PULSE RATE ANALYSIS FROM THE PHOTOPLETHYSMOGRAPHIC SIGNAL FOR TURBULENCE DETECTION

E. Gil[1,2], P. Laguna[1,2], J.P. Martínez[1,2], L. Sörnmo[3]

[1]*Communications Technology Group (GTC), Aragon Institute of Engineering Research (I3A), IIS Aragón, Universidad de Zaragoza, Spain*
[2]*Centro de Investigación Biomédica en Red en Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Zaragoza, Spain*
[3]*Signal Processing Group, Department of Electrical and Information Technology, Lund University, Lund, Sweden*

Abstract

In this paper we assessed the possibility of using the pulse rate (PR) extracted from the photoplethysmographic signal for turbulence detection as an alternative to the heart rate (HR). The study is based on analysis of the rhythm changes observed during 4131 ventricular premature beats of 27 subjects.

Classical features for turbulence analysis, turbulence onset and turbulence slope were estimated based on HR and PR. Then, patients were classified as turbulence or no-turbulence based on PR features, the accuracy of the method was evaluated considering subjects classification based on HR as the reference. Features analyzed produce an Acc=95% in turbulence detection and subject classification among HR turbulence categories produce an Acc=91% for PR analysis.

These results show that PR analysis could be used as a surrogate technique for turbulence detection.

Keywords: heart rate, turbulence, photoplethysmography, pulse rate, ventricular premature beat

I. INTRODUCTION

Heart rate turbulence (HRT) refers to a short-term fluctuation in heart rate, triggered by a single ventricular premature beat (VPB) [1]. Such turbulence is considered to be a blood-pressure-regulating mechanism which, in normal subjects, compensates for the VPB-induced drop in blood pressure by an accelerated sinus rate. Blunted or missing turbulence reflects autonomic dysfunction and is associated with various conditions. In particular, HRT has been established as a powerful risk predictor of mortality and sudden cardiac death following acute myocardial infarction.

HRT is commonly assessed by two parameters: turbulence onset (TO) and turbulence slope (TS), both computed from the sequence of beat-to-beat intervals (RR intervals) following VPBs. TO measures the change in RR interval length immediately after the VPB, whereas TS quantifies the speed of RR interval increase following the initial shortening [1].

Pulse photoplethysmography (PPG) is a simple and useful method for measuring the relative blood volume changes in the microvascular bed of peripheral tissues and evaluating peripheral circulation [2]. The PPG waveform contains an ac component which is attributable to the pulsatile component of the vessels, i.e. the arterial pulse, which is caused by the heartbeat pumping. PPG has been applied in many different clinical settings, including the monitoring of blood oxygen saturation, heart rate, blood pressure, cardiac output and respiration.

Two recent studies suggest that pulse rate (PR) variability analysis, determined from the PPG signal, can be used as a surrogate of heart rate (HR) variability analysis, both in the time and the frequency domain [3, 4]. Given its simplicity, low-cost and that it is widely used in the clinical routine, it would be highly attractive if information on HRT could be inferred from the PPG signal instead of ECG.

The purpose of this study is to investigate whether PR can be used as a surrogate of HR for turbulence analysis.

II. METHODOLOGY

A. *Data set*

The study is based on analysis of the rhythm changes observed during 4131 ventricular premature beats (VPB) of 27 subjects recorded during hemodialysis treatments, intensive care units stays or electrophysiological studies. ECG and PPG signals were acquired in all databases and were interpolated or decimated depending on the recording device in order to obtain a sampling rate of 1000 Hz.

In this work, the ECG signal serves as the “gold standard” for assessing the results of HRT analysis based on Pulse Rate.

B. *Reference annotations for VPB and turbulence criteria*

VPBs were selected based on information in the ECG signals. Following detection of QRS complexes, VPBs were determined by exploring information on rhythm and beat morphology. VPBs were excluded from further analysis when either artifacts, as visually identified, were present in the ECG or the PPG signal, or when other VPBs occurred within the 5 previous or 20 subsequent beats.

Quantification and measurement of HRT was based on TO and TS parameters measured from ECG. TO<0% and TS>2.5 ms/beat where considered normal. According to [1] HRT values were classified into 3 categories: 1) HRT category 0 (c0) means TO and TS are normal; 2) HRT category 1 (c1) means one of TO or TS is abnormal; and 3) HRT category 2 (c2) means both TO and TS are abnormal.

C. *Pulse detection*

The PPG signals were low-pass filtered using a FIR filter with a cut-off frequency of 35 Hz in order to reduce the effect of noise; the filtered signal is denoted $x(n)$. The onset n_{Oi} and the apex location n_{Ai} of the *i-th* pulse were determined as follows:

First, a threshold, γ, is defined in a 10-s running window without overlap as

$$\gamma(n) = 0.15\left(p80 - p20\right)$$

where $p80$ and $p20$ are the 80th and 20th percentile of $x(n)$ within the running window, respectively.

Then the times when the derivative of $x(n)$, $x'(n)$, cross an asymmetric threshold with positive slope $n_{d\max}$ or negative slope $n_{d\min}$ are estimated.

$$n_{d\max} = \arg\max_{n}\left(sign\left(x'(n-1) - 3\gamma(n)\right) - sign\left(x'(n) - 3\gamma(n)\right)\right)$$

$$n_{d\min} = \arg\min_{n}\left(sign\left(x'(n-1) + \gamma(n)\right) - sign\left(x'(n) + \gamma(n)\right)\right)$$

Finally, these times are mapped to PPG signal looking for a maximum or minimum within a 80ms window

$$n_{Ai} = \underset{n \in \{n_{d\max} - 0.04fs, n_{d\max} + 0.04fs\}}{\arg\max} \left(x(n)\right)$$

$$n_{Oi} = \underset{n \in \{n_{d\min} - 0.04fs, n_{d\min} + 0.04fs\}}{\arg\min} \left(x(n)\right)$$

A similar analysis to HR turbulence was carried out for studying PR response to VPB, with the main difference that the beat temporal reference was derived from PPG instead of ECG. Given that the pulse wave of the PPG is less sharp than the QRS in the ECG and therefore, the localization error of the PPG pulse peak is likely to be larger than that of the ECG, the time instant at half the PPG pulse amplitude was considered as the pulse fiducial point in PPG. So the pulse fiducial point, n_{Pi}, is defined as

$$n_{Pi} = \underset{n \in [n_{Oi}, n_{Ai}]}{\arg\min} \left\{ x(n) - \frac{x(n_{Oi}) + x(n_{Ai})}{2} \right\}.$$

Thus, pulse to pulse (PP) interval, $d_{PP}(i)$, was computed for PPG pulses after every VPB as $d_{PP}(i) = n_{Pi} - n_{Pi-1}$.

D. *Clinical study*

To characterize HRT we computed the classical features TO and TS for HR and PR analysis, and denoted as TO_{HR}, TO_{PR}, TS_{HR} and TS_{PR}. Subjects were classified as turbulence or no-turbulence depending on each PR-based feature and in HRT categories (i.e. c0, c1 or c2). Performance measurement for PR analysis was assessed in terms of Sensitivity (*Se*), specificity (*Sp*), and accuracy (*Acc*).

III. RESULTS

Results are shown for all patients with more than 20 VPB, 22 in total. Figure 1 illustrates the average of HR, PR during VPB for four representative subjects, two with turbulence (first two columns) and two without (last two columns). The panels on the top show the classical HR analysis from ECG, whereas the panels on the bottom show the equivalent analysis from PPG, the PR analysis.

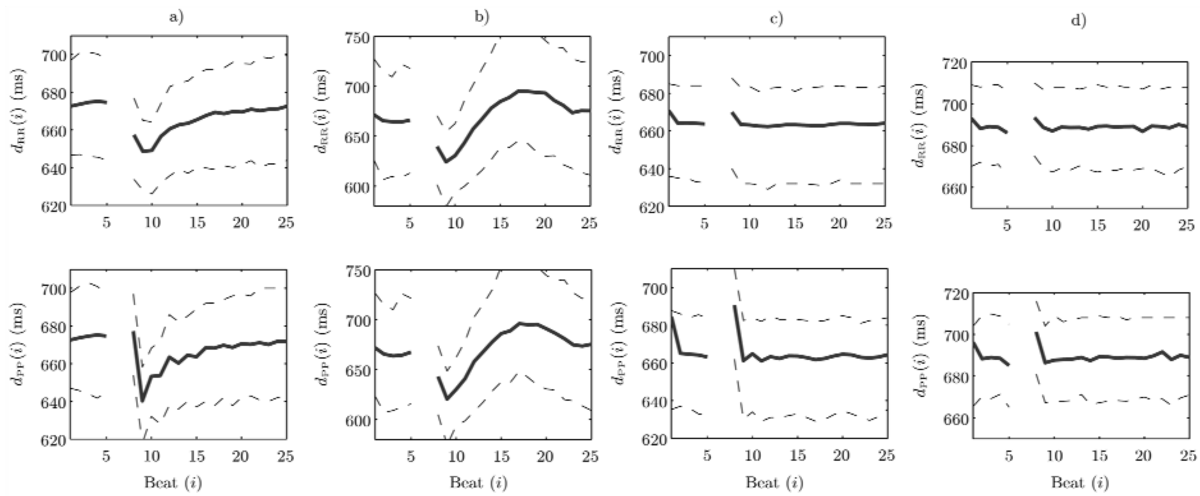

Fig.1. Average (solid line) and percentile 25 and 75 (dashed lines) of HR (first row) and PR (second row) during VPB for four representative subjects (a and b with turbulence, c and d without)

Figure 2 shows TO and TS derived from HR or PR analysis where circle represents c0, asterisk c1 and cross c2 and lines show the thresholds defined for HRT categories.

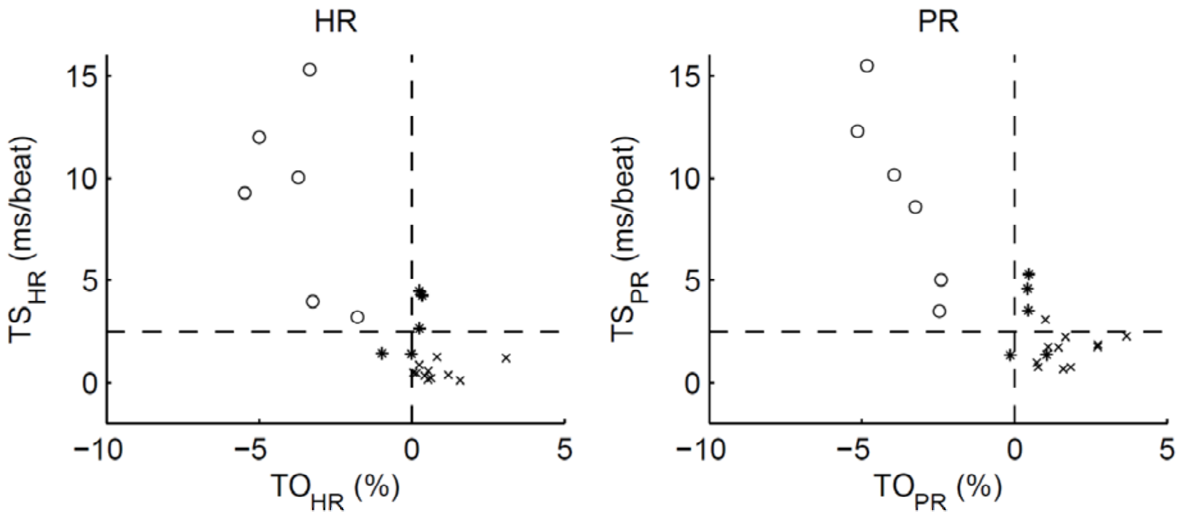

Fig.2. TO and TS derived from HR and PR. Circle represents c0, asterisk c1 and cross c2.

Classification performance and related confusion matrices for PR analysis are presented in Table 1.

Table 1. Clinical results

		TO_{RR} N	TO_{RR} T
TO_{PP}	N	14	1
	T	0	7
	Se	1	
	Sp	0.88	
	Acc	0.95	

		TS_{RR} N	TS_{RR} T
TS_{PP}	N	12	0
	T	1	9
	Se	0.92	
	Sp	1	
	Acc	0.95	

		$TO_{RR} + TS_{RR}$ c0	c1	c2
TO_{PP}	c0	6	0	0
+	c1	0	4	1
TS_{PP}	c2	0	1	10
	Se	1	0.8	0.91
	Sp	1	0.94	0.91
	Acc	1	0.91	0.91
Total *Acc*			0.91	

IV. DISCUSSION AND CONCLUSION

PR response analysis showed results similar to HR. The signal trend in both analysis was similar and the typical turbulence pattern can be appreciated in PR analysis, see Fig. 1.
Note that VPB must be detected from PPG signal, without ECG information, for turbulence detection based on PR analysis. A previous study [5] demonstrated that VPBs can be detected from the PPG signal with an accuracy of 99.3% using a simple linear classifier, so the ECG recording is not needed.

The clinical study showed PR-based features can discriminate subject between turbulence and non-turbulence with an Acc=0.95. Subject can be classified among HRT categories with a total Acc=0.91, getting a perfect classification for c0 (Acc=1).

In conclusion, although an extended study including more subjects would be desirable, our results show that despite some differences between HR and PR exist, PR analysis could be used as surrogate technique for turbulence detection.

Acknowledgements

This work is supported by the Ministerio de Cienciay Tecnologa, FEDER, under project TEC2010-21703-C03-02, by CIBER de Bioingeniera, Biomateriales y Nanomedicina through Instituto de Salud Carlos III, ARAID and Ibercaja under project Programa de APOYO A LA I+D+i, by CAI under Programa Europa, Grupo Consolidado GTC from DGA, and Gambro Lundia AB, Sweden.

References

1. Schmidt G., Malik M., Barthel P., Schneider R., Ulm K., Rolnitzky L., Camm A.J., Bigger Jr J.T., Schomig A.: Heart-rate turbulence after ventricular premature beats as a predictor of mortality after acute myocardial infarction. Lancet 1999, 353, 1390–1396
2. Allen J.: Photoplethysmography and its application in clinical physiological measurement. Physiol. Meas. 2007, 28 R1–39
3. Selvaraj N., Jaryal A.K., Santhosh J., Deepak K.K., Anand S.: Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography. Journal of Medical Engineering & Technology 2008, 32(6), 479–484
4. Gil E., Orini M., Bailón R., Vergara J.M., Mainardi L., Laguna P.: Photoplethysmography pulse rate variability as a surrogate measurement of heart rate variability during non-stationary conditions. Physiol. Meas. 2010, 31, 1271–1290
5. Gil E., Sörnmo L., Laguna P.: Detection of Heart Rate Turbulence in Photoplethysmographic Signals. Computing in Cardiology 2011, 38, 665-668

Address for correspondence:

Dr. Eduardo Gil
C/ María de Luna 1, Ada Byron, 50018 Zaragoza, Spain
edugilh@unizar.es