Comparison of methods for determining pulse arrival time from Doppler and photoplethysmography signals

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***Abstract*—The aim of this study was to compare three foot-finding methods applied to ultrasound Doppler and photoplethysmographic (PPG) signals: maximum 1st derivative, maximum 2nd derivative and an 'intersecting tangents' method. The pulse arrival times of each method were compared. Also the precision of each method was evaluated by comparing instantaneous cardiac periods derived using each method from simultaneous Doppler and PPG with a reference measurement: the R–R interval calculated from a simultaneously recorded ECG. The results show that the maximum 1st derivative method produced significantly larger pulse arrival times than the other two methods. The intersecting tangents method produced greatest precision for cardiac periods compared with ECG than maximum 1st or 2nd derivatives for both Doppler (r^2 = 0.975) and PPG (r^2 = 0.987) signals.**

I. Introduction

Various noninvasive monitoring techniques including photoplethysmography (PPG) [1] are used for measurement of heart rate as well as more specialized clinical variables such as pulse wave velocity [2–4]. PPG-derived pulse wave velocity has been shown to be a predictor of cardiovascular mortality and morbidity [5] and several commercial medical devices based on the technique are available [6]. Additionally, heart rate variability (HRV) analysis has been performed in multiple studies using PPG pulse signals [7–9] instead of more conventional ECG. Accurate and precise determination of heart rate, arterial pulse wave velocity (PWV) and pulse transit time (PTT) depend on precise measurement at two locations of the arrival time of the pulse wave at a peripheral monitoring site. This is usually defined by the 'foot point' of the incident pressure wave, typically detected by ultrasound Doppler (UD) [10] or photoplethysmography (PPG) probes.

Several foot-finding methods have been described [11] and different methods have been shown to produce different arrival times for a given pulse under identical conditions. These methods include finding the maximum gradient of the pulse wave, corresponding to the peak velocity of the vessel wall (in the case of PPG) or the peak acceleration of blood cells (in the case of UD) and found by taking a numerically computed 1st derivative of the wave signal. An alternative approach is to take the 2nd derivative of the wave signal corresponding to the maximum rate of 'upswing' of the pulse wave signal, or the maximum vessel wall acceleration in the case of the PPG signal. Note that the maximum 2nd derivative usually precedes the point of the maximum 1st derivative in a typical PPG (or Doppler) pulse wave. A third method is to take the minimum of the pulse signal, i.e. the 1st derivative of the pulse is zero (and the 2nd derivative is positive, indicating a minimum). A fourth and more complicated method is the so-called 'intersecting tangents' method whereby two preliminary foot points are found using two different methods (e.g. max 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. Other methods of finding position of the foot point have also been described, for example the '10% maximum method' which is achieved by taking the time point following the minimum value where the signal reaches 10% of its maximum value).

Chui et al. reported one of the earliest computerized methods of foot finding and compared four methods [11]. They concluded that the maximum second derivative and intersecting tangents methods were probably 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 had no method however of comparing the precision of each method.

Kazanavicius et al. studied several foot-point finding methods applied to the derivation of pulse transit times from arterial pulse wave (APW) signals [12]. 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 methods produced most errors with noisy signals. The most accurate results for all signals was found to be a novel 'foot approximation' method whereby a curve is fitted to a region of the curve using a least-square method and the foot of the curve is used as the correct foot-point.

As different methods seem to produce different results, i.e. estimates of heart rate or pulse wave velocity, then selection of the most suitable method for a particular study is important, however most published studies largely overlook the actual selection of foot finding method. The aim of this study was to obtain an objective comparison between three methods of finding the foot point of Doppler and PPG waveforms recorded in healthy volunteer subjects. Firstly the pulse arrival times were compared for each foot-finding method. Secondly the cardiac period estimated from the Doppler and PPG waves using each foot-finding method were compared with cardiac periods derived from ECG signals.

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II. MATERIALS AND METHODS

A. Data recording

The study protocol was approved by the Senate Research Ethics Committee at City University London. Radial artery ultrasound Doppler signals were recorded from the left wrist using a 5 MHz Dopplex MD1 handheld ultrasound Doppler monitor (Huntleigh Healthcare Ltd., Cardiff, UK) for 4 minutes from six resting healthy volunteers (3M, mean age 33.0y). Simultaneous PPG signals from the left forefinger were recorded using a custom made PPG system and ECG signals recorded using a custom-made bio-potential amplifier circuit. Analog signals from the three monitoring devices were sampled using 1 kHz per channel sample rate into a National Instruments USB-6009 data acquisition card (National Instruments Inc., Austin, TX, USA). The signals were recorded using a LabVIEW (National Instruments Inc.) virtual instrument and archived for later analysis.

B. Foot-point finding methods

All signal processing was implemented using a dedicated LabVIEW virtual instrument. The signals were filtered to remove high frequency noise using a Savitzky-Golay smoothing filter using 40 consecutive points of a 3^{rd} order polynomial function fitted to the signal at each sample point. Individual pulse waves were identified using a peak detection algorithm. The foot points at the position of the maximum first and second derivatives were found for each pulse using a numerical derivative function.

The foot points defined by intersecting tangents method were found for each pulse as follows. The tangent of the downstroke of the pulse wave was found using a linear regression fit to 60 sample points prior to the minimum point of the waveform. The tangent of the wave at the point of the maximum gradient of upstroke (the maximum first derivative) was then found. The foot point was then defined as the intersection point of the two tangents.

C. Comparison of pulse arrival times (PATs).

The pulse arrival times (PATs) found using each foot-point finding method were compared by taking the time difference between the ECG R-wave and the following foot-points of the pulse waves as shown in Fig. 1. As the PPG signals were derived from a more distal site than the Doppler signals, PATs found using each foot finding method were only compared for one modality at a time (either Doppler or PPG), not between modalities. The mean PATs were averaged for all subjects. Significant differences in PAT were tested for using a Students t-test on pairs of PATs derived using each foot-finding method.

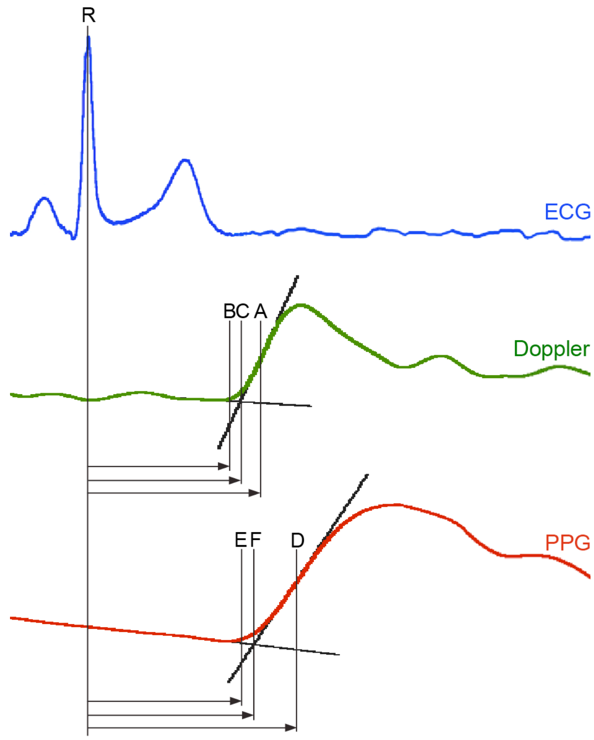

Fig. 1. Pulse arrival times (PATs) were measured for each Doppler pulse (middle trace) by taking the time difference between the ECG R-wave (upper trace) and the following foot-point of the pulse wave defined by three methods: *max. 1^{st} der.* (RA), *max. 2^{nd} der.* (RB) and *int. tan* (RC). The corresponding PATs for the PPG pulses (lower trace) are RD, RE and RF respectively.

D. Comparison of cardiac periods.

The cardiac periods were calculated for each heart beat from successive pairs of Doppler and PPG pulses using the maximum first derivative (*max. 1^{st} der.)*, maximum second derivative (*max. 2nd der.*) and intersecting tangents (*int. tan)* methods. Instantaneous ('beat-by-beat') cardiac intervals were calculated from the time interval between foot-points of successive Doppler and PPG pulses, found by each of the three foot-finding methods (see Fig. 2). The cardiac intervals were compared with those obtained from successive pairs of R-waves in the ECG signal (as the R-R interval is considered a 'gold-standard' method of heart rate measurement) using statistical correlation, namely linear-regression (r-squared) and root mean square error (RMSE) methods.

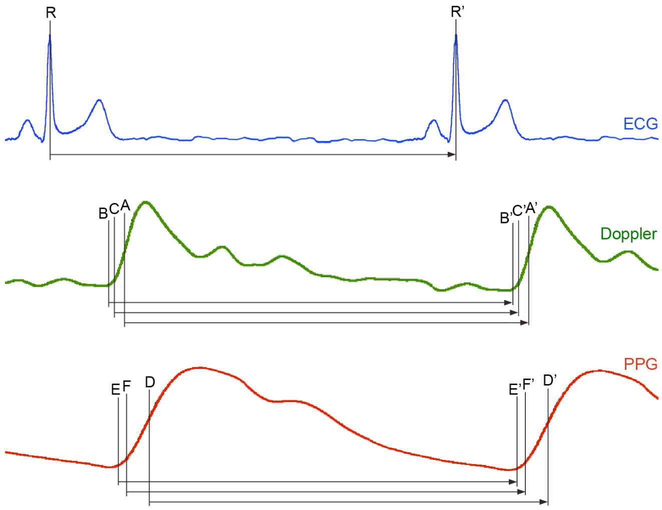

Fig. 2. Instantaneous cardiac periods were measured for each Doppler pulse (middle trace) by taking the time difference between successive pairs of foot-points of the pulse wave defined by three methods: *max. 1st der.* (AA'), *max. 2nd der.* (BB') and *int. tan* (CC'). The corresponding cardiac periods for the PPG pulses (lower trace) are DD', EE' and FF' respectively. The reference cardiac period was derived from pairs of ECG (upper trace) R-waves (RR').

III. Results

A. Comparison of pulse arrival times (PATs)

Fig. 3 shows the mean (±SD) PATs for Doppler and PPG signals relative to the ECG R-wave for all pulses recorded in all six subjects. The pulse arrival times calculated from the position of the foot defined by the *max. 2nd der.* method were shortest for both Doppler and PPG signals. The intersecting tangents method produced slightly longer PATs for both Doppler and PPG compared with *max. 2nd der.* Finally, *max. 1st der.* produced significantly longer PATs for both Doppler and PPG compared to *int. tan* ($P < 0.001$ for *int. tan. vs* both other methods).

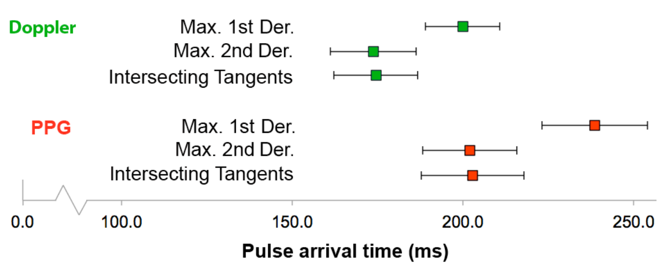

Fig. 3. Mean (±SD) pulse arrival times (PATs) for Doppler (top) and PPG (bottom) signals averaged for all six subjects.

B. Comparison of cardiac periods

Table I shows root-mean-square error (RMSE) and correlation coefficient (r^2) values between Doppler-derived and ECG-derived cardiac periods, averaged for all subjects (n=6). The results show that all methods produce good correlation between Doppler-derived and ECG-derived cardiac period. However the intersecting tangents method applied to the Doppler signals produced better correlation (lower RMSE and higher r^{-2}) with ECG-derived cardiac period than the maximum 1st and maximum 2nd derivative methods.

TABLE I. Root Mean Square Error (RMSE) and R-squared correlation between cardiac periods estimated from successive pairs of Doppler pulses and from successive pairs of ECG R-waves. Values shown for each foot-finding method averaged for all subjects.

	Doppler	
	RMSE (ms)	r^2
Max. 1st derivative	10.1	0.955
Max. 2nd derivative	11.9	0.928
Intersecting tangents	7.57	0.975

Table II shows the same data for PPG-derived cardiac periods and shows that the intersecting tangents method applied to PPG signals also showed better correlation with ECG than the maximum 1st and maximum 2nd derivative methods.

TABLE II. Root Mean Square Error (RMSE) and R-squared correlation between cardiac periods estimated from successive pairs of PPG pulses and from successive pairs of ECG R-waves averaged for all subjects.

	PPG	
	RMSE (ms)	r^2
Max. 1st derivative	6.50	0.981
Max. 2nd derivative	9.27	0.960
Intersecting tangents	5.57	0.987

IV. Discussion

The maximum 1st derivative method produces estimates of the arrival time of the pulse wave that are significantly longer than for the other two methods (for both Doppler and PPG signals). Examination of a 'typical' Doppler or PPG wave shows that the steepest part of the upstroke occurs at an inflection point roughly halfway between the minimum and maximum amplitudes (as shown clearly in Fig. 2). In practice this delay would not in itself affect estimates of either pulse wave velocity or heart rate; in the former case, the reported values are time differences between the foot points of similar pulse waves measured at two sites, and in the latter case, differences between foot points of successive pulse waves. The pulse arrival times do not therefore suggest that one method is superior to another, but the differences seen between methods are significant and are therefore of interest.

The difference in time between the arrival of the pulse wave at the radial artery (measured by Doppler) and the finger (PPG) was clearly apparent from the results of all three foot finding methods. This suggests that pulse wave velocity could be determined with reasonable accuracy using a pair of sensors separated by a small distance only (e.g. 10-15 cm).

The difference in cardiac periods highlight the relative suitability of each foot point finding method to clinical applications, namely determination of pulse wave velocity and heart rate (including heart rate variability analysis). The experimental data presented here shows that the intersecting tangents method potentially offers more precise estimation of foot position than maximum first or second derivatives for both Doppler and PPG signals. The results therefore suggest that the intersecting tangents method would offer more accurate and precise estimation of pulse wave velocity and heart rate variability in the clinical setting than the other methods. It should be noted that the experiment assumes that the pulse wave velocity is constant for the duration of one cardiac period (< 1 s in most cases). It is interesting to note also that the intersecting tangent and the foot approximation method favorably described by Kazanavicius et al. [12] are both derived from more than one point on the waveform, whereas the 1st and 2nd derivative foot-points are defined by a single point.

Despite this conclusion, the choice of an appropriate foot-finding method for use in clinical applications should be made very carefully. In the case of heart rate measurement, successive beats are compared, so the morphology of the pulse waves is largely consistent (neglecting movement-induced artifacts or ectopic beats). However pulse wave velocity measurements rely on comparison of pulse signals measured at two sites, sometimes leading to large differences in amplitude and morphology of the waveforms. These differences are likely to shift the position of the foot-point of each wave regardless of the foot-finding method chosen. Furthermore the work presented here does not include any investigation of the possible effects of noise and artifacts on the derived foot-points. The study was conducted in healthy volunteers only, so the effect of pathologies such as stiff arteries were not investigated. The study was also limited by the sample size, so further studies in a larger and more diverse population is planned.

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