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Photoplethysmographic measurements of arterial and aortic pulse waveform characteristics

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Abstract

The photoplethysmographic (PPG) signal is a complex signal, composed of the peripheral pulse synchronized to each heartbeat (the fluctuating component), and modulated by a slow component that varies due to respiration, vasomotor activity and vasoconstrictor waves, ECG and pulse waves from healthy subjects. Decomposition of the PPG pulse waves produces five components: percussion, tidal, dicrotic, repercussion, and retidal waves. Pulse wave decomposition parameters PPG are compared to detect variables for information on person's arterial elasticity. Nowadays, promising cardiovascular parameters registration method is PPG, which is relatively simple to be applied in eHealth, clinical applications, homecare, drives' sleepiness, or even endothelial dysfunction. Results show that elasticity information in the form of pulse wave decomposition from PPG waves is easily obtainable and shows clear shortening between percussion wave and tidal wave peak time in PPG waveforms as a function of age. Decomposition analysis is valuable in assessment of the arterial elasticity. In addition, PPG measurement is absolutely non-invasive and safe. In PPG measurement, the sensors are on the opposite sides of the fingertip to obtain accurate waveforms. A further challenge is the calibration of the PPG measurement systems in order to achieve comparative diagnostic relations, because PPG waveforms in different regions of the body and in different subjects do not allow us to find a universal calibration function for reliable estimations of the clinical data.

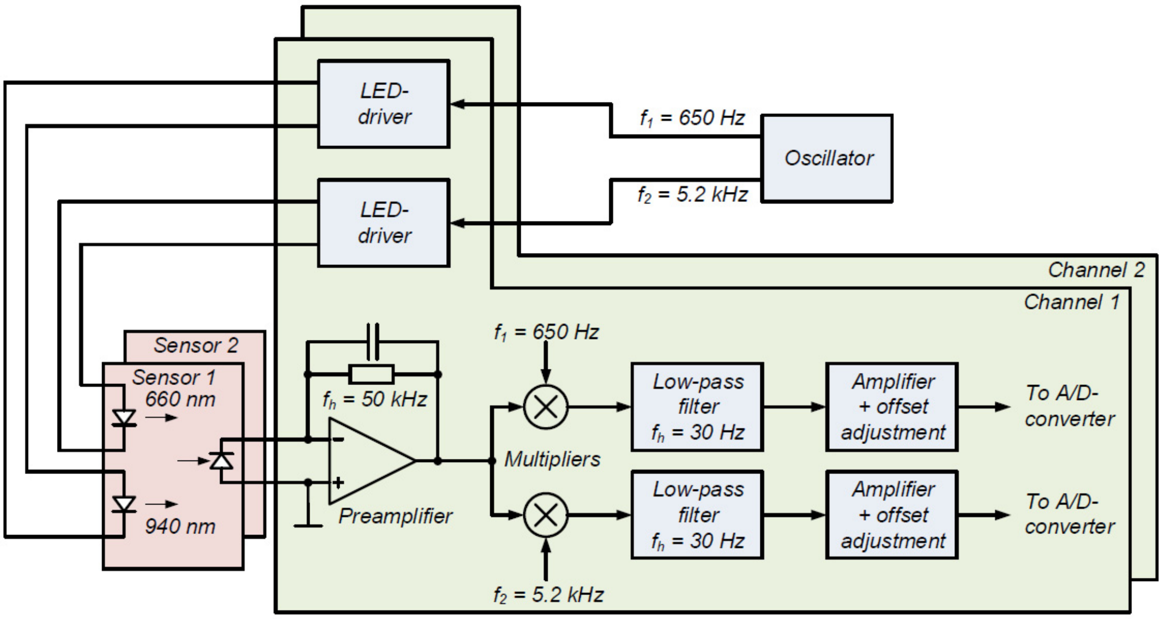
Keywords: arterial elasticity measurement, photoplethysmography (PPG), pulse wave decomposition, logarithmic transform

Introduction

Arterial pulse wave is defined as a heart-beat driven impulse wave of blood that propagates via each artery tree into veins through capillaries. Biomedical information can be obtained by the detection of pulse wave and its detailed analysis. This information is not obtainable from the blood pressure or electrocardiographic measurements. In a PPG device, a photodetector measures the very small variations of tissue transmitted light which is amplified by a transimpedance amplifier. The obtained pulse wave is the peripheral pulse that can be decomposed into five logarithmic Gaussian components. Despite its simplicity, the origins of the different components of the PPG signal are not fully understood. We believe that these parallel pulse waves can provide valuable information about the circulatory system with patient-friendly and safe means. It could be possible to make diagnosis on the basis of the pulse wave analysis. Especially atherosclerosis is the main cause of cardiovascular diseases (CVD), and premature ventricular contraction (PVC) is functional, but not a structural cause of a vascular disease, if PVC is monotonous. Its quantitative assessment is essential for making an early diagnosis of such diseases. In addition, persons with CVD may have asymptomatically decreased arterial elasticity compared with those people free of CVDs. Change of arterial elasticity is one of the early markers of accelerated arterial aging and can correlate with many coronary risk factors. Especially arterial elasticity reflects the arterial and aortic expanding during left ventricular contraction. Arterial elasticity can be measured indirectly provided the measurement method is relevant and accurate enough. In this work, biophysical function and structure of the arteries have been measured by photoplethysmographic (PPG) sensors. The interaction of light with tissue is complex and includes the optical processes of scattering, absorption, refraction, reflection, and transmission [1]. Biomedical researchers have investigated the bio-optical processes in relation to PPG measurements. The light received by the photodetector is also a function of the blood volume, blood vessel wall movement, oxyhemoglobin and deoxyhemoglobin concentration, and the orientation of red blood cells, and blood glucose concentration [2]. The recorded pulses do bear a direct relationship with perfusion, and the greater the blood volume the more the light source is attenuated. However, PPG pulse amplitude calibration has been unsuccessful. In the elderly and in the stiff arteries, the forward and reflected pulse waves travel faster, i.e., pulse wave velocity (PWV) is higher than in a young person's arteries which are elastic. The arterial waves reflected from the periphery of the arterial tree, return earlier merging with the systolic part of the incident wave causing augmentation of the workload of the heart. Favorable softness between coupling of the left ventricle and the arterial tree is thus progressively lost also by PVC function. This loss can be greatest in the aorta, and least in the upper limbs. The wave reflection of the pulse wave due to increase in PWV also increases with age, but can be largely prevented by physical activity and proper diet. Here we applied pulse wave logarithmic Gaussian decomposition (GD). GD products reflect clearly the elasticity of the aorta, arteries, and peripheral circulation.

Materials and methods

In this study, the PPG sensors are based on LEDs and photodetector, and optoelectronic amplifier circuit which make possible to consider the origins of the photoplethysmography waveform characteristics. Finger and toe pulse waves are measured by 660 (red) & 940 (infrared) nm in the PPG probes based on phase sensitive detection (PSD). Figure 1 shows the PSD schematic picture (upper), the PPG device with measurement box and PC (lower). Pulse wave series from PPG finger and toe were processed by Origin software as follows. Firstly, the alternating baseline on each signal bottom (minimum) was searched and then subtracted. Secondly, the peak of each signal (maximum) was searched, and the average of the peak values was calculated. The signal was divided by the average to obtain the baseline removed and normalized waveforms which has amplitude from the zero to round one (0, 1). For the measurement data, we applied pulse wave logarithmic Gaussian decomposition (GD). GD products reflect clearly the elasticity of the aorta, arteries, and peripheral circulation. In addition, logarithmic transform of the time axis of the PPG pulse waveform speed up the GD of the PPG pulse waveforms.



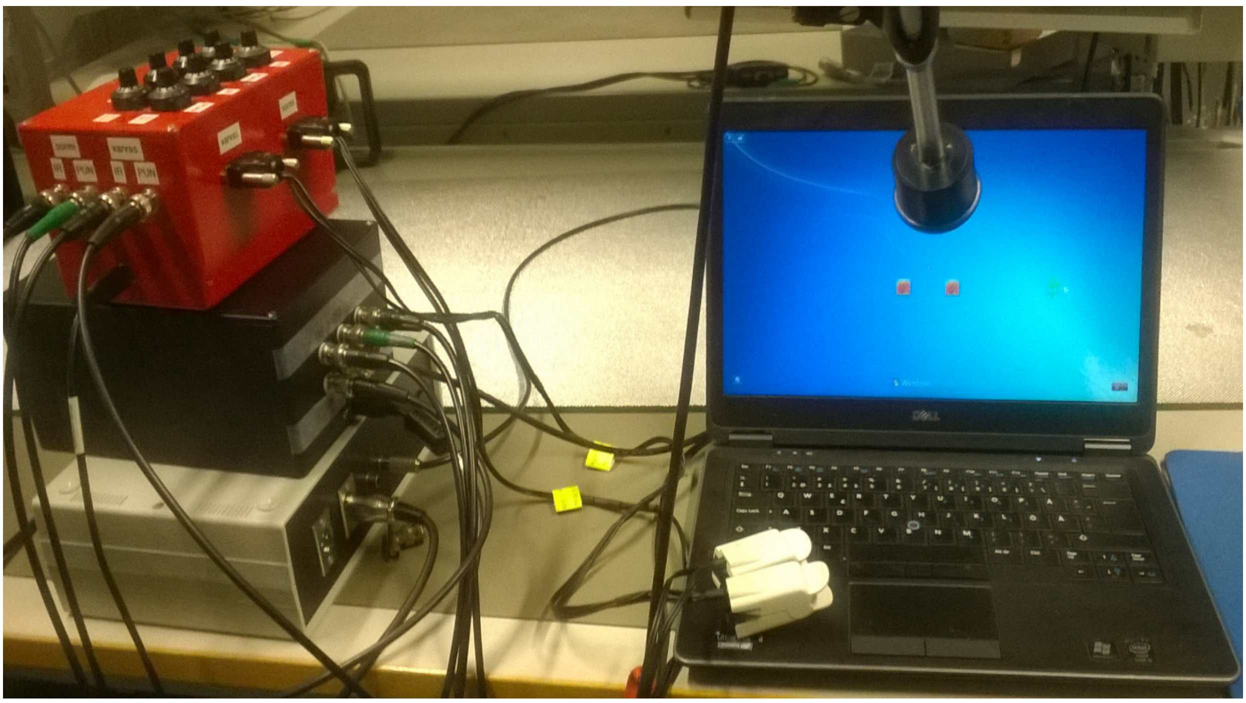


Figure 1. Phase sensitive detection (PSD) block schematic (top), the PPG device on the top and the measurement box (bottom).

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Results

An example pulse waveform series at time 1000 s for 2.6 s ECG and from right, left index finger, right, and left second toe PPGs are shown in Figure 2. The normalized PPG waveforms are shown from finger and toe in Figure 3. Decomposed pulse waves are shown in the Figure 4.

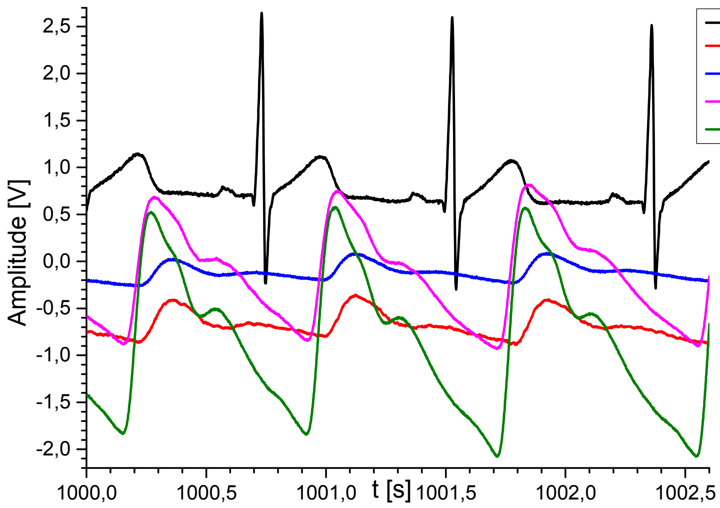

Figure 2. The measured ECG (black), and PPG pulse waves from right (magneta), left (olive) index fingers, right (red), and left (blue) second toes.

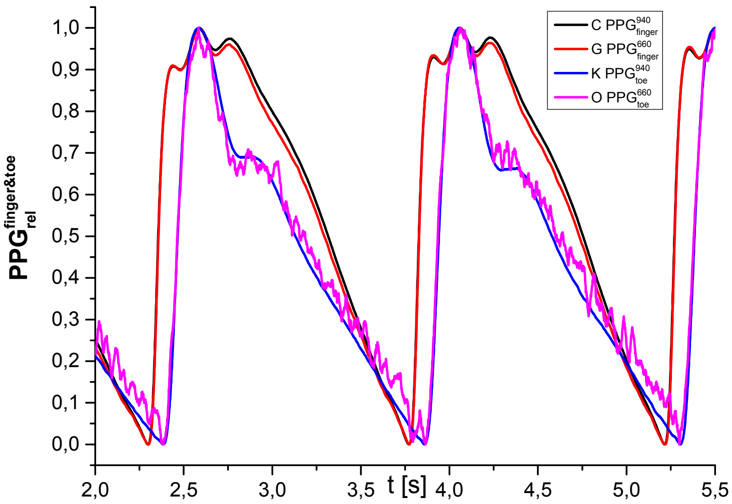

Figure 3. PPGs from finger, toe with infrared (black, red), and with red wavelength (blue, magneta).

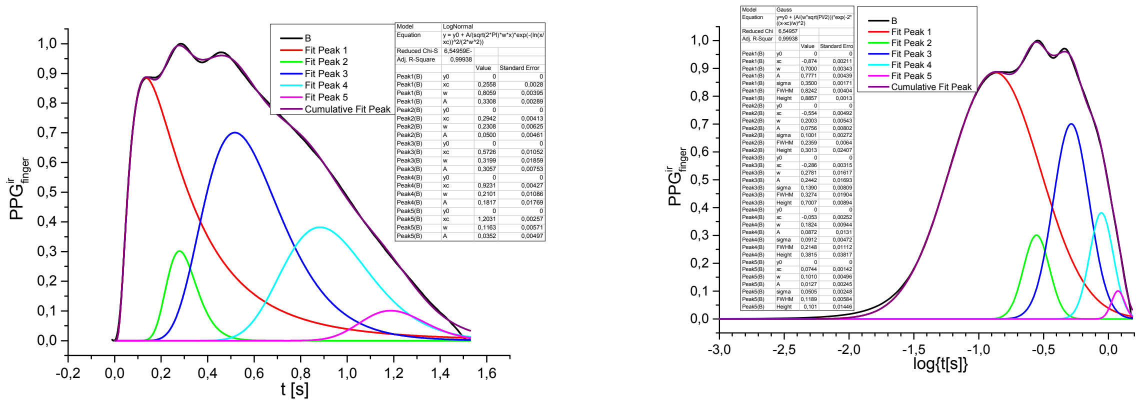

Figure 4. A PPG decomposed into components in linear scale by the GD (iterations 8447) (left): percussion (red), tidal (green), dicrotic (blue), repercussion (cyan), and retidal wave (magneta). The measure PPG is black and constructed wave is (purple) (left), the same PPG decomposed after logarithmic transform (its 158) (right). On the right Figure the component colors are the same as in the linear scale.

The comparison of the PPG pulse wave in the linear and logarithmic scale shows the same time locations but the tidal wave smaller areas in the logarithmic scale, Figure 4. We believe that the tidal component of the PPG wave reflects the aortic elasticity function. This study shows PPG pulse waveforms can be decomposed to their component waves, namely, percussion wave, tidal wave, dicrotic wave, repercussion, and retidal waves both in the linear and logarithmic scale. However, after the logarithmic transform the decomposition converges faster than in the linear scale. This indicates that the logarithmic scale is the correct axial form, and also the model is the better one.

Discussion

Clinical research is necessary to quantify the ageing effects in relation to the obtained variables and also to explore pulse waveform changes with subject age. However, based on the PPG measurement method shows the changes in the pulse waveform both in the linear and logarithmic scale. In PPG, the sensors are on the opposite sides of the finger tip. The tidal component of the PPG wave origin would be verified also by other methods that it reflects the aortic elasticity function. The elasticity is obtained quantitatively from PPG pulse signals both in time and logarithmic domain. In studies, PPG theory should be described when analyzing arterial pulse wave signals because they contain effects of respiration, autonomous nervous activity, gastric mobility, health status, and also arterial properties, i.e., arterial diseases.

References

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