A Computer Based Photoplethysmographic Vascular Analyzer through Derivatives

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Abstract

A computer based photoplethysmographic analyzer was developed. The signal was obtained by infrared light through the finger. It was converted into digital domain by a signal processing circuitry. First, second and fourth derivatives of the signal were computed. The acquisition and mathematical processing programs were implemented in object-oriented programming C. A study with 38 people, 19 healthy volunteers and 19 subjects with previously diagnosed cardiovascular disease (atherosclerosis, hypertension, diabetes mellitus) was carried out. A t–tested distribution between healthy volunteers and patients showed a significant differences in calculated parameters. Photoplethysmographic augmentation index has shown to be a noninvasive parameter for vascular assessments. Using derivatives, the inflection points identification of the digital volume pulse is simpler and more accurate.

1. Introduction

Photoplethysmography (PPG) is a non invasive technique where non visible infrared light is emitted into the skin. PPG device should measure the blood volume by optical methods. Light may be transmitted through a capillary bed such as is found in the ear lobe or finger tip. As arterial pulsations fill the capillary bed, the changes in the volume of the blood vessels modify the absorption, reflection and scattering of the light. Depending on the blood volume in the skin, more or less light is absorbed. By measuring the non-absorbed light, the changes in the blood volume can be measured [1]. The detected optical radiation 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. The figure 1 shows the different components of detected optical radiation [2].

Although the origins of the components of the PPG signal are not fully understood, it is generally accepted that they can provide valuable information about the cardiovascular system. There has been a resurgence of interest in the technique in recent years, driven by the demand for low cost, simple and portable technology for the primary care and community based clinical settings, the wide availability of low cost and small semiconductor components, and the advancement of computer-based pulse wave analysis techniques.

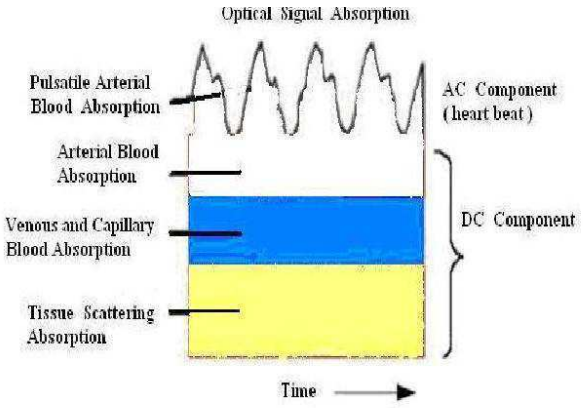

Figure 1 Variable and constant components of detected optical signal.

The photoplethysmogram is measured by a device comprising an infrared light source (typically a photodiode emitting light at a wavelength of around 900 nm) and a photodetector (phototransistor). The light intensity is modulated in a complex fashion by the increase in haemoglobin content and expansion of the vascular and tissue volume between the light source and the detector, such that there is a reduction of the signal with each heart beat [3].

The first part of the PPG waveform (systolic component) is formed as a result of pressure transmission

along a direct path from the aortic root to the finger. The second part (diastolic component) is formed by pressure transmitted from the ventricle along the aorta to the lower body where it is reflected back along the aorta to the finger. The upper limb provides a common channel for both the directly transmitted pressure wave and the reflected wave and, therefore, has little influence on the contour of the PPG signal as is shown in figure 2.

Photoplethysmographic signals have been applied in many different settings including clinical physiological monitoring, vascular assessment and autonomic function. Photoplethysmography is a simple, non invasive and low cost optical technique. Features of the signal, such as the height of the inflection point relative to pulse height, have been used to quantify haemodynamic parameters as wave reflection. However, because of the smooth appearance of the signal due to damping, other features, such as early and late systolic inflections, cannot be detected readily [4]. Thus, time derivatives of the signal have been proposed as a means to accentuate and locate inflection points.

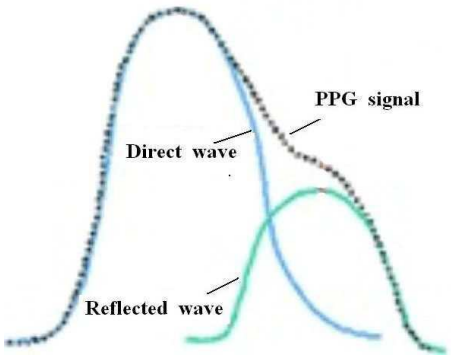

Figure 2. PPG signal and its component waves.

The aim of this work is to show, that the derivatives of photoplethysmographic signal enhance the location of inflection points. Evenmore, using the signal fourth derivative, it is possible to locate early and late systolic inflections points as photoplethysmographic augmentation index.

2. Methods

A computer based PPG analyzer was developed. The signal was obtained by infrared light through the finger. It was converted into digital domain by a signal processing circuitry, which contains amplifying and filtering steps, a microcontroller and an analog to digital 16 bits converter. The acquired signal was displayed and analyzed. The acquisition and mathematical processing programs were implemented in object-oriented programming C++.

First, second and fourth derivatives of the signal were computed. Using the first derivative, the stiffness index (SI) was calculated. PPG signal usually exhibits an early systolic peak and a later peak or point of inflection that occurs a short time (□t) after the first peak in early diastole [5]. The first peak is formed mainly by pressure transmitted along a direct path from the left ventricle to the finger (where it generates a change in blood volume). The second peak is formed in part by pressure transmitted along the aorta and large arteries to sites of impedance mismatch in the lower body, where it is reflected back up the aorta. □t can thus be used to infer the transit time taken for pressure to propagate along the aorta and large arteries to the major sites of reflection in the lower body and back to the root of the subclavian artery. This path length is unknown, but can be assumed to be proportional to subject height (h). The stiffness index was obtained from the body height divided by the time delay between the pulse systolic peak and the diastolic peak/inflection point of the reflection wave SI= h/□t. The diastolic peak/inflection point is defined as the point at which dPPG/dt is closest to zero. The diastolic peak occurs when dPPG/dt is zero, whereas an inflection point occurs when dPPG/dt approaches zero as is shown in figure 3 [6].

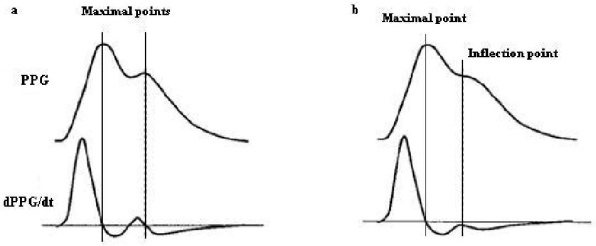

Figure 3. PPG and its first derivative (dPPG/dt) for waveforms exhibiting (a) a diastolic peak and (b) a point of inflection.

With the second derivative, four separate systole waves (named a – d) and a diastole wave (named e) were obtained. The a and b waves on the second derivative of PPG are included in the early systolic phase of the PPG whereas the c and d waves are included in the late systolic phase. The height of each wave from the baseline was measured and their ratios b/a, c/a, d/a and e/a were calculated [7,8]. These waves are shown in figure 4.

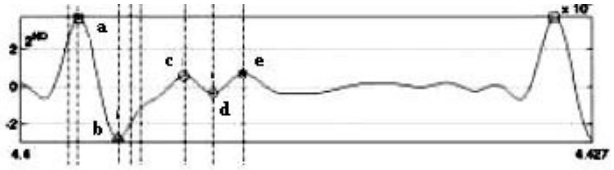

Figure 4. Systole and diastole waves of second derivative of PPG signal.

The photoplethysmographic augmentation index (PAI) was quantified by fourth derivative. PAI is calculated similar to augmentation index for pressure (AIx). The AIx is obtained as the difference between late and early systolic inflections (P_2 - P_1) expressed as a percentage of the pulse pressure (P_2 - P_0), thus AIx= □P/ PP. See figure 5.

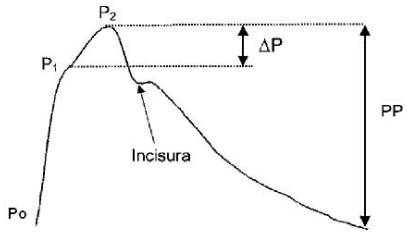

Figure 5. Ascending aortic pressure waveform.

The equation for PAI is:

$$PAI = \frac{PTmax - PTi}{PTmax - PTmin} \qquad (1)$$

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 38 people, 19 healthy volunteers and 19 subjects with previously diagnosed cardiovascular disease (atherosclerosis, hypertension, diabetes mellitus) was carried out.

3. Results

The analysis of PPG signal is obtained as follows. The acquired PPG signals from a healthy volunteer are shown in figure 6.

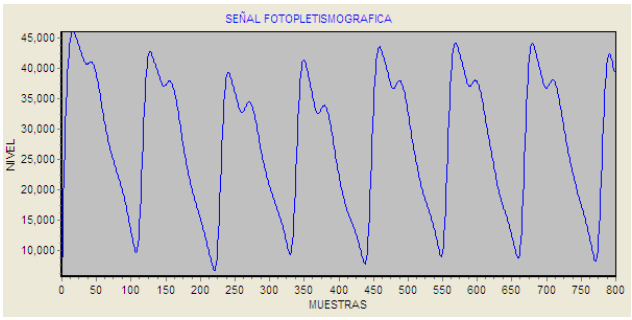

Figure 6. PPG signals from a healthy volunteer.

One of the PPG signals is chosen for be analyzed. Figure 7 shows the displayed original and first derivative of PPG signal from a healthy volunteer.

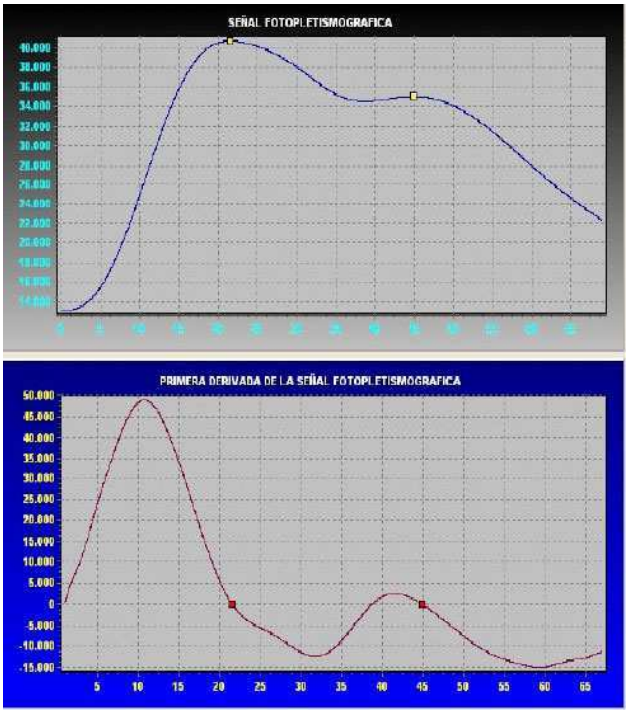

Figure 7. Original and first derivative of PPG signal.

The analysis of the second derivative of PPG signal and how are obtained four separate systole waves (named a – d) and a diastole wave (named e) through the third derivative are shown in figure 8. The height of each wave from the baseline was measured and their ratios b/a, c/a, d/a and e/a were calculated.

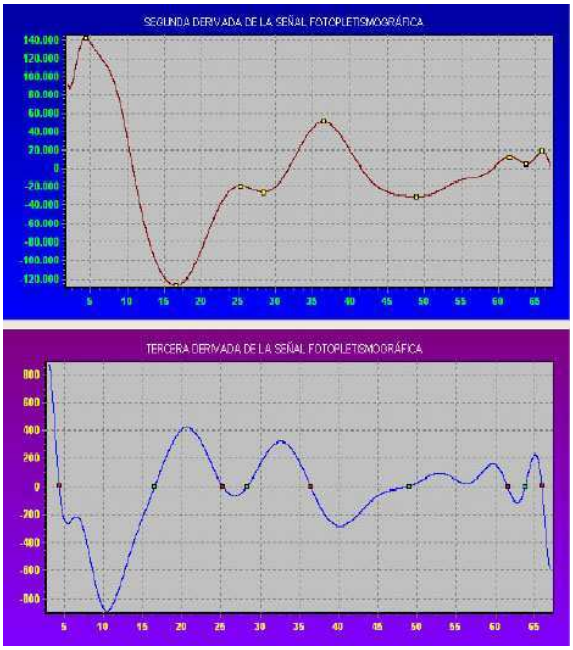

Figure 8. Second and third derivatives of PPG signal.

The fourth derivative and its original PPG signal of a healthy volunteer are shown in figure 9. With the analysis of fourth derivative of PPG signal it can obtain the early and late systolic inflections.

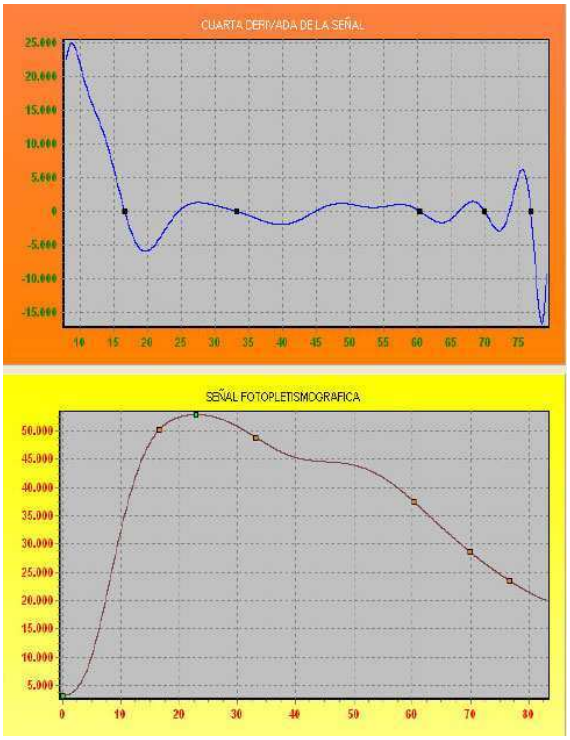

Figure 9. Fourth derivative and its original PPG signal of a healthy volunteer.

A t–tested distribution between healthy volunteers and patients showed a significant differences in calculated parameters: stiffness index (8.089 vs 13.0, $p<0.0001$), photoplethysmographic augmentation index (0.0225 vs 0.4542, $p < 0.0001$), b/a (-0.739 vs -0.379, $p < 0.0001$), d/a (-0.081 vs -0.471, $p < 0.0001$), e/a (0.179 vs 0.066, $p < 0.0001$), and for c/a (-0.034 vs -0.144, $p < 0.005$).

4. Discussion and conclusions

The analysis of PPG signals was carried out by a computer based photoplethysmographic analyzer. The calculated parameters: stiffness index, b/a, c/a, d/a , e/a and the photoplethysmographic augmentation index have shown significant differences between healthy volunteers and patients.

Photoplethysmographic augmentation index has shown to be a noninvasive indicator for vascular assessments. Using derivatives, the inflection points identification of the PPG signal is more accurate.

References

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