Photoplethysmographic Augmentation Index Using the Signal Fourth Derivative

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Abstract

This work aimed to provide, that using the derivatives of photoplethysmographic signal enhance the location of inflection points. Furthermore, using the signal fourth derivative, it is possible to locate inflections points as photoplethysmographic augmentation index (PAI).

A computing photoplethysmographic analyzer was developed. The first, second, third and fourth derivatives were obtained by the mean square error interpolation method. The PAI was quantified by fourth derivative. PAI was calculated similar to augmentation index for pressure (AIx). The AIx is obtained as the difference between late and early systolic inflections expressed as a percentage of the pulse pressure .

A study with 36 people, 18 healthy volunteers and 18 subjects with previously diagnosed cardiovascular disease was carried out. A t–tested distribution between healthy volunteers and patients showed a significant differences in calculated PAI (0.0231 vs 0.4678, $p < 0.0001$).

In conclusion, PAI has shown to be a noninvasive indicator for vascular assessments. Using the fourth derivative, inflection point identification on the photoplethysmographic signal is more accurate mainly in subjects with previously diagnosed cardiovascular disease.

1. Introduction

Photoplethysmography (PPG) is an optical technique, which typically operates using infrared light, allowing the transcutaneous registration of venous and/or arterial blood volume changes in the skin vessels. The complex interaction between the heart and connective vasculature are the components of the mechanism that generates the PPG signal [1]. The PPG waveform comprises a pulsatile ('AC') physiological waveform attributed to cardiac synchronous changes in the blood volume with each heart beat, and is superimposed on a slowly varying ('DC') baseline with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation. See figure 1.

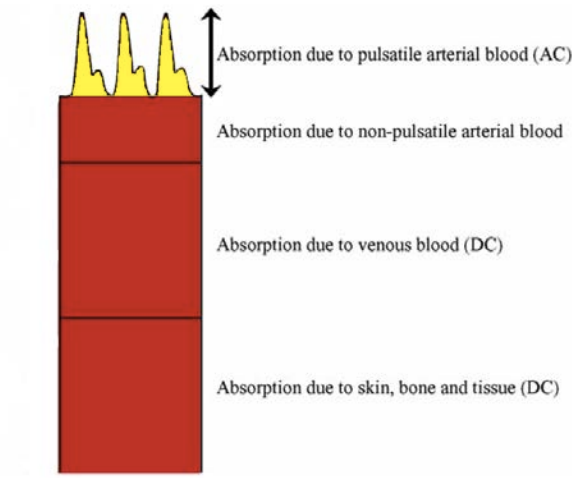

Figure 1. Photoplethysmographic signal components.

The pulsatile AC PPG waveform is named PPG signal. It has been demonstrated earlier that the contour of the PPG signal contains similar information to that of the peripheral pressure pulse [2]. Because the peripheral volume blood flow pulse is essentially due to a propagating pressure pulse, the time course of the signal indicating flow changes bears a relationship to pressure changes [3]. The contour of the PPG signal is determined mainly by the characteristics of the systemic circulation, including pressure wave reflection and pulse wave velocity of the pressure wave in the aorta and large arteries [4].

The PPG waveform is formed due to wave transmission and reflection, which is illustrated in figure 2. The first part of the volume waveform in the finger is the result of pulse transmission along a direct path from the aortic root to the finger. The second part is formed by the pulse transmitted from the aortic root to the lower body, where it is reflected back along the aorta and subclavian artery to the finger. The time delay between the first and second peak is determined by the transit time of the pressure pulse from the root of the subclavian artery to the apparent sight of reflection and back to the subclavian artery. The height of the second peak relates to

the amount of pressure wave reflection.

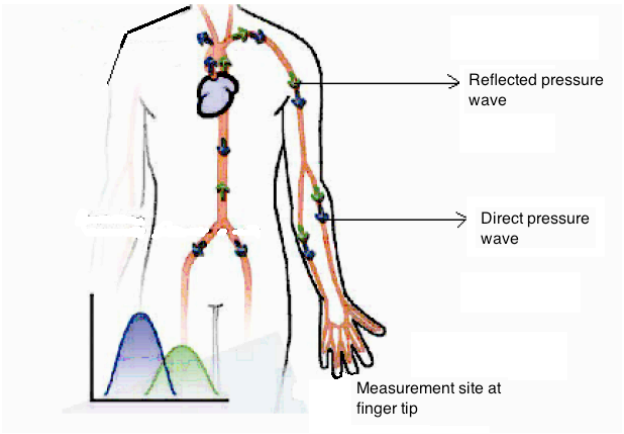

Figure 2. The PPG waveform is formed due to wave transmission and reflection.

There has been published data in the literature, which quantify pulse transit timing changes with age [5]. Frequency analysis of the PPG signals at different body sites with respect to age has been carried out [6,7] and it has been shown that there is a general reduction in the harmonic components of the pulse in older subjects. Work has also been done using the second derivative of the photoplethysmogram (SDPPG) to study age-related indices and other risk factors for atherosclerotic vascular disease [8,9]. This has proved to be particularly useful when the dicrotic notch in the PPG signal becomes less prominent, making it difficult to detect minute changes in the phase of the inflections using the pulse wave contour itself. The contour of the pulsatile component of the PPG has been used for the calculation of certain age related indices [10,11].

This work aimed to show that using the derivatives of photoplethysmographic signal enhance the location of inflection points. Furthermore, using the signal fourth derivative, it is possible to locate inflection points as photoplethysmographic augmentation index (PAI).

2. Methods

A computer based PPG analyzer was developed. The signal was obtained by infrared light through the finger. It was conditioned and converted into digital domain by a signal processing circuitry, which contains amplifying and filtering steps, a microcontroller and an analog to digital converter. The acquired signal was displayed and analyzed. The acquisition and mathematical processing programs were implemented in object-oriented programming C++.

First, second, third and fourth derivatives of the signal were computed by mean square error interpolation method. The PAI was quantified by fourth derivative. PAI was calculated similar to augmentation index for pressure (AIx).

The AIx is obtained as the difference between late and early systolic inflections (AP) expressed as a percentage of the pulse pressure (PP), thus AIx= AP / PP [13]. See figure 3. Augmentation index is a sensitive marker of arterial status. AIx has been shown to be a predictor of adverse cardiovascular events in a variety of patient populations, and higher augmentation index is associated with target organ damage.

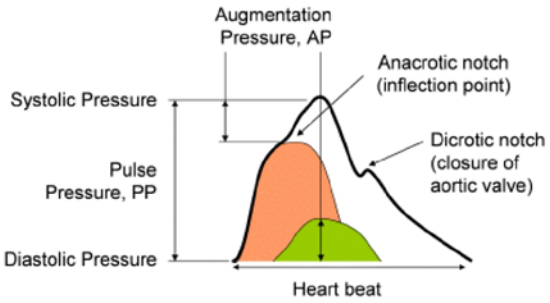

Figure 3. Augmentation index for pressure.

The equation for PAI is:

$$PAI=(PTmax - PTi)/(PTmax - PTmin) \quad (1)$$

Where:
PAI = Photoplethysmographic augmentation index.
PTmax = Maximal point of PPG signal.
PTmin = Minimal point of PPG signal.
PTi = Point of PPG signal in which fourth derivative is zero.

A study with 36 people, 18 healthy volunteers and 18 subjects with previously diagnosed cardiovascular disease (diabetes mellitus, atherosclerosis, hypertension) was carried out

3. Results

The analysis of PPG signal is obtained as follows. One of acquired PPG signals from a healthy volunteer is chosen for be analyzed. In figure 4 is shown how is it displayed, the original PPG signal and its fourth derivative, where is it illustrated PTi, point of PPG signal in which fourth derivative is zero.

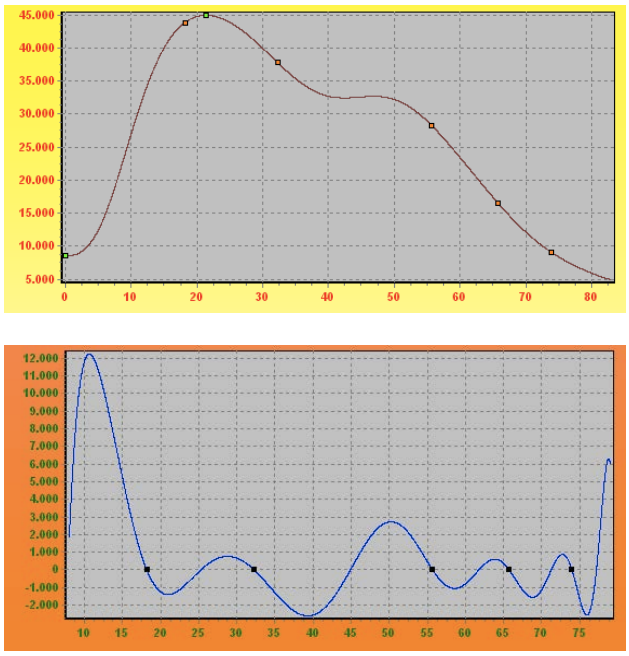

Figure 4. PPG signal and its fourth derivative from healthy volunteer.

Figure 5 shows a PPG signal and its fourth derivative from a second healthy volunteer. In figures 4 and 5 the fourth derivatives are different but both PTi are near of top of PPG signal.

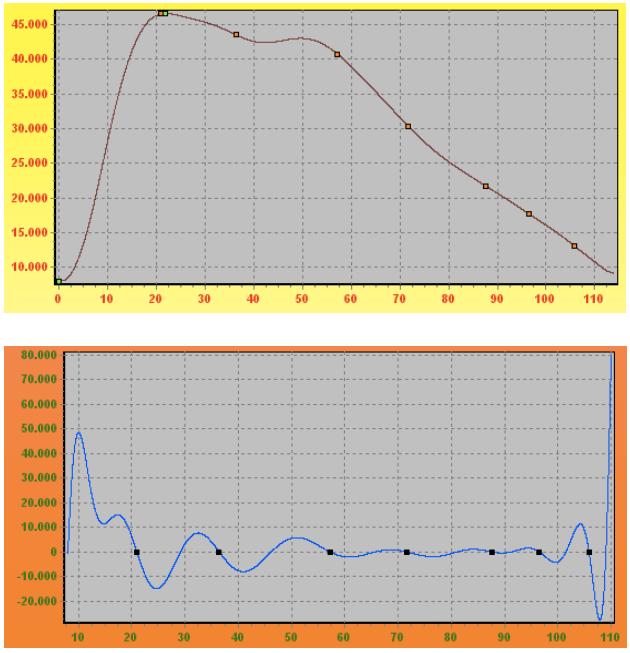

Figure 5. PPG signal and its fourth derivative from a second healthy volunteer.

Analyzed PPG signal and its fourth derivative from a patient are shown in figure 6.

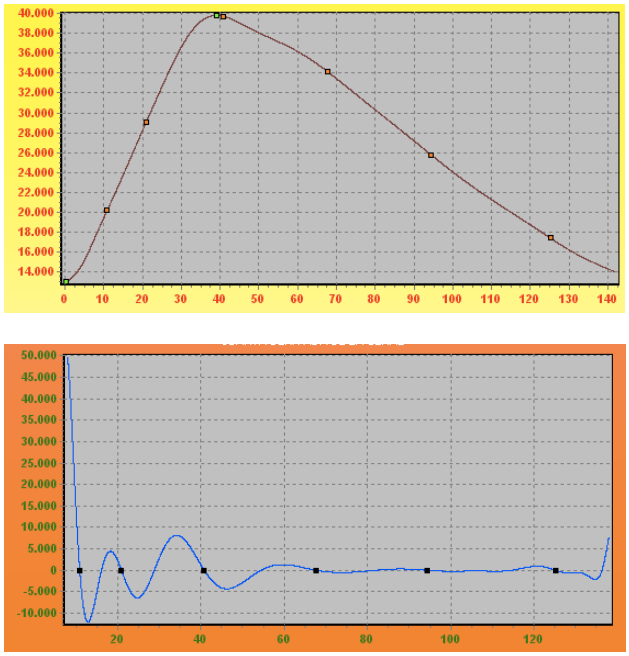

Figure 6. Analyzed PPG signal and its fourth derivative from a patient.

In figure 7 are shown the analyzed PPG signal and its fourth derivative from a second patient. For healthy subjects the dicrotic notch was predominantly seen in PPG signal whereas in patients owing to the increase in arterial stiffness and a faster reflected wave augmenting the forward wave the pulse becomes rounded. It was noticed that the peripheral pulse has a steep rise and a notch on the falling slope in healthy volunteers whereas in patients a more gradual rise and fall and no pronounced dicrotic notch.

Analizing the fourth derivatives from patients the PTi are in the middle section of the peripheral pulse rise becoming a higher PAI than healthy volunteers.

In subjects with previously diagnosed cardiovascular disease, the pulse can become smoothed, with changes in the blood pressure pulse producing less dramatic changes in the blood volume pulse at the periphery.

The results show an overall elongation of the systolic rising edge, which could be explained on the basis of changes in resistance and compliance properties of arteries with cardiovascular diseases. The diminishing of the dicrotic notch in patients is mainly due to disease related increases in pulse wave velocity resulting in a faster reflected wave augmenting the forward wave.

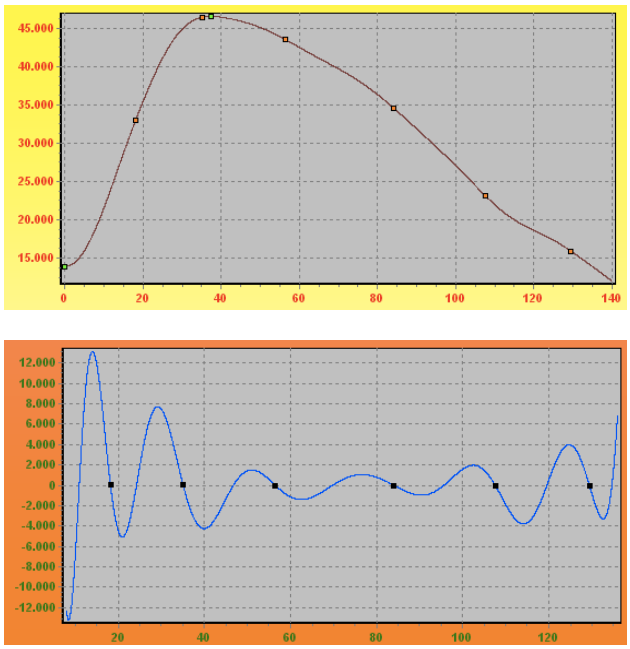

Figure 7. Analyzed PPG signal and its fourth derivative from a second patient.

A t–tested distribution between healthy volunteers and patients showed a significant differences in calculated PAI (0.0231 vs 0.4678, $p < 0.0001$).

4. Discussion and conclusions

Pulse shapes for healthy volunteers and subjects with previously diagnosed cardiovascular disease have been analyzed. In subjects with previously diagnosed cardiovascular disease it is difficult to locate the dicrotic notch, thereby increasing the uncertainty in timing measurements related to the reflected wave. Here, by making use of the fourth derivative of PPG signal, delicate changes in the waves were emphasized and easily quantified by differentiating four times the original PPG signal with respect to time.

From the recording of the original PPG, sometimes there is a difficulty in detecting minute changes in the phase of the inflections. So, by four times differentiating the PPG, the fourth derivative of the PPG signal is obtained (PAI), which helps in more accurate recognition of the inflection points and an easier interpretation of the original signal. The PAI is used as a means to accentuate and locate inflection points

In conclusion, PAI has shown to be a noninvasive indicator for vascular assessments. Using fourth derivative, inflection points identification of the photoplethysmographic signal is more accurate mainly in subjects with previously diagnosed cardiovascular disease.

Acknowledgements

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