Sternal Pulse Rate Variability Compared with Heart Rate Variability on Healthy Subjects

Shadi S. Chreiteh, Bo Belhage, Karsten Hoppe, Jens Branebjerg, and Erik V. Thomsen

Abstract— **The heart rate variability (HRV) is a commonly used method to quantify the sympathetic and the parasympathetic modulation of the heart rate. HRV is mainly conducted on electrocardiograms (ECG). However, the use of photoplethysmography (PPG) as a marker of the autonomic tone is emerging. In this study we investigated the feasibility of deriving pulse rate variability (PRV) using PPG signals recorded by a reflectance PPG sensor attached to the chest bone (sternum) and comparing it to HRV. The recordings were conducted on 9 healthy subjects being in a relaxed supine position and under forced respiration, where the subjects were asked to breathe following a visual scale with a rate of 27 breaths/min.**
HRV parameters such as the mean intervals (meanNN), the standard deviation of intervals (SDNN), the root mean square of difference of successive intervals (RMSSD), and the proportion of intervals differing more than 50 ms (pNN50) were calculated from the R peak-to-R peak (R-R) and pulse-to-pulse (P-P) intervals. In the frequency domain the low and high frequency ratio of the power spectral density (LF/HF) was also computed. The Pearson correlation coefficient showed significant correlation for all the parameters ($r > 0.95$ with $p < 0.001$) and the Bland-Altmann analysis showed close agreement between the two methods for all the parameters during resting and forced respiration condition. Thus, PRV analysis using sternal PPG can be an alternative to HRV analysis on healthy subjects at rest.

I. INTRODUCTION

The heart rate variability (HRV) obtained from electrocardiographic (ECG) recordings is a commonly used method that reflects the balance between sympathetic and parasympathetic modulation of the heart rate [1]. HRV is used in many clinical areas especially in the research of diabetes, cardiovascular diseases, and stress management [1]. Predominance of sympathetic activity and reduced parasympathetic cardiac control have been seen in patients with acute myocardial infarction [2]. As a complication of diabetes mellitus, autonomic neuropathy occurs and this often affects the autonomic control of the heart. Pontet et al. [3] reported that a depressed autonomic modulation may be an early indication of deterioration of septic patients in the intensive care unit. This finding was confirmed by Barnaby et al. [4] and in addition they reported that HRV may predict significant morbidity and mortality rates for septic patients in the emergency department.

Currently, HRV parameters are derived by analysis of the temporal relationship between successive heart beats (R-R intervals) in the ECG signal. From these intervals we can compute time and frequency domain, and nonlinear dynamics analysis to extract features to assess the autonomic nervous system (ANS) modulation of the heart rate [1].

A wide range of studies have investigated the use of Photoplethysmography (PPG) to quantify the cardiac autonomic tone as an alternative to ECG. PPG is a low-cost noninvasive optical technique for monitoring beat to beat relative blood volume changes in the microvascular bed of peripheral tissues [5]. The PPG signal contains two components; a small pulsatile component (AC), which corresponds to arterial pulsations from the cardiac cycle. The AC component is superimposed onto a large quasi-DC component that relates to the optical character of the underlying tissue, the ambient light, and the average blood volume. The DC component also varies due to respiration [6]. The morphology of the PPG signal is useful for the study of autonomic control of the peripheral vascular tone [5]. In fact, Wong et al. [7] reported that the PPG signal might have an additional information in regards to cardiac autonomic tone compared to the ECG, because the peripheral vasculature is also modulated by the ANS. The physiological information derived from the R-R intervals can also be derived from the pulse-to-pulse (P-P) intervals of the PPG signal. Studies on pulse rate variability (PRV) have been conducted on the peripheral location of the body, mainly at the fingertip and the earlobe using a traditional pulse oximetry probe [8]. Lu et al. [9] have shown that PRV obtained from a finger can be used as surrogate for HRV. However, Wong et al. [7] reported the opposite finding and reported that it could be due to the pulse wave modification in the arterial system. Constant and colleagues [10] conducted a study on pulse wave recordings on the 3rd finger of the right hand, and showed that the PRV did not precisely reflect HRV in healthy subjects.

In the literature there is a lack of results about the influence of sensor location, when extracting HRV parameters using the PPG. However, Johnston et al. [11] and Schafer et al. [12] reported that an approach to place a PPG sensor on a more central location could be beneficial for the assessment of the cardiac autonomic tone. To our knowledge the PRV has not been investigated at the sternum. Thus, in this study we examine whether the PRV at the chest bone (sternum) can be used as a marker of the cardiac autonomic tone when

The study was supported by the Danish Business Innovation Fund, the Danish Ministry of Science, Innovation and Higher Education.

Shadi S. Chreiteh is with the Department of Micro- and Nanotechnology, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark and also with DELTA Microelectronics, Venlighedsvej 4, 2970 Hørsholm, Denmark (e-mail: ssc@delta.dk).

Bo Belhage is with the Bispebjerg Hospital, University of Copenhagen, 2400 Copenhagen NV, Denmark.

Karsten Hoppe and Jens Branebjerg are with DELTA Microelectronics, Venlighedsvej 4, 2970 Hørsholm, Denmark.

Erik V. Thomsen is with the Department of Micro- and Nanotechnology, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark.

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

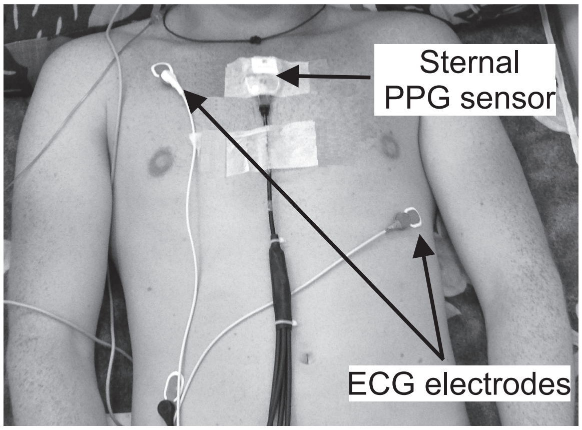

Fig. 1. Placement of the PPG sensor on the sternum. For this controlled experiment the sensor is positioned using adhesive tape.

comparing to traditional HRV in healthy subjects at rest and under paced respiration.

II. Methods & Materials

A. Data acquisition

A group of 9 healthy volunteers (8 males, 1 female) with mean age of 41.1±11.7 years and a mean Body Mass Index of 24.7±3.2 kg/m^2 were recruited for this preliminary study. The Danish Law and the Helsinki Declaration does not require a clinical protocol for this setup. The room temperature was $20-22\,^{\circ}$C. A novel infrared reflective PPG prototype sensor was used to obtain the PPG signals. The sensor was positioned on the skin over the sternum with adhesive tape, cf. Fig 1. ECG electrodes were attached to the subject and used to record standard lead-II ECG signals. All analog signals were collected simultaneously and digitized with a sampling rate of 1000 Hz (Powerlab 8/35, 16 bit ADC, ADInstruments, USA) and stored on a laptop computer using Lab Chart 7 Pro (Lab Chart Version 7.3.7, ADInstruments, USA) as data acquisition software. For each subject being in supine position 10 min recordings has been conducted under natural respiration and under paced respiration frequency of 27 breaths/min. However, a 5 min segment of each recording was used for HRV analysis. The analysis was computed using MATLAB (MATLAB R2012b, The MathWorks, Inc., USA).

B. Heart rate and pulse rate analysis

Prior to the extraction of R-R and P-P intervals, the ECG signals were bandpass filtered using a second order Butterworth filter with cut-off frequencies of 0.05 Hz and 40 Hz. As for the PPG signals the cut-off frequencies were 0.05 Hz and 15 Hz. The QRS detection was performed using Pan and Tompkins QRS detection algorithm [13]. The R-R intervals were extracted from the located R peaks. As for the PPG signals, the systolic peaks were located using a custom made peak detection algorithm, cf. Fig. 2. The systolic peaks were then used to produce the P-P intervals. Fig. 3, shows a P-P and R-R interval from one of the subjects.

To compare the HRV and PRV methods, the commonly used time and frequency domain parameters were computed according to the standard definitions of HRV parameters [1]. As for the time domain parameters, the mean value of the R-R and P-P intervals (mean NN), the standard deviation of NN intervals (SDNN), the square root of the mean of the squares of differences between successive NN intervals (RMSSD), and the pNN50, which is the proportion of differences of successive intervals differing more than 50 ms was calculated. Prior to the frequency domain calculations the R-R and P-P intervals were resampled at 4 Hz and cubic spline interpolated [1]. From the power spectrum density the normalized low frequency (LF) power (0.04-0.15 Hz), the normalized high frequency (HF) power (0.15-0.4 Hz), and the LF/HF ratio has been computed. The time domain parameters are related mostly with the overall variability of the heart rate. The LF components represents the sympathetic and parasympathetic tones, while the HF components is more related to parasympathetic modulation.

C. Statistics

The Pearson correlation coefficient was used to correlate the calculated parameters derived from the ECG and PPG respectively. In addition the lower and the upper limits of agreement (LOA) and the mean system bias between the two methods is compared using a Bland-Altman analysis. Furthermore, the mean squared error is computed between the values of the HRV parameters derived from the R-R and P-P intervals.

III. Results

Fig. 2 shows a 10 seconds segment of a typical recording. The upper graph represents the PPG signal and the lower represents the ECG signal. Fig. 3, shows a time series of R-R and P-P intervals derived from the PPG and the ECG respectively. For all subjects the derived parameters obtained from PRV and HRV are represented in Table I. All the computed parameters derived from the PRV had correlation coefficients of $> 95\%$ (p <0.001) when compared to HRV. The error analysis showed insignificant differences between the parameters derived from the two methods (p <0.05). The Bland-Altmann analysis showed close agreement between the parameters derived from ECG and PPG. During natural respiration the average system bias for the mean NN interval was -0.03 ms and the lower and upper LOA was -0.561 ms and 0.501 ms respectively, cf. Fig. 4. As for the LF/HF ratio, the average system bias was -0.0064 ms and the lower and upper LOA was -0.27 ms and 0.25 ms respectively as seen in Fig. 5. Similarly, high degree of agreement was found for the rest of the parameters under natural respiration. During forced respiration the average system bias increased in the same direction for all parameters. It is also seen in Table I, that the LF/HF ratio increased from 1.045 to 2.99 for HRV and from 1.05 to 2.76 for PRV.

IV. Discussion

The results of this study clearly showed a close agreement between the HRV parameters derived from the PPG signals

TABLE I
THE TIME AND FREQUENCY DOMAIN PARAMETERS, CORRELATION COEFFICIENTS AND BLAND-ALTMANN ANALYSIS DERIVED FROM P-P AND R-R INTERVALS RESPECTIVELY.

	Parameters	HRV (Mean±SD)	PRV (Mean±SD)	Bias	Lower LOA	Upper LOA	Correlation coefficient	Absolute error
Natural respiration	*Time domain:*							
	Mean NN (ms)	1011.49±133.95	1011.52±133.86	-0.03	-0.56	0.5	0.999	0.000
	SDNN (ms)	63.25±34	63.43±34.58	-0.178	-2.50	2.15	0.999	0.0028
	RMSSD (ms)	50.51±41.23	50.64±41.58	-0.132	-5.79	5.53	0.998	0.0026
	pNN50 (%)	21.01±23.65	20.97±23.27	0.041	-5.86	5.94	0.993	0.0019
	Frequency domain:							
	LF/HF	1.045±0.61	1.05±0.65	-0.0064	-0.27	0.25	0.98	0.006
Forced respiration	*Time domain:*							
	Mean NN (ms)	953.34±111.86	953.48±112	-0.13	-1.35	1.07	0.999	0.000
	SDNN (ms)	51.68±23.6	54.74±23	-3.07	-9.09	2.96	0.992	0.056
	RMSSD (ms)	45.12±32.8	53.78±35.68	-8.65	-23.2	5.89	0.98	0.16
	pNN50 (%)	22.5±21.7	29.45±24.62	-6.93	8.83	-22.69	0.95	0.24
	Frequency domain:							
	LF/HF	2.99±1.86	2.76±1.68	0.23	-0.89	1.35	0.95	0.08

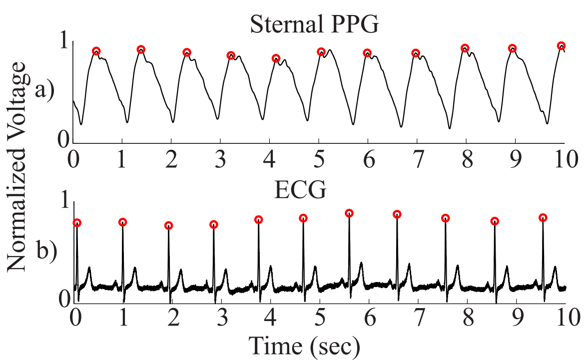

Fig. 2. A characteristic block of signals: (a) The sternal PPG signal. Note the signal waveform is inverted, upside deflection represents the systole. (b) the ECG signal. The circular markers corresponds to the detected peaks.

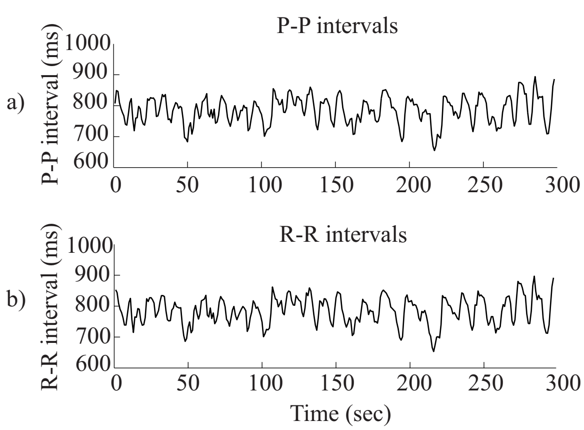

Fig. 3. Comparison of the (a) P-P interval derived from the sternal PPG signal and (b) R-R interval derived from the ECG signal.

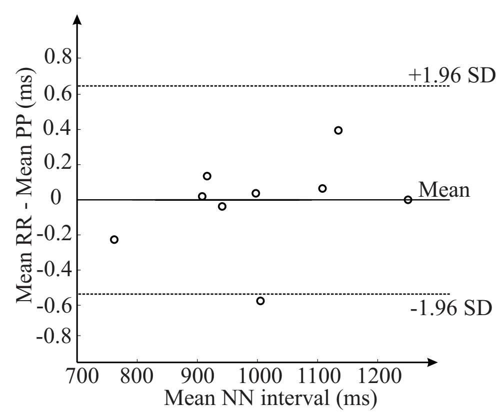

Fig. 4. Bland-Altman plot of the Mean NN derived from the sternal PPG signal and the Mean NN derived from the ECG signal. The majority of points are close to zero and within the 95% confidence interval showing a close agreement between the two methods.

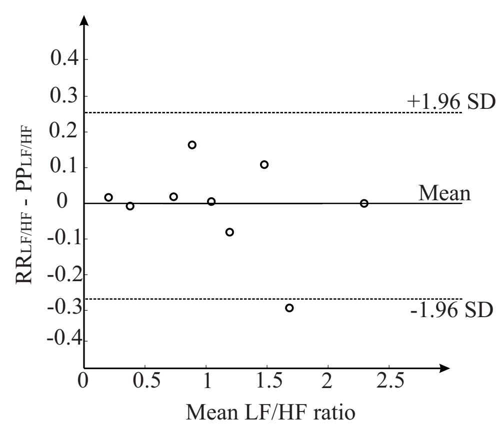

Fig. 5. Bland-Altman plot of the LF/HF ratio derived from the sternal PPG signal and the LF/HF ratio derived from the ECG signal. The majority of points are close to zero and within the 95% confidence interval showing a close agreement between the two methods.

and the ECG signals on a healthy group of subjects at rest and under forced respiration. Although, the average system bias increased between the parameters derived from PRV and HRV, the absolute values changed in the same direction as seen in Table I. The LF/HF ratio derived from PRV increased during forced respiration, confirming that the change in the autonomic tone was also reflected in the PRV as it did in the HRV. The sternal PPG sensor is reliable for recording a PPG signal from, which HRV parameters can be derived, at least in healthy subjects at rest. The morphology of the PPG signal acquired at the sternum has also a clear systolic, end-diastolic and diacrotic notch as seen in Fig. 2. This might be useful for different types of pulse wave analysis since other clinically relevant features may be extracted. As explained in the introduction, recent studies have reported that the use of PPG recordings might be a more convenient method for the measurement of HRV in clinical environments and for ambulatory recordings than ECG. However, there has been a difference in the accuracy between the PRV derived from finger PPG and HRV both at rest and during physical and mental tasks [12]. Furthermore, there is a clear uncertainty regarding the measuring site [12].

We suggest that the reason behind the close agreement of both methods in our study is the proximal measuring site relative to the heart. This is in agreement with Johnson and Mendelson [11], who reported similar correlations between heart rate intervals derived from ECG and reflective forehead PPG. Our findings are also in agreement with [14], who reported high accuracy between the two methods when measuring on the earlobe. Although, the PPG also reflects the cardiac rhythm, the pulse wave and the heart rate are different by nature. The ECG signals are electrical signals originating from the SA node, while the pulse waves are mechanical signals mainly measured in the periphery. The blood vessels can be considered as transmission lines rather than a (rigid) pipe system. So when the pulse waves propagate from the heart to the periphery it undergoes significant changes in the arterial system due to for example the ANS modulation on the blood vessels and the viscosity of the blood. These factors will impact the pulse waveform, resulting in difference between the HRV and PRV. We expect that most of these factors are minimal when measuring at the sternum because of the relative location to the heart. However, it is worth to notice the change in the average system bias and limits of agreements when the subjects were asked to breathe with a rate of 27 breath/min.

It is known that motion artifacts impact PPG signals [5]. Therefore, future perspectives are to examine the correlation between the HRV and the PRV parameters in more demanding conditions like; during different body motion; in different postural positions and in long-term recordings. This can be useful in sleep studies. Additionally, elderly people who suffer from cardiovascular diseases might also be an interesting group to examine the similarities between the two approaches.

The concept of PPG and pulse oximetry at the sternum is has been demonstrated recently by [15]. Our findings showed that the parasympathetic and sympathetic autonomic modulation of the heart rate can be measured from PRV analysis using sternal PPG on a healthy group of subjects at rest. Thus, being able to monitor these physiological parameters using a low-cost sternal PPG sensor will simplify many aspects of monitoring systems.

ACKNOWLEDGMENT

The study was supported by the Danish Business Innovation Fund, the Danish Ministry of Science, Innovation and Higher Education. The authors would like to thank the test subjects who participated in the study.

REFERENCES

[1] A. Camm, M. Malik, J. Bigger, and G. Breithardt, "Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology." *European heart journal*, vol. 17, no. 3, pp. 354–81, 1996.

[2] R. E. Kleiger, P. K. Stein, and J. T. Bigger, "Heart rate variability: measurement and clinical utility." *Journal of the International Society for Holter and Noninvasive Electrocardiology, Inc*, vol. 10, no. 1, pp. 88–101, 2005.

[3] J. Pontet, P. Contreras, A. Curbelo, J. Medina, S. Noveri, S. Bentancourt, and E. R. Migliaro, "Heart rate variability as early marker of multiple organ dysfunction syndrome in septic patients." *Journal of critical care*, vol. 18, no. 3, pp. 156–63, 2003.

[4] D. Barnaby, K. Ferrick, D. T. Kaplan, S. Shah, P. Bijur, and E. J. Gallagher, "Heart rate variability in emergency department patients with sepsis." *Journal of the Society for Academic Emergency Medicine*, vol. 9, no. 7, pp. 661–70, 2002.

[5] J. Allen, "Photoplethysmography and its application in clinical physiological measurement." *Physiological measurement*, no. 3, pp. R1–39, Mar. 2007.

[6] L. M. Nilsson, "Respiration signals from photoplethysmography." *Anesthesia and analgesia*, vol. 117, no. 4, pp. 1–7, Feb. 2013.

[7] J.-S. Wong, W.-A. Lu, K.-T. Wu, M. Liu, G.-Y. Chen, and C.-D. Kuo, "A comparative study of pulse rate variability and heart rate variability in healthy subjects." *Journal of clinical monitoring and computing*, vol. 26, no. 2, pp. 107–14, 2012.

[8] N. Selvaraj, a. Jaryal, J. Santhosh, K. K. Deepak, and S. Anand, "Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography." *Journal of medical engineering & technology*, vol. 32, no. 6, pp. 479–84, 2008.

[9] S. Lu, H. Zhao, K. Ju, K. Shin, M. Lee, K. Shelley, and K. H. Chon, "Can photoplethysmography variability serve as an alternative approach to obtain heart rate variability information?" *Journal of clinical monitoring and computing*, vol. 22, no. 1, pp. 23–9, 2008.

[10] I. Constant, D. Laude, I. Murat, and J.-L. Elghozi, "Pulse rate variability is not a surrogate for heart rate variability," *Clinical Science*, vol. 97, no. 4, p. 391, 1999.

[11] W. Johnston and Y. Mendelson, "Extracting heart rate variability from a wearable reflectance pulse oximeter," *Proceedings of the IEEE 31st Annual Northeast Bioengineering Conference, 2005.*, pp. 157–158, 2005.

[12] A. Schäfer and J. Vagedes, "How accurate is pulse rate variability as an estimate of heart rate variability? A review on studies comparing photoplethysmographic technology with an electrocardiogram." *International journal of cardiology*, vol. 166, no. 1, pp. 15–29, 2013.

[13] J. Pan and W. J. Tompkins, "A real-time QRS detection algorithm." *IEEE transactions on bio-medical engineering*, vol. 32, no. 3, pp. 230–6, 1985.

[14] G. Lu, F. Yang, J. a. Taylor, and J. F. Stein, "A comparison of photoplethysmography and ECG recording to analyse heart rate variability in healthy subjects." *Journal of medical engineering & technology*, vol. 33, no. 8, pp. 634–41, 2009.

[15] J. Solà, O. Chételat, and J. Krauss, "On the reliability of pulse oximetry at the sternum." *IEEE Engineering in Medicine and Biology Society.*