A PULSE WAVEFORM DATA DECOMPOSITION BASED ON MULTI COMPONENT CURVE FIT COMPARED WITH SECOND DERIVATIVE PHOTOPLETHYSMOGRAPHY AND PHASE PLANE PLOT

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Abstract: With a new photoplethysmographic (PPG) device we have been attending to photoplethysmographic signals of different ages for signal decomposition purpose. Because PPG is a non-invasive, and easily attachable measurement technique both suitable in health care applications we concentrated on its comprehensive signal analysis and waveform interpretation. By means of PPG it is easy to capture data for further analysis. In the world cardiovascular diseases are the frequent cause of death that's why we are concern on cardiovascular diseases. The main cause of incidents can be high arterial stiffness which is symptomless and increases the risk as a function of age causing cardiovascular diseases. Arteries stiffen normally as a consequence of age, but also because of insalubrious mores and many diseases. Normal age related stiffness occurs when the elastic fibers within the arterial walls begin to weaken due to age, but diseases as arteriosclerosis accelerate this process. However, we believe that it is possible to prevent arterial stiffening if detected early enough. For this reason we have derived indexes to indicate a possible arterial stiffness value..

1 INTRODUCTION

Many photoplethysmographic (PPG) devices exist, but they are not practical and not accurate enough for the purpose of the recent study. Infra red light emitting diode (LED) is used as the light source as it is cheap, small, secure to human eye and energy-friendly.

Cardiovascular diseases or even arterial stiffness does not cause any symptoms, but after the person exercises the symptoms appear. During the first symptoms 60% of the affected persons die. These persons are and have been in danger for long time. But measuring blood pressure is not enough, because it do not see the arterial stiffness at all. That's why we have been developing an optical device for arterial stiffness measurement and software for analysis of the measurement results.

The extracted PPG pulse wave was evaluated by a pulse waveform analysis for 10-20 s every single pulse of the finger and toe records.

2 MATERIALS AND METHODS

The new PPG system consists of two optical measurement probes, one for a finger and the other for a toe, and a compound electronics unit for handling the optically measured signals based on phase sensitive detection (PSD). The measurement head consists of two LEDs and one large area semiconductor photo detector for collecting light emitted by the LEDs through the finger or toe. The compound electronic unit contains electronics for driving the LEDs (940 nm), two preamplifiers for signals, four PSD channels, an analog-to-digital converter and an USB-interface for transferring the digitized results onto a laptop. In addition, parallel methods of electrocardiogram (ECG) and phonocardiogram (PCG) have been measured simultaneously to support the later PPG analyses. The subjects were measured a.m. in supine position without coffee or tobacco in the morning. Each measurement took about five minutes to obtain

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consecutive 300 pulses, of which parallel 10 to 20 most stable were selected for pulse wave decomposition analysis. In this research, the index finger and index toe were always under measurement. After measurements we depict the toe PPG as a function of the finger PPG which describe complex non-harmonic motion in all cases. The phase shifts were apparent that delay semantics can be difficult to define and used with a causal system relations.

In the pulse wave decomposition analysis, each pulse wave was divided into four lognormal wave components. The compound decomposed waveforms were after computation and fitting visually compared to the original waves to make sure the best fitting. This comparison and the four lognormal functions can be used to obtain a residual error curve and its chi-square value will describe the goodness of the fit. The verification of multi-lognormal functions can be justified as they well represent the vascular network with many asymmetric arterial double-branching and lognormal distribution of the length of capillary arteries and also the blood flow velocities in these capillaries (Qian et al. 2000).

The Origin 7.5 (OriginLab®) lognormal procedure was utilized for analyzing the pulse waves in time domain to obtain best mathematical fitting with minimal residual error. In this procedure, the Levenberg-Marquart algorithm (LMA) is a very popular curve-fitting algorithm used in many applications for solving non-linear curve-fitting problems, e.g., logarithmic normal function curves. LMA provides a numerical solution to the problem of minimizing a function which can be nonlinear, over a space of parameters of the function. In our case we have selected four similar lognormal components which have 4x3 parameters and the requirement for the correlation coefficients (R^2) to be 0.995 or over. We used the peak time values of the 1st and the 2nd lognormal function, called percussion and tidal component to find out arterial stiffness values for the population measurements. We also determined the 2nd derivative function of the PPG wave which contains the parameters **a, b, c, d,** and **e**, respectively in each pulse wave. The second derivative of the finger photoplethysmography (SDPPG) has been applided as a rapid and convenient method for pulse-wave inspection. The determination of vascular aging is possible throughout the SDPPG, but especially effective it is through the third derivative of the finger PPG (TDPPG). In the case of typical SDPPG waveform were characteristic waves are missing, the TDPPG can still more uncover the characteristic waves. PPG waveforms are varied by very little with each subject. Therefore there are some cases when characteristic wave of PPG was not found by one technique we selected another one. The derivatives of waveforms are changed by the area, width and the function's peak value.

3 RESULTS AND DISCUSSION

In Figure 1 it is shown as an example consecutive PPG waveforms of the pulse wave signal at 940 nm (IR) measured through the index finger tip pulse wave (PPG1, straight) and the second toe tip (PPG2, dash). Signals are normalized for the amplitude.

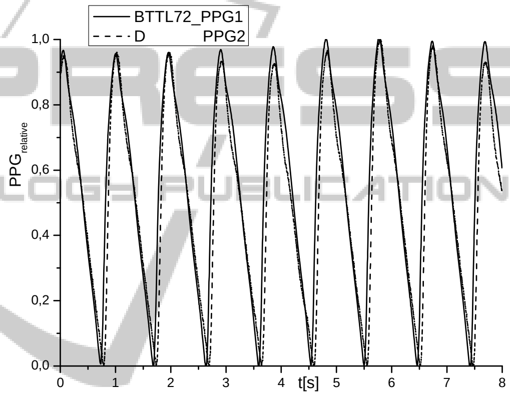

Figure 1: The finger (straight) and toe (dash) PPG of a 72 years male person.

Figure 2 shows the causal relation between the PPG1 and PPG2 in a phase plane, the PPG2 as a function of the PPG1. When the PPG1 increases the PPG2 still decreases, but after a certain value of the PPG1 the PPG2 begins to increase. After the peak value, the both signals decreases almost linearly to the end of each pulse wave.

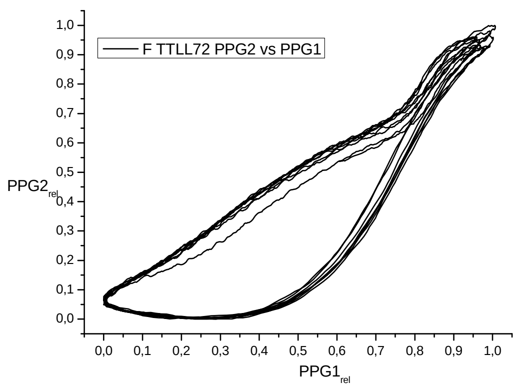

Figure 2: PPG2 vs. PPG1 of the pulse waves in Figure 1.

In Figure 3 it is illustrated an analyzed compound finger PPG waveform. It contains the typical PPG components. In this case the PPG waveform analyses are covering the following four pulse components in each pulse wave: percussion, tidal, dichrotic, and peripheral reflection component. Percussion is caused by the contraction of the heart left ventricular muscle. The second component is the tidal wave, occurring during the later part of the systole, caused by the elastic properties of aorta. The dichtrotic component is the reflected pulse from lower periphery elasticity and vessel branching (A G Scandurra et al. 2007).

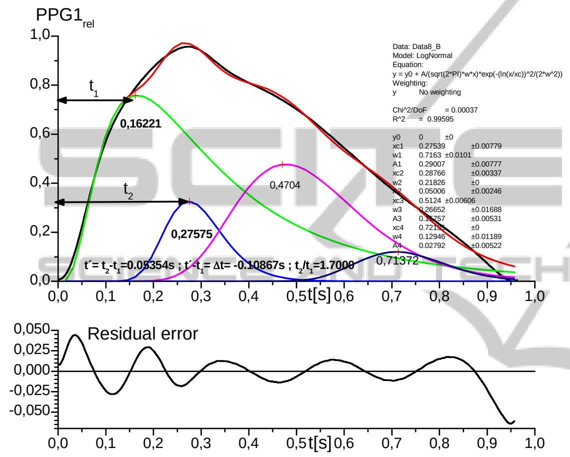

Figure 3: An analyzed finger PPG waveform which contains the percussion component (green), the tidal component (blue), the dicrotic component (magneta), and the peripheral reflection component (navy). The lower part of the figure shows the residual error and R^2=0.99595.

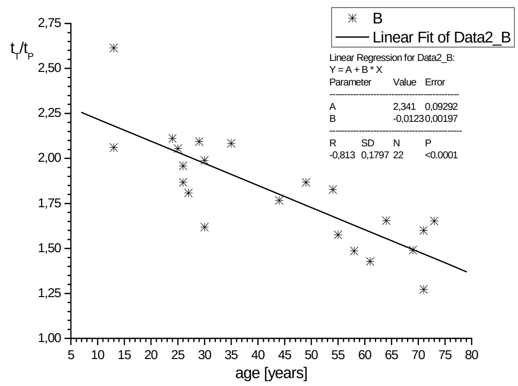

Figure 4: The tidal peak time divided by the percussion peak time as a function of the age for 22 persons of different ages (R=-0.813).

Figure 4 shows the tidal peak time divided by the percussion peak time of each PPG waveform R=-0.813 which is rather good correlation coefficient.

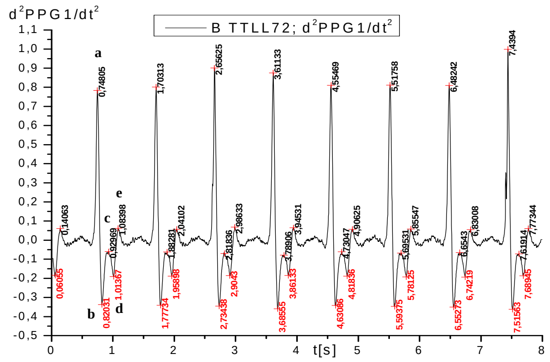

Figure 5: The SDPPG waveform for the PPG1 in Figure 4. The 2nd derivative of PPG1 contains the parameters a, b, c, d, and e for each consecutive pulse wave. All peaks were completely found in this case, but only marked for the first pulse wave.

In Figure 5 it is shown a 2nd derivative of the finger PPG waveform. They well hit into the search window and all the peaks were found. However, their biophysical meaning is open. It is known that the components **a, b c**, and **d** belong to the first part of systole, and **e** belongs to the late part of the systole (J Hashimoto et al. 2002).

The characteristic points of the finger PPG can be also extracted using the 3rd derivative PPG (TDPPG) as shown in the Figure 6. The positions of the peak of the percussion wave and the dicrotic wave can be evaluated also from the inflection points, where the third derivative of the PPG changes sign, such as the zero crossing points.

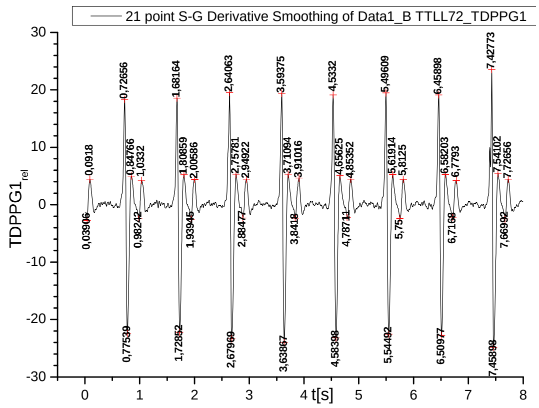

Figure 6: The TDPPG waveform for the PPG1 in Figure 1. The 3rd derivative of PPG1 contains more clearly that the SDPPG the similar parameters a, b, c, d, and e for each consecutive pulse wave.

Figure 7 shows that the tidal peak times divided by the percussion peak times of each PPG waveform have clearly concentrated on the value 0.5 and the

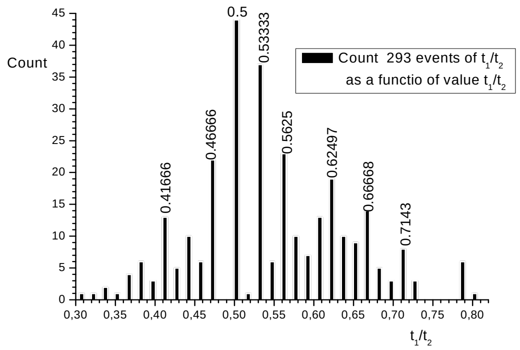

Figure 7: The percussion peak time divided by the tidal peak time count as a function of the percussion peak time divided by the tidal peak time for 293 events in 83 persons of different ages. (see also Figure 3).

on some discrete values in 83 persons for 293 PPG pulses.

This research studies the potential of PPG for early diagnosis of arterial stiffness. PPG technology is widely available at the pulse oxygen saturation measurements and is relatively cheap and does not require special expertise. PPG can be utilized for detecting pulse waveforms. In the blood circulatory system, the arterial pulse wave reflections depend on the arterial wall stiffness. This study includes creating a mathematical model for pulse wave-forms for analyzing the four wave components of the human pulse. This information based on the second derivative photoplethysmogram can be further used for estimating arterial stiffness which is normally determined based on pulse wave velocity (A Qasem, A Avolio 2008).

4 CONCLUSIONS

The location of a tidal wave seems to drift earlier by the age, while the percussion wave drifts to the opposite direction. By analyzing the four components, one may be able to make conclusions relating to arterial stiffness. It might be beneficial to measure pulse waves instead of blood pressure due to more information being available on the condition of veins.The use of lagged gamma function might also prove interesting (Qian et al. 2000).

Because the tidal peak time divided by the percussion peak time of each PPG waveform (R=-0.813) which is rather good correlation coefficient as a function of age, this could be used as a measure of arterial aging. The further investigation would be warranted to see if a predictive index of blood pressure changes might be obtained from pulse wave analysis of PPG waveforms. The determination of age-related changes in the arterial pulse wave by the high fidelity PPG device, thus, provides important supplementary information to that obtained by use of the blood pressure measurements.

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