

Pulse wave transit time measured by imaging photoplethysmography in upper extremities

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Abstract. We describe highly reliable measurement method of the pulse wave transit time (PWTT) to human limbs by using simultaneous recordings of imaging photoplethysmography and electrocardiography. High accuracy of measurements was achieved by access to a larger number of statistically independent data obtained simultaneously in different points. The method is characterized by higher diagnostic reliability because of automatic selection of the regions less affected by environmental noise. The technique was tested in the group of 12 young healthy subjects aged from 21 to 33 years. Even though PWTT in right and left hands was comparable after averaging over the whole group of subjects, significant difference in the time delay of pulse wave between the hands was found in several individuals. The technique can be used for early-stage diagnostics of various vascular diseases.

1. Introduction

Pulse wave velocity (PWV) is an important indicator of arterial stiffness in clinical practice [1]. Moreover, PWV is a marker of cardiovascular risk in hypertensive patients [2] and in diabetics [3]. Pulse wave transition time (PWTT) is a parameter to be measured for assessment of PWV. It can be defined as a time taken for arterial pulse pressure wave to travel from the aortic valve to the peripheral site of the body. Inaccuracy of PWTT measurements affects reliability of medical diagnostics. Development of new, noninvasive, easy for practical use, and cost-efficient methods for measuring this parameter is important for obtaining vital information related to arterial conditions, which can contribute to further improvement of the diagnostic potential of this important parameter. In this paper, we study feasibility of PWTT measurements by imaging photoplethysmography (IPPG) of high spatial resolution [4] simultaneously applied with electrocardiography (ECG). The method possesses higher accuracy of PWTT estimation owing to joint analysis of two-dimensional data obtained with IPPG. In addition, PWTT measured in right and left hands of the same subject was compared.

2. Subjects and methods

2.1. Participants

Twelve apparently healthy volunteers (3 women and 9 men) participated in the experiment. Age of subjects ranged from 21 to 33 years. The study was conducted in accordance with ethical standards presented in the 1964 Declaration of Helsinki. The Ethics Committee of the Federal Almazov



North-West Medical Research Center approved the protocol of this study prior the research. All subjects gave their informed consent in the written form of participation in the experiment.

2.2. Experimental configuration

Spatial distribution of blood pulsations was measured in the area of subject's palm by using custom made IPPG system in reflectance geometry as shown in figure 1. It includes just two elements: illuminator and video camera. The palm was illuminated by light emitting diode (LED) operating at the wavelength of 530 nm. The illuminating light was linearly polarized by means of the film polarizer attached to the illuminator. Another polarizer was attached to the camera lens. The transmission axes of the polarizers were mutually orthogonal to minimize light reflection from the skin. Such polarization filtration allowed us to diminish influence of motion artefacts on the revealed blood pulsations [5]. Light reflected from subject's palm was collected into the digital black-and-white CMOS camera (8-bit model GigE uEye UI-5220SE of the Imaging Development Systems GmbH). The camera was continuously recording a series of video frames with the focused images of the palm at the frame rate of 22 frames per second (fps). The series of images sizing 752×480 pixels was saved into a personal computer for digital data processing.

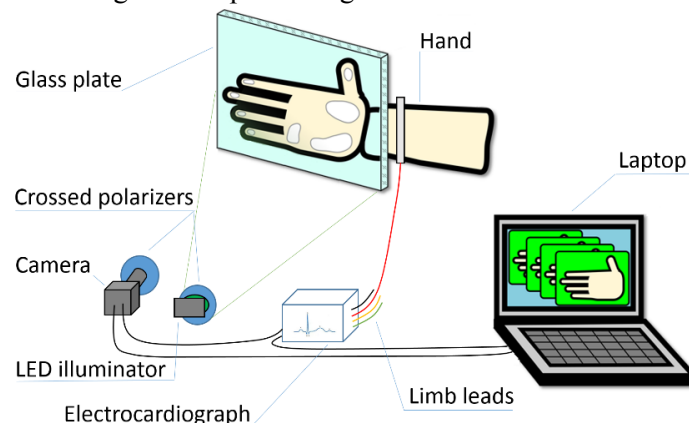


Figure 1. Simplified layout of the experimental setup for simultaneous video and ECG recordings.

Simultaneously with video for each subject we recorded an electrocardiogram (ECG) by means of digital electrocardiograph (model KAP-01-“Kardiotekhnika-EKG” of the Incart Ltd.). ECG was recorded at the data acquisition frequency of 1 kHz by using disposable electrodes attached to the left and right wrists with the reference electrodes on the legs. To synchronize ECG and video recordings, electric pulses corresponding to the beginning of each frame were recorded in one of the free channels of the electrocardiograph. By this way, the difference in the time scale between video and ECG recordings did not exceed 1.0 ms.

2.3. Experimental protocol

Each subject was asked to sit comfortably and lean its palm to the vertically fixed 4-mm thick glass plate (see figure 1). The back side of the palm was adhered to the glass by transparent adhesive tape. Such a procedure was applied to increase the signal-to-noise ratio in IPPG measurements. This was achieved because of (i) diminishing of motion artefacts during video recording, and (ii) significant increase of the IPPG-signal amplitude at the heartbeat frequency due to more efficient modulation of the capillary density in the dermis by pulsatile arterial transmural pressure [6, 7]. Duration of the video recording was 30 s. Measurements were carried out with both left and right hands of each subject.

2.4. Data processing

The whole set of the recorded data was processed offline by custom designed software implemented in the MATLAB® platform. First, we calculated spatial distribution of the amplitude of photoplethysmographic (PPG) signal pulsations over the palm area. In contrast with our previous

IPPG algorithms [4, 6], here we used more straightforward approach for calculations the pulsations amplitude. We considered a frame-to-frame evolution of the pixel values as a PPG-waveform. It was calculated by averaging pixel values in the Region of Interest (ROI) sizing 11×11 pixels which corresponds to the area of about $3 \times 3 \text{ mm}^2$ at the subject's palm. As any PPG signal [8], it typically consists of the alternating (AC) part at the heartbeat frequency and slowly varying (DC) parts. After detrending and calculating the ratio of AC/DC, one can obtain a waveform which is shown in figure 2 by the red curve. As conventionally accepted in the literature devoted to plethysmography [8], the PPG waveform was inverted to positively correlate with variations of arterial transmural pressure. The ROI was movable over the palm area with the step of a half of the ROI size in both directions.

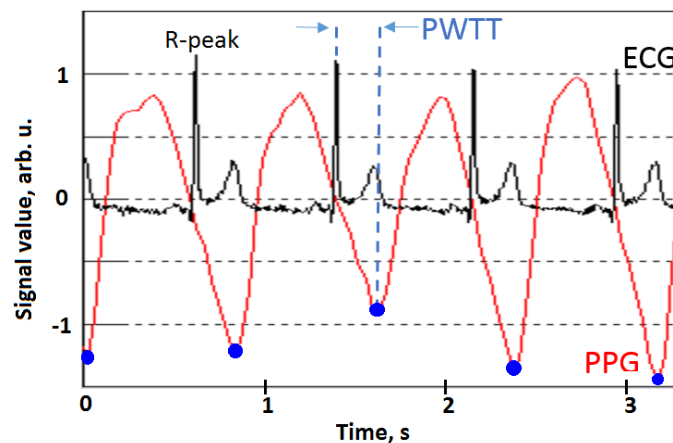


Figure 2. A fragment of simultaneously recorded PPG waveform (red curve) and ECG signal (black curve). Blue circles show end-diastole moments determined from the PPG waveform.

In the next step of the algorithm, we computed a ‘goodness metric’ for the whole set of ROIs. Two criteria were adapted to select the ‘good’ ROI in which the PWT parameter was calculated: (i) the number of the cardiac cycles estimated from PPG and ECG recordings is the same during the measuring window of 30 s, and (ii) cross-correlation between occurrence of the PPG-waveform minima and R-peaks of ECG is significant ($p < 0.05$). To resolve each cardiac cycle from IPPG recordings, positions of the PPG-waveform minima in the time axis were found for every ROI. As an example, blue circles in figure 2 show the end-diastole points determined for the particular PPG waveform. The minimum of the inverted PPG waveform is a physiological equivalent of the R-peak of ECG because the latter corresponds to the electrical systole coinciding with the phase of isovolumic contraction of the left ventricle when the blood pressure is at its minimum (end-diastole). Therefore, one can calculate PWT as the time delay between the R-peak and respective minimum of the PPG waveform [9, 10] which corresponds to the moment when the pulse wave reaches the selected ROI at the hand. The PWT was estimated only in the selected ‘good’ ROIs as the time delay averaged over all cardiac cycles within the measuring windows.

3. Results

3.1. Selection of ‘good’ ROIs

Spatial distribution of ‘good’ ROIs in the palm of one of the examined subjects is shown in figure 3. It is seen that all ‘good’ ROIs are situated in the areas where the skin is contacted with the glass plate. Similar distributions with the most of ‘good’ ROIs at the palm-glass contact were obtained for all studied subjects. This fact provides an additional confirmation of the recently proposed model of PPG signal formation in which pulsatile arterial pressure deforms the connective-tissue components of the dermis resulting in periodical changes of both the light absorption and scattering [6]. The contact with glass plays a role of the mechanical border for enhancement of the dermis compression thus providing better correspondence to variations of arterial transmural pressure [7]. Only 7% of the total number of

ROIs were selected as ‘good’ in the particular case shown in figure 3. For other subjects this ratio was varying from 1% to 68% with the mean of 22%. In spite of small percentage of ‘good’ ROIs in three palms, the absolute number of the selected ROI was high enough (the smallest was 19) for the reliable estimation of the pulse wave transit time because of initially large number of independent ROI in the palm area.

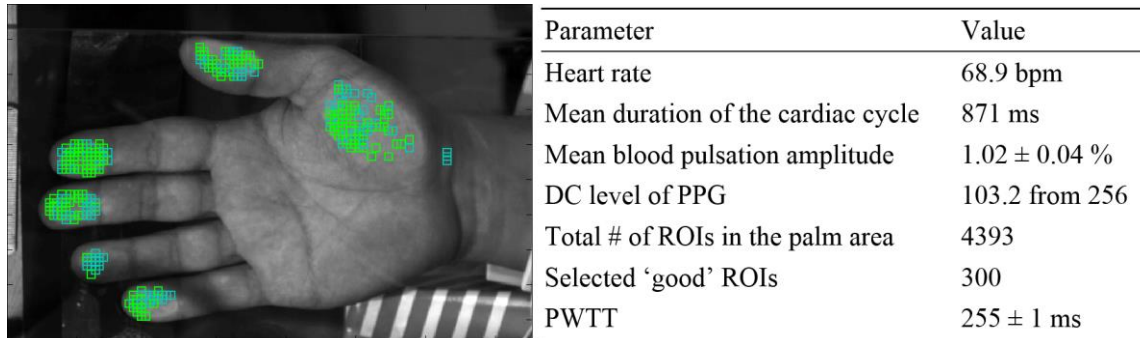


Figure 3. Example of data processing: a palm with selected ‘good’ ROIs and calculated parameters.

3.2. PWTT measurements

In each selected ROI, the estimated time delay between the R-peak and PPG-waveform minimum has rather high dispersion: the standard deviation is typically of the order of the time delay, which could be caused by moderate frame rate (22 fps) used for video recording in our experiments. Nevertheless, mean PWTT values (after averaging over all cardiac cycles) possess small standard deviation difference from the magnitude averaged over the all selected ‘good’ ROIs in the palm. For example, for the palm shown in figure 3, PWTT is 255 ms with the measurement error of 1 ms calculated with the confidence level of 95% for the set of 300 ‘good’ ROIs. The measurement error of PWTT for the palms of other subjects was between 1 and 8 ms.

Figure 4 shows the PWTT parameter for both right and left hand of all subjects participated in the experiment. The PWTT of the right hand averaged over the whole cohort was 244 ± 20 ms, which was comparable with that of the left hand: 240 ± 14 ms. In spite of comparable values in average, the right-left hands difference in PWTT of some individuals was significant (up to 28 ms) and with different sign: the time delay in the right hand was larger in seven subjects of twelve as seen in figure 4. It was found that there is no significant dependence of PWTT on the subjects’ age ($r = 0.13$, $p > 0.05$). We hypothesize that it may be related with small dispersion of the volunteers’ age in the group under study.

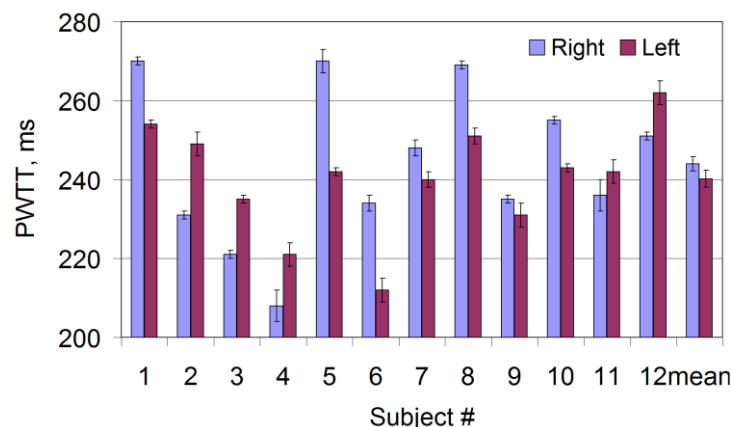


Figure 4. PWTT calculation results. Violet and vinous columns show PWTT of the right and left hands of each subjects, respectively. The last pair of columns represents respective mean values.

4. Discussion

The study revealed that dispersion of the PWTT parameter measured in selected ‘good’ ROIs for any subject does not exceed 8 ms, which is of the same order of value as synchronization error between video camera and electrocardiograph. In contrast to similar technique of PWTT assessment using classical photoplethysmograph of the contact type (which measures the time delay in a single point, e.g. in the finger) [9, 10], the IPPG system allows us to measure PWTT with higher accuracy due to access to a larger number of statistically independent measurements obtained simultaneously in different points. Moreover, the restrictions imposed on the selection of ‘good’ ROIs resulted in exclusion of an insecure ROI in which the PPG waveform is spoiled by either motion or physiological type of noise. Therefore, the proposed IPPG method is characterized by higher diagnostic reliability.

Asymmetry and asynchronicity of peripheral blood pulsations in human limbs could be assessed with even higher reliability by simultaneous video recordings using two or more synchronized cameras. The data simultaneously obtained from multiple cameras could reveal the difference in pulse wave propagation with higher accuracy since they are not spoiled by instability of both environmental and internal physiological conditions as it occurs in the case of measuring in different moments. The PWTT difference measured at different hands or legs of the same subject might serve as a good tool for preliminary (screening) diagnostics of various types of problems with the bloodstream such as remodelling, atherosclerosis plaques, stenoses, congenital features, etc.

5. Conclusion

A technique for measuring the pulse wave transit time with increased accuracy has been proposed. It is based on joint processing of the digital data obtained after synchronized recordings of imaging photoplethysmogram and electrocardiogram. Due to calculation PWTT within the large representative set of statistically independent ROIs, the proposed technique is more reliable and of higher diagnostic accuracy compare to the conventional method using ECG and classical single-point PPG. PWTT measured in properly selected ‘good’ ROIs of any palm are of small dispersion. Even though PWTT in right and left hands averaged over the whole group of subjects was comparable, significant difference in the time delay of pulse wave between the hands was found in some individuals. The technique can be used for early-stage diagnostics of various vascular diseases.

Acknowledgments

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