Investigation of Photoplethysmogram Morphology for the Detection of Hypovolemic States

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Abstract

Medics and first responders to emergencies are often faced with monitoring and assessing victims with very limited resources. Therefore, there is an inherent need for a real-time ambulatory monitoring capability that is portable and low power. This is particularly important for physiological monitoring of life-threatening conditions such as internal hemorrhaging. We propose the use of photoplethysmogram (PPG) morphology as an indicator of hypovolemic states and study its correlation with blood pressure. In this paper, we compared the PPG morphology with pulse transit time (PTT), which has been investigated for clinical and ambulatory applications. The indicators were tested on data obtained from experiments using lower body negative pressure (LBNP) as a model to simulate hemorrhage in humans. The results of this study indicate that PPG morphology is associated with pulse pressure (systolic minus diastolic blood pressure) and is therefore a promising feature for detection and real-time tracking of hypovolemic states.

Keywords— **Photoplethysmogram, Blood Pressure, Real-time processing, Hemorrhage, Hypovolemic states.**

I. INTRODUCTION

In mass casualty or remote emergency situations, medics and first responders are typically faced with poor working conditions and limited resources while attending to and monitoring victims. For these scenarios, there are limited medical personnel and insufficient patient monitoring systems to provide adequate decision support for assessing the victims' conditions. To support these missions, there is a need for a portable, lightweight, and potentially wearable system that can provide real-time monitoring and alert medical personnel to victims with life-threatening conditions such as hemorrhaging. The common ambulatory measures of trauma patients (systolic, diastolic and mean blood pressures, heart rate, and arterial oxygen carrying capacity (SpO2) have been shown to be insufficient in detecting internal hemorrhaging in the early stages [1]. Acute uncontrolled hemorrhage, subsequent hemodynamic collapse, and resulting shock account for about 50% of the deaths on the battlefield [2] and up to 82% of the early operative

deaths from trauma in the civilian arena [3]. We are developing algorithms for portable physiological monitoring that could be used in real-time for assessing hemorrhage severity. Potential applications include monitoring for remote triage and en route care on the battlefield, emergency room monitoring, and other ambulatory applications [4][5] .

Physiological changes during reduction of central blood volume have been modeled using: a) anesthetized animals subjected to hemorrhage; b) application of lower body negative pressure (LBNP) in human subjects [6]; c) blood donation experiments in humans; and, d) data obtained from trauma patients [5]. Application of LBNP to healthy human subjects moves blood from the thorax into the legs and elicits acute hemodynamic and compensatory reflex effects similar to those induced by true hemorrhage [6]. The LBNP experimental model is therefore widely accepted as a useful investigatory tool to determine the physiological responses to central hypovolemia in human subjects.

The PPG signal is associated with the change in the volume of red blood cells in the peripheral micro-vascular bed with each pressure pulse initiated by the heart. It can be measured by an optically-based pulse oximeter, which is an affordable, wearable sensor. Fluctuations in the waveform of the PPG signal are correlated with some of the physiological parameters of the cardiovascular system. It is hypothesized that the PPG can provide useful information on the beats of aortic origin, characteristics of the vascular system, properties of the peripheral vessels, and the state of blood flow. Researchers have shown that the pulse transit time (PTT) assessed by the time delay between the characteristic points on ECG and PPG signals could be used for non-invasive estimation of arterial blood pressure [7].

Reductions in pulse pressure have previously been shown to be highly correlated with decreased central blood volume and stroke volume in humans exposed to progressive LBNP [8]. We therefore tested the hypothesis that a time-domain PPG morphology metric would represent an indicator of central hypovolemia by correlating with pulse pressure during progressive hypovolemia induced by LBNP. We also compared features of the PPG morphology with PTT.

This research protocol was approved by the Institutional Review Board at Brooke Army Medical Center and the U.S. Army Institute of Surgical Research, Fort Sam Houston, TX. Ten volunteer subjects gave written informed consent before participating in the protocol. The demographics of the subjects are shown in Table 1.

Subject	Age	Sex	Height (cm)	Weight (kg)
1	44	M	185	106
2	29	F	170	58
3	31	M	183	91
4	25	F	155	44
5	32	M	178	91
6	36	M	183	92
7	29	M	183	87
8	25	F	160	66
9	22	F	168	57
10	20	M	180	83

Table 1: Demographics of subjects.

Subjects were instrumented for continuous and synchronized recording of electrocardiogram (ECG), PPG and blood pressures at 500 Hz during progressive LBNP. ECG recordings were obtained using a 3-lead ECG amplifier and signal conditioner using standard lead-II placements. Finger PPG waveforms were collected with a commercial pulse oximeter (BCI Capnocheck Plus, Waukesha, WI). A Finometer® Blood Pressure Monitor (TNO-TPD Biomedical Instrumentation, Amsterdam, The Netherlands) was used to record beat-by-beat finger arterial pressure. We used our custom program for R-peak detection [9] with cubic spline interpolation to generate interbeat interval with 1 ms precision. The PPG signals had a moderate amount of 60 Hz noise which caused a significant amount of jitter which affect the analysis algorithms. It was determined that the noise was fairly Gaussian, and a Butterworth low pass filter with a cutoff around 30 Hz was used to remove the aliasing and the 60 Hz line noise.

Researchers have shown that the PTT assessed by the time delay between the characteristic points on ECG and PPG signals could be used for non-invasive estimation of arterial blood pressure [7]. It is a measure of the time between the peak of the ECG signal and the base of the PPG signal where it begins to rise. When analyzing the PPG signal and how it changes with blood pressure and heart rate, a few features are readily apparent. The minimum and maximum values of each beat are easily detectable. Previous research utilized the 50% point because it is the "point in PPG where the signals change the sharpest and it can more easily be detected" than the minimum or beginning of the PPG pulse [10]. This is detected by finding the peak of the derivative of the signal

and is especially useful with this data set where many minima or maxima are clipped. Note that while this point is called the 50% point and is approximately located half-way up the rising slope, it may not be positioned exactly at the halfway point due to the derivative method of determining it. For this study, the 50% point on the rising slope of the PPG signal was used as it is the most precisely detectable feature in the signal due to clipping of the lower values of the PPG waveform. We refer to this parameter as Half Rise to Dicrotic Notch (HRDN). A plot of the PPG waveform and derivative is shown in Fig. 1.
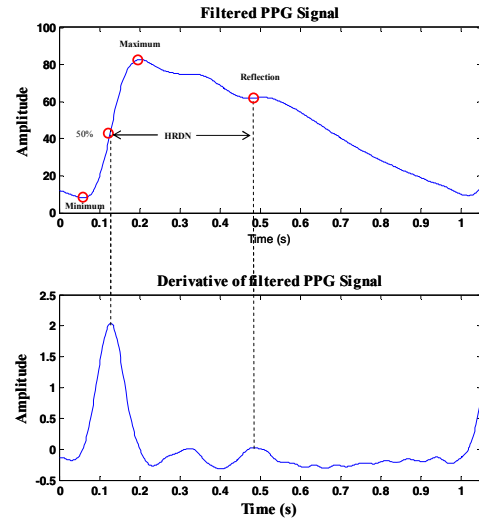

Fig. 1: An example of a PPG waveform and its derivative. The upper plot shows an example of a PPG waveform and key points utilized in the analysis. The lower plot is the derivative of the PPG waveform and lines are drawn from key points in the PPG waveform to the associated points in the derivative waveform.

The primary pulse peak is followed by two smaller peaks - "renal reflection" and "iliac reflection". Often, the iliac reflection is pronounced enough that the slope before it is actually increasing, making it easy to detect as a local maximum. In many of the datasets, however, this only becomes pronounced later in the series when the LBNP chamber is at much lower pressures than the beginning of the run. For this reason, it was decided to detect the reflections where the derivative of the signal has a local maximum, thus allowing the reflection to be detected earlier. This means the point detected is actually on the rising edge of the reflection's leading slope when the bump actually does begin to rise.

III. RESULTS

In Fig. 2, an example of the PTT is shown for one trial during an LBNP experiment. The pressure in the chamber is overlaid. At the beginning of the trial, the PTT increases noticeably with changes in the LBNP chamber pressure. Later, the PTT remains somewhat constant and then begins to decrease with changes in pressure. This

suggests that the use of PTT as an indicator of LBNP level may be restricted to later in the progression of central hypovolemia.
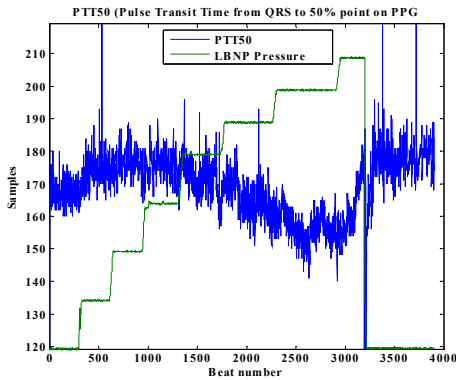

Fig. 2: Example of the PTT feature. The graph shows the PTT feature overlaid with the chamber pressure.

The graph in Fig. 3 shows the HRDN feature. There is a very clear decrease in the HRDN feature even in the early stages of the test.
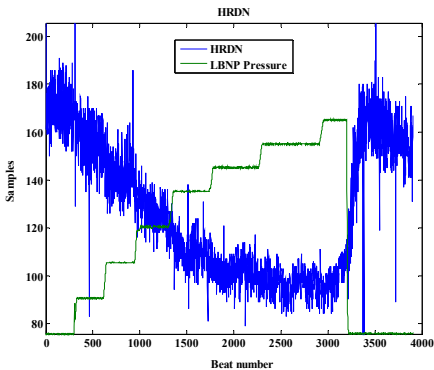

Fig. 3: Example of the HRDN feature. The graph shows the HRDN feature overlaid with the chamber pressure. There is a continuous decrease throughout the test.

Fig. 4 compares the correlation of the PTT and the HRDN features with pulse pressure. A diagonal scatter plot indicates a strong correlation while a vertical or horizontal plot indicates weak correlation. In the early stages of testing, there was a high correlation between HRDN and pulse pressure. This indicates that HRDN may be associated quantitatively with blood pressure - or more

accurately, venous return and stroke volume. The PTT indicates very low correlation as depicted by the vertical structure in the scatter plot. Both plots seem to carry similar attributes, especially the curvature at the bottom which demonstrates the weak correlation of both features with the blood pressure during the most extreme pressures in the LBNP chamber.
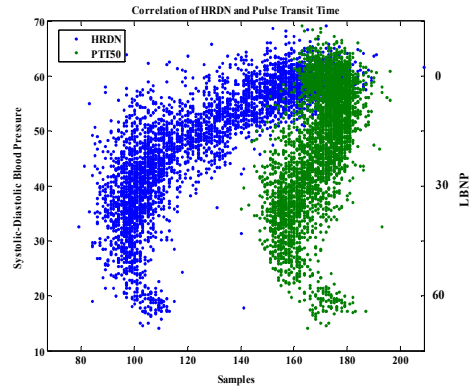

Fig 4: Comparison of correlation of the PTT and HDRN features with pulse pressure. The LBNP level is shown on the right axis of the plot. The blue pattern is for the HRDN feature and the green pattern is for the PTT feature.

An additional analysis was performed to compare the RR interval derived from the ECG to the HRDN. Histograms were generated for the HRDN feature and RR interval to show graphically the possibility of detecting a pressure change using either of the two features as shown in Fig. 5. These histograms indicate that identification of the degree of central hypovolemia is delayed using heart rate alone, while the use of the dicrotic notch width (i.e., HRDN), and provides an immediate and pronounced change during the initial stage of central blood volume reduction. Nine of the ten subjects demonstrated similar results. The 10th subject's dicrotic notch was difficult to identify with the detection algorithm until later in the experiment at lower LBNP pressures. The fact that the distance from the HRDN is quantitatively different from baseline at low LBNP levels suggests this type of analysis might provide a more sensitive indicator for monitoring early reductions in blood volume. Unfortunately, the dicrotic notch is either absent or difficult to detect accurately in some subjects, therefore requiring further analysis using additional features.

RR - Intervals **HRDN**

LBNP - 0
LBNP - 15
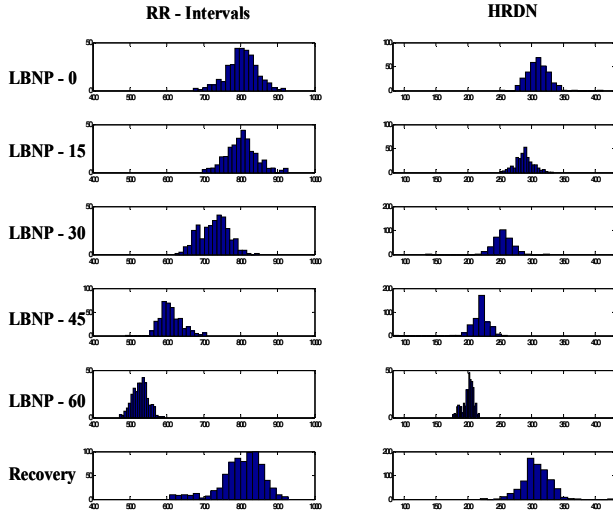LBNP - 30
LBNP - 45
LBNP - 60
Recovery

Fig 5: Comparison of histograms of RR interval and HRDN features. The left set of histograms represents an example of the RR interval (x-axis) with pressure change. The right set of histograms represents an example of the HRDN feature (x-axis) with pressure change.

In Table 2, the mean values for the HRDN and RR interval are shown for each of the 10 subjects at LBNP – 0 and LBNP – 15. The RR interval shows no common pattern for the change of LBNP–0 to LBNP-15. For example, with subject 1 the RR interval decreases; with subject 2 the RR interval increases; and subject 4 the RR interval remains essentially the same. The HRDN feature decreases for all the subjects except for the last subject. Further analysis is needed to understand why there was an increase in the HRDN parameter in subject 10.

Subject	Mean HRDN LBNP-0	Mean HRDN LBNP-15	Mean RR-interval LBNP-0 (msec)	Mean RR-interval LBNP-15 (msec)
1	340.386	312.538	1000.27	978.024
2	343.748	323.623	829.366	897.54
3	330.863	303.842	918.540	936.226
4	310.437	288.587	803.785	802.601
5	323.047	297.164	934.467	888.567
6	328.757	300.549	911.052	884.571
7	331.889	306.996	931.698	937.404
8	315.69	258.13	908.858	907.894
9	329.321	312.83	993.457	1038.51
10	382.777	427.388	1069.07	1126.51

Table 2: Mean values for the HRDN and RR interval (msec) for each of the 10 subjects at LBNP – 0 and LBNP – 15.

IV. CONCLUSIONS

In this investigation, we presented the use of PPG morphology as an indicator of hypovolemic states and studied its correlation with blood pressure. HRDN demonstrated better correlation with pulse pressure than PTT during progressive central hypovolemia induced by LBNP in healthy human subjects. The results support our hypothesis that HRDN is highly associated with pulse pressure and therefore represents a promising feature for detecting and tracking hypovolemic states in the absence of continuous blood pressure monitoring capability.

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