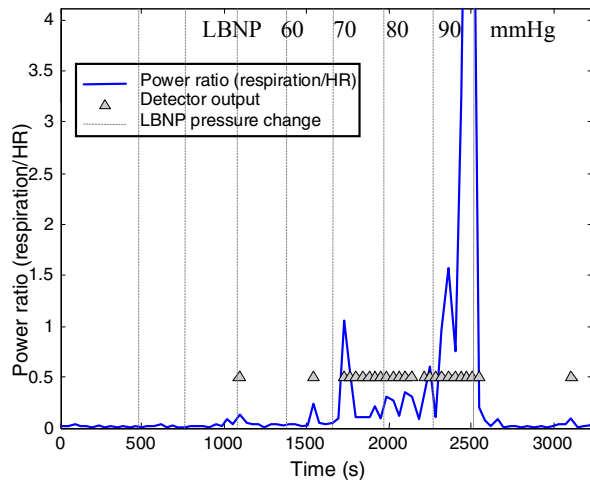


Figure 4. The ratio of the respiratory power to the heart rate power increases as the LBNP decreases pressure. The triangles indicate when this ratio exceeds 0.1. This threshold detector consistently detects simulated hypovolemia during LBNP ≥ 70 mmHg. This data was collected from the forehead sensor in Trial 2.

The ratio of the total respiratory power to the total heart rate power was calculated for each window:

$$Ratio_{resp/hr} = P_{resp_total} / P_{hr_total}$$

A simple threshold detector was implemented using this ratio. From visual inspection, the

$$Ratio_{resp/hr} \geq 0.1$$

yielded good sensitivity with few false alarms.

3. Results

As seen in Figure 2, an increase in the respiratory induced variation of the PPG (P_{resp_total}) and a simultaneous decrease in the power from the heart rate signal (P_{hr_total}) were observed. This allowed for the detection of simulated hypovolemia from the forehead sensor while the LBNP pressure was between 70 and 90 mm Hg for both trials. Figure 3 and Figure 4 show the detector output superimposed on a graph of the power ratio. As seen in Figure 4, we observed significant, but transitory, increases in respiratory variations as early as 45 mm Hg in the second trial.

However, because of the small number of subjects and the inconsistency between trials we could not at this time fully tune the threshold detector and statistically validate the results.

4. Discussion

This preliminary study yielded consistent results with work from other groups regarding the respiratory induced variations.

As seen in Figure 2 when the LBNP is increased two major morphological changes occur:

- (1) the amplitude of the cardiac cycle decreases, and
- (2) the amplitude of the respiratory increase.

We believe that this simultaneous increase in relative power of the respiratory component and decrease in the pulse amplitude is a good indicator of hypovolemia.

5. Future work

This study will be supplemented with further LBNP studies on a diverse, healthy population in the summer and fall of 2006. These experiments will allow us to tune the detector and statistically quantify the ratio parameter using ROC curves.

6. Acknowledgement

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References

- Cannesson, M., C. Besnard, et al. (2005). "Relation between respiratory variations in pulse oximetry plethysmographic waveform amplitude and arterial pulse pressure in ventilated patients." *Critical Care* 9(5): R562-568.
- Cooke, W. H., K. L. Ryan, et al. (2004). "Lower body negative pressure as a model to study progression to acute hemorrhagic shock in humans." *Journal of Applied Physiology* 96(4): 1249-61.
- Gesquiere, M. J., A. A. Awad, et al. (2004). *Can Ear Plethysmography Detect Moderate Blood Loss in Healthy, Non-Intubated Vol-*

- unteers?* ASA Annual Meeting, Las Vegas, Nevada, Anesthesiology.
- Jablonka, D. H., A. A. Awad, et al. (2004). *Ear Plethysmographic Changes during Hemodialysis*. ASA Annual Meeting, Las Vegas, Nevada, Anesthesiology.
- Linder, S. P., S. Wendelken, et al. (2006). "Using the Morphology of Photoplethysmogram Peaks to Detect Changes in Posture." *J Clin Monit* **in press**.
- Nilsson, L., A. Johansson, et al. (2003). "Macro-circulation is not the sole determinant of respiratory induced variations in the reflection mode photoplethysmographic signal." *Physiol Meas* **24**(4): 925-37.
- Partridge, B. L. (1987). "Use of pulse oximetry as a noninvasive indicator of intravascular volume status." *J Clin Monit* **3**(4): 263-8.
- Shamir, M., L. A. Eidelman, et al. (1999). "Pulse oximetry plethysmographic waveform during changes in blood volume." *Br J Anaesth* **82**(2): 178-81.
- Shelley, K. H., R. G. Stout, et al. (1999). *The use of joint time frequency analysis of the pulse oximeter waveform to measure the respiratory rate of ventilated patients*. Society for Technology in Anesthesiology Annual Meeting, Anesthesiology.