

Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography

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Heart rate variability (HRV) is traditionally derived from RR interval time series of electrocardiography (ECG). Photoplethysmography (PPG) also reflects the cardiac rhythm since the mechanical activity of the heart is coupled to its electrical activity. Thus, theoretically, PPG can be used for determining the interval between successive heartbeats and heart rate variability. However, the PPG wave lags behind the ECG signal by the time required for transmission of pulse wave. In this study, finger-tip PPG and standard lead II ECG were recorded for five minutes from 10 healthy subjects at rest. The results showed a high correlation (median = 0.97) between the ECG-derived RR intervals and PPG-derived peak-to-peak (PP) intervals. PP variability was accurate (0.1 ms) as compared to RR variability. The time domain, frequency domain and Poincaré plot HRV parameters computed using RR interval method and PP interval method showed no significant differences ($p < 0.05$). The error analysis also showed insignificant differences between the HRV indices obtained by the two methods. Bland-Altman analysis showed high degree of agreement between the two methods for all the parameters of HRV. Thus, HRV can also be reliably estimated from the PPG based PP interval method.

Keywords: Photoplethysmography; Electrocardiography; Heart rate variability

1. Introduction

Heart rate variability (HRV) analysis is a common practice for assessment of the cardiovascular autonomic nervous system. The oscillations present in the beat-to-beat pacing intervals of heart rate are of clinical relevance for both diagnostic and prognostic purposes as they are directly influenced by the sympathetic and parasympathetic systems [1]. Traditionally, time and frequency domain and non-linear methods have been used to interpret the physiological information embedded in the HRV signal. The classical spectral analysis of the HRV signal, generally determined from the sequences of successive inter-beat RR intervals of the ECG signal, enables separation of power distribution in different frequency bands. The low

frequency (LF) band corresponds mainly to sympathetic activity, whereas the high frequency (HF) band is related to respiratory sinus arrhythmia mediated by parasympathetic activity. The LF/HF ratio and LF and HF band powers are good indicators for the assessment of alterations in the nervous system behavior [1,2].

Photoplethysmography (PPG) is a noninvasive optical technique for monitoring beat-to-beat relative blood volume changes in the microvascular bed of peripheral tissues. The PPG pulsatile waveform reflects the fluctuations in finger blood volume and vasculature characteristics. The autonomic influences on spontaneous fluctuations in finger blood volume have been assessed by spectral analysis of the PPG signal [3,4]. The PPG waveform characteristics such as amplitude, baseline and cycle period are useful for the study

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of autonomic control of the peripheral vascular tone [5–8]. As the pulse period of blood volume pulse is directly related to the cardiac activity, the physiological information derived from RR intervals of ECG can also be derived from the pulse period of PPG (figure 1). The PP interval variability of the PPG signal was proven to be reasonably accurate compared to RR interval variability of ECG signal with high correlation [9,10]. The authors suggested the possibility of determining HRV parameters using PPG technique. Selvaraj *et al.* [11] and Bolanas *et al.* [12] have supported the same idea.

Electrical activity of the heart (ECG) is followed by spread of the pulsatile wave of blood to the periphery. The pulse travel time shows very minor (a few milliseconds) beat-to-beat fluctuations [13–15], such that heartbeat intervals derived from ECG and PPG are very similar but they are not exactly the same. Such small variations in the heartbeat interval between the two methods do not appear to be significant in the time domain analysis but may potentially and significantly affect the frequency domain and nonlinear analysis of HRV. This issue has not been addressed in previous studies. In the present study, a comprehensive and systematic analysis of PPG based HRV as compared to ECG based HRV has been conducted to demonstrate the feasibility and reliability of deriving all the traditional HRV parameters from the PPG based method.

2. Materials and methods

Ten healthy subjects (age 21–28 years, nine males and one female) with no history of cardiovascular diseases and hypertension were included in this study. The experimental

protocol was explained to the subjects and written consent was obtained. The protocol was approved by the institutional ethics committee, All India Institute of Medical Sciences, New Delhi, India. The experiments were conducted at Autonomic Function Laboratory, All India Institute of Medical Sciences, New Delhi, India. The subjects were given a resting period of 15 minutes prior to the study.

2.1. Experimental set-up

The photoplethysmograph transducer TSD200 (BIOPAC Systems, Inc., CA, USA), a reflectance type sensor primarily designed for finger attachment, consisted of a matched infrared emitter of wavelength 860 ± 6 nm and a photo diode to detect variation in infrared reflectance resulting from blood flow variation. This transducer was strapped on to the right middle finger of the subject and connected to the PPG amplifier (PPG100C) through a shielded cable to record the blood volume pulse (BVP) waveform with band-pass cut-off frequencies of 0.05–10 Hz and gain of 100. Disposable Ag-AgCl electrodes were used to record standard lead II ECG signal. An ECG amplifier (ECG100C) was used to amplify the ECG signal with band-pass cut-off frequencies of 0.05–35 Hz and gain of 1000. The MP 150 (BIOPAC Systems), a computer-based data acquisition system with software AcqKnowledge[®] 3.8.2, was used to acquire the standard lead II ECG and PPG data simultaneously at a sampling rate of 1 kHz. The data were recorded for a duration of five minutes under relaxed supine condition. The signal processing techniques were implemented offline with Matlab[®] 7.0 (The Mathworks, Natick, MA, USA).

2.2. Data analysis

The recorded ECG and PPG signals were extracted separately. The short-term recordings were free of ectopic beats, missing data and noise. The R wave peaks of the ECG signal were identified and an RR tachogram representing heartbeat intervals was constructed. The following HRV measures were computed from the RR tachogram.

1. Time domain HRV measures: mean normal-to-normal (NN) interval, mean HR, standard deviation of NN interval (SDNN), the square root of the mean squared differences of successive NN intervals (RMSSD), standard deviation of differences between adjacent NN interval (SDSD), the number of interval differences of successive NN intervals greater than 50 ms (NN50) and the proportion derived by dividing NN50 by the total number of NN intervals (pNN50).
2. Frequency domain measures: total band power, normalized very low frequency (VLF), low frequency

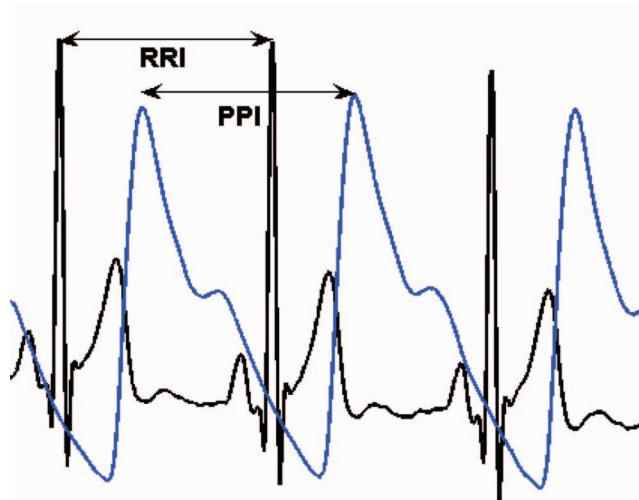


Figure 1. The RR interval (RRI) and PP interval (PPI) representing cardiac beat-to-beat interval extracted from the simultaneously recorded ECG and PPG signals respectively.

(LF) and high frequency (HF) band powers and LF/HF ratio.

3. Poincaré plot measures: short-term HRV (SD1), long-term HRV (SD2) and SD ratio (SD1/SD2).

In frequency domain analysis, the series of RR intervals was cubic interpolated and re-sampled at 4 Hz [2], as RR intervals were non-uniformly spaced according to the heartbeat intervals. The DC component of the HRV signal was removed and then the power spectrum was obtained using discrete Fourier transform (DFT). The HRV power spectrum was divided into three bands: VLF (0.003–0.04 Hz), LF (0.04–0.15 Hz) and HF (0.15–0.4 Hz) to evaluate the sympathetic and parasympathetic activities of the ANS [1]. The Poincaré plot, one of the most accepted techniques of nonlinear HRV analysis, is a diagram which plots each RR interval against the previous interval. The standard deviations of the distances of the HR intervals to the lines $y = x$ and $y = -x + 2 \times \text{mean}$ (RR intervals) were quantified as SD1 and SD2 respectively [16].

The systolic peaks of the PPG signal were identified and a PP tachogram was constructed from the time difference between successive systolic peak instances of PPG signal. The time domain and frequency domain and Poincaré plot parameters were obtained for PP tachogram by the above mentioned procedures used for ECG based HRV analysis. The Pearson correlation coefficient was determined to correlate the beat-to-beat changes of RR interval and PP interval derived from ECG and PPG respectively.

The absolute difference (actual error) between the values of each HRV parameter derived by two methods was calculated for each individual. Then, the overall actual error for each parameter was calculated as mean \pm SD from the group of 10 subjects. The agreement between two methods for every derived HRV parameter was assessed using Bland-Altman technique by GraphPad Prism version 4.00 for Windows (GraphPad Software, USA). Further, paired t -test was used to test any significant difference between each parameter derived from two methods.

3. Results

Figures 2–5 show the HRV parameters derived from ECG and PPG based methods for a representative subject (male, 22 years). A high correlation (0.998) was found between beat-to-beat RR intervals and PP intervals (figure 2). Figure 3 shows a good match between PP tachogram and RR tachogram. Similarly, the HRV power spectrum (figure 4) and Poincaré plot (figure 5) were well matched between the two methods.

For 10 subjects, the mean correlation between RR and PP intervals was 0.87 ± 0.19 with median of 0.97. Table 1 shows the various HRV parameters derived by the two methods. The mean NN interval derived from PP variability was accurate with actual error ~ 0.1 ms

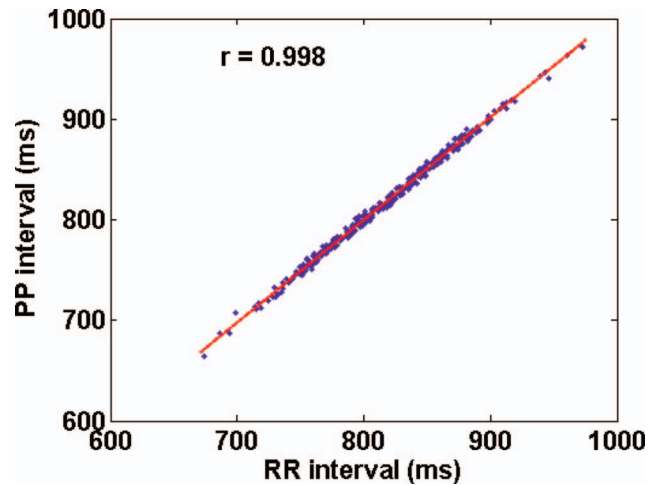


Figure 2. The Pearson correlation coefficient between beat-to-beat changes of ECG-derived RR intervals and PPG-derived PP intervals for a representative male subject of age 22.

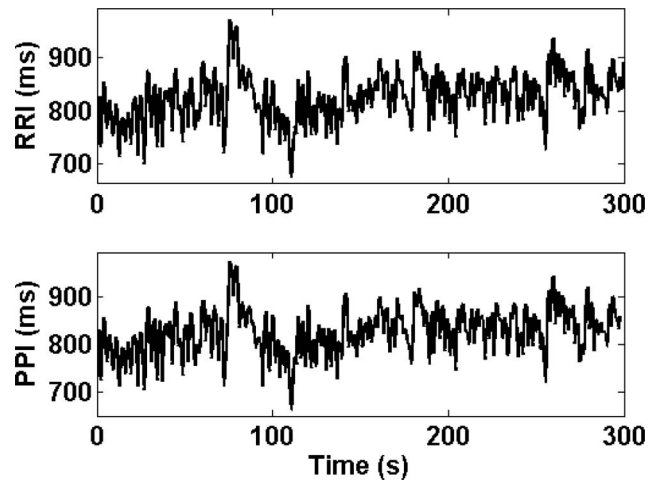


Figure 3. Comparison of tachograms derived from RR intervals (RRI) of ECG signal (top) and PP intervals (PPI) of PPG (bottom) represented in figure 1 after cubic interpolation at 4 Hz. The PP variability matched RR variability all along the time scale.

compared to RR variability. The error analysis also showed insignificant differences between all the HRV indices obtained by the two methods. More over, all the HRV parameters showed no significant difference ($p < 0.05$) between the two methods.

The degree of agreement between two methods was assessed using Bland-Altman analysis (figure 6). The Bland-Altman plot showed the mean difference of NN interval, LF/HF ratio and SD ratio as -0.02 ms, -0.02 and 0.02 respectively and their corresponding 95% limits of

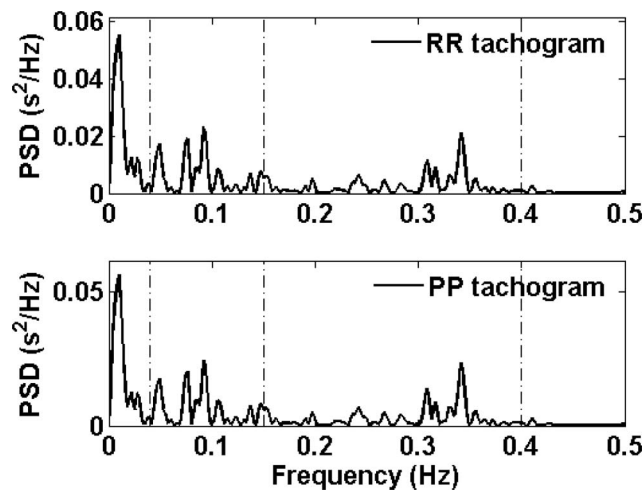


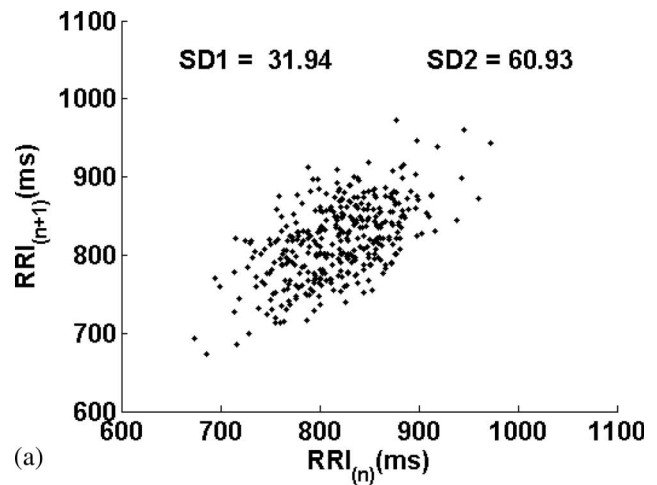
Figure 4. The comparison of discrete Fourier transform based HRV power spectra of RR (top) and PP (bottom) tachograms represented in figure 2. The frequency characteristics of RR and PP tachograms were found to be similar.

agreement were -0.41 to 0.38 ms, -0.12 to 0.09 ms and -0.04 to 0.07 ms, respectively. Similarly, high degree of agreement was found for all the parameters derived by two methods of HRV analysis.

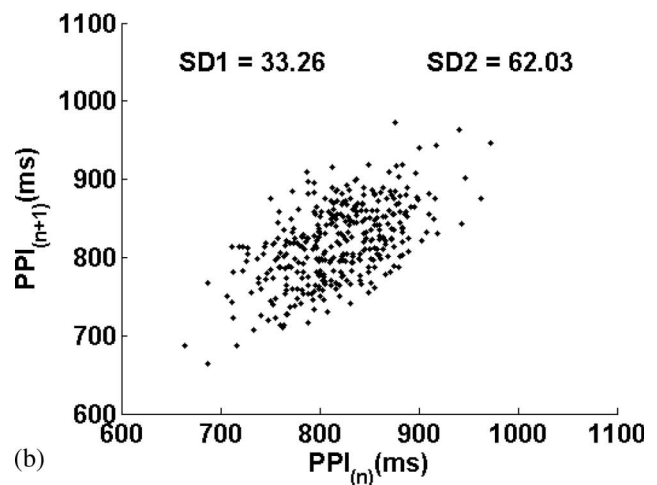
4. Discussion

The results clearly demonstrate an excellent correspondence between the HRV parameters derived by ECG and PPG based methods. A high correlation was found between the beat-to-beat RR interval and PP intervals. This is in agreement with Teng and Zhang [9] and Johnson and Mendelson [10], who reported similar correlations between heart rate intervals derived from ECG and PPG. However, the authors did not derive and compare HRV parameters from the PPG signal with the ECG method. In the present study, a complete HRV analysis as recommended by the task force has been performed and the comparison of derived HRV measures showed insignificant actual errors between the two methods. Further, the Bland-Altman technique demonstrated good agreement between the two methods.

The PP intervals were calculated from systolic peak of PPG waveform. Teng and Zhang [9] used similar method to compute the PP interval. Nitzan *et al.* [5] and Bolanos *et al.* [12] used end-diastolic point and dicrotic notch, respectively, of the PPG waveform to compute the pulse period. From our point of view, changes in the baseline can potentially affect the identification of end-diastolic point and dicrotic notch may not be sharply demarcated in all the subjects. Therefore, a method based on identification of systolic peak is practical and accurate, as shown in the results.



(a)



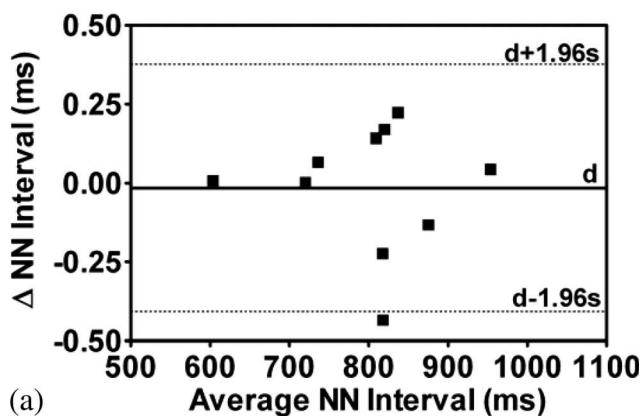
(b)

Figure 5. The Poincaré plot of RR intervals (a) and PP intervals (b) represented in figure 1. SD1 and SD2 are referred to short term and long term HRV respectively.

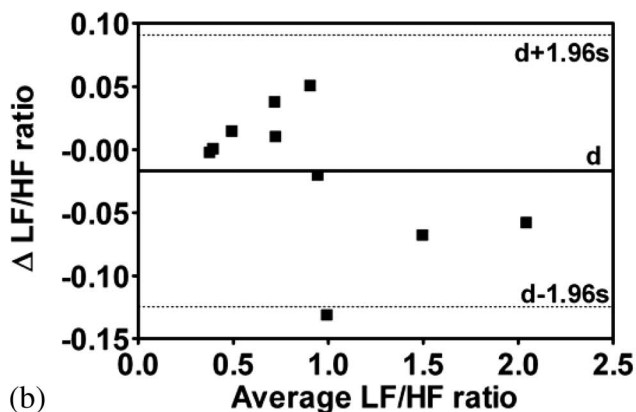
Table 1. The comparison of time domain, frequency domain and Poincaré plot parameters derived from ECG and PPG for group of subjects ($n = 10$) using error analysis.

| Parameters | ECG | PPG | Actual error |
|-------------------------|-------------------|-------------------|-----------------|
| <i>Time domain</i> | | | |
| Mean NN (ms) | 800.0 ± 94.7 | 800.0 ± 94.7 | 0.1 ± 0.1 |
| SDNN (ms) | 52.0 ± 15.8 | 52.4 ± 15.4 | 0.9 ± 0.5 |
| RMSSD (ms) | 49.0 ± 25.0 | 50.3 ± 23.1 | 2.4 ± 1.4 |
| SDSD (ms) | 49.1 ± 25.0 | 50.4 ± 23.1 | 2.4 ± 1.4 |
| NN50 (count) | 45.1 ± 24.5 | 46.2 ± 24.1 | 3.9 ± 2.4 |
| <i>Frequency domain</i> | | | |
| LF nu* | 44.72 ± 13.17 | 44.39 ± 12.43 | 1.93 ± 2.02 |
| HF nu | 55.28 ± 13.17 | 55.61 ± 12.43 | 1.93 ± 2.02 |
| LF/HF ratio | 0.92 ± 0.54 | 0.90 ± 0.51 | 0.04 ± 0.04 |
| <i>Poincaré plot</i> | | | |
| SD1 (ms) | 34.7 ± 17.7 | 35.6 ± 16.4 | 1.7 ± 1.0 |
| SD2 (ms) | 64.4 ± 16.3 | 64.6 ± 16.1 | 1.1 ± 0.8 |
| SD ratio | 0.51 ± 0.15 | 0.53 ± 0.13 | 0.03 ± 0.02 |

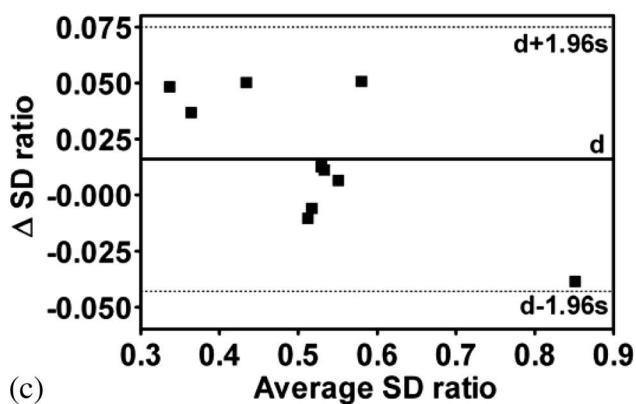
*nu—normalized unit; all the values are mean \pm SD.



(a)



(b)



(c)

Figure 6. Bland-Altman agreement analysis between ECG and PPG methods showed higher agreement of HRV parameters: heart rate interval (a), LF/HF ratio (b) and SD ratio (c). Solid lines indicate mean difference and dotted lines refer to boundaries of 95% limits of agreement.

The PPG pulse is generated due to contractility of the heart and flow of blood from the heart to the peripheral tissue. Thus, the PPG waveform lags behind the R wave of ECG by a time period required for the mechanical activity of the heart and time required for transit of blood to the

peripheral tissue. This lag time is called the pulse transit time (PTT). The PTT shows beat-to-beat fluctuations [13–15] and thus it can potentially introduce errors in the estimation of pulse period and HRV parameters by PPG method. The present results show that the errors are negligible in all the HRV parameters of the PPG method during resting conditions.

Methods other than ECG and PPG have also been used to derive HRV parameters. McKinley *et al.* [17] and Giardino *et al.* [18] used the arterial blood pressure waveform to compute HRV parameters and found it to be reliable. PPG is a simple and highly cost-effective method and it is not subjected to electrical interference and drying and dropping-off of electrodes. Hence, it can be used for long-term recordings with minimal discomfort to patients. Apart from HRV estimation, PPG has been shown to be of clinical utility in measurement of oxygen saturation, cardiac output, arterial compliance, endothelial functions, etc. [19]. Although the ECG based method is the gold standard for estimation of HRV, the PPG based method can also be employed for HRV estimation when it is in use for other applications with patients as single recording procedure.

In conclusion, PPG waveforms can easily be recorded from finger and digitized to compute reliable estimates of HRV. The correspondence between the ECG and PPG derived HRV parameters suggests that PPG based method can be used for estimation of short term HRV and long term monitoring of patients for diagnostic and prognostic purposes.

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