Pulse waveforms are an indicator of the condition of vascular system

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Abstract— **Arterial stiffness index is one of the biomechanical indices of vascular healthiness. These indexes are based on detailed pulse waveform analysis which is presented here. After photoplethysmographyic (PPG) pulse wave measurement, we decompose the pulse waveform for the estimation and determination of arterial elasticity. Actually, it is electro-optically measured PPG signal that is analyzed and investigated by dividing each wave into five logarithmic normal function components. For the PPG waveform we can find a relative good fit between the original and overlapped and summed wave components. Each wave component is assumed to resemble certain phenomenon in the arteries and certain indexes can be calculated for example based on the mutual timing of the components. Several studies have demonstrated that these kinds of indexes which have been calculated based on actual biomechanical processes can predict future cardiovascular events. Many dynamic factors, e.g., arterial stiffness, depend on fixed structural features of the arterial wall. For more accurate description, arterial stiffness is indirectly estimated based on pulse wave decomposition analysis in the radial and tibial artery measured by PPG method in parallel. Elucidation of the precise relationship between endothelial function and arterial stiffness can be done through biomechanics. However, there is no clinically accepted technique for directly assessing the biomechanical properties of the arterial walls. Arterial wall elasticity awaits still further biomechanical studies with clinical relations and the influence of arterial flexibility, resistance and ageing inside of the radial pulse waveform.**

Keywords— **Arterial stiffness, photoplethysmography, pulse wave analysis, decomposition.**

I. Introduction

The changes of the optical absorption through fingers can be easily monitored by photoplethysmography which measures the opacity changes in arteries, in this case, the distal arteries of the index finger and second toe. The waveforms of the signals measured reflect some average property of a whole arterial system, especially arterial and aortic walls. The technique is simple, noninvasive, and does not cause any damage or discomfort to the subject, because no press is applied [1].

As a motive, we know that when arteries stiffen the pulse wave velocity increases which has been shown by many techniques [2, 3]. Arteries stiffen as a consequence of normal aging process, but also caused by the arteriosclerosis which is a group of diseases characterized by thickening and loss of elasticity of the arterial walls. There are many phenomena behind of the elasticity loss [4]. Age related hardening occurs when the elastic fibers within the arterial wall muscles (elastin) begin to lose their resistance to rupture due to mechanical stress. Cardiovascular diseases (CVD) are the world's largest killers, claiming 17.1 million lives a year according to WHO (World Health Organization). Most countries face high and increasing rates of CVD. Arteries stiffen as a consequence of age, smoking, high cholesterol, lipid concentrations, obesity and sedentary life style. Sedentary life style also increases the risk for developing diabetes and arteriosclerosis [3].

Here we are optically investigating by non-invasive means measuring heart pulse waveforms detected in the periphery, namely on the finger and toe tip. Photoplethysmographic (PPG) device is typically used in analysis of oxygen saturation, but it enables assessing peripheral pulse waveforms, monitoring anesthesia, breathing, and apnoea. In addition PPG waveform based indexes can be used to follow changes in the elastic properties of the arteries causing arterial wall stiffening during ageing and in cases of CVD. However, these indicative indexes can inform about the necessity for life style changes [2, 5].

Analysis of the arterial pulse waveform becomes an important tool to find out and assess the pulse wave components and their relations, e.g., on personalized medical treatment which support for CVD prevention. The wave contains information on arterial physical properties and useful information on left ventricle activity, dynamics of autonomic nervous systems and heart-brain interaction, and arterial stiffness [6]. In addition to the arterial tree structure, the compound arterial pulse wave depends on ventricular ejection pattern which is determined by cardiac output and simply by palpation at the periphery as a percussion wave. Much important information can be received based on the wave shape of the arterial pulse waveform, e.g., arterial stiffness, effects of drugs [7]. The calculated parameters of arterial stiffness index and the photoplethysmographic index are shown to be different for healthy volunteers and patients [8]. The method is still waiting for clinical validation. The time domain analysis presented here could give valuable information on the state of peripheral arteries when we fit

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by a component separation method. This time domain component separation method presented here is based on logarithmic normal function which fits relatively accurately giving information on the arterial pulse waveform when we analyze each component separated by this method parallel with residual errors giving a good goodness of fit after iteration process. Except that the normal Gaussian and lognormal function forms are closely related, the normal Gaussian functions do not fit well to the PPG data according to visual inspection. The normal Gaussian function is symmetric but the PPG pulse waveforms are not [9]. In the analysis on noiseless PPG waveforms, the PPG pulse waveform is processed by Levenberg-Marquart algorithm (LMA). Each iteration works well and we didn't need to guesswork parameters in young healthy persons but on the elderly healthy PPG pulse waveforms.

II. MATERIALS AND METHODS

Photoplethysmographic (PPG) device was constructed based on phase sensitive detection (PSD) in transmission mode. For the measurement of a high quality PPG record, IR LED lighted through a left index finger and second toe tip and the resulting LED light was measured and amplified with the principle of phase sensitive detector circuit. The PSD circuit cancels the ambient light and also power line noise producing low noise PPG signal from the finger and toe simultaneously. The lower cutoff frequency of the PPG device is DC which make possible to analyze also very low frequency autonomic nervous fluctuation in the PPG measurements. The higher cutoff frequency is over 30 Hz which make possible to analyze accurately the pulse waveform in all cases. The experiments were carried with 24 volunteers a.m. in supine position for five minutes.

The measured PPG signals were analyzed by the Origin 7.5 software (Origin Lab Corporation, 2002). The arterial pulse wave decomposed into the five lognormal functions with three parameters that were identified in the pulse separation procedure. This optimization procedure is based on LMA which is an iterative technique that locates the minimum of a function that is expressed as the sum of squares of nonlinear functions, such as logarithmic normal functions fitted in the radial and tibial arterial pulse wave. Measured intensity of light in PPG detectors differs between subjects and skin sites because of skin structure and human age. Thus, absolute PPG values cannot be compared quantitatively if we don't find the right parameters. We calculate two arterial pulse wave indexes called ageing index. The first one (AGI1), presented in [10], is based on the second derivative of the pulse wave signal and defined as:

$$AGI1 = \frac{b - c - d - e}{a} \tag{1}$$

The other index (AGI2) is based on the peak values of the decomposed wave components and defined as:

$$AGI2 = \frac{t2 + t3 + t4 + t5}{t1} \tag{2}$$

where t1 is the peak value of the percussion, t2 the tidal, t3 the dicrotic, and t4 and t5 the pre-systolic wave components, see Fig. 1. Correlation between the two indexes is also presented as a function of age for the subjects' age between 13-74.

III. RESULTS AND DISCUSSION

Fig. 1 shows an example PPG waveform of a healthy 24 year male. It is possible mathematically to decompose the measured PPG waves to analyze their time domain features. Each five components, percussion, tidal, dicrotic, and two pre-systolic components are shown. The whole PPGs are shown in Fig. 2 from where the first pulse waves of each record are taken for analysis based on the LMA. The measured PPG and its fit lines well overlap but not at the start and at the end of the pulse wave. The difference between measured and calculated function forms can be seen as the residual error function in Fig. 1. The residuals plot provides insight into the quality of the fitted curve. Residuals mean the deviation of the PPG data from the fitted curve.

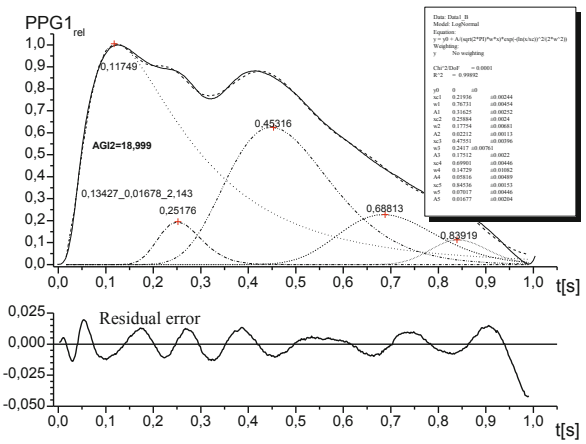

Fig.1 Radial arterial PPG pulse wave (solid) (male, 24 years) with the percussion (dotted), tidal (dash dot), dicrotic (dash dot dot), and two pre-systolic (short dash, short dot) time peaks defined. The summed fitted pulse waveform is marked by dash with the parameter table (insert). The calculated ageing index AGI2=18.999. The other values are the time interval (0.13427 s) between the tidal peak time (0.25176 s) subtracted by the percussion peak time (=0.11749 s), the time difference between percussion and tidal (=0.01678 s), and the ratio of the tidal wave from the start (=0) divided by the percussion peak time is 2.143. On the bottom the residual error curve is as a function of time between the measured PPG waveform and the fitted waveform. The goodness of fit is R^2=0.99892.

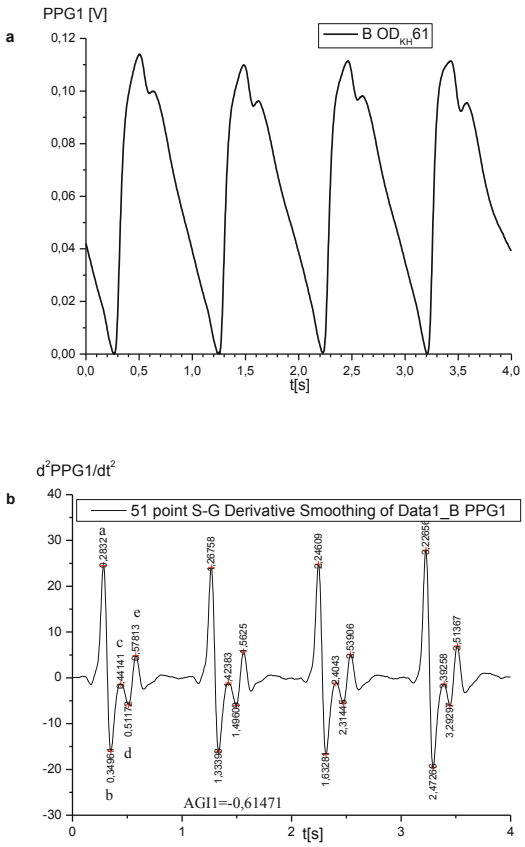

Fig. 2 PPG signal from the finger of 61 years male for four seconds (a) and its second derivative (b) marked with the characteristic values: a, b, c, d and e with AGI1= -0,61471.

In all measurements, the finger and toe PPGs was diverse between the young and elderly healthy subjects. The decomposed PPG waveforms fit well into its five logarithmic normal components indicating the coefficient of determination R2=0.995 or over. The residual errors are also close to zero during the pulse waves. The logarithmic normal function describes the response of the arterial system. The first wave component is the percussion, originating from the contraction of the left ventricle. The second component is the tidal, occurring during the latter part of the systole, caused by the elasticity of aortic wall. The third component is the dicrotic occurring during the beginning of diastole, caused by the reflection from the lower body bifurcation to the legs. The fourth and fifth component, so called presystolic components occur during the end of diastole coming back from the bifurcations and reflection sites [12].

The determination of age-related changes in the arterial pulse wave by the high fidelity PPG device provide important supplementary information to that obtained by use of the blood pressure measurements. The use of the device enhances new investigations of the effects of ageing and also early CVD states on cardiovascular function. In the future studies, more experiments will be conducted to examine the variation in parameters of logarithmic normal function which were extracted from PPG pulse waveforms, especially radial pulse signals based on percussion, tidal, but also dichrotic wave detection using the technique presented in this paper. As a combination of forward wave and reflected wave components establish the compound radial pulse waveform. The time domain features revealed by the LMA with the logarithmic normal function gives conspicuous information on the arterial pulse waveform with other analysis techniques like first, second, or third derivatives, principal component analysis, or wavelet based analysis [8]. In this preliminary study the aim was to find out whether parameters from radial artery pulse waveforms acquired by PPG method were different for different subjects (young, old) and what might cause the variations of parameters, especially aortic wall elasticity which analysis is done next.

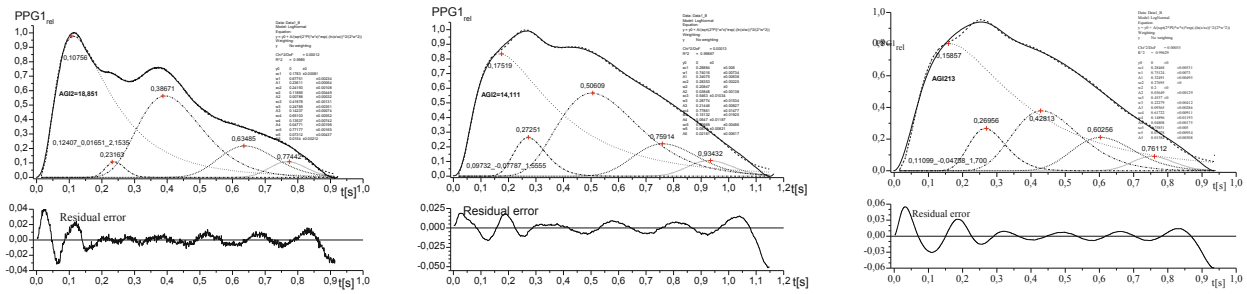

Fig. 3 Radial arterial pulse waveforms (left, age 24 male), (middle, age 61 male), and (right, age 70 male) decomposed. The peak value of each component is shown with its ageing index value (AGI2) 18.851 for 24 years old, 14.111 for 61 years old, and 13.000 for 70 years old. See Fig. 1 for the markings.

For the pulse wave derivative and decompositon analysis, it is drawn the ageing index 1 (second derivative based index, AGI1, numbered) and the ageing index 2 (decomposition based index, AGI2, alphabet) as a function of human age in Fig. 4 a. The straight lines have the correlation coefficient 0.605 and 0.666 which demonstrate good correlation between different indexes as a function of age. In Fig. 4 b the AGI1 is a function of AGI2 when the human age is parameter (the correlation coefficient=-0.7695).

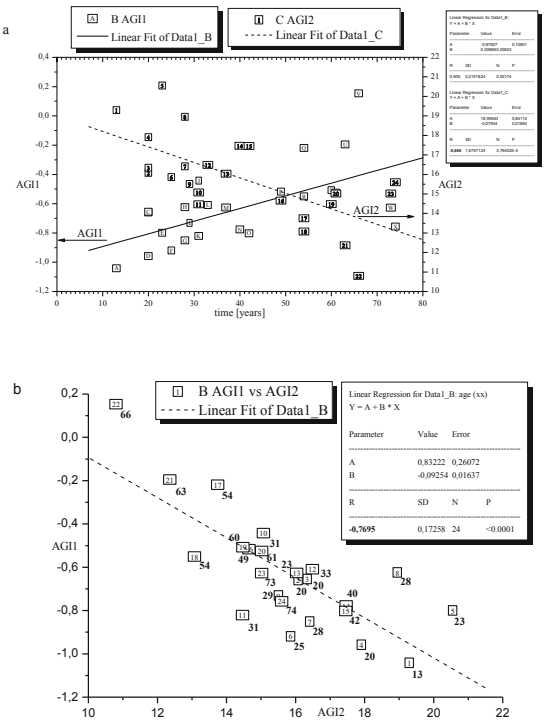

Fig.4 (a) The ageing index 1 (second derivative based index, AGI1) and the ageing index 2 (decomposition based index, AGI2) as a function of human age from 13 to 74 years for 24 subjects. The squared values are row numbers with the age in years. The correlation coefficient is 0.605 for AGI1 and 0.666 for AGI2. (b) The AGI1 as a function of AGI2 when the human age is parameter (outside of the square) (the correlation coefficient=-0.7695). In the insert it is represented the parameter data for fit.

The proposed method can provide a simple decomposition for radial and also tibial pulse waveforms. Future work is currently under way to investigate on different patients the techniques to improve further the classification of arterial elasticity. Here we demonstrated the correlation between vascular ageing so that the both calculated ageing indexes depend on human age very strongly. The second derivative of the pulse wave may give useful information when evaluating the vascular ageing and it is readily calculated providing that the signal is not too weak and noise.

As a conclusion, the heart pulse waveform can be divided into pulse wave components as done here, which could be used in evaluating the condition of the vascular system. The AGI1 and AGI2 indices showed significant correlations as a function of age, but they also are of particular interest as a value in assessing the arterial elasticity. Because the growing number of people lives to older ages, there is also an urgent need to find effective pre-symptomatic CVD treatments.

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REFERENCES

1. G. Uretzky & Y Palti (1977) Elastic properties of blood vessels determined by photoelectric plethysmography. Angiology 28: 75-83.
2. J. Allen (2007) Photoplethysmography and its application in clinical physiological measurement. Physiol. Measurements 28 , R1–R39.
3. G. Mancia (2007) Guidelines for the management of arterial hypertension. European Heart Journal 28, 1462–1536.
4. I. Korhonen & A. Yli-Hankala (2009) Photoplethysmography and nociception. Acta Anaesthesiol Scand.; 53: 975–985.
5. L. Gbaoui & E. Kaniusas Decomposition of Photoplethysmographical Arterial Pulse Waves by Independent Component Analysis: Possibilities and Limitations, Advances in Biomedical Sensing, Measurements, Instrumentation and Systems, Lecture Notes in Electrical Engineering ISSN1876-1100 vol. 55.
6. M. Nitzan (1998) The variability of the photoplethysmographic signal--a potential method for the evaluation of the autonomic nervous system. Physiol. Measurement 19(1), 93-102.
7. M. F. O'Rourke (2009) Time domain analysis of the arterial pulse in clinical medicine. Med. Biol. Eng. Comput. 47:119-129.
8. R. Gonzalez et al. (2008): A Computer Based Photoplethysmographic Vascular Analyzer through Derivatives. Computers in Cardiology 35:177−180.
9. U. Rubins (2008) Finger and ear photoplethysmogram waveform analysis by fitting with Gaussians. Med. Biol Eng Comput. 46:1271–1276.
10. K. Takazawa, et al. (1998) Assessment of vasoactive agents and vascular aging by the second derivative of photoplethysmogram waveform. Hypertension; 32: 365-370
11. H. SikShin, C. Lee, M. Lee (2009) Adaptive threshold method for the peak detection of photoplethysmographic waveform . Computers in Biology and Medicine 39 1145–1152.
12. H. E. Ulmer, et al. (1982) Mechanocardiographic assessment of systolic time intervals in normal children. Basic Res. Cardiol. 77, 197-212.

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