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Detection of ventricular premature beats based on the pressure signals of a hemodialysis machine

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ABSTRACT

Monitoring of ventricular premature beats (VPBs), being abundant in hemodialysis patients, can provide information on cardiovascular instability and electrolyte imbalance. In this paper, we describe a method for VPB detection which explores the signals acquired from the arterial and the venous pressure sensors, located in the extracorporeal blood circuit of a hemodialysis machine. The pressure signals are mainly composed of a pump component and a cardiac component. The cardiac component, severely overshadowed by the pump component, is estimated from the pressure signals using an earlier described iterative method. A set of simple features is extracted, and linear discriminant analysis is performed to classify beats as either normal or ventricular premature. Performance is evaluated on signals from nine hemodialysis treatments, using leave-one-out crossvalidation. The simultaneously recorded and annotated photoplethysmographic signal serves as the reference signal, with a total of 149,686 normal beats and 3574 VPBs. The results show that VPBs can be reliably detected, quantified by a Youden's *J* statistic of 0.9, for average cardiac pulse pressures exceeding 1 mmHg; for lower pressures, the *J* statistic drops to 0.55. It is concluded that the cardiac pressure signal is suitable for VPB detection, provided that the average cardiac pulse pressure exceeds 1 mmHg.

1. Introduction

It is well-known that ventricular premature beats (VPBs) are frequent in dialysis patients [1,2], and increase in number when excess potassium is removed [3]. Ventricular arrhythmias in dialysis patients have been studied in long-term, ambulatory electrocardiogram (ECG) recordings, showing that VPBs are much more frequent during hemodialysis than during the postdialysis period [4]. Patients with regional wall motion abnormalities, ischemic heart disease, and left ventricular hypertrophy have a higher rate of VPBs during hemodialysis than have patients without these diseases. Rapid changes in this rate may be a sign of cardiovascular instability and electrolyte imbalance, and the significance of such changes have been investigated for prediction of acute, intradialytic hypotension [5].

Pulse pressure waves propagate from the heart through the arteries to the fistula , where the waves enter the extracorporeal blood circuit of the dialysis machine. In this blood circuit, the waves are measured by the arterial and the venous pressure sensors. A peristaltic blood pump generates a pulsatile blood flow through the extracorporeal circuit. The blood flows from an arterial needle inserted into the fistula, through the dialyzer, purifying the blood, and then back to the fistula through a venous needle. The amplitude of the pressure pulses generated by the blood pump is drastically larger than is the amplitude of the pressure pulses generated by the heart.

We have previously shown that a cardiac pressure signal can be extracted from the signals produced by arterial and venous pressure sensors [6], (see also [7]). In these studies, we compared heart rate and heartbeat occurrence time estimated from the extracted cardiac pressure signal to the corresponding quantities obtained from the photoplethysmographic (PPG) signal. The results showed

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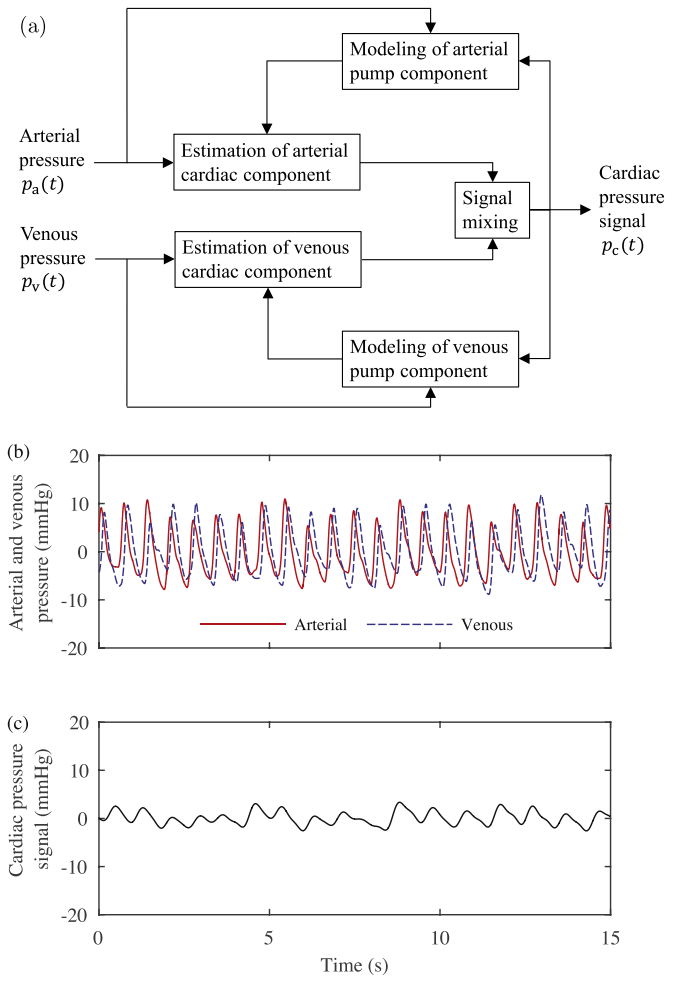

Fig. 1. (a) Block diagram of the method for cardiac pressure signal estimation. Note that the output signal is referred to as "cardiac pressure signal", whereas the intermediate signals are referred to as "components". (b) The arterial and the venous pressure signals are the input to the method, whereas (c) the cardiac pressure signal is the output. Note the considerable difference in amplitude between the signals in (b) and (c).

that the proposed method offers excellent accuracy of heart rate and heartbeat occurrence time, also at low signal-to-noise ratios.

In the present paper, we investigate, for the first time, whether the extracted cardiac pressure signal is suitable for VPB detection. A set of features, describing amplitudes, durations, and areas, is proposed and used to classify detected beats as either VPBs or normal based on linear discriminant analysis. Using leave-one-out crossvalidation, the performance is evaluated by comparing the results from the proposed classifier to the annotated reference PPG signals.

2. Background

2.1. Cardiac pressure signal estimation

The cardiac pressure signal is estimated using the iterative method described by Holmer et al. [6]. The method alternates between modeling of separate arterial and venous pump components, and estimation of a cardiac pressure signal. The resulting estimate is based on both the arterial and the venous pressure signals, by mixing the arterial cardiac component with the venous cardiac component. The mixing consists of time shifting and averaging, where the time shift is determined by maximizing the correlation between the arterial and venous cardiac components. The arterial and the venous cardiac components are obtained by subtracting the arterial and the venous model pump components from the respective arterial and venous pressure signals. The arterial and the venous pump signal estimates are determined by subtracting the cardiac pressure signal estimate from the respective signals. The pump signal estimates are, in turn, used to iteratively refine the arterial and the venous model pump components, so that the pump component remainders in the cardiac pressure signal estimate are reduced. The iteration continues until the difference in successive cardiac pressure signal estimates no longer improves. The main building blocks of the method are shown in Fig. 1(a), where the input signals and the output signal are illustrated in Fig. 1(b) and (c), respectively.

3. Experiment and database

3.1. Clinical study

The data originate from a clinical study performed at Skåne University Hospital, Lund, Sweden. The study was approved by the local ethical review board, and all patients signed an informed consent form before participating.

The data set includes 9 treatments from 7 patients with kidney failure who underwent hemodialysis treatment for at least three months prior to the study onset. The treatments were performed according to the regular prescription provided by the nephrologist, and lasted 4–5 h. Four patients had a history of heart complication. One patient had a graft as vascular access, whereas all others had fistulas. The average cardiac pulse pressure $\bar{P}_{np}$ was determined during a blood pump stop at the treatment onset, see Table 1. Treatments with $\bar{P}_{np}$ below 0.5 mmHg [6], as well as patients with pacemaker, patients undergoing hemodiafiltration treatment, and patients participating in other studies, were not included.

The patients were treated with AK 200 hemodialysis machines from Gambro. An external device with pressure sensors was connected to the extracorporeal blood circuit to acquire the arterial and the venous pressure signals. The external device was used instead of the built-in pressure sensors to avoid the time-consuming work that comes with a software update of a dialysis machine. However, the recorded data can be regarded as originating from the built-in sensors, since the external and built-in sensors were of identical brand and type.

As reference, a PPG signal was acquired using the LifeSense™ finger pulse oximeter. The PPG signal and the estimated cardiac pressure signal were lowpass filtered, using a cut-off frequency of 5 Hz. All analyzed signals had a time resolution of 10 ms. The use of the PPG signal as a reference is discussed in Section 6.

3.2. Annotation of the reference PPG signal

Firstly, pulse detection was performed on the reference PPG signal, using a lowpass differentiator filter and a time-varying threshold, where the time of the peak amplitude of each heart pulse was used as reference [8,9]. Secondly, the detected pulses were classified as either normal or VPB using the method of Gil et al. [9]. Next, all VPBs were manually reviewed to avoid incorrect annotations. Segments with motion artifacts were manually excluded, leading to that 9% of the total treatment time were excluded. For each treatment, Table 1 presents its duration, the duration of discarded segments, $\bar{P}_{np}$, the mean and standard deviation of the peak-to-peak interval in the PPG signal, and the number of annotated normal and premature beats.

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