FOREHEAD MEASUREMENTS OF HEART RATE AND HEART RATE VARIABILITY FROM A PHOTOPLETHYSMOGRAPHIC REFLECTANCE SENSOR: EFFECT OF MOTION ARTIFACTS

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Abstract: Although steady progress has been made towards the development of more robust wearable pulse oximeters to aid in remote monitoring by emergency first responders, the ability to acquire accurate and reproducible heart rate (HR) information from a small forehead pulse oximeter during extended periods of rigorous field activities remains challenging. This field study was undertaken to examine some of the challenges involved in the accurate time-domain determination of HR and heart rate variability (HRV) by a reflectance pulse oximeter during various degrees of motion artifacts. The study revealed that movement artifacts associated with different field exercises can cause significant interferences that can lead to inaccurate measurements of HR and HRV. However, despite this limitation, this study demonstrates that sufficiently accurate measurements can be obtained during walking and hiking. This vital information may be helpful for emergency first responders during remote diagnosis and in life-saving triage operations following critical injuries.

Introduction

Providing remote medical diagnosis can expedite rescue operations and improve the treatment of injured soldiers on the battlefield or firefighters operating inside burning buildings. Effective field triage in military and civilian applications can be important in making critical and often life-saving decisions. In addition, it can be used to facilitate more efficient distribution of limited resources in situations involving mass casualties [1–6].

When administering medical care remotely, having quick access to multiple cardiovascular measurements can aide in making more accurate diagnosis and provide more effective treatment. In an effort to facilitate better treatment of casualties in the field, we have focused on the development of more robust wearable devices that could be used to wirelessly transmit vital physiological information to emergency first responders.

While SpO_2 and HR are commonly measured by every pulse oximeter, and HRV can be determined from an ECG, having the additional capability to measure also HRV from a PPG might be helpful as an indicator of autonomic nervous activity and for potential prediction of mortality in critical injuries [7−10]. In particular, variations in HR can often correspond to detrimental physiological changes sooner than average or instantaneous HR (IHR), because in critical injuries depressed HRV is often considered a poor prognosis for long-term survival.

In previous studies, we showed that reflectance pulse oximetry can be used to provide simultaneous measurements of arterial oxygen saturation (SpO_2), HR, HRV and respiratory rate (RR) from a single set of photoplethysmographic (PPG) signals acquired from the forehead during rest [11−14]. In this study, we investigated the effect of motion artifacts on the ability to obtain accurate HR and HRV data from a reflectance forehead pulse oximeter during various field activities.

Materials and Methods

Figure 1 describes the experimental setup used to record the PPG waveforms from the forehead. The setup consist of a Dell Inspiron™ 8500 laptop PC that was worn by a volunteer and used as a primary computer platform for data acquisition.

A Nonin Xpod® (Nonin Medical Inc., Plymouth, MN) pulse oximeter outfitted with a reflection type sensor was used to simultaneously record the subject's PPG. The sensor was sewn to the inside of an elastic headband and positioned on the forehead, as illustrated in Figure 2.

Reference HR readings were recorded by a Polar S810i (Polar Electro Inc., Inc., Lake Success, NY) heart rate monitor that was positioned across the subject's

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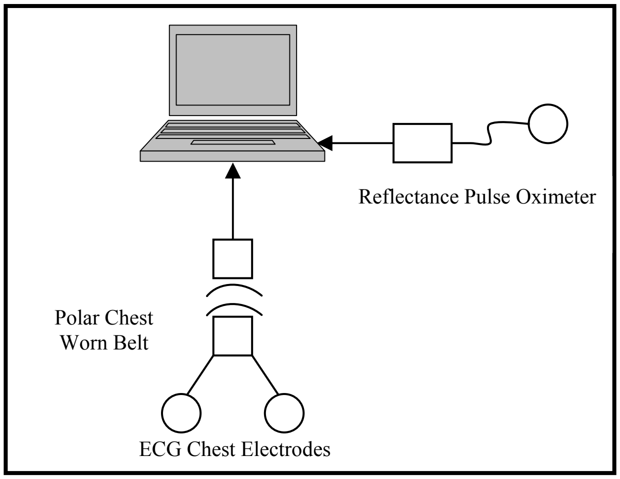

Figure 1: Data acquisition system for real-time monitoring during field testing.

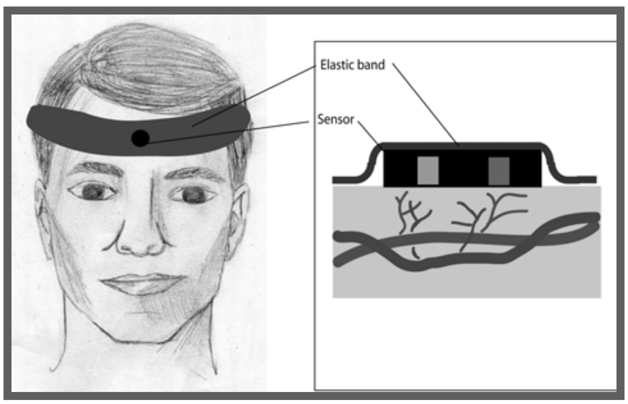

Figure 2: Sensor attachment on the forehead.

chest. ECG readings acquired from the chest belt were transmitted to the recording PC via a wireless infrared data link. Data were recorded in real-time using a LabVIEW™ program and custom software provided by the manufacturers.

Initial tests were conducted in the laboratory by instructing each subject to rest comfortably and then perform short exercises that included walking, jogging, or running. Each experiment was repeated four times. Subsequent HR measurements were acquired from the chest belt and PPG during a one hour hike over forest terrain.

HR was computed using a time-based derivative algorithm to demarcate the individual heart beats in the PPG waveform. This was accomplished by identifying the sharp transition in the slope of the leading edge of each PPG waveform during the onset of the systolic phase as the beginning of a new cardiac cycle. After each heart beat was identified, a time-domain searching algorithm was deployed to find the corresponding reciprocal of the beat-to-beat time intervals which were used to calculate a group of IHR values for each data set.

The conventional approach used in clinical medicine to compute HRV is based on analyzing the standard deviation of several minutes of successive IHR values. Therefore, the standard deviations of IHR values derived from the PPG signal analysis and reference ECG measurements acquired from the Polar monitor were used to compare corresponding HRV values.

Results

A comparison of typical PPG waveforms recorded during rest (0–5s) and movement (5–10s) is shown in Figure 3. These waveforms clearly highlight a number of possible distortions in the shape of the PPG signals recorded while subjects were walking (average speed: 1.7 mph), jogging (average speed: 4.2 mph), and running (average speed: 6.0 mph).

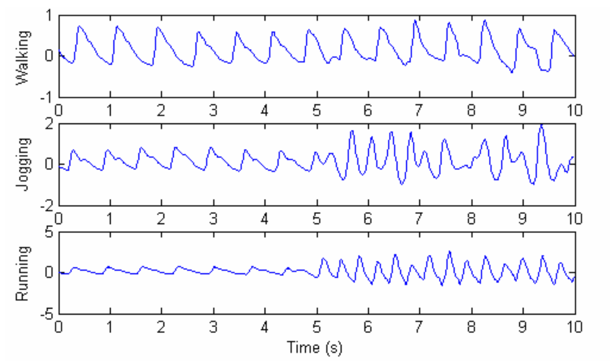

Figure 3: Comparison of typical PPG waveforms recorded during movement. Activities begin at the 5s time mark.

Table 1 summarizes the HR and HRV values extracted from a two minute snap-shot PPG recording that was paired with corresponding values obtained from the ECG for the various field activities. The average differences between HR and HRV obtained from the PPG signals for each activity and reference ECG measurements are summarized in Table 2.

The data presented in Figures 4 and 5 show the linear correlation between the HR and HRV data points, respectively. This analysis is based on PPG waveforms recorded during resting, walking, and hiking.

Discussion

Steady progress has been recently made towards the development of a more robust wearable pulse oximeter to aid in remote monitoring and triage operations by emergency first responders. Although the forehead has been used in clinical settings as an alternative site for noninvasive monitoring of HR and SpO_2, the ability to

Table 1: Summary of average HR and HRV from reference ECG and PPG recordings obtained during resting, walking, and hiking.

	HR (bpm)		HRV (bpm)	
	ECG	PPG	ECG	PPG
Resting	84.1 ± 6.0	84.0 ± 6.0	4.9 ± 1.0	5.1 ± 0.9
Walking	88.3 ± 4.4	87.6 ± 4.4	4.5 ± 0.9	4.9 ± 1.0
Hiking	126 ± 17.4	124.8 ± 16.9	6.6 ± 1.0	6.9 ± 1.6
Jogging	96.5 ± 8.4	106.3 ± 19.2	7.3 ± 2.6	32.6 ± 15.4
Running	112.3 ± 7.5	140.0 ± 5.1	13.1 ± 2.4	37.2 ± 4.8

Table 2: Summary of average differences between HR and HRV determination based upon PPG and reference ECG recordings.

	HR (bpm)	HRV (bpm)
Resting	0.06	0.20
Walking	0.08	0.46
Hiking	1.50	1.23
Jogging	10.23	25.35
Running	27.73	24.08

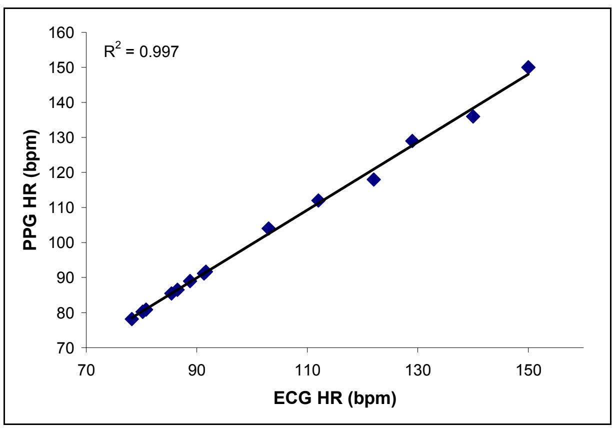

Figure 4: Comparison of HR values computed from PPG and ECG signals recorded during resting, walking, and hiking.

obtain accurate HR information from a reflectance pulse oximeter during various field activities has not been widely documented.

A comparison of PPG waveforms shown in Figure 3 clearly illustrate that significant signal perturbations can be caused by motion artifacts as seen during joggings and

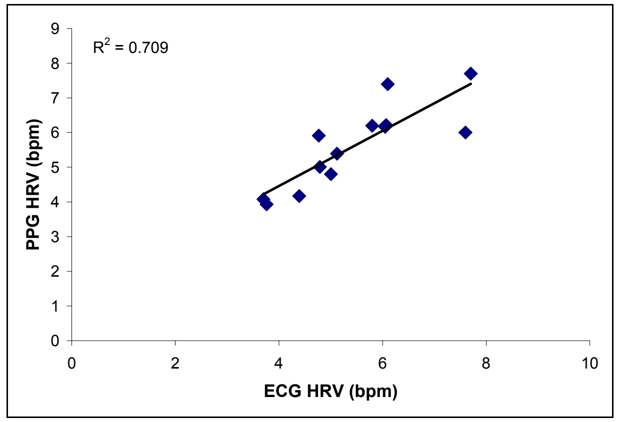

Figure 5: Comparison of HRV computed from PPG and ECG signals recorded during resting, walking, and hiking.

running. These rather large perturbations could lead to distortions of the PPG waveform. In addition, they can also introduce large variations in the fundamental frequency of the PPG signal that is normally used by a pulse oximeter to compute HR. Depending on the type of movements involved, repetitive movements (for example, during steady-paced running) can generate "artificial" high-frequency components that resemble a normal looking PPG waveform. This, in turn, can be misinterpreted by the signal processing software, leading to large errors in HR readings.

The data presented in Tables 1 and 2 suggest that tolerable errors in computing HR and HRV can be expected from PPG waveforms acquired during, walking and hiking. However, the large deviations in HR and HRV that were observed during jogging and running are clearly unacceptable for clinical applications.

A possible explanation for the large errors in HR and HRV stems from the fundamental shape of the PPG signal. Compared to the R-wave in the ECG, which has a very distinct feature that is normally utilized in time-domain analysis of IHR, a typical PPG waveform is much more difficult to process. For example, even under relatively noisy-free conditions, the rounded portion of the peak systolic phase, or the relatively noisy and shallow trough associated with the end diastolic phase of the PPG, can introduce a certain uncertainty in the identification of individual heart beats. These uncertainties can produce inaccuracies in the calculation of IHR and HRV values. Obviously, the added uncertainty in the identification of individual heart beats from motion corrupted PPG signals, which was clearly present during jogging and running, leads to significantly greater computational errors in IHR and HRV determination.

Although we used a time-domain analysis to derive HR and HRV data, it is important to note that these variables can be also derived using more advanced statistical and frequency-domain analysis such as the FFT. While the use of more advanced signal processing may offer certain advantages, the goal of this study was to examine whether a time-domain approach can yield sufficiently accurate HR and HRV information because our long-term goal is to incorporate these algorithms into a microcontroller-based wearable device having limited speed, storage, and power capabilities.

The particular pulse oximeter used in this study is primarily intended for spot checking applications in relatively motionless environments. Therefore, further studies are required to evaluate more advanced "motion-resistant" pulse oximeters to determine if improved signal processing can help to lower measurement inaccuracies when subjects are engaged in stressful physical activities. Nonetheless, considering the likelihood that a person wearing a pulse oximeter in the field will quickly become immobile upon critical injury, it is reasonable to expect that HR and HRV data obtained from a forehead pulse oximeter will provide sufficiently accurate readings for use by emergency medical responders during remote triage.

The majority of the interferences observed during this study were most likely caused by variations in the optical coupling between the sensor and the skin, including local perturbations in blood circulation associated with body movement. While it is not possible to completely eliminate these perturbations when subjects remain highly active, sufficiently stable and accurate readings from an injured person wearing a properly secured forehead pulse oximeter sensor during high-risk missions should be feasible [15]. This vital information may be helpful especially for emergency first responders during remote diagnosis and in life saving triage operations.

Conclusion

This study demonstrates that IHR and HRV can be accurately extracted from a reflected PPG signal acquired from the forehead by a wearable pulse oximeter during walking and hiking. However, more motion-intensive activities, such as jogging or running, produce significant movement artifacts that can result in large and clinically unacceptable errors. Despite this limitation, it should be possible to obtain sufficiently accurate and reproducible readings from critically injured workers wearing a properly secured small pulse oximeter sensor during high-risk missions. This vital information may be helpful especially for emergency first responders during remote diagnosis and life-saving triage operations.

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