Detection of Hypotension during Hemodialysis Using the ECG

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Abstract

There is today a lack of clinical techniques for detecting acute hypotension during conventional hemodialysis treat -ment, despite the fact that hypotension remains the most common acute complication during hemodialysis. Hypotension is often followed by nausea, vomiting, and even fainting, not only strenuous for the patient but requires considerable attention from the nursing staff. The problem of detecting hypotension was studied by means of a multimodal database. The database consists of 30 treatments in which each treatment includes several simultaneously acquired signals. Acute symptomatic hypotension occurred in 2 of the 30 treatments. An ECG-based method for detecting hypotension has been developed. The method involves information on heart rate variability (HRV) and ectopic beat patterns. The proposed method does not only detect the two cases of acute hypotension but also provides information of the patient's propensity to hypotension at an early stage of hemodialysis.

1. Introduction

The human body consists of approximately 60% water, a level which is important to maintain for survival. While it is unproblematic to provide the body with water, getting rid of surplus water is a major problem in renal patients. The task of normal kidneys is to remove superfluous fluid and substances from the blood such as water, urea, and other waste products. With malfunctioning kidneys, disorders may develop in most of the major body organs, a syndrome called uremia. If uremia remains untreated, it will lead to death. Uremia is treated either by kidney transplantation or dialysis. To fast or to much water removal during dialysis, increases the risk of hypotension. Appropriate actions from either nursing staff or hemodialysis settings can prevent or reverse a hypotension.

The analysis of HRV is a useful noninvasive tool for assessing information on the state of the autonomic nervous system. If HRV is analyzed in the frequency domain, the spectrum is often divided into two subbands: low frequency (LF) band (0.04 – 0.15 Hz) and high frequency (HF) band (0.15 – 0.40 Hz). Most attention has been focused on the relation between power in LF and HF band, the so-called LF/HF ratio. Morphology and occurrence time of ectopic beats during dialysis are also investigated in this paper using a new method called Ectopic Beat Count (EBC) analysis.

2. Data acquisition and material

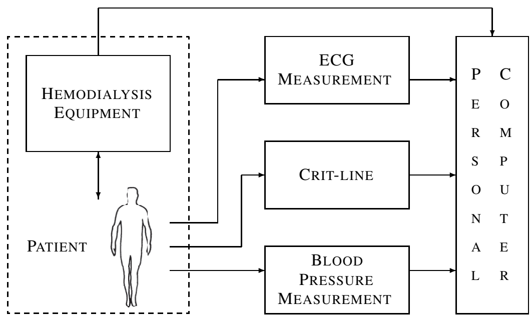

Figure 1. The four systems operating in parallel during the data recording. The conventional hemodialysis system is illustrated with the dashed box.

In addition to the conventional dialysis instruments, the data acquisition involves an ECG recorder, a blood pressure monitor, and a Crit-line instrument, see the system overview in Fig. 1. All four systems were operating simultaneously and the resulting recordings were stored on related PCs. The dialysis machine used in this study was: Gambro AK 100-200. The Crit-line instrument measures hematocrit, oxygen saturation, and blood volume change. The ECG was recorded during dialysis using the standard 12-lead configuration, sampled at 1000 Hz. An arterial blood pressure signal was acquired with a Finapres and sampled at 200 Hz with a Biopac MP100 data acquisition system.

Sixteen patients with end-stage renal failure, who underwent regular hemodialysis three times a week, participated in the study. Each patient was classified as being either hypotension-resistant or hypotension-prone based on previous clinical history. Altogether 30 sessions were acquired from the 16 patients. An overview of the 16 patients is given in Table 1.

Table 1. Patient characteristics for hypotension resistant and prone patients. Values are given in mean ± std.

Characteristic	*Hypotension Resistant*	*Hypotension Prone*
# Patients	7	9
# Sessions	11	19
Male/Female	6/1	6/3
Diabetes mellitus	3	5
Age (yr)	58.6 ± 13.5	65.6 ± 10.6
Weight (kg)	86.9 ± 19.5	83.1 ± 19.9
Duration of HD (yr)	1.3 ± 1.5	2.4 ± 1.8
Duration of treatment (h)	4.3 ± 0.7	4.4 ± 0.5
UF volume (net) (l)	2.5 ± 1.8	2.9 ± 1.0
UF rate (l/h)	0.6 ± 0.4	0.7 ± 0.2
Dialysis fluid Na^+ (mmol/l)	136.9 ± 1.1	136.9 ± 1.1
Blood flow (ml/min)	364 ± 93	397 ± 74
Dialysis flow (ml/min)	500 ± 0	572 ± 91
Dialysis fluid temp. (°C)	36.3 ± 0.3	36.0 ± 0.3

3. Methods

This section describes a method for detection of hypotension during hemodialysis. The method is noninvasive and exploits different rhythm characteristics of the ECG signal. Two parallel complementary analyses are performed with respect to HRV and EBC. The analysis of HRV and EBC reflects entirely different mechanisms of the cardiac activity and are complementary since EBC analysis, in contrast to HRV analysis, can be used when several ectopic beats are present. Prior to HRV and EBC analysis the measured ECG signal has to be preprocessed. The processing of the ECG can be divided into three processing blocks, see Fig. 2. The first block performs signal preprocessing and feeds subsequent blocks (HRV and EBC analysis) with the necessary information (beat occurrence times and classifications). The signal preprocessing block performs baseline filtering, QRS detection, beat characterization, and beat classification. Each beat is classified as a normal sinus beat, ectopic beat, artifact or noise based on a crosscorrelation method. Based on the results from HRV and EBC analysis a decision concerning changes in blood pressure is done.

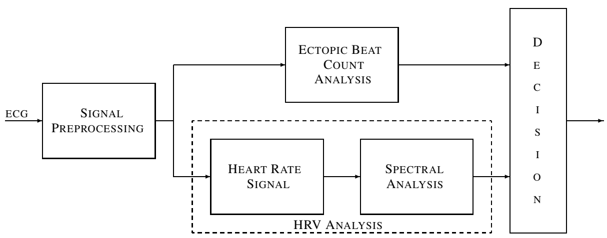

Figure 2. An overview of the three processing blocks used to process the measured ECG signal.

3.1. HRV analysis

The analysis of heart rate variability is based on the so-called heart timing (HT) representation. This is a recently published method based on the well-known integral pulse frequency modulation (IPFM) model [1]. The IPFM model is used for simulating the variability of a series of occurrence times for normal sinus beats, and reflects basic electrophysiological properties of the atria [2]. The input signal to the IPFM model consists of the sum of a DC level, related to average heart rate, and a modulating signal, $m(t)$.

The heart timing signal $d_{HT}(t)$ is defined at the occurrence time t_k as the difference between the occurrence time t_k and the expected occurrence time at the mean heart rate, $k\overline{T}_0$, i.e., $d_{HT}(t_k) = k\overline{T}_0 - t_k$ [1]. The heart timing signal is closely related to the IPFM model and its modulating signal $m(t)$. With the help of the heart timing signal, the modulating signal $m(t)$ and especially its Fourier transform can be determined in order to produce an estimate of the HRV power spectrum.

If the Fourier transforms of $m(t)$ and $d_{HT}(t)$ are denoted with $D_m(\Omega)$ and $D_{HT}(\Omega)$, respectively, it can be shown that [1]

$$D_m(\Omega) = j\Omega D_{HT}(\Omega) \tag{1}$$

where $\Omega = 2\pi F$. Hence, once the Fourier transform of the heart timing signal, $D_{HT}(\Omega)$, is known, the desired spectral estimate $D_m(\Omega)$ can easily be computed.

Ectopic beats introduce errors in the analysis of HRV. The errors are due to an impulse-like artifact in the RR intervals introduced by the RR intervals adjacent to an ectopic beat. Since ectopic beats interrupt the normal sinus modulated heart rhythm, ECG segments containing frequent ectopic beats should be excluded from further HRV analysis.

The heart timing representation can be modified to handle the presence of occasional ectopic beats, in this paper by using a computationally very efficient method [3]. In the description below, we assume that sinus beats occur at the times $t_0, t_1, \ldots, t_K$, and that one ectopic beat occurs at time t_e in the signal. The time t_e is not included in the series $t_0, t_1, \ldots, t_K$, and the sinus beat immediately preceding the ectopic beat occurs at t_{k_e} and the sinus beat immediately following occurs at t_{k_e+1}.

An approach to dealing with ectopic beats is introduced by first concluding that an ectopic beat shifts the occurrence times of subsequent normal heart beats. By estimating this time shift, δ, the presence of ectopic beats can be accounted for by the following equation

$$d_{HT}(t_k) = \begin{cases} k\overline{T}_0 - t_k & k = 0, \ldots, k_e, \\ k\overline{T}_0 - t_k + \delta & k = k_e + 1, \ldots, K, \end{cases} \tag{2}$$

and δ estimated according to [3]

$$\hat{\delta} = t_{k_e+1} - 2t_{k_e} + t_{k_e-1} \tag{3}$$

3.2. Ectopic beat count (EBC) analysis

The EBC analysis is based on the occurrence times of the ectopic beats. The occurrence times may be modeled by a point process, and characterized by its intensity. The EBC analysis tracks changes in the mean intensity of ventricular ectopic beats and "missing" beats. The analysis is performed in a window which slides over the signal, thus the EBC analysis follows changes in the intensity blockwise.

It is assumed that the occurrence times of the ectopic beats obey a Poisson process. Thus, the distances between successive occurrence times are independent and exponentially distributed with intensity λ. Assuming a fixed intensity λ within a block, the ML estimate of λ is given by

$$\hat{\lambda} = \frac{K}{\sum_{k=1}^{K} t[k]} \tag{4}$$

where $t[k]$ denotes the distance between two occurrence times and K the number of distances.

4. Results

The first results relate to different patient characteristics in terms of hypotension-resistant (HR) and hypotension-prone (HP) patients, see Table. 2. Symptomatic hypotension occurred in five of the thirty sessions. Two of these episodes were due to acute symptomatic hypotension, where the time of hypotension was well defined. In the other three episodes, hypotension was not caused by a drastic change in blood pressure but by a slow decrease until hypotension occurred; in these episodes the time of hypotension was not possible to define.

Table 2. Patient characteristics for HR and HP patients. If possible asymptotic p-value from the Kolmogorov Smirnov test between HR and HP were determined: not significant (NS), 0.05, 0.01, or 0.001. Values are given in mean ± std.

Characteristic	*Hypotension Resistant*	*Hypotension Prone*	*p-value*
# Patients	7	9	—
# Sessions	11	19	—
# Symptomatic hypotension	1	4	—
# Acute symp. hypotension	1	1	—
HRV analysis performable	6	12	—
EBC analysis performable	6	9	—
Blood pressure, start (mmHg)	151 / 88 ± 41 / 26	147 / 74 ± 24 / 14	NS / NS
Blood pressure, end (mmHg)	132 / 76 ± 37 / 25	118 / 64 ± 14 / 12	NS / NS
Heart rate, start/end (bpm)	83 / 92 ± 15 / 17	79 / 80 ± 18 / 18	NS / NS
Rel. BV, end (%)	-9.9 ± 9.0	-6.1 ± 4.6	NS
Hematocrit (%)	34.2 ± 4.6	37.5 ± 4.8	NS
O_2 Sat., start (%)	93.2 ± 1.3	91.0 ± 3.5	NS
LF/HF ratio, start	1.43 ± 0.61	0.56 ± 0.19	0.01

There is a statistical difference in the LF/HF ratio at the start of the dialysis between HR and HP patients; the start values were obtained as mean and standard deviation of the mean LF/HF ratio during the first 30 minutes of treatment. Heart rate variability analysis could be performed in 18 of the 30 sessions, while the remaining were excluded due to frequent ectopic beats. Ectopic beat count analysis was performed in 15 of the 30 sessions. An estimate of the intensity of the ectopic beats could not be done in the other sessions, since the ECG did not contain any (or contained very few) ectopic beats. Both HRV and EBC analysis could be performed in three sessions, in the other 27 sessions either HRV or EBC analysis was performed. This demonstrates the important complementary significance of the method, since about 50% of the sessions are either acceptable for HRV or EBC analysis.

4.1. HRV analysis

The HRV analysis was performed according to Sec. 3.1 and all ectopic beats were handled prior to HRV analysis. Examples of the LF/HF ratio in three different sessions (two HP and one HR) are shown in Fig. 3. The LF/HF ratio in these sessions illustrates the statistical difference in LF/HF ratio between HR and HP patients. A plausible threshold of the LF/HF ratio to distinguish between HR and HP patients would be to use a value around one, i.e., equal energy in the LF and HF band, see Fig. 3. The LF/HF ratio increases and then decreases markedly prior to an acute symptomatic hypotension, see Fig. 3(a). In case of a symptomatic hypotension, but not acute, the LF/HF ratio tends to be very low, see Fig. 3(b). Two occasions with a slight head-up tilt occurred in Fig. 3(a). Thus, the large increase in the LF/HF ratio prior to acute symptomatic hypotension can partly by due to the tilt, since tilting causes an increase in the LF/HF ratio. The increase of the LF/HF ratio due to a tilt can also be seen in Fig. 3(b).

4.2. EBC analysis

The Poisson-based method tended to generate disturbances for small values of the denominator in (4). In order to deal with such disturbances, a simple method was used which counts the number of ectopic beats within a block. Examples of the EBC analysis in three different sessions are shown in Fig. 4. The intensity of ectopic beats appears to increase markedly during acute symptomatic hypotension, see Fig. 4(a) and (b). The marked increase in intensity is not observed in stable patients, see Fig. 4(c). An absolute threshold to distinguish acute symptomatic hypotension is not possible to determine, since the amount of ectopic beats present during treatment is individual, and differs from treatment to treatment. An intensity can be associated

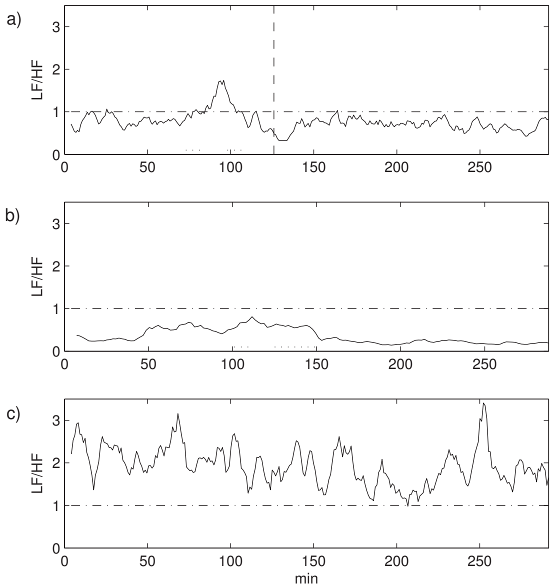

Figure 3. LF/HF ratio in three different sessions: (a) An HP patient with acute symptomatic hypotension occurring at the vertical dotted line. (b) An HP patient with symptomatic hypotension occurring towards end of dialysis. (c) An HR patient with stable blood pressure. Equal energy in the LF and HF band is illustrated with a dashdotted line. The two dotted lines in (a) indicates where a slight head-up tilt occurs, due to eating and urination. A head-up tilt was performed in (b) during the two dotted lines due to eating.

with stable blood pressure in one patient and an acute symptomatic hypotension in another, see Fig. 4(b) and (c). Thus, detection of acute symptomatic hypotension requires a relative threshold, since a change in intensity is of interest; a relative intensity threshold could, for example, be four times the mean intensity during treatment.

5. Discussion and conclusions

There are very few articles in the field of hemodialysis and HRV which deals with the presence of ectopic beats, and none performs, to our knowledge, any kind of ectopic beat analysis. It is well-known that ectopic beats are common in dialysis patients [4] (about 50% of the patients were excluded from HRV analysis in the present study). Thus, HRV analysis is insufficient as a marker of hypotension, and a detector must perform complementary analysis to deal with substantial amounts of ectopic beats. The proposed ECG-based method detects the two cases of acute hypotension and provides information of the patient's propensity to hypotension at an early stage during hemodialysis. The acquisition of another database is needed to further evaluate the method.

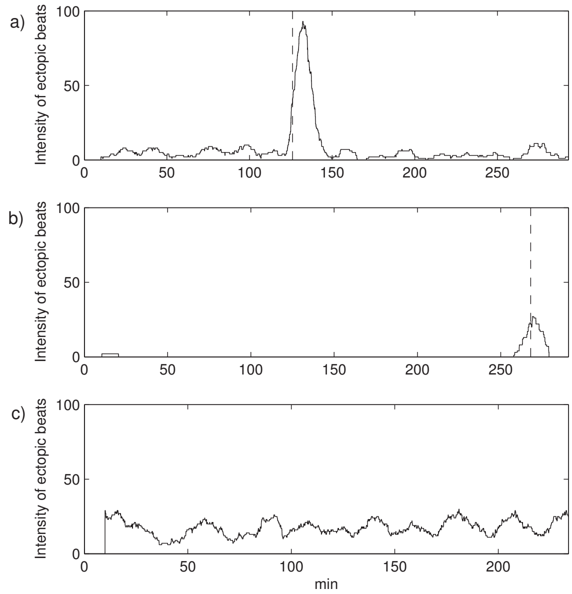

Figure 4. The intensity of ectopic beats in three different sessions: (a,b) Both sessions with an acute symptomatic hypotension occurring at the vertical dotted line. (c) A session with stable blood pressure.

Acknowledgements

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