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Title: Comparison of foot finding methods for deriving instantaneous pulse rates from photoplethysmographic signals.

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ABSTRACT

Purpose

The suitability of different methods of finding the foot point of a pulse as measured using earlobe photoplethysmography during stationary conditions was investigated.

Methods

Instantaneous pulse period (PP) values from PPG signals recorded from the ear in healthy volunteer subjects were compared with simultaneous ECG-derived cardiac periods (RR interval). Six methods of deriving pulse period were used, each based on a different method of finding specific landmark points on the PPG waveform. These methods included maximum and minimum value, maximum first and second derivative, 'intersecting tangents' and 'diastole patching' methods. Selected time domain HRV variables were also calculated from the PPG signals obtained using multiple methods and compared with ECG-derived HRV variables.

Results

The correlation between PPG and ECG was greatest for the intersecting tangents method compared to the other methods (RMSE = 5.69 ms, $r^2 = 0.997$). No significant differences between PP and RR were seen for all PPG methods, however the PRV variables derived using all methods showed significant differences to HRV, attributable to the sensitivity of PRV parameters to pulse transients and artifacts.

Conclusions

The results suggest that the intersecting tangents method shows the most promise for extracting accurate pulse rate variability data from PPG datasets. This work has applications in other areas where pulse arrival time is a key measurement including pulse wave velocity assessment.

KEYWORDS

Pulse rate variability, photoplethysmography, foot-finding, pulse wave velocity.

INTRODUCTION

Photoplethysmography, the optical detection of the pulse signal as used in pulse oximeters has a growing base of clinical applications beyond pulse oximetry (16). Recent developments in wearable health monitoring devices have generated renewed interest in the potential capability of photoplethysmography (PPG) sensors (17). Deriving instantaneous pulse rate values from PPG signals is desirable in many applications, not least pulse rate variability (PRV) analysis as a surrogate for heart rate variability (HRV) analysis. HRV analysis is almost universally performed on an ECG-derived instantaneous heart rate (or cardiac interval) time series (1). The ECG signal contains recognizable and reproducible features, most notably the R-wave, produced by depolarization of the ventricular myocardium. Instantaneous, or 'beat-by-

beat' cardiac period values may be obtained straightforwardly from the time interval between successive pairs of R-waves in the recorded ECG and a time series of R-R intervals (RR) from a large number of heart beats analyzed (18). As the R-wave signal has very rapid rise and decay time, it is detectable with very precise time resolution. Also, since nerve impulses travel at high speed, there is no measurable transit time from the source (ventricular myocardium) to the detector (ECG electrode). As a result, even small variations in RR are readily detectable (20).

Acquisition of PPG signals is more convenient and less invasive than ECG and allows the instantaneous pulse period (PP) to be derived, a surrogate for RR interval (9). PRV analysis has been performed in multiple studies using PPG signals recorded from the finger or earlobe and report varying levels of accuracy compared to HRV (2, 4, 5, 7, 8, 15, 21). By comparison to ECG signals, PPG waveforms are characteristically smooth and do not contain a clearly defined and detectable 'landmark' feature. Extraction of an accurate and precise time series from the PPG signal is therefore less straightforward than for ECG, and relies on careful selection of an appropriate method. The effect of the selected method on the accuracy of PP compared to ECG-derived RR, and hence on the reported PRV statistics, has not been described explicitly.

By far the most common method used in PRV studies for finding the PPs is to detect the maximum values of the PPG signal, corresponding approximately with the systolic phases of the cardiac cycle, and to record the time elapsed between successive PPG maxima. The pulse maximum occurs some time after ventricular contraction, when the elastic recoil of the arteriolar wall overcomes the intravascular pressure and the vessel starts to contract. As such the timing of the peak depends on many factors including the arterial stiffness, blood pressure, pulse wave velocity, distance of the measurement site from the aorta etc. An alternative to the PPG peak method is to take the difference between the 'foot-points' of successive PPG pulses.

There is no single definition of the exact position of the foot-point of a pulse wave, however several foot-finding methods have been described (3). These methods include finding the minimum of the pulse wave signal, the maximum gradient, i.e. the maximum 1st derivative, or the 2nd derivative of the pulse wave signal. A slightly more complicated method is the so-called 'intersecting tangents' method whereby two preliminary foot points are found using two different methods (e.g. maximum 1st derivative and minimum value) and the point of intersection of the tangent lines to the signal waveform at each foot point defines a third foot point (6, 10, 13). Other novel methods have also been described, including a 'diastole-patching' technique (19) where the foot point regions of two waves are correlated to find the time difference between the arrival time of the wave.

The aim of the present work is to obtain an objective comparison between instantaneous pulse periods derived from PPG with cardiac periods derived from ECG, the established reference method for heart rate measurement. The methods described above were used to calculate a series of instantaneous PP values from

PPG signals recorded from the ear in healthy volunteer subjects during stationary conditions. The PP values were estimated from consecutive pairs of PPG pulses using each method. The resulting PPG-derived PPs were compared with a 'gold-standard' method: RR values derived from simultaneously recorded ECG signals. Selected time domain HRV variables were also calculated from the PPG signals (obtained using multiple methods) and compared with ECG-derived HRV variables.

As well as applications relating to pulse rate measurement, the foot-finding techniques investigated are also applicable to pulse wave velocity assessment, so this study will be of interest to workers in this discipline. The foot position, and hence the pulse arrival time, of the PPG as well as of other physiological wave signals including blood pressure and ultrasound Doppler waves may be determined using these methods.

MATERIALS AND METHODS

Measurement system

Acquisition of PPG and ECG signals was performed using a 'Zen PPG' dual channel photoplethysmograph fitted with a single channel ECG card, manufactured in the Biomedical Engineering Research Centre at City University London (14). A single PPG channel was used to acquire the infrared signal from a commercial ear pulse oximetry probe (Masimo Inc., Irvine, CA, USA). The PPG and simultaneous ECG signals were digitized using a 16-bit NI USB-6210 data acquisition card (National Instruments Ltd, Austin, TX, USA) using a sampling rate of 1000 Hz per channel. Signals are saved to a tab-delimited text file for analysis using a LabVIEW (National Instruments) virtual instrument.

Experimental protocol

The protocol was approved by the Senate Research Ethics Committee at City University London. Twelve resting subjects (6M/6F, mean ±SD age: *27.2 ± 3.8* years) were recruited from the students and staff of the department. Subjects were seated and a three lead ECG placed on the chest. An ear pulse oximeter probe (Masimo Inc., Irvine, CA, USA) was placed on the right earlobe. Simultaneous ECG and infrared photoplethysmography signals were recorded from each subject while resting and breathing spontaneously. Signals were recorded for period of 15 minutes from each subject.

Signal processing – foot finding.

Signal processing was performed using custom LabVIEW (National Instruments Inc.) and Matlab (Mathworks Inc., Natick, MA, USA) programs. The PPG signals were filtered using a Savitzky-Golay smoothing function with a side-point value of 100 data points (equal to 0.1 s of acquisition time) to remove high frequency noise. Pulses were isolated for each heart beat using a peak detection function, taking the beginning of the pulse as 400 ms before the pulse maximum. A numerical array (the 'pulse array') representing all the 1 kHz samples of the pulse amplitude over one pulse cycle (between 700 and 1000 array

elements, depending on each subject's heart rate) was analysed. The time points of six 'landmarks' in the PPG wave were calculated using the following methods:

1. **Maximum Value (Max.).** the maximum value in the pulse array.
2. **Minimum Value (Min),** the minimum value in the pulse array.
3. **Maximum First Derivative (Max 1st D.),** the maximum positive gradient of the pulse, i.e. the maximum rate of 'upswing' of the pulse wave signal corresponding to the peak velocity of the vessel wall. This is calculated numerically from the maximum positive value of the first derivative of the pulse waveform.
4. **Maximum Second Derivative (Max 2nd D.),** the maximum positive rate of change of gradient, i.e. the maximum vessel wall acceleration. This is calculated from the maximum positive value of the second derivative of the pulse waveform.
5. **Intersecting Tangents (Int. Tan.),** the intersection point of the tangent of the maximum gradient and tangent of the minimum value. Note that the tangent of the minimum value is horizontal by definition, as the gradient at a minimum point is zero.
6. **Diastole patching (Dias. Patch),** the foot region ('patch') of one pulse waveform is superimposed onto the subsequent waveform and the time shift that produces the least error between the two pulses, i.e. the minimum value of the sum of square differences (SSD), indicates the time delay between each pulse.

A set of RRs for each recording were estimated for every pair of successive ECG R-waves, by taking the R-R interval of the ECG. The positions of each R-wave were found from an array of ECG samples using a peak detection function. A set of PPs were derived from each PPG recording by taking the time difference between successive landmark points derived from each method. It should be noted that a constant pulse wave velocity between the aorta and the earlobe over one cardiac cycle is assumed.

Figure 1 shows an example PPG waveform, 1st derivative and 2nd derivatives of the waveform signal. The diagram shows the typical positions of each landmark time point derived from four different methods: maximum value, minimum value, maximum 1st derivative and maximum 2nd derivative. The maximum and minimum values coincide with zero values of the 1st derivative. Figure 2 shows an example PPG waveform illustrating the intersecting tangents method. The time point is the intersection of the tangent of the minimum value, which is horizontal, and the tangent of the maximum 1st derivative of the PPG.

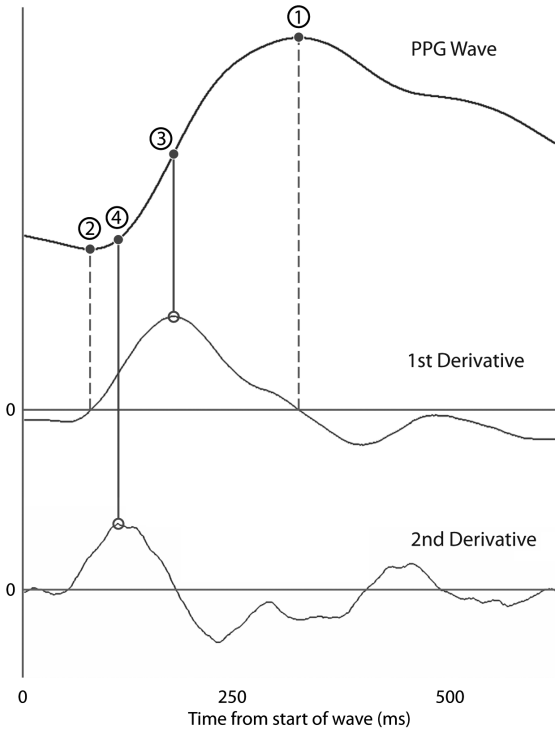


Figure 1 Example PPG waveform, with 1st and 2nd derivatives, showing typical time-points of (1) Maximum value, (2) minimum value, (3) maximum 1st derivative and (4) maximum 2nd derivative.

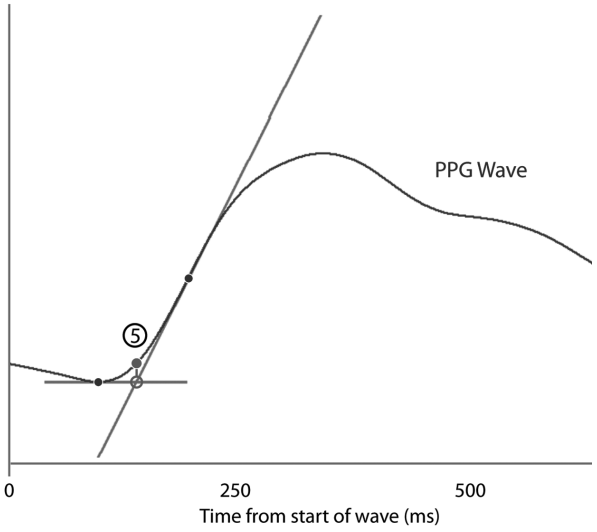


Figure 2 Example PPG waveform illustrating the intersecting tangents method. The time point (5) is the intersection of the tangent of the minimum value and the tangent of the maximum 1st derivative.

A diastole patching method for finding the time difference between two waves is illustrated in Figure 3. The method, developed for estimation of pulse transit times, requires identification of a segment of the foot region of the first wave (the 'patch'). The patch is centered on the minimum value time point and includes the wave signal recorded between the minimum value and the maximum first derivative as well as the signal from an equal time interval prior to the maximum position. The patch is then superimposed with the second wave in a series starting before the foot region and ending after. At each point, the sum of square differences

(SSD) between the patch and the overlapping data points in the second wave is calculated. The point where the SSD has a minimum value gives an indication of the time delay between the waves.

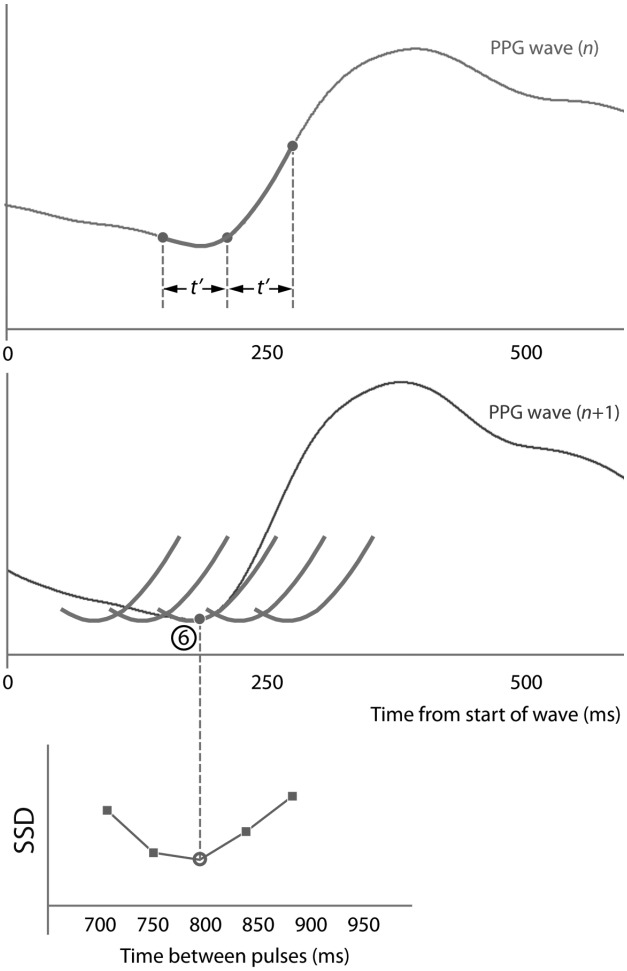


Figure 3 Simulated PPG waveform illustrating the diastole patching method for finding the time difference between two waves. The 'patch' is a segment of the first wave centred on the minimum value time point (Min) and including the wave signal recorded over Min–*t*' and Min+*t*' where *t*' is the time difference between (Min) and the maximum 1st differential (Max 1st Diff.). The derived time point (6) shows the position where the patch and the second wave shows least error when they are superimposed.

Note that the minimum value, maximum 2nd derivative, intersecting tangents and diastole patch time points are usually located near the apparent 'foot' of the pulse wave (they are referred to as foot-finding methods in the remainder of the text), whereas the maximum 1st derivative and maximum value points typically occur later in the cardiac cycle.

Signal processing – data analysis.

Figure 4(a) shows a typical 16-second sample of simultaneously acquired ECG and ear PPG signals. The six sets of PPG-derived PPs, one set for each method, were compared with the corresponding ECG derived RRs for each subject as illustrated by Figure 3(b).

The mean pulse period derived from the PPG using each method was then calculated. The most accurate PPG-derived method of obtaining the PP was determined by calculating the root mean squared error (RMSE) for each PPG-derived set of PPs *vs*. ECG-derived RRs where:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(PP_i - RR_i)^2}{n}}$$

where PP_i and RR_i are the pulse/cardiac periods calculated from the *i*th PPG and ECG pulses respectively in the recording consisting of a total of *n* pulses. The correlation between the PPG methods and ECG, expressed as coefficient of determination (r^2) was also calculated as a secondary method of assessing the accuracy of each method. The Student's t-test was used to test for statistical significance between PP and RR. *P*-values less than 0.05 were considered to be statistically significant.

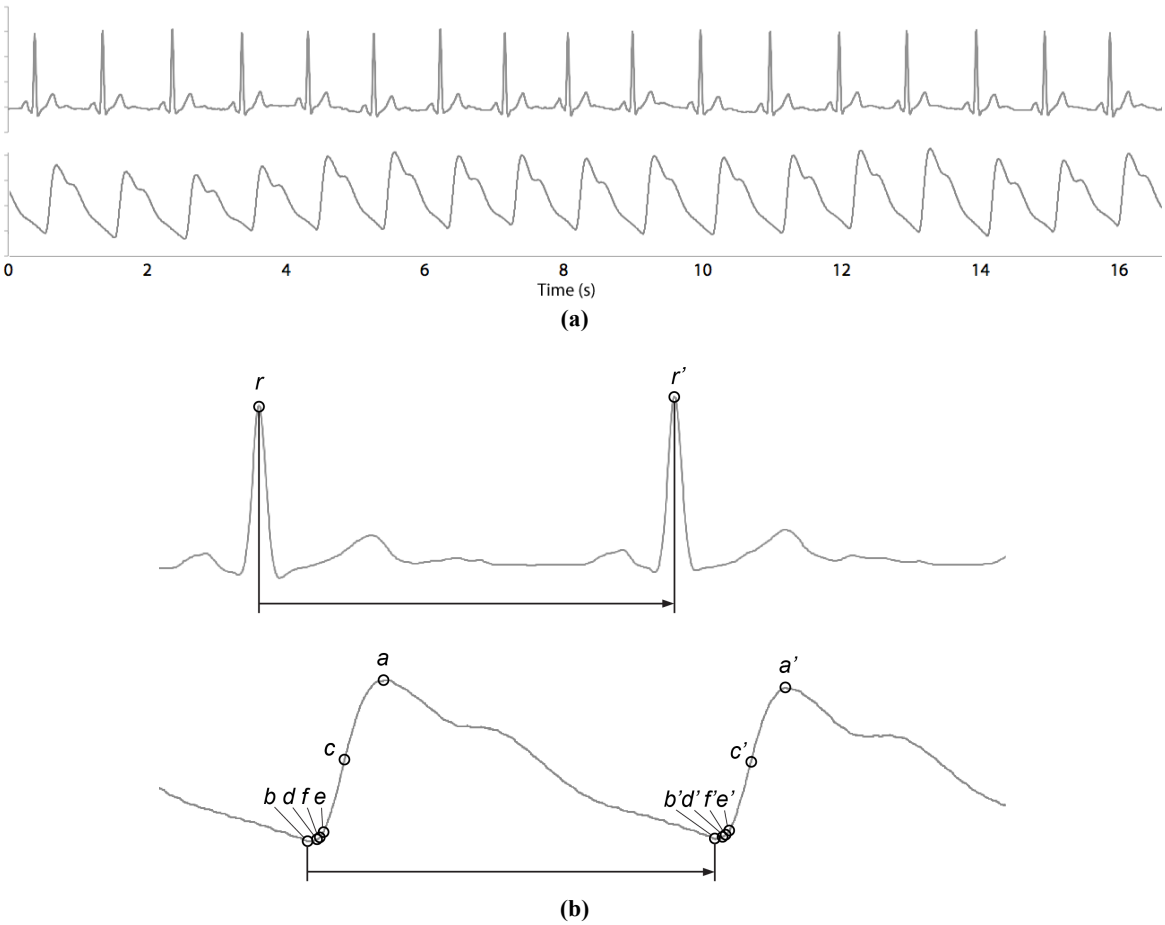


Figure 4 (a) Example of simultaneously acquired ECG and ear PPG signals. (b) Pairs of consecutive ECG complexes and consecutive PPG waves showing *rr*' = ECG-derived RR interval and typical positions of PPG-derived PPs for each of the six landmark finding methods investigated: *aa*' = maximum value; *bb*' = minimum value; *cc*' = max 1st derivative; *dd*' = maximum 2nd derivative; *ee'* = intersecting tangents; *ff*' = diastole patch. For clarity only the PP defined by *bb',* the minimum value method, is indicated.

Using the time series of PPG-derived PPs, the following time domain based PRV variables were derived:

1. SDNN – standard deviation of the PP (equivalent of the 'N-N' interval in HRV studies).
2. RMSSD – root mean square of successive differences in PP.
3. pNN50 – proportion of successive differences in PP greater than 50 ms.

The PPG-derived PRV variables were compared with equivalent ECG-derived variables using statistical tests to infer the most suitable (i.e. the most accurate) method of deriving PPs from PPG for the purposes of PRV analysis. The Student's t-test was used to test for statistical significance between PRV and HRV. *P*-values less than 0.05 were considered to be statistically significant.

RESULTS

Instantaneous pulse periods – all subjects combined

Table 1 shows the mean ECG-derived cardiac periods for the entire dataset recorded from all subjects compared with mean PPG-derived pulse periods. The RMSE and r^2 values are also shown. The mean pulse period derived from the diastole patch method was closest to the ECG-derived mean cardiac period. However, the intersecting tangents method shows the lowest RMSE compared with the reference method (ECG). The results also show that of the six methods, the intersecting tangents method shows the greatest r^2 value, i.e. the best correlation with the reference.

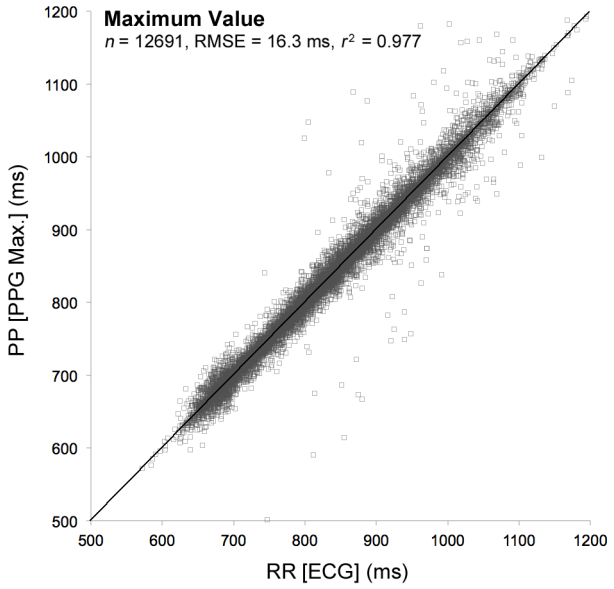
Table 1 Mean ECG-derived cardiac periods calculated from all heartbeats (n = 12,961) recorded in all subjects, compared with mean PPG-derived pulse periods. The mean difference (MD), P-values, root-mean squared errors (RMSE) and coefficients of determination (r^2) between ECG and PPG using each method are also shown.

	ECG	PPG					
		Max.	Min.	Max. 1st	Max. 2nd	Int. Tan.	Dias. Patch
Mean (ms)	834.9370	834.9333	834.9470	834.9383	834.9391	834.9375	834.9370
MD (ms)	-	-0.00370	0.01000	0.00130	0.00210	0.00050	0.00000
t-test (*P*)	-	0.970	0.881	0.964	0.991	0.973	0.906
RMSE (ms)	-	16.3	8.94	6.74	13.5	5.69	10.4
r^2	-	0.977	0.993	0.996	0.984	0.997	0.991

Figure 5(a) shows an X-Y plot of instantaneous pulse periods (PPs) calculated from the time elapsed between the maximum values of pairs of successive PPG pulses against the PP calculated from the simultaneously recorded RR (i.e. the time elapsed between successive ECG R-waves). The plot shows the combined results recorded from all subjects, corresponding to a total of 12,691 heartbeats. Root mean square error (RMSE) and *r*-squared values are also shown on the graph.

Figures 5(b)–5(f) show the corresponding X-Y plots for PPs calculated using the minimum value, max. 1st derivative, max. 2nd derivative, intersecting tangents and diastole patch methods respectively (in all cases

plotted against RR) for all recorded heartbeats. It can be seen from the graphs that good correlation with ECG ($r^2 > 0.97$) is achieved for PPG-derived values using all six methods. The best correlation is seen using the intersecting tangents method ($r^2 = 0.997$). A paired Student's t-test showed no significant differences between RR and PP derived by all six methods ($P > 0.05$).



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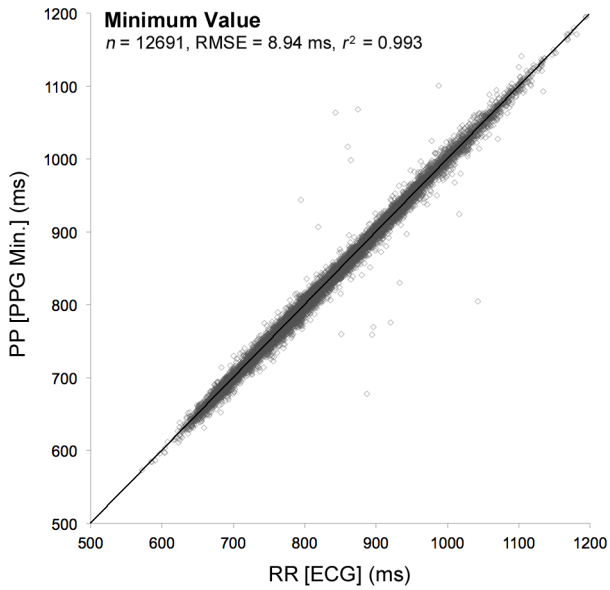

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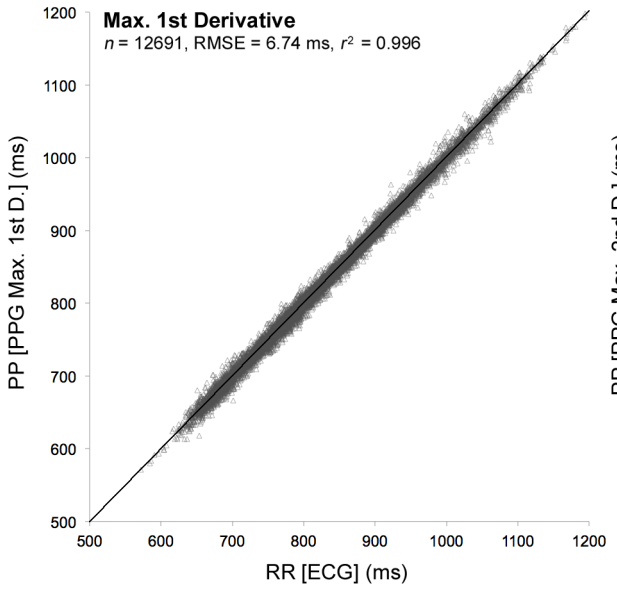

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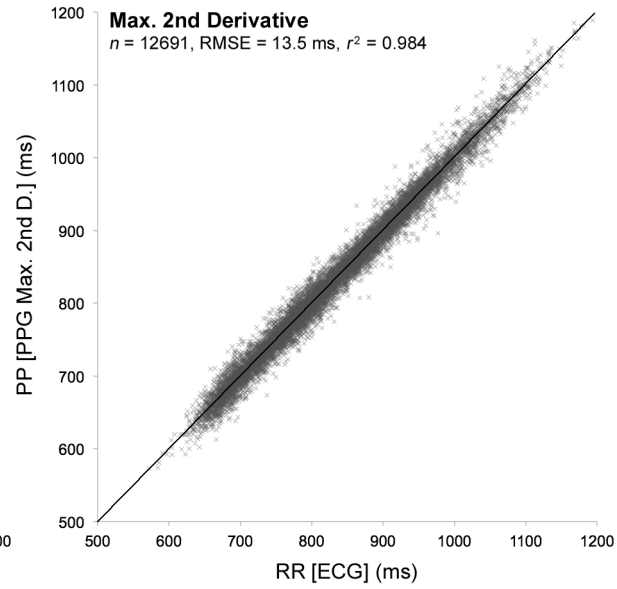

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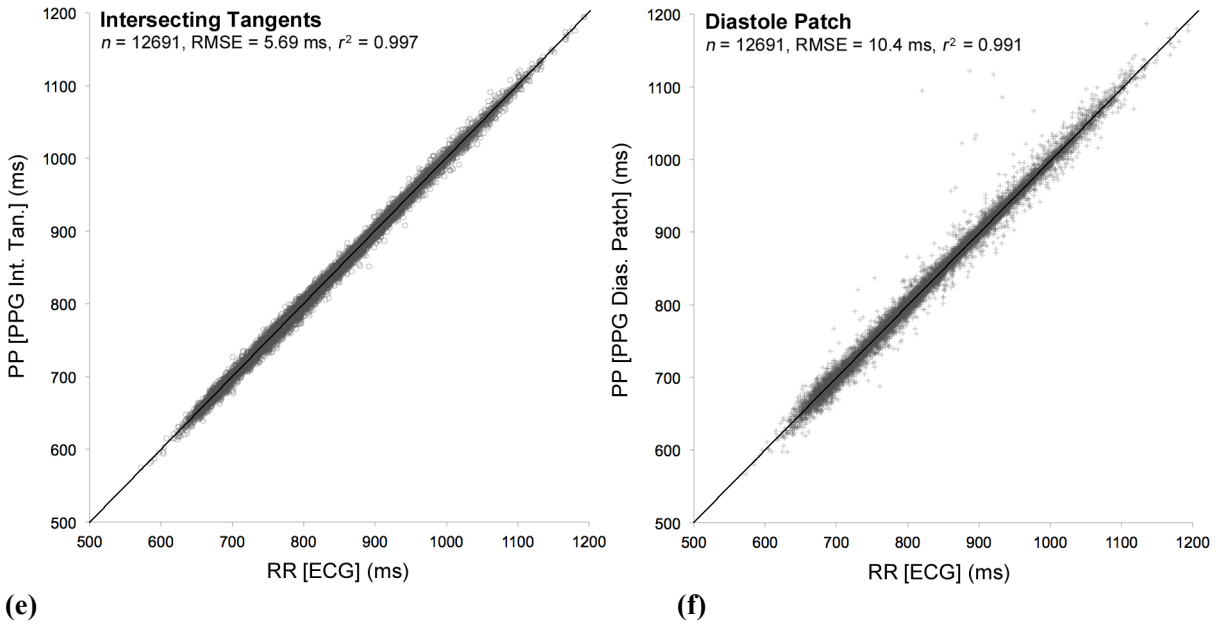

Figure 5 X–Y plots of PPG-derived PP values, against ECG-derived RRs, using six different PPG landmark finding methods: (a) maximum value, (b) minimum value, (c) maximum 1st derivative, (d) maximum 2nd derivative, (e) intersecting tangents and (f) diastole patch. Identity lines are shown on the graphs.

Instantaneous pulse periods – by subject

Table 2 shows mean ECG-derived cardiac periods by subject compared with mean PPG-derived pulse periods. The mean cardiac/pulse periods averaged for all subjects are also shown in the bottom row. It can be seen that the mean PP values agree closely with RR for all PPG methods.

Table 2 Mean ECG-derived cardiac periods (RR) by subject compared with mean PPG-derived pulse periods (PP).

	ECG	PPG					
		Max.	**Min.**	**Max. 1st**	**Max. 2nd**	**Int. Tan.**	**Dias. Patch**
Subject #1	948.082	948.046	948.080	948.084	948.100	948.085	948.673
Subject #2	791.967	791.949	791.963	791.970	791.984	791.973	792.153
Subject #3	690.336	690.367	690.346	690.354	690.356	690.346	690.452
Subject #4	908.778	908.733	908.691	908.796	908.764	908.782	908.030
Subject #5	715.324	715.312	715.326	715.324	715.320	715.325	715.402
Subject #6	956.921	956.889	957.165	956.923	956.878	956.929	956.994
Subject #7	844.326	844.342	844.317	844.317	844.329	844.321	844.481
Subject #8	858.801	858.850	858.803	858.809	858.801	858.808	858.930
Subject #9	915.340	915.360	915.366	915.366	915.368	915.362	914.764
Subject #10	764.946	764.917	764.885	764.871	764.935	764.886	762.826
Subject #11	973.139	973.173	973.156	973.143	973.103	973.149	974.372
Subject #12	773.609	773.582	773.612	773.601	773.622	773.609	773.920
Mean (ms)	834.937	834.933	834.947	834.938	834.939	834.938	834.937

Figure 6(a) shows a graph of the root mean square error (RMSE) between PP values and the reference (ECG-derived mean RR) for each subject, by each of the six PPG methods. Figure 6(b) shows a graph of the correlation, expressed as coefficient of determination (r^2), between PP and the reference. Both graphs show that the PPG-derived PP calculated using the intersecting tangents method provides the closest correlation with ECG derived RR.

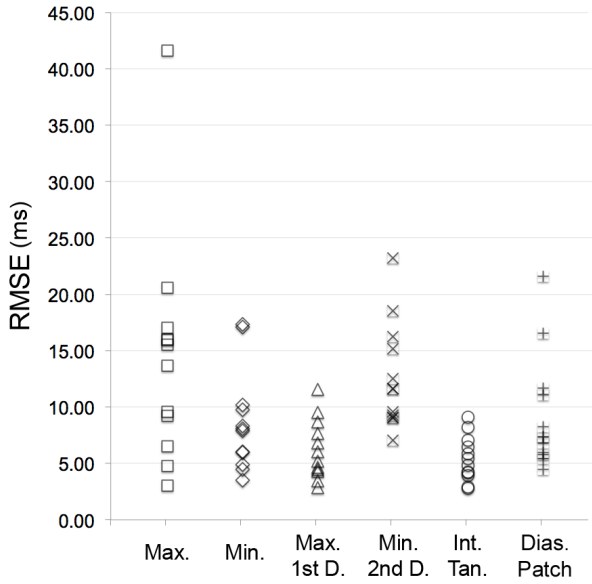

Figure 6(a) Root mean square error (RMSE) between mean pulse/heart rate values and the reference (ECG) for each of the 12 subjects by each of the six PPG methods.

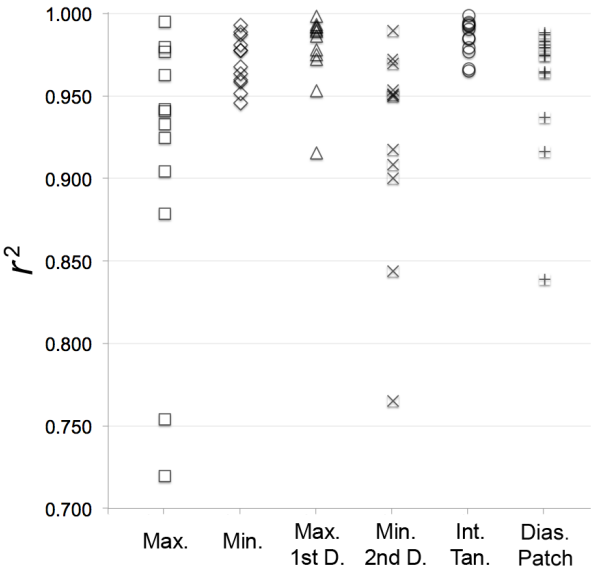

Figure 7 Coefficient of determination (r^2) between mean pulse/heart rate values and the reference (ECG) for each of the 12 subjects by each of the six PPG methods.

Basic PRV analysis

Tables 3-5 show a summary of the PRV analysis of the PPs derived from PPG using all six methods. The ECG-derived HRV parameters are also shown. Values were calculated for each subject and the mean is the average for all subjects. Coefficients of determination (r^2) show correlation between the values for each subject and the ECG-derived value. It can be seen that the mean SDNN values derived using the diastole patching method is closest to the ECG derived mean SDNN. The correlation between PPG and ECG-derived SDNN is greatest for the intersecting tangents method. For RMSSD and pNN50, the intersecting tangents method yields best closeness of mean values and greatest correlation between PPG and ECG derived parameters. There was no significant difference ($P = 0.116$) in SDNN derived from PPG using the PPG maximum method compared to ECG for all subjects as shown by a Student's *t*-test. For all other HRV parameters and PPG methods however, there was a significant difference ($P < 0.05$) between parameters derived from PPG compared to those derived from ECG.

Table 3 Mean SDNN values from PRV analysis for all subjects (n = 12) derived from ECG and the six PPG methods. Mean differences (MD), P-values and coefficients of determination (r^2) between ECG and PPG derived SDNN values are also shown for each PPG method.

SDNN	ECG	PPG					
		Max.	Min.	Max. 1st	Max. 2nd	Int. Tan.	Dias. Patch
Mean (ms)	49.42	50.97	50.70	50.47	52.07	50.39	50.27
MD (ms)	-	1.55	1.28	1.05	2.65	0.97	0.85
t-test (P)	-	0.116	<0.001	<0.001	<0.001	<0.001	0.022
r^2	-	0.9779	0.9990	0.9993	0.9944	0.9995	0.9969

Table 4 Mean RMSSD values for all subjects derived from ECG and the six PPG methods with mean differences (MD), P-values and coefficients of determination (r^2) between ECG and PPG derived RMSSD values.

RMSSD	ECG	PPG					
		Max.	Min.	Max. 1st	Max. 2nd	Int. Tan.	Dias. Patch
Mean (ms)	43.10	48.44	45.69	44.81	49.44	44.47	45.03
MD (ms)	-	5.34	2.59	1.71	6.34	1.37	1.93
t-test (P)	-	0.036	<0.001	<0.001	<0.001	<0.001	0.006
r^2	-	0.9410	0.9975	0.9954	0.9530	0.9975	0.9856

Table 5 Mean pNN50 values for all subjects derived from ECG and the six PPG methods with mean differences (MD), P-values and coefficients of determination (r^2) between ECG and PPG derived pNN50 values.

pNN50	ECG	PPG					
		Max.	Min.	Max. 1st	Max. 2nd	Int. Tan.	Dias. Patch
Mean	0.06063	0.07872	0.06829	0.06655	0.09428	0.06599	0.06703
MD	-	0.01809	0.00766	0.00592	0.03365	0.00536	0.00640
t-test (P)		0.038	0.004	0.017	0.001	0.003	0.025
r^2	-	0.9153	0.9936	0.9941	0.9057	0.9980	0.9652

Figure 7 shows a set of bar graphs showing the bias in PRV parameters (SDNN, RMSSD and pNN50) derived using each PPG method compared to the equivalent parameters derived from the ECG recordings for each of the 12 subjects. For SDNN and RMSSD the percent difference in each parameter from the reference is plotted for each subject, whereas for pNN50 the absolute differences are shown. Coefficients of determination (r^2) are also shown on each graph. The results suggest that the intersecting tangents method provides most accurate measurement of SDNN and pNN50 of the six methods. The intersecting tangents and PPG minimum methods are equally accurate in measurement of RMSSD and more accurate than the other three methods.

DISCUSSION

The results of the studies presented here show that values of the pulse period derived from PPG signals are affected by the choice of derivation method. Although the mean pulse periods agree closely with the mean cardiac period over the 15 minute measurement period, the instantaneous pulse period (PP) showed noticeable variation with instantaneous cardiac period (RR) depending on the PP derivation method. The PPs derived from all twelve 15 minute recordings showed the poorest correlation (RMSE = 16.3 ms, r^2 = 0.977) with the ECG-derived reference RRs when the PPG maximum value method was used. Although the relationship between the PPG signal and vascular mechanics has not been fully elucidated, the position of the PPG maximum or peak is certainly affected by several factors. Assuming that the PPG signal only arises from changes in the volume of the arterioles in the tissue, in this case the earlobe, the peak occurs just after the decreasing intra-arteriolar pressure is balanced by the combination of vessel wall tension and extravascular pressure, the time point when elastic recoil of the arterioles commences. The factors affecting the position of the PPG maximum, i.e. maximum optical absorbance, must therefore include changes in transmural pressure, vascular stiffness and downstream vascular resistance (including venous pooling) from one cardiac cycle to another. The individual PP measurements from each subject also showed that the PPG maximum methods produced the poorest correlation between PPG and ECG of the six methods used. These results suggest that the 'foot' of the PPG wave gives more reliable indication of the timing of the pulse than the peak.

The maximum 2nd derivative method, which corresponds to the maximum rate of increase of arteriolar volume during systolic filling, is positioned approximately at the foot of the wave. Like the maximum value method however, it showed relatively poor correlation with ECG (RMSE = 13.5 ms, r^2 = 0.984). It is difficult to identify a physiological cause of the variation in timing relative to the ECG R-wave, however, unlike the other methods, the calculation of this time point is dependent on two successive numerical derivative functions. Analysis of other signal types has shown that a decrease in signal to noise ratio with increasing derivative order is often seen, which could lead to errors in location of the foot point (11).

The minimum value and maximum 1st derivative methods showed comparable good correlation with ECG. The PPG minimum coincides with the beginning of systolic filling and is affected by downstream flow resistance to a much lesser extent than the peak value. The maximum 1st derivative, the inflection point in the PPG upstroke, corresponds to the point where the rate of vessel filling peaks and begins to slow. The downstream resistance might be expected to have a greater effect on this time point than the 'foot point' methods (Max 2nd D. and Min.), however the results do not support this.

The correlation between PPG and ECG was greatest for the intersecting tangents method compared to the other five methods (RMSE = 5.69 ms, r^2 = 0.997). The accuracy of the method could be attributed to the fact that the position of the time point is determined by two separate events, namely the PPG minimum and the

maximum gradient of the upstroke. Variations in either time point could cancel out to some extent, although of course the exact timing of each event are not completely independent for a given pulse wave.

The basic pulse rate variability analysis produced further evidence that the intersecting tangents method is the more accurate than the other methods. The intersecting tangents and minimum value methods produced equally good correlation with ECG for the RMSSD results. For the other two measurements (SDNN and pNN50), the intersecting tangents method was the most accurate method. Despite this, with one exception, across the 12 subjects there were significant differences in the PRV values derived from PPG compared to ECG for all PRV measurements using all six methods. This was possibly due to the short measurement period; HRV/PWV analysis is usually performed on data acquired for several hours. Further work is needed on a larger dataset to fully evaluate the performance of PPG-derived PRV analysis. It can be seen from the bar graphs in Figure 6 that the differences between PPG-derived PRV and ECG-derived HRV values are generally in the positive direction, i.e. PPG-derived values tended to show greater apparent variability compared to the equivalent HRV variables.

The maximum value and maximum 2nd derivative values overestimated the variability noticeably more than the other methods as shown by greater mean difference for most HRV variables compared with the other methods. No significant differences between PP and RR were seen, however the PRV variables showed significant differences to HRV as shown by a Student's t-test, possibly due to shorter measurement periods than are normally used in HRV analysis. Also HRV variables are sensitive to small variations in cardiac period over short timescales, so the presence of a small number of transient pulses, e.g. caused by movement artifact, could have a strong effect on the reported PRV parameters. Removal of transients prior to analysis would no doubt improve the correlation and would probably be necessary in clinical PRV assessments.

Based on the results presented here, the authors recommend the intersecting tangents method for deriving instantaneous measurements of pulse rate from PPG signals. There is limited work in this area, particularly relating to PRV analysis. Studies comparing PRV with HRV generally focus on the analysis of the pulse period time series and pay little attention to the exact method of derivation of the PP. The majority of such studies (2, 4, 5, 7, 9, 15, 21) are based on PPG measurements from the finger, from which the PPs are calculated from the time difference between pairs of consecutive PPG peaks. The general consensus (2, 5, 9, 15) is that parameters of PPG-derived PRV variables are highly correlated with the equivalent HRV variables, suggesting that PRV could be used as an alternative to HRV, at least for monitoring relatively healthy individuals. In a 2009 study, Lu et al. used earlobe PPG signals, obtaining a very high degree of correlation of pulse period measurements compared to ECG (8).

Constant et al in 1999 (4) compared pulse-derived PRV with HRV and concluded that it does not precisely reflect HRV in the respiratory frequency range in standing healthy subjects and in patients with low HR variability. They suggested that HRV is preferred to PRV, however, when ECG is not available, the distal

pulse wave is an acceptable alternative. Khandoker et al (7) concluded that PRV agrees with HRV under normal breathing in sleep but does not precisely reflect HRV in sleep disordered breathing.

As described in the introduction, the main application of this work is in the area of pulse rate variability analysis, however accurate PPG foot finding techniques could also be applied to measurements of arterial pulse wave velocity (PWV) for assessment of vascular stiffness. PWV measurements require simultaneous measurements from proximal and distal measurement sites and accurate determination of the arrival of the pulse wave at each site.

In 1991, Chui et al. reported one of the earliest computerized methods of foot finding and compared four methods (3). They concluded that the maximum second derivative and intersecting tangents methods were generally more accurate than minimum value and maximum 1st derivative as they yield foot points that are closer to the visible foot of the wave as confirmed by inspection. They did not use a reference technique however to compare the accuracy of each method. Kazanavicius et al. studied several foot-point finding methods applied to the derivation of pulse transit times from arterial pulse wave (not PPG) signals (6). They found that all methods were sensitive to signal noise and studied the effect of applied noise to the signal on the reported foot-points. They concluded that the 2nd-derivative method was most prone to error in clean signals, while an intersecting tangents method produced most errors with noisy signals.

Vardoulis et al (19) compared the minimum value, intersecting tangents, maximum 1st derivative maximum 2nd derivative methods and proposed the diastole-patching method aiming to increase the accuracy and precision in PWV measurement. The results, based on simulated data showed that the diastole-patching method yielded PWV measurements with the highest agreement to the true heart rates. The findings of the work presented here contradicts this, as the intersecting tangents method showed better agreement with HRV.

Some limitations of this work are acknowledged. Firstly the PPG methods assume constant pulse wave velocity between the aorta and the earlobe over the time period of one cardiac cycle, otherwise variations in pulse arrival time at the ear would affect the PPG-derived PP values. Most variations in pulse wave velocity occur over much longer timescales, the shortest being caused by constriction of the arterial smooth muscle as part of the process of blood pressure regulation; this is known to occur over timescales of at least several seconds.

The effects of signal noise and other artifact on the results was not investigated in this study. To facilitate applications in a wide range of environments including the use of wearable sensors, further work is needed to fully evaluate and compare each foot-finding method, including the robustness of the heart rate variables obtained from noisy signals. Previous work has shown that PPG signals from different measurement sites

have markedly different morphology (12) due to physical and physiological differences between sites. An ideal landmark finding method would therefore need to be insensitive to these effects.

In conclusion, the results suggest that of the methods investigated, the intersecting tangents method offers the most accurate estimation of instantaneous pulse period from PPG signals in stationary conditions.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

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Figure Captions

Figure 1 Example PPG waveform, with 1st and 2nd derivatives, showing typical time-points of (1) Maximum value, (2) minimum value, (3) maximum 1st derivative and (4) maximum 2nd derivative.

Figure 2 Example PPG waveform illustrating the intersecting tangents method. The time point (5) is the intersection of the tangent of the minimum value and the tangent of the maximum 1st derivative.

Figure 3 Example PPG waveform illustrating the diastole patching method for finding the time difference between two waves. The 'patch' is a segment of the first wave centred on the minimum value time point (Min) and including the wave signal recorded over Min–*t*' and Min+*t*' where *t*' is the time difference between (Min) and the maximum 1st differential (Max 1st Diff.). The derived time point (6) shows the position where the patch and the second wave shows least error when they are superimposed.

Figure 4 (a) Example of simultaneously acquired ECG and ear PPG signals. (b) Pairs of consecutive ECG complexes and consecutive PPG waves showing *rr*' = ECG-derived RR interval and typical positions of PPG-derived PPs for each of the six landmark finding methods investigated: *aa*' = maximum value; *bb*' = minimum value; *cc*' = max 1st derivative; *dd*' = maximum 2nd derivative; *ee'* = intersecting tangents; *ff*' = diastole patch. For clarity only the PP defined by *bb',* the minimum value method, is indicated.

Figure 5 X–Y plots of PPG-derived PP values, against ECG-derived RRs, using six different PPG landmark finding methods: (a) maximum value, (b) minimum value, (c) maximum 1st derivative, (d) maximum 2nd derivative, (e) intersecting tangents and (f) diastole patch. Identity lines are shown on the graphs.

Figure 6(a) Root mean square error (RMSE) between mean pulse/heart rate values and the reference (ECG) for each of the 12 subjects by each of the six PPG methods. **(b)** Coefficient of determination (r^2) between mean pulse/heart rate values and the reference (ECG) for each of the 12 subjects by each of the six PPG methods.

Figure 7 Bar graphs of difference between PPG-derived and ECG-derived PRV parameters (left column: SDNN, middle column: RMSSD, right column: pNN50) against subject number. Each row of graphs shows results derived using each of the six PPG methods.