Comparison of HRV Parameters Derived from Photoplethysmography and Electrocardiography Signals*

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Abstract— Heart rate variability (HRV) has become a useful tool in analysis of cardiovascular system in both research and clinical fields. HRV has been also used in other applications such as stress level estimation in wearable devices. HRV is normally obtained from ECG as the time interval of two successive R waves. Recently PPG has been proposed as an alternative for ECG in HRV analysis to overcome some difficulties in measurement of ECG. In addition, PPG-HRV is also used in some commercial devices such as modern optical wrist-worn heart rate monitors. However, some researches have shown that PPG is not a surrogate for heart rate variability analysis. In this work, HRV analysis was applied on beat-to-beat intervals obtained from ECG and PPG in 19 healthy male subjects. Some important HRV parameters were calculated from PPG-HRV and ECG-HRV. Maximum of PPG and its second derivative were considered as two methods for obtaining the beat-to-beat signals from PPG and the results were compared with those achieved from ECG-HRV. Our results show that the smallest error happens in SDNN and SD2 with relative error of 2.46% and 2%, respectively. The most affected parameter is pNN50 with relative error of 29.89%. In addition, in our trial, using the maximum of PPG gave better results than its second derivative.

I. INTRODUCTION

Heart rate variability (HRV) signal is a popular non-invasive marker of the autonomic nervous system and is widely used to assess cardiac health. For heart rate and HRV monitoring applications, ECG is usually measured either with disposable adhesive electrodes attached to torso or with textile electrodes worn on the chest as in traditional heart rate monitors. Both of these electrode types may cause discomfort and inconvenience. ECG signals are mostly affected by different noise and artifact sources. In addition, morphological variations in the ECG signal can affect the recognition of R waves from tall peaked P and T waves [1]. Because of the aforementioned drawbacks, photoplethysmography (PPG) signal has been introduced as an alternative for ECG and is used in some applications such as modern optical wrist-worn heart rate monitors.

PPG signal is often recorded by using a pulse oximeter which emits light to skin and measures changes in light absorption. These pulses do not include high frequency components at the location of the corresponding heartbeats as the ECG does. Although, this may introduce some other

problems such as finding the correct peaks or waves in general or choosing such fiducial points in the peak that gives the best accuracy for the temporal location of the peak relative to ECG R-peaks.

In previous years, many works have been done to understand if pulse rate variability (PRV) can be used instead of HRV. Some of the studies have shown that PRV is a surrogate for HRV [1-6] while in some others the opposite result has been concluded [7-9]. These different conclusions underscore the need to provide more results regarding the problem.

Chiu et al. studied several methods for locating the wave front of the arterial blood pressure signal in [10], which can be directly extended to volumetric PPG signal. In their study, high-fidelity aortic pressure recordings were obtained with a multi-sensor micromanometer catheter. Additionally non-invasive brachial and radial pressure waveforms were measured with external piezoelectric transducers from 11 subjects. The maximum second derivative and the intersecting tangent methods were proven to be the most consistent methods for this task.

In this work, ECG-HRV and PPG-HRV are compared for 19 healthy subjects. Useful HRV parameters are directly presented in this study, which were obtained from PPG and ECG signals for each subject. In addition, two different ways of defining the fiducial points in the PPG signals have been considered for reconstructing of PRV to study which method gives better results.

The outline of the paper is organized as follows. In Section II, the procedure of gathering the signals, analysis, and their parameters are described. The results of comparisons are given in Section III. Finally, some concluding remarks are given in Section IV.

II. METHODS

In order to obtain HRV parameters from ECG signals, interpolation, R wave detection and generating the R-R interval signals are usually performed. The similar procedure can be applied to PPG signals and their second derivatives, which constructs a P-P interval signal for each. These steps are described in following.

All the processing tasks are done in MATLAB (2014b) from MathWorks Inc., Natick, MA, USA. The results of HRV parameters were also verified by Kubios software, which is an open license HRV analysis software developed in University of Kuopio, Finland [11].

A. Database

The signals in this work were measured from 19 subjects with the monitoring system proposed in [12]. ECG and PPG

signals were measured with sampling rate of 250 and 500 samples per second, respectively. The signals were recorded using two different sensor nodes of the wireless body sensor network (WBSN), thus preserving their temporal relation with each other. The resolution of the A/D converters in the WBSN sensor nodes was 16 bits.

All the subjects were healthy male with age of 38.2±13.1. One 5 minute long segment was selected from each recording for the analysis. PPG signals were filtered by a FIR band-pass filter with cut-off frequencies of 0.5 and 10 Hz.

The data collection and preservation has been done according to the principles of World Medical Association's Declaration of Helsinki.

B. Interpolation

To have a better resolution for peak detection procedures a cubic interpolation was applied on the signals. In [13] by using the cubic interpolation a resolution of 1 ms and deviation of ±1 ms was achieved in more than 99% of the RR intervals for the sampling rate of 250 Hz compared to the original 1kHz sampling rate. In our work, all the signals (both ECG and PPG signals) were interpolated to 1000 Hz samples per second.

C. R and Pulse Wave Detection

The detection of R wave fiducial points was done by the widely used algorithm proposed by Pan and Tompkins in 1985 [14]. This method is based on analysis of slope, amplitude, and width of the QRS complex.

The steps of detection include band-pass filtering, differentiation, squaring and integration. By the band-pass filter all the additional frequencies other than QRS frequency band are removed, which results in reducing T wave interference, baseline drift and power line interference. Differentiation and squaring emphasize high frequency components and attenuate non-significant waves. Finally, the moving window integrator produces a signal that includes information about both the slope and the width of the QRS complex.

The peaks of the PPG signals and their second derivatives were detected by scaling the signals, thresholding, local peak detection and removing too close detected points and keeping the larger ones.

All the detected points were double checked visually to make sure that there was no missing wave or false detection. The difference between the locations of the successive detected peaks represents the beat-to-beat interval signal which was then used for the HRV analysis.

D. HRV Parameters

To show the effect of using PPG instead of ECG in HRV analysis, some of the important time domain HRV parameters were calculated. Based on [15] the definitions are as follows

- SDNN: Standard deviation of all RR intervals
- RMSSD: Root mean-square of successive differences of adjacent RR intervals
- pNN50: Percentage of pairs of adjacent RR intervals differing by more than 50 ms.
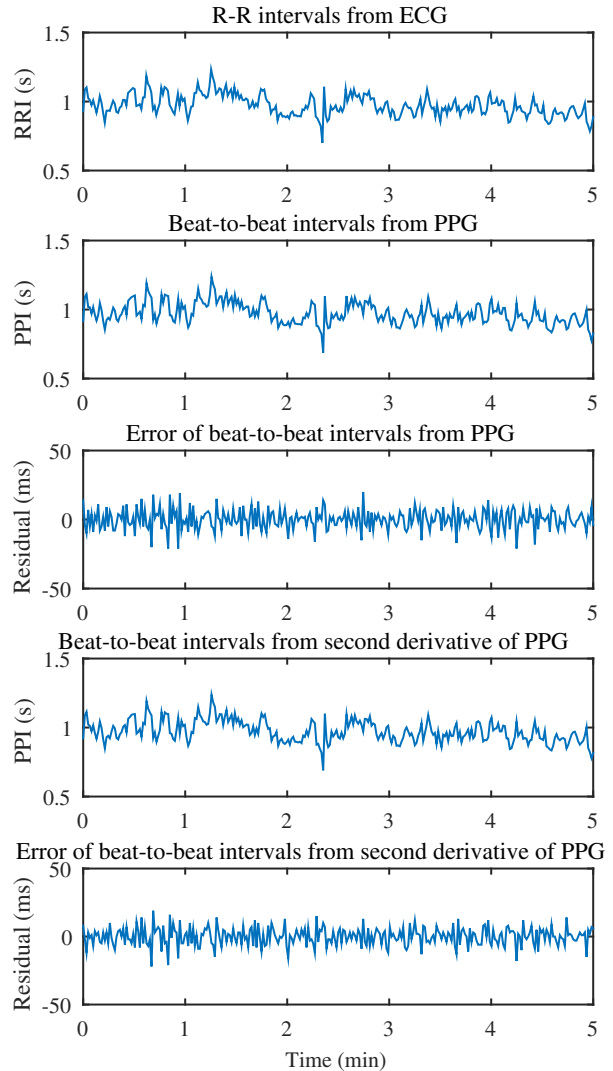

Fig. 1. Peak-to-peak intervals obtained from maximum of PPG and its derivative for subject number 8. The errors of these signals with respect to ECG-RRIs are also illustrated.

- SD1: Standard deviation of data against the axis x = y in Poincaré plot
- SD2: Standard deviation of data against the axis, which is orthogonal to the axis x = y (crosses this axis at the mean value of the data) in Poincaré plot.

Poincaré plots were constructed by plotting the R-R interval signal as a function of itself with a delay of one sample. Poincaré plots were also checked for false detection of R and pulse waves.

III. RESULTS AND DISCUSSION

The HRV analysis results for 19 subjects are presented. One subject was discarded because of poor signal-to-noise ratio of the PPG signal, which resulted in large errors in the heartbeat detection. All the results were verified by Kubios software to make sure about their validity.

Fig. 1 shows the R-R interval (RRI) signal and P-P interval (PPI) signals obtained in two different ways for the subject number 8; one with the maximum of PPG and the other with

TABLE I

HRV PARAMETERS FOR 18 SUBJECTS FROM BEAT-TO-BEAT ANNOTATION OBTAINED FROM ECG, PPG AND ITS SECOND DERIVATIVE (PPG*).

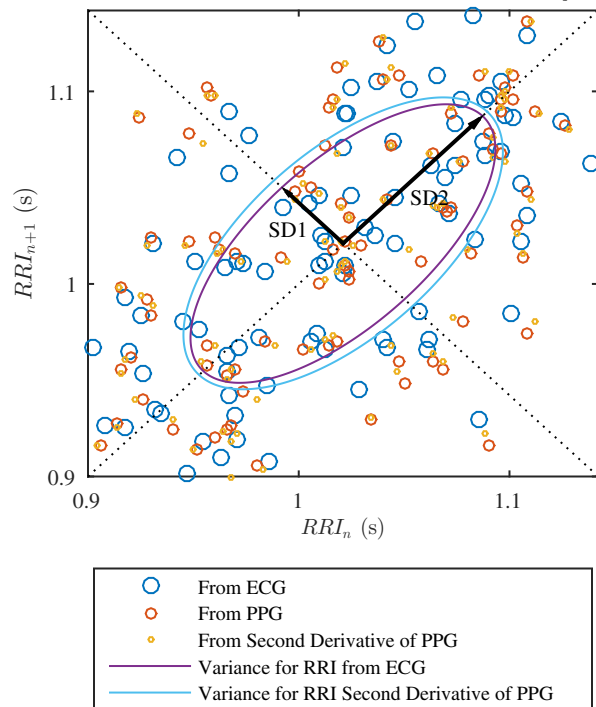|	SDNN (ms)			rMSSD (ms)			pNN50 (%)			SD1 (ms)			SD2 (ms)		
	ECG	PPG	PPG*	ECG	PPG	PPG*	ECG	PPG	PPG*	ECG	PPG	PPG*	ECG	PPG	PPG*
P1	47.34	47.67	48.46	28.45	29.40	31.98	7.55	8.46	12.99	20.15	20.82	22.64	64.04	64.31	64.90
P2	26.20	27.61	28.54	20.48	22.27	24.14	0.61	1.82	1.82	14.50	15.77	17.09	34.14	35.77	36.62
P3	60.26	63.05	63.23	54.47	58.19	57.91	36.14	37.07	38.63	38.58	41.21	41.01	75.94	78.98	79.34
P4	105.69	107.02	108.74	103.52	105.10	108.08	64.96	67.52	70.09	73.35	74.48	76.59	130.91	132.43	134.03
P5	76.82	79.35	82.67	59.95	58.02	64.02	37.39	35.41	41.24	42.45	41.08	45.33	98.73	101.59	105.61
P6	30.95	31.99	32.21	17.82	18.67	18.93	1.21	1.82	1.52	12.62	13.22	13.40	42.00	43.32	43.62
P7	50.66	52.34	51.00	51.79	54.17	52.18	30.56	37.21	32.56	36.71	38.39	36.98	61.63	63.57	62.16
P8	74.75	77.23	77.40	56.43	62.19	61.97	31.49	37.13	37.79	39.96	44.04	43.89	98.09	99.93	100.22
P9	62.48	63.98	64.07	41.24	43.88	42.99	24.63	26.22	25.47	29.21	31.08	30.45	83.42	84.89	85.28
P10	54.41	54.38	55.22	39.40	38.63	40.67	21.21	25.54	25.11	27.92	27.38	28.82	71.97	72.12	72.85
P11	44.44	43.50	47.32	24.60	25.31	31.66	3.04	5.79	11.25	17.42	17.92	22.42	60.57	59.04	63.25
P12	38.08	37.89	39.40	26.32	24.55	27.41	5.39	4.30	6.72	18.64	17.39	19.41	50.57	50.75	52.29
P13	33.04	32.95	33.98	13.80	14.07	15.71	0.00	0.00	0.00	9.77	9.96	11.13	45.74	45.60	46.83
P14	30.18	28.75	31.80	35.39	30.98	39.22	13.21	8.30	20.00	25.07	21.95	27.79	34.73	34.38	35.56
P15	61.05	61.69	62.52	37.42	37.59	38.99	15.71	16.86	18.00	26.50	26.62	27.61	82.09	83.01	83.93
P16	69.36	69.51	70.33	39.66	39.44	41.76	14.68	13.85	18.28	28.08	27.92	29.57	93.93	94.17	94.92
P17	39.43	40.32	40.68	24.57	25.99	26.23	5.19	7.08	5.90	17.39	18.40	18.57	52.62	54.06	54.58
P18	14.06	14.84	14.84	7.49	8.81	8.76	0.00	0.00	0.00	5.31	6.24	6.20	19.20	20.03	20.06

Fig. 2. A part of Poincaré plot for the first 100 samples of R-R intervals for subject 8. The semi-major and semi-minor axes of ellipses represent SD2 and SD1, respectively. Two ellipses belong to R-R intervals from ECG and second derivative of PPG.

maximum of its second derivative. The differences between these two signals and R-R intervals from ECG are also illustrated. The Root Mean Square Errors (RMSEs) for PPG beat-to-beat and the one obtained from second derivative of PPG are 7.096 and 6.579 ms, respectively. Mean Absolute Errors (MAEs) for these signals are 5.538 and 5.238 ms,

respectively. Therefore, there is no significant improvement in the signal obtained from the second derivative of PPG compared to the one resulted from PPG peaks.

Fig. 2 shows the Poincare plots for subject 8. For a better illustration, only the first 100 samples of beat-to-beat interval signals are used in this figure. Two ellipses are related to ECG and second derivative of PPG. The semi-major and semi-minor axes of ellipses represent SD2 and SD1, respectively. It can be seen that there are some samples in which, the results from PPG is closer to ECG-HRV samples than the ones derived from second derivative of PPG.

Table I shows the HRV parameters for 18 subjects. HRV analysis is done for beat-to-beat intervals obtained from ECG, as ground truth, PPG and its second derivative. The relative errors (in percentage) for HRV parameters are shown in Table II. It can be seen that the accuracy of the HRV parameters varies between individuals. In some cases pNN50 is the most affected parameter (e.g. in subjects 2, 8, 12) while in subject 3 pNN50 has less error than rMSSD and SD1. Although, pNN50 has the largest error (can be seen from the mean values) with the mean relative error of 29.89% and 42.75% for beat-to-beat interval obtained from maximum of PPG and its second derivative, respectively. On the other hand, mean of relative errors for other HRV parameters are small. This table also indicates that in most cases the error for HRV parameters from the second derivative of PPG is larger than the error of those derived from PPG, except for a few cases.

IV. CONCLUSIONS

In this work, PPG signal measured from a finger has been studied as an alternative for ECG in HRV analysis. The study is done on 19 healthy male subjects. In addition,

	Method	SDNN	rMSSD	pNN50	SD1	SD2
P1	PPG	0.70	3.33	12.00	3.33	0.42
	PPG*	2.38	12.40	72.00	12.40	1.33
P2	PPG	5.38	8.74	199.98	8.74	4.78
	PPG*	8.92	17.85	199.98	17.85	7.27
P3	PPG	4.63	6.83	2.60	6.83	4.00
	PPG*	4.93	6.31	5.90	6.31	4.49
P4	PPG	1.25	1.53	3.95	1.53	1.16
	PPG*	2.88	4.41	7.89	4.41	2.39
P5	PPG	3.30	3.22	5.30	3.22	2.89
	PPG*	7.62	6.78	10.29	6.78	6.96
P6	PPG	3.34	4.80	50.46	4.80	3.15
	PPG*	4.06	6.21	25.39	6.21	3.86
P7	PPG	3.31	4.59	21.78	4.59	3.15
	PPG*	0.66	0.74	6.55	0.74	0.86
P8	PPG	3.32	10.21	17.91	10.21	1.88
	PPG*	3.54	9.83	19.98	9.83	2.17
P9	PPG	2.40	6.42	6.46	6.42	1.77
	PPG*	2.55	4.25	3.42	4.25	2.23
P10	PPG	0.05	1.94	20.41	1.94	0.21
	PPG*	1.49	3.23	18.37	3.23	1.22
P11	PPG	2.13	2.89	90.58	2.89	2.52
	PPG*	6.47	28.71	270.00	28.71	4.43
P12	PPG	0.51	6.72	20.21	6.72	0.35
	PPG*	3.46	4.14	24.66	4.14	3.41
P13	PPG	0.25	1.95	0.00	1.95	0.31
	PPG*	2.87	13.87	0.00	13.88	2.38
P14	PPG	4.74	12.47	37.14	12.47	1.00
	PPG*	5.35	10.82	51.43	10.82	2.39
P15	PPG	1.06	0.44	7.27	0.44	1.12
	PPG*	2.41	4.18	14.55	4.18	2.24
P16	PPG	0.21	0.57	5.66	0.57	0.25
	PPG*	1.39	5.30	24.53	5.30	1.05
P17	PPG	2.26	5.80	36.36	5.81	2.77
	PPG*	3.17	6.77	13.64	6.79	3.75
P18	PPG	5.54	17.52	0.00	17.52	4.32
	PPG*	5.54	16.93	0.00	16.93	4.46
Mean	PPG	2.47	5.55	29.89	5.56	2.00
	PPG*	3.87	9.04	42.75	9.04	3.16

two different locations for finding the fiducial points are considered in PPG. Some common HRV parameters have been calculated for each method and compared with the ones obtained from ECG to validate the accuracy of PPG based HRV monitoring. In our study, the largest error was obtained for pNN50 parameter with the relative error of 29.89%. The errors for the other HRV parameters were less than 6%.

Choosing PPG for HRV analysis depends on the application and the margins defined for categorizing the status of the person being monitored. In addition, HRV parameters are affected by age, gender and are measure-dependent patterns. These variations might have a different impact on PPG (e.g. changing the pulse transit time by age, because of the variation of the stiffness of the arteries) which may complicate the analysis.

In addition, using second derivative of PPG did not give any better results in our trial; even though opposite results have been reported earlier [10]. This issue probably depends on the subjects and measurement specifications and need further evaluation.

The most important parts of the future work would be evaluation of other ways to define the peak location in the PPG signal and also to evaluate the accuracy of PPG based HRV parameters with elderly as well cardiovascular patients.

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