

Detection of Heart Rate Turbulence in Photoplethysmographic Signals

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Abstract

In this study, alterations in the cardiovascular system caused by ventricular premature beats (VPBs) are investigated by analyzing the photoplethysmographic (PPG) signal. A simple algorithm for PPG-based detection of VPBs is devised and evaluated, and then employed for the analysis of heart rate turbulence (HRT), here labelled “pulse rate turbulence” (PRT). The pulse transit time is also studied as it constitutes the main difference between HRT and PRT. The data sets included a total of 3872 VPBs and 13169 normal beats. The results showed that VPBs can be detected from the PPG signal with a sensitivity of 92.8%, a specificity of 99.8% and an accuracy of 99.3%, using six features and a simple linear classifier. The shape of PRT was found to resemble that of HRT, the latter type of turbulence resulting from ECG-based analysis, suggesting that PRT analysis can be used as a replacement for HRT analysis when the ECG is not available.

1. Introduction

Intradialytic hypotension continues to be a major complication in end-stage renal disease patients undergoing hemodialysis, despite considerable effort to shed light on its underlying cause. Several factors contribute to dialysis-induced hypotension, of which hypovolemia (reflected by factors such as relative blood volume) and failing compensatory mechanisms (e.g., cardiac output, peripheral resistance, and heart rate variability) are often considered. Intradialytic hypotension not only causes discomfort to the patient, but may also increase mortality. Dialysis-induced hypotension also requires considerable attention from the nursing staff, leading to increased medical service and financial load. Thus, better knowledge of intradialytic hypotension is of great importance and may lead to early detection, and even prevention, of such events.

Heart rate turbulence (HRT) [1] reflects the heart's compensatory mechanisms. Its quantification has been established as a powerful risk predictor of mortality after acute myocardial infarction. HRT may be viewed as a measure-

ment of a subject's ability to recover from a local blood pressure decrease induced by a ventricular premature beat (VPB). When there is an important change in physiological conditions, the body reacts in order to recover baseline levels and keep all variables in a suitable balance, e.g., baroreflex mechanisms. Some recent studies have suggested that the occurrence of VPBs in hemodialysis patients may convey information on proneness to intradialytic hypotension. The number of VPBs has been found to increase significantly before intradialytic hypotension [2]. Heart rate turbulence has been found a useful marker for classifying patients as being either hypotension-resistant or hypotension-prone [3].

In this study, alterations in the cardiovascular system caused by VPBs are investigated by analyzing the photoplethysmographic (PPG) signal. The study consists of two parts of which the first, PPG-based detection of VPBs, serves as the basis for the other. If such detection can be performed with accurately, PPG-derived information on VPBs can be substituted for the information derived from the ECG. The second part concerns PPG-based analysis of HRT, here labelled as “pulse rate turbulence” (PRT) since changes in pulse rate that follow a VPB are quantified. The main difference between HRT and PRT analysis is the pulse transit time (PTT) which will influence PRT. The PTT is defined as the time it takes for the pulse wave to travel from the heart to the PPG sensor, which usually is attached to a finger.

2. Data

Two databases were analyzed, namely one recorded during hemodialysis treatment and another known as the Multi-parameter Intelligent Monitoring for Intensive Care (MIMIC). The former database consists of 11 patients (7 females) with end-stage renal failure who underwent regular hemodialysis treatment. All patients were classified as hypotension-prone by a nephrologist. The data were acquired during the entire treatment session at the Department of Nephrology at Rigshospitalet in Copenhagen, Denmark, lasting from 3 to 5 hours. The study was ap-

proved by the local ethics committee. A total of 28 treatments were acquired from the 11 patients. Data were acquired in parallel with the routine hemodialysis equipment. The standard ECG leads V1, V5, and II were recorded at a sampling rate of 1000 Hz using the Biopac MP150 data acquisition system (BIOPAC Systems Inc., USA). The PPG signal and oxygen saturation were continuously acquired with a pulse oximeter (LifeSense R, Medair AB, Sweden), also sampled at a rate of 1000 Hz using the Biopac MP150.

The MIMIC database consists of multimodal data recorded in the intensive care unit from more than 90 patients, of which the ECG and PPG signals were analyzed here. Patients with more than 200 VPBs or with good quality signals were included for further analysis, resulting in a total of 6 patients. In order to comply with recommendations on sampling rate when analyzing heart rate variability [4] and HRT [3], the ECG was interpolated to a rate of 500 Hz. The PPG signal, originally recorded at 125 Hz, was interpolated so that a time resolution equivalent to that of the ECG signal was obtained, thereby reducing the error in the pulse rate analysis.

2.1. Reference annotations for VPBs

Ventricular premature beats were selected based on information in the ECG. Following QRS detection using a wavelet-based algorithm [5], VPBs were determined by exploring information on rhythm and beat morphology [6]. VPBs were excluded from further analysis when artifacts were present either in the ECG or the PPG signal, or when other VPBs occurred within the 5 previous or 20 subsequent beats. The total number of VPBs were 1013 and 2859 in the hemodialysis and MIMIC database, respectively.

The ECG signal served as the “gold standard” for evaluating the performance of detecting normal beats and VPBs, and for evaluating the accuracy of PRT in relation to HRT.

3. Methodology

3.1. VPB detection from PPG

Pulse detection. The PPG signal was lowpass filtered using an FIR filter with a cut-off frequency of 35 Hz in order to reduce the influence of noise. The onset n_{O_i} and the apex location n_{A_i} of the i -th pulse were determined from the derivatives of the filtered signal denoted $x(n)$.

Different types of pulse patterns can be discerned from the PPG signal when a VPB is occurring. Depending on the degree of blood pumping efficiency, the VPB may or may not be associated with a PPG pulse, labelled either VPB_1 and VPB_2 .

Four pulse types were considered for PPG-based detection of VPBs:

- A normal pulse associated with a normal beat (NP).

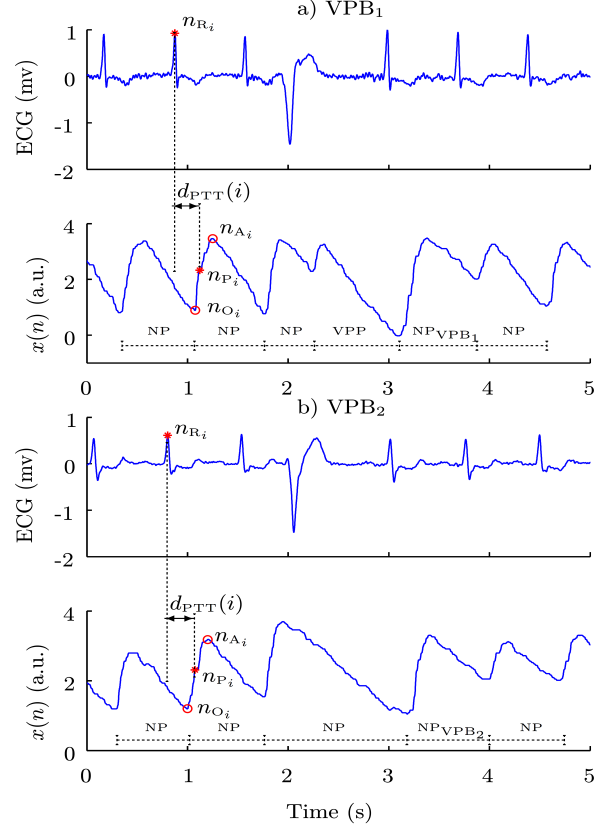


Figure 1. ECG and PPG signals including a VPB associated (a) with a PPG pulse (VPB_1) or (b) not (VPB_2). The four PPG pulse types, i.e., NP, VPP, NP_{VPB_1} , and NP_{VPB_2} , and significant points, i.e., n_{R_i} , n_{O_i} , n_{P_i} , and n_{A_i} , are illustrated.

- A pulse caused by a VPB, i.e., ventricular premature pulse (VPP).
- The first normal pulse after a VPB causing a PPG pulse (NP_{VPB_1}).
- The first normal pulse after a VPB not causing a PPG pulse (NP_{VPB_2}).

Note that VPP and NP_{VPB_1} are related because a PPG pulse of type NP_{VPB_1} always follows a pulse of type VPP. Figure 1 illustrates the four different types of PPG pulses.

Pulse classification. Three simple features characterizing pulse amplitude and timing were defined:

- Pulse upslope amplitude, $a_+(i) = x(n_{A_i}) - x(n_{O_i})$.
- Pulse downslope amplitude, $a_-(i) = x(n_{A_i}) - x(n_{O_{i+1}})$.
- Apex-to-apex interval, $d_{AA}(i) = n_{A_i} - n_{A_{i-1}}$.

Due to a large inter-subject variability and the fact that the PPG signal does not provide an absolute blood volume measurement, all these features were normalized for each pulse with respect to their mean value computed from the five previous normal pulses.

Due to the close relationship between PPG pulses of

type VPP and type NP_{VPB_1} , the total feature set characterizing a pulse was defined by $a_+(i)$, $a_-(i-1)$, $d_{AA}(i)$ as well as $a_+(i-1)$, $a_-(i-2)$, $d_{AA}(i-1)$.

Linear discriminant analysis was used for VPB detection. Every pulse was assigned to type $k \in \{NP, VPP, NP_{VPB_1}, NP_{VPB_2}\}$ of the four possible types, using a linear classifier based on the six features just described. The discriminant function was evaluated for each type, and the pulse is assigned to the type with the largest value of the discriminant function.

Performance assessment. The VPBs of the hemodialysis database were used for evaluating the pulse classifier. PPG pulses at the VPB and subsequent pulses were manually labeled as VPP, NP_{VPB_1} , or NP_{VPB_2} according to the PPG pattern. The normal pulse type was made up of the three previous and the ten following normal PPG pulses to VPB. The total number of pulses were 13169 NP, 201 VPP, 201 NP_{VPB_1} , and 812 NP_{VPB_2} .

Cross-validation was used for evaluating performance. A confusion matrix was obtained for every subject by comparing the reference with the classifier outcome when it was trained using all PPG pulses in the database, except those belonging to the subject under analysis. Finally, the classifier confusion matrix was computed by accumulating the confusion matrix of every subject. The different types were balanced in the training process in order to assign the same weight to all of them, regardless of their prior probability.

The performance was evaluated not only for the above-mentioned case with four types of PPG pulses, but also for the case with two types when all VPB-related pulse types were merged into one type consisting of VPP, NP_{VPB_1} , and NP_{VPB_2} , collectively denoted VPP_{1+2} .

3.2. Pulse rate response to VPB

Analysis similar to that of HRT was carried out for the PR response to a VPB, the main difference being that the beat temporal reference was derived from PPG instead of from ECG. A definition of the fiducial point for a PPG pulse is needed. Given that the pulse wave is less sharp than the QRS, and that an error in the localization of the PPG pulse peak is more likely than in the ECG, the time instant at half the PPG pulse amplitude was considered as the pulse fiducial point in PPG due to its lower variability. The fiducial point n_{p_i} of the PPG pulse is defined as

$$n_{p_i} = \arg \min_{n \in [n_{O_i}, n_{A_i}]} \left\{ x(n) - \left(x(n_{O_i}) + \frac{x(n_{A_i}) - x(n_{O_i})}{2} \right) \right\}, \quad (1)$$

see Fig. 1. The pulse-to-pulse (PP) interval $d_{pp}(i)$ was computed for PPG pulses after every VPB as $d_{pp}(i) = n_{p_i} - n_{p_{i-1}}$.

Table 1. Performance measurement

Performance accuracy (4 types)					Performance accuracy (2 types)		
	NP	VPP	NP_{VPB_1}	NP_{VPB_2}		NP	VPP_{1+2}
<i>Se</i>	96.6%	93.0%	92.5%	97.0%	<i>Se</i>	99.8%	92.8%
<i>Sp</i>	97.6%	98.4%	98.3%	99.9%	<i>Sp</i>	92.8%	99.8%
<i>Acc</i>	96.6%	98.4%	98.2%	99.7%	<i>Acc</i>	99.3%	99.3%
Total <i>Acc</i>	96.5%				Total <i>Acc</i>	99.3%	

Confusion matrix (4 types)					Confusion matrix (2 types)		
	NP	VPP	NP_{VPB_1}	NP_{VPB_2}		NP	VPP_{1+2}
NP	12916	14	12	3	NP	13140	73
VPP	222	187	0	0	VPP_{1+2}	29	940
NP_{VPB_1}	220	0	186	21			
NP_{VPB_2}	11	0	3	788			

The PTT was computed in order to obtain a better understanding of differences between HRT and PRT. It was measured as the distance between the R-wave in the ECG, denoted n_{R_i} , and the fiducial point of the corresponding pulse in the finger pad measured by PPG, i.e., $d_{PTT}(i) = n_{p_i} - n_{R_i}$, see Fig. 1. The relationship between RR and PP intervals is described by

$$d_{pp}(i) = n_{p_i} - n_{p_{i-1}} = d_{RR}(i) + \Delta d_{PTT}(i), \quad (2)$$

where $\Delta d_{PTT}(i) = d_{PTT}(i) - d_{PTT}(i-1)$ represents the increase in PTT.

4. Results

Classification performance (expressed in terms of sensitivity *Se*, specificity *Sp*, and accuracy *Acc*) and the related confusion matrix are presented in Table 1 when considering either four or two PPG pulse types. The total accuracy was 96.5% for the four types VPP, NP_{VPB_1} , and NP_{VPB_2} , whereas it increased to 99.3% when assuming two pulse types (VPP_{1+2}).

Figure 2 illustrates HRT, PRT, and PTT for two representative subjects, one with turbulence and another without. The largest difference between HRT and PRT occurs in the first PP interval after the VPB ($d_{pp}(8)$) compared with $d_{RR}(8)$). According to (2), this difference is due to $\Delta d_{PTT}(8) = d_{PTT}(8) - d_{PTT}(7)$. Figures 2(e) and (f) show a decrease in PTT(7) and an increase in PTT(8) which produce the increase in $d_{pp}(8)$.

Figure 3 displays the well-known indices for characterizing HRT labelled turbulence onset (TO) and turbulence slope (TS) [1]. Parameter values are displayed for all patients with more than 50 VPBs, 10 patients in total. It should be noted that only one patient has a clear turbulence pattern as is evident from both HRT and PRT analysis, see Figs. 2 (a) and (c).

5. Discussion

To the best of our knowledge, this study is the first to attempt PPG-based analysis of alterations in the cardiovascular system caused by VPBs. The results presented in Table 1 indicate that very good VPB detection performance

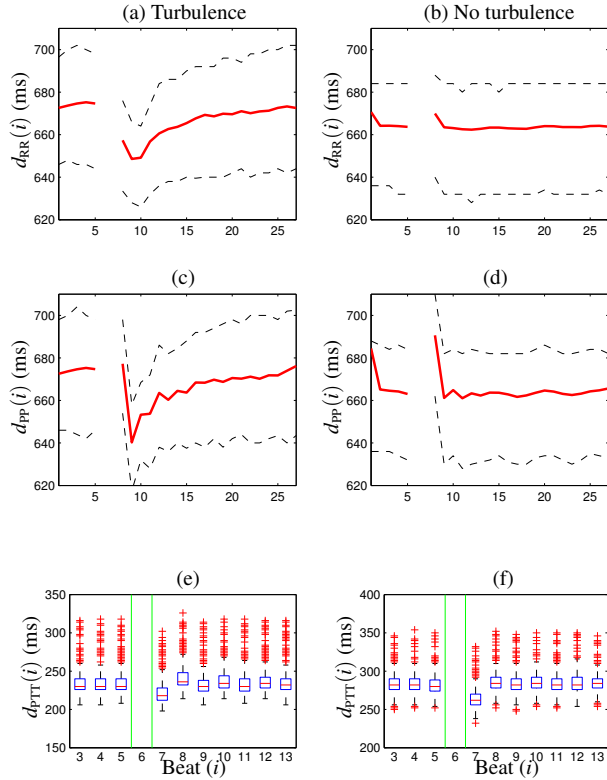


Figure 2. a, b) Mean RR interval (solid line), 25th and 75th percentiles (dashed line); c, d) mean PP interval (solid line), 25-th and 75-th percentiles (dashed line) and e, f) PTT. One subject with turbulence (panels a, c and e) and another without (panels b, d and f).

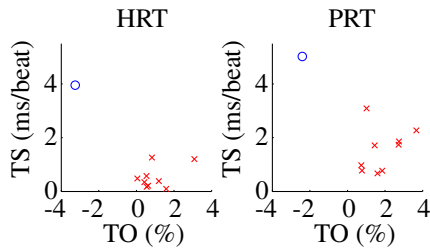


Figure 3. TO and TS derived from HRT or PRT analysis for one subject with turbulence ('o') and nine subject with no-turbulence ('x').

can be achieved from PPG signals (96.5% when classifying four types and 99.3% for two types); this accuracy was achieved for a simple linear classifier and six features characterizing amplitude and duration. The results suggest that VPBs can be reliably detected from the PPG signal, and thus the ECG is not needed for PRT analysis.

During the compensatory pause the heart is filled with more blood than otherwise, so that the first beat after the VPB ($i = 7$) is associated with a higher pressure which causes the pulse wave to travel faster and, consequently,

a decrease in PTT. The opposite effect applies to the subsequent pulse ($i = 8$). According to (2), this phenomenon represents the main difference between HR and PR, and occurs in the first PP interval after the VPB, see Fig. 2.

The main limitation with the present study is that there is only one subject with HRT. Although an extended study including more subjects with HRT is highly desirable, our results suggest that the PPG signal is suitable for turbulence detection.

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