Detection of Blood Loss in Trauma Patients using Time-Frequency Analysis of Photoplethysmographic Signal

Natasa Reljin, Gary Zimmer, Yelena Malyuta, Yitzhak Mendelson, Chad E. Darling, and Ki H. Chon, *Senior Member, IEEE*

***Abstract*— In this study we explored the possibility of detecting blood loss in patients with hemorrhage symptoms (*N*=14) from photoplethysmographic (PPG) signals collected with pulse oximeters (PO) at forehead, ear and finger sites. We used variable frequency complex demodulation (VFCDM) technique to estimate amplitude modulations in heart rate frequency range (AM_{HR}) of PPG signals. We determined the trend of these AM_{HR} values over time, and used it to classify each patient's recording. The obtained results were compared to the clinical classifications made by physicians at the UMass Medical Center, which were considered as references. The accuracy of our algorithm was about 79%. These are the preliminary results of an ongoing study, and we foresee that this device and technique can be applied in battlefield and combat casualty care.**

I. Introduction

Blood loss is the leading cause of death at the battlefield [1, 2]. It was shown that the cause in 83% of potentially survivable deaths in combat was hemorrhaging [2]. Also, in the emergency and operative rooms, it represents very frequent medical condition that may lead to death [3]. At the early stage of bleeding, initial decrease in blood volume is leading to the vasoconstriction of arteries and increase of heart rate (HR) in order to maintain normal blood pressure (BP). As blood volume further drops and falls to a critical level, which is usually 30% of the normal level (Class III hemorrhage), sympathetic vasoconstrictor drive withdraws, bradycardia is present and blood pressure decreases, which further leads to decrease in blood flow to brain and heart, loss of consciousness, and death [3, 4]. Routinely measured vital signs, such as heart rate and blood pressure, do not reflect blood loss symptoms until at least 30% of blood volume is lost by which time the patient's health is progressively worsened and at risk [5]. Therefore, early detection of blood loss is very challenging and important task, and an algorithm being able to discover early symptoms is needed. In addition, the development of portable system that can be used in battlefield settings can greatly improve the combat casualty care and decrease the rate of deaths.

N. Reljin and K.H. Chon are with the Department of Biomedical Engineering, University of Connecticut, Storrs, CT 06269 USA (N. Reljin is corresponding author, phone: 860-486-5838; e-mail: reljin@engr.uconn.edu, kchon@engr.uconn.edu).

G. Zimmer, Y. Malyuta and C.E. Darling are with the Department of Emergency Medicine, University of Massachusetts Medical School, Worcester, MA 01655 USA (e-mail: Gary.Zimmer@umassmed.edu, Yelena.Malyuta@umassmed.edu, Chad.Darling@umassmed.edu).

Y. Mendelson is with the Department of Biomedical Engineering, Worcester Polytechnic Institute, Worcester, MA 01609 USA (email: ym@wpi.edu).

Regarding this goal, pulse oximeter (PO) has become more popular because it is a noninvasive and easy-to-use device commonly used to monitor heart rate and arterial oxygen saturation (S_pO_2). Photoplethysmographic (PPG) signals are recorded by pulse oximeters, and they reflect light absorption of blood vessels. Thus, these signals have found many applications in detection of blood loss [6-9]. Gesquiere *et al*. found significant increase in the spectral power of PPG at respiratory frequency during blood withdrawal of 450 mL from healthy subjects [6], while McGrath *et al*. used time-domain PPG features to show their decrease during increase in the lower body negative pressure (LBNP) in healthy subjects [7]. In recent studies performed by our group, high-resolution time-frequency analysis was proposed to estimate amplitude modulations in heart rate and breathing rate frequency ranges of PPG signals in spontaneously breathing healthy subjects under LBNP [8], and during blood withdrawal of 900 mL [9]. The results showed significant decrease of spectral amplitudes during the blood loss.

Since our group's prior studies showed promising results in controlled conditions [8, 9], in this paper, we extend the idea to intraoperative and trauma care settings, where the algorithm is applied to PPG signals obtained from patients with suspected hemorrhage. We apply the high-resolution time-frequency analysis to estimate amplitude modulations in HR frequency range of the PPG signals obtained from sensors placed at three sites (forehead, ear and finger) [8, 9]. We hypothesize that the amplitudes in the heart rate frequency range in the PPG signal will significantly change (decrease) in patients who are experiencing blood loss, and conversely increase in patients who are recovered, *i.e.*, normovolemic.

II. Methods and Materials

A. Subjects and Signal Acquisition

The set of subjects used in this paper consisted of fourteen trauma patients (*N*=14) admitted to the UMass Medical Center. Before any signals were acquired, all participants signed consent form approved by the Institutional Review Board of UMass Medical School.

After the patients have provided the informed consent, three miniature multi-channel pulse oximeters developed in our lab were placed at the finger, forehead and ear as early as possible upon their arrival to the hospital. PPG data are stored internally in the PO device, and analyzed later. Simultaneously, intravenous (IV) fluid and blood intakes and outputs were compiled during the entire data collection by the UMass physicians. At the end of data collection, every patient was assigned to one of the classes

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(hypovolemia/normovolemia) by adjudication of all available clinical information by 2 or 3 physicians.

B. Data Processing

The sampling frequency of photoplethysmographic signals was 80 Hz. We extracted 2 minute PPG sequences at various time instances throughout the whole signal. Within every sequence, 1 minute window was shifted in 10 seconds increments. This way, 7 segments were formed for one 2 minute PPG sequence. Each segment was downsampled to 20 Hz. Furthermore, mean value and linear trend were removed. After preprocessing, time-frequency spectrum of every segment was obtained using variable frequency complex demodulation (VFCDM) [8]-[12].

The amplitude and frequency of HR obtained from PPG signals from patients with hemorrhage symptoms are expected to change over time, which makes the time-frequency analysis suitable tool for the task at hand. At each time point, the maximum amplitude in the heart rate frequency range was extracted from the segment's spectrum. This way, the sequence of amplitude values was formed. In this paper, we defined heart rate frequency range as the heart rate found in the frequency spectrum of segment ± 0.2 Hz. For every PPG segment (7 segments in total), the median value of sequence of maximum amplitudes was calculated. This results in 7 median values per one 2 minute PPG sequence. Finally, the mean of these 7 median values was computed, and denoted as AM_{HR}. Fig. 1 illustrates processing steps of this algorithm for the estimation of the amplitude of heart rate (HR) from PPG signal. Since this procedure was repeated for 2 minute PPG sequences at various time instances, percent changes in AM_{HR} were also calculated. Statistical analysis between all pairs of AM_{HR} values was performed using repeated measures ANOVA with Bonferroni *post-hoc* tests, where $p < 0.05$ was considered significant (SPSS Statistics 20, IBM Corporation, Armonk, NY, USA).

C. VFCDM

Variable frequency complex demodulation is a technique for estimating time-frequency spectrum of time-varying signals such as photoplethysmographic signals. This technique is briefly summarized here, while for further details reader should see [8, 10, 11, 12]. VFCDM consists of two steps. In the first step, the fixed frequency complex demodulation (FFCDM) is applied to obtain the time-frequency spectrum (TFS), while in the second step only dominant frequencies of interest are selected [8, 11, 12]. This way, the high-resolution TFS is generated. During the first step of VFCDM, the signal is decomposed into a sequence of band-limited signals using a bank of low pass filters (LPFs). Then, Hilbert transform is applied to each band-limited signal in order to obtain instantaneous amplitude, phase and frequency information [8, 11, 12]. Flow chart illustration of the VFCDM procedure is summarized in Fig. 2.

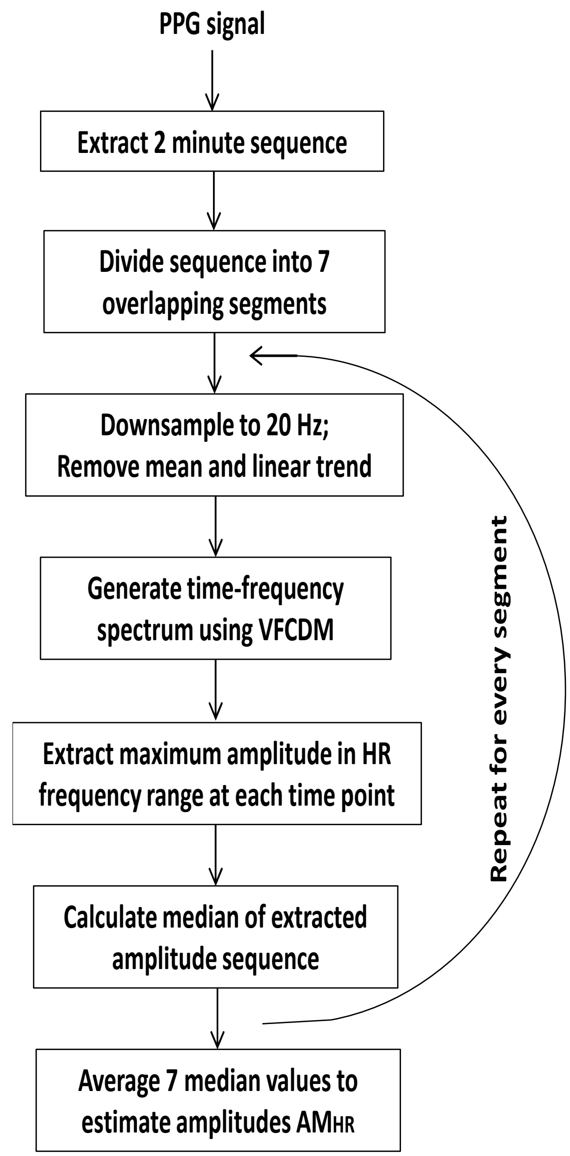

Figure 1. Algorithm used to estimate amplitudes from the HR from PPG signal

III. Results

Fourteen (N=14) patients with suspected hemorrhage were enrolled in an urban, academic emergency department. We extracted 2 minute sequences from PPG signals at various time instances throughout the whole recording, in order to determine and to track changes in estimated amplitudes.

For every patient we plotted the estimated amplitudes of HR against the corresponding time points, and determined the trend of the data. If the trend has significantly increased from the initial to the last time point, we concluded that patient is recovered, *i.e.*, normovolemic. In contrast, if the trend has significantly decreased, the patient was denoted as still hypovolemic. The clinical classifications, based on the all relevant clinical data, were made by UMass physicians, who were blinded to PPG data. Estimated results obtained from hypovolemia detection algorithm were then compared to the clinical classifications.

An illustrative example of a plot of the estimated amplitudes of HR (AM_{HR}) as function of time points for one patient is presented in Fig. 3. On the x-axis are the time

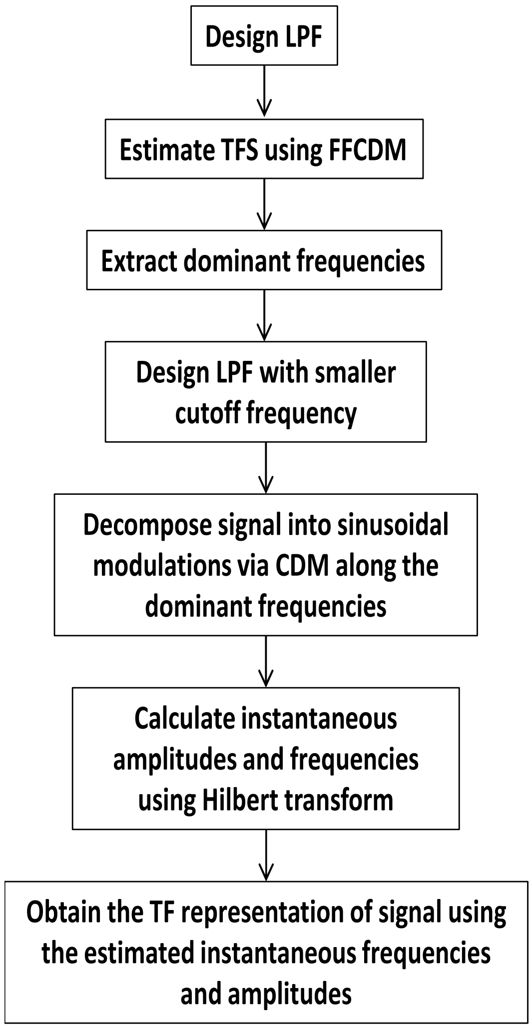

Figure 2. Flow chart illustration of the procedure for calculating VFCDM

points, while the corresponding AM_{HR} values estimated by

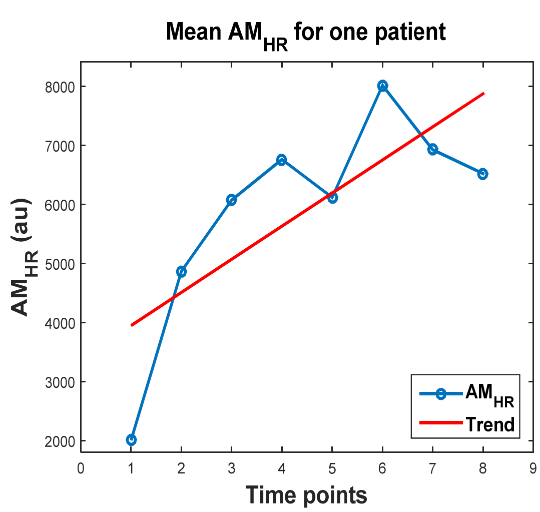

Figure 3. Illustrative example of estimated AM_{HR} values as function of time points for one patient. AM_{HR} values are presented in blue, while the trend of the data is shown as red line.

our algorithm are shown on y-axis and are presented in blue. For the estimated values, the trend analysis was performed, and the least squares line was determined and is depicted in red. As can be noted, estimated amplitudes from the HR from the PPG signal show increasing trend. Furthermore, this patient was admitted to the emergency room with signs of hemorrhage. After the treatment, the patient was classified to be normovolemic by the UMass physicians. Therefore, our algorithm was able to correctly classify PPG data from this particular patient, and to show the increase in estimated AM_{HR} values, which supports the fact that after the medic's care, patient's condition improved, *i.e.*, patient is no longer having blood loss.

Similar analysis and classification were performed for every patient. The performance of our algorithm was measured with confusion matrix, which is presented in Table I. The classification accuracy and specificity are provided in Table II. Classification accuracy of normovolemic patients is represented as specificity.

TABLE I. CONFUSION MATRIX FOR TRAUMA PATIENTS (*N*=14)

	True hypovolemia	True normovolemia
Predicted hypovolemia	0	3
Predicted normovolemia	0	11

TABLE II. ACCURACY AND SPECIFICITY FOR TRAUMA PATIENTS (*N*=14)

Accuracy (%)	Specificity (%)
78.57	78.57

It is worth mentioning that, so far, all of the enrolled patients were fully recovered, *i.e.*, in the normovolemic state and none of them were showing signs of blood loss by the end of the data collection. This is understandable, since patients were receiving intravenous fluids and blood units, their wounds were mended and bleeding was under control by the end of recording. As can be noted, our results indicate that there were no patients with ongoing blood loss, which is in agreement with the clinical classifications. Moreover, in previous study performed by our group, 900 mL of blood was withdrawn during spontaneous breathing in healthy volunteers, which simulates blood loss [9]. The authors of [9] showed significant decrease in estimated amplitudes from heart rate, with the sensitivity (classification accuracy of 900 mL withdrawal) above 75%. The algorithm was able to detect blood loss in spontaneously breathing healthy volunteers, and therefore we can expect that it would perform correctly in patients as well.

In this study, the accuracy of normovolemic patients is 78.57%. These are preliminary results, and after enrolling more patients we expect this value to be higher.

IV. Conclusion

Blood loss is one of the frequent conditions in operative rooms and in battlefield that very often leads to death. Since routinely measured vital signs do not reflect symptoms of blood loss promptly, an early detection is of great importance both for trauma and combat casualty care. Constant monitoring of patients and prompt reaction can lower the death rates. In order to achieve this, a reliable algorithm for accurate detection of blood loss before patient develops hemorrhagic shock is needed.

We proposed an algorithm based on variable frequency complex demodulation to track changes in the amplitudes of the PPG signal in the heart rate frequency range over time in patients with hemorrhage. The estimated results were compared to the independently performed adjudications obtained by physicians. The preliminary results from this ongoing study of a novel, wearable medical device to detect blood loss demonstrate modest specificity and accuracy. We expect that with enrollment of more patients we will be able to obtain higher values of accuracy and specificity, which in turn may help refine the clinical utility of this device.

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