Vital Signs Monitoring using a New Flexible Polymer Integrated PPG Sensor

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Abstract

In this paper, we assessed feasibility of using Photoplethysmography (PPG) signal from flexible biosensor as an alternative solution to ECG for monitoring of cardiovascular and pulmonary performance. The potential advantage of this methodology is reduction in power consumption and improvement of complexity of body worn wireless multisensory platform for human physical activity and vital sign monitoring Hence, we propose an alternative mechanically flexible device for monitoring, Photoplethysmography (PPG) and computationally inexpensive algorithm for extraction of cardiovascular and pulmonary performance form the recorded PPG signal. The respiration rate was obtained from finger and forehead of ten healthy subjects and compared to reference methods using Bland and Altman methodology.

1. Introduction

Increasing survivability by improving response time to detect critical physiological conditions non-invasively, in the field is a primary factor for continuous registration of vital signs [2]. Numbers of occupations require employees to perform duties under hazardous conditions. This includes but is not limited to, fire fighters, miners and soldiers. In case of danger, continuous remote monitoring of employees vital signs reduces emergency response time and assists medics to estimate severity of the injury. Electrocardiography was considered the golden standard for remote monitoring of cardiovascular activity [1]. However, employment of ECG electrode on human skin in the field is a challenging task. It requires access to specific area of skin, which may limit mobility and comfort of employees. Towards simplification of remote ECG body worn devices, Chuo [1] introduced a flexible multi sensory biosensor. This device was engineered on flexible polymer. It was equipped with ECG, tri-axes accelerometer and a miniaturized thermometer.

Attachment of ECG on user's chest on daily base, introduces discomfort to users, requires access to specific areas of skin and consumes significant amount of power for continuous remote monitoring of cardiovascular performance. Whereas, photoplethysmography (PPG) could be obtained reliably and non-invasively from forehead, finger and ear [6] regardless of age. Additional advantage of PPG over ECG is ability of estimation respiration from the same signal. Respiration rate could be estimated from PPG regardless of age, anesthesia, ventilated or spontaneous breathing [7]. Hence, in this paper, we assessed feasibility of monitoring cardiovascular and pulmonary performance form single mechanically flexible sensor.

2. Methodology

Two sets of experiments were performed. First experiment was performed for development of algorithms and second experiment was performed to evaluate the morphology of PPG recorded by the flexible sensor designed by us.

2.1. Setup for evaluation of PPG from flexible sensor

The device was tested on forehead of 2 healthy subjects in sitting position for ten minutes. These type of signals were obtained in parallel with PPG from flexible sensor; ECG (Biopac ECG100C, US, CA), PPG (Nonin 8600, US) and respiration effort from respiration transducer belt (Biopac RSP100C, US, CA). All data were recorded using NI DAQ using Labview software at 1kHz sampling rate.

2.2. Setup for development of algorithm

A total of 10 participants took part in this study, including three healthy female (age: 25.5±4.3 years) and seven healthy male subjects (age: 28.4±4.8 years). Subjects participated in three measurement sets: breathing at normal pace, controlling respiration rate by following a visual sinusoidal signal at 0.2 Hz, and at 0.3 Hz, all in sitting position. The subjects breathed for 5 minutes at normal pace, and 1 minute at controlled respiration rate of

0.2 Hz and 0.3 Hz. Total of four signals were captured using NI DAQ (NI 9205) via labview with 75 Hz sampling rate. PPG from forehead (Nonin, Xpod), PPG from Finger (Nonin, Xpod), End-Tidal gas Co2 (SprintIR 20Hz, 20%) and respiration rate (Biopac RSP100C, US, CA). Utilization of fast response Co2 sensor was established on AVR microcontroller (AVR, Arduino Uno, Italy) and connected to the same Labview sketch. As Folke recommended, we chose to locate Co2 sensor close to oronasal area of subject without using a mask or cannula [8].

3. Algorithm development

We have developed two different algorithms, one in Lab View to detect respiration rate and one in Matlab to detect the heartbeat variability. Many previous authors had applied complex statistical methods for extraction of the HBR from PPG. Implementations of these methods are computationally expensive for applications of body worn devices, where the mobile processing units in body worn devices are limited to power consumption, memory and processing capabilities. However, our method for estimation of HRV from PPG is compatible with inexpensive microcontrollers (Arduino, Uno, Italy).

3.1. Estimation of respiration

The following algorithm was developed in Lab View in order to measure Respiration Induced Intensity Variation (RIIV) from the PPG. In total five steps were followed: 1. Obtain PPG, 2. Apply Butterworth Low Pass Filter (Order: 5, cut-off: adjusted for each subject), 3. Obtain envelop of signal by Hilbert transform, 4. Apply peak detector to obtain peaks of the envelope, 5. Apply a second peak detector to obtain peaks of S1 (RIIV: 2nd measured peak vector). The algorithm needed a learning cycle to determine the corresponding cut-off frequency. In this learning cycle, Fast Fourier Transform (FFT) was used to analyze the frequency spectrum of the unprocessed PPG signal in a range of 0.69 Hz To 0.70 Hz for each subject. In the 3rd step, Hilbert transform reads the envelop of the low pass filtered signal, and in the 4th a peak detector recovers peaks of the signal along with their occurrence time. In the last step 5th RIIV will be the measured second local maxima values of the envelope.

3.2. Estimation of heartbeats

We have adapted Linder's [10] algorithm to detect peaks of each cardiac cycle from PPG and estimate interval between peaks of each heartbeat. In Lower Body Negative Pressure test, Linder showed that during progressive hypervolemia, most of morphological characteristics of PPG would disappear but the height of the cardiac cycle from the base line to the peaks of the pulse would remain. This algorithm was used on personal computer to evaluate variation of heartbeats, however, the simplicity of this code enables it to be implemented on Atmel's 8-bit AVR microcontrollers. This type of the microcontrollers is small, inexpensive and appropriate for application of remote vital monitoring.

The algorithm initially fragmented PPG into different frames. Initial constants such as maximum and minimum expected peak to valley values, maximum window size, and maximum or minimum window change were set. The algorithm actively allocated a variable sized window to each frame. A peak detector was used to measure the peaks, valleys and the associated time index values, within each window frame. The size of the window was then varied based on initial window size, interval between the peaks and pulse width to frame ratio. The peaks, valleys and their time index of each window were padded in to a vector. Hence, the spontaneous heartbeat was obtained by differentiating consecutive time index values.

4. Results

First algorithm and the second algorithm were executed on Labview and Matlab, respectively. Figure 1 demonstrates results of the first algorithm for 30 seconds of data at 0.3 Hz breathing rate. It was demonstrated that respiration rate derived from the End-tidal Co2 sensor and RIIV obtained from peaks of the PPG signal were synchronized with our reference signal. This figure conveys that the peaks of the vector S1 (S1=peaks of the PPG signal envelop) correlates positively with the respiration rate.

Respiration was estimated from three different sensors as shown in figure 1. Variation in level of end-tidal Co2 gas from Co2 sensor matched to respiration effort from respiration belt transducer. In parallel, estimation of respiration rate (RIIV) from forehead and finger PPG sensors also matched with respiration rate from gauge transducer.

The accuracy of the first algorithm was assessed using Bland and Altman analysis, as shown in Table 1. Note that respiration rate from PPG (RIIV) and Co2 (End-Tidal Co2) sensors were close to the mean and remain between the upper and lower limit of standard deviation of reference respiration signal.

Table 1 shows upper and lower levels of mean difference between respiration rate from End tidal CO2, PPG finger and PPG forehead sensors to respiration rate from reference gauge respiration transducer. The analysis was performed on data at three stages; first during spontaneous breathing, controlled breathing at 0.2 Hz and 0.3 Hz.

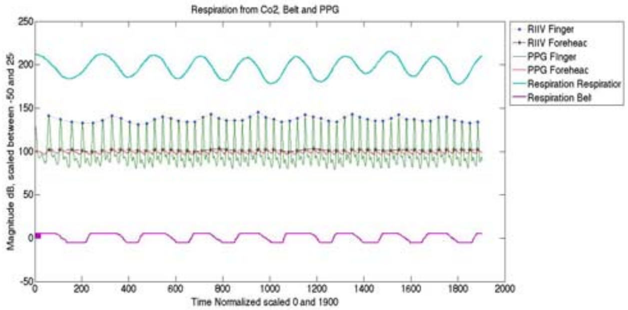
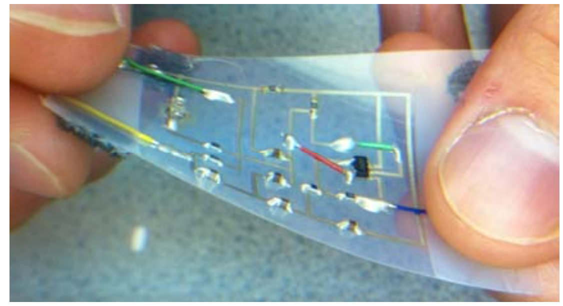


Figure 1. Comparison of respiration rate derived from End-Tidal CO2 sensor, strain gauge transducer and PPG from forehead and finger, subject #7, 30 seconds data, breathing at 0.3 Hz.

Table 1. Analysis of Bland-Altman indices for three different breathing manoeuvres.

Bland-Altman	Co2	Forehead PPG	Finger PPG
	Uncontrolled Breathing		
Mean Difference	0	-0.2	-0.1
Upper Level	0	2.09	1.84
Lower Level	0	-2.6	-2.04
	Controlled 0.2 Hz		
Mean Difference	0	-0.5	-0.7
Upper Level	0.92	1.8	1.37
Lower Level	-0.92	-2.8	2.77
	Controlled 0.3 Hz		
Mean Difference	0.1	-0.3	-0.2
Upper Level	0.71	0.64	1.6
Lower Level	-0.51	-1.24	-2.001

Figure 2.a demonstrates possibility of engineering an inexpensive and reliable PPG sensor on plastic substrate as an alternative of ECG nodes for monitoring of vital sings. As shown in figure 2.b, PPG waveform obtained form the flexible sensor matches to morphology of the PPG obtained by the commercial pulse oximetry device. Our device contained AC components of the PPG signal, which is essential for estimation of RIIV, whereas the commercial device removes baseline of the PPG. AC component of the PPG from flexible sensor varies by effects of respiration sinus arrhythmia, as demonstrated with respiration belt transducer. Also peaks of ECG signal demonstrated valid reflection of each cardiac pulse on PPG.

a. 

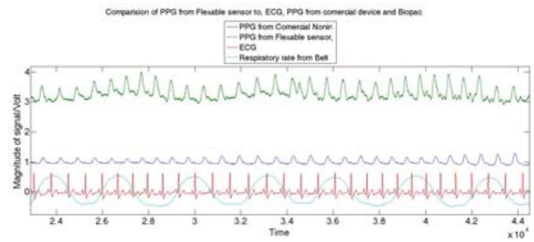
b. 

Figure 2 a. Assembled PPG sensor printed on plastic substrate, 2b. Comparison of PPG from flexible sensor by PPG from Commercial Nonin pulse oximetry, ECG and respiration rate.

5. Conclusion

The aim of this paper was to assess feasibly of replacing ECG in flexible body worn sensor, with an alternative inexpensive method for monitoring cardiovascular and pulmonary systems [1]. The PPG signal was used as an alternative to ECG for monitoring cardiovascular performances. A flexible biosensor was engineered on a flexible polymer to demonstrate a proof-of-concept. Results conveyed the PPG obtained by flexible sensor is a rich signal with the potential to represent multi parameters of cardiovascular and pulmonary performance. In feature work we will investigate application of the algorithm developed in current dissertation on data collected from our flexible device and study feasibility of employment of the device for detection of respiration rate and heart beat variability during Lower Body Negative Pressure test.

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References

[1] Chuo Y, Marzencki M, Hung B, et al. Mechanically flexible wireless multisensor platform for human physical

activity and vitals monitoring. IEEE Transactions on Biomedical Circuits and Systems 2010;4:281-294.
[2] Gao T, Greenspan D, et al. Vital signs monitoring and patient tracking over a wireless network. 27th Annual International Conference of the. IEEE Engineering in Medicine and Biology Society 2005:102-105.
[3] Montgomery K, Mundt C, et al. Lifeguard-a personal physiological monitor for extreme environments. 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society 2004;1:2192-2195.
[4] Anliker U, Ward JA, et al. AMON: a wearable multiparameter medical monitoring and alert system. IEEE Transactions on Information Technology in Biomedicine 2004;8:415-427.
[5] Fensli R, Gunnarson E, Gundersen T. A wearable ECG-recording system for continuous arrhythmia monitoring in a wireless tele-home-care situation. 18th IEEE Symposium on Computer-Based Medical Systems 2005:407-4-12.
[6] McGrath SP, Ryan KL, et al. Pulse oximeter plethysmographic waveform changes in awake, spontaneously breathing, hypovolemic volunteers. Anesthesia & Analgesia 2011;112:368-374.
[7] Nilsson L, Johansson A, Kalman S. Respiration can be monitored by photoplethysmography with high sensitivity and specificity regardless of anaesthesia and ventilatory mode. Acta anaesthesiologica scandinavica 2005;49:1157-1162.
[9] Folke M, Granstedt F, Hok B, Scheer H. Comparative provocation test of respiratory monitoring methods. Journal of clinical monitoring and computing 2002;17:97-103.
[10] Linder SP, Wendelken S, Using the morphology of the photoplethysmogram envelope to automatically detect hypovolemia. 19th IEEE International Symposium on Computer-Based Medical Systems 2006:371-371.
[11] Wendelken S, Clayman J, Steiner PR. Noninvasive detection of the hemodynamic stress of exercise using the photoplethysmogram. Journal of clinical monitoring and computing 2008;22:269-278.

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