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Estimation of Cardiovascular Aging in Healthy and Diabetic Subjects Using Second Derivative Photoplethysmographic Signals

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Abstract: ***Arterial stiffness is an independent risk factor for cardiovascular illness indication and can be evaluated by photoplethysmographic (PPG) waveforms and their derivatives. The ability to recognise arterial stiffness in its early stage is of significant value in preventing cardiovascular diseases. The aging index (AI), which can be calculated by using the second derivative of the PPG (SDPPG) waveform, has been utilised as one method for arterial stiffness estimation and the assessment of cardiovascular ageing. The present study was conducted to verify that the structural of indices of the SDPPG were indeed able to show the difference in levels of aging index values between healthy subjects and subjects with diabetes. PPG and SDPPG waveforms of 15 normal and 15 diabetic subjects belonging to three distinct age groups were analysed in this study.***
Keywords: Photoplethysmography (PPG), Second Derivative Photoplethysmographic (SDPPG) waveform, Arterial stiffness, Aging Index (AI), Cardiovascular risk.

I. INTRODUCTION

In recent years there has been a significant interest in the advancement of inventive non-invasive approaches and devices for the analysis of cardiovascular diseases; The study of Photoplethysmographic waveforms has been used as one such method [1]. Photoplethysmography is a non-invasive optical technique for computing changes in blood flow that is mainly used for monitoring blood volume changes in the tissue which can be measured at the surface of the skin.

The device used to acquire the PPG signals is made up of a light emitting diode (LED), which is mostly infrared or red, and a sensor that is light sensitive, that is, a phototransister (PT) [2].

The PT and LED are placed on the either sides of the finger. When the LED emits light on to the skin, the emitted light is received by the PT with some fractional changes in the intensity, which are associated with various factors like blood circulation, blood volume, movement of vessel walls that carry the blood, and the alignment of red blood cells in the primary tissue.

The characteristic components of a PPG signal are: DC and AC components and noise.

Motion artifacts are the main cause for noise in the PPG signal. Noise can be removed by using various filtering techniques available. The AC constituent of the PPG signal is synchronous with the heart rate and relies upon the variations in pulsatile blood volume and pressure[1].

A typical PPG waveform of a healthy individual is illustrated in Fig. 1(a).

There are numerous methods that can be used to analyze the PPG waveform and they can also be applied for estimating arterial stiffness and to estimate the extent of cardiovascular aging [3–5]. One of the methods is to use the derivatives of the PPG waveform, specifically, the second derivative (SDPPG), which was originally proposed by Takazawa et al. [7]. The SDPPG is analyzed by utilizing the peak amplitude values of the distinctive waves obtained in the SDPPG, the “a”, “b”, “c”, “d”, and “e” waves, that are located in the systolic phase of the cardiac cycle (Fig. 1(b)).

The normalized amplitudes of these waves are given by: b/a, c/a, d/a, and e/a. It has been shown that the increase in normalized amplitude of b/a and the decrease in other normalized amplitudes is directly proportional to the increase in the subject’s age. Therefore, an aging index (AI) parameter was proposed giving AI = (b/a)−(c/a)−(d/a)−(e/a), where a, b, c, d, and e are the peak amplitudes of the waves.

The value of AI defines the cardiovascular age of the subject[1].

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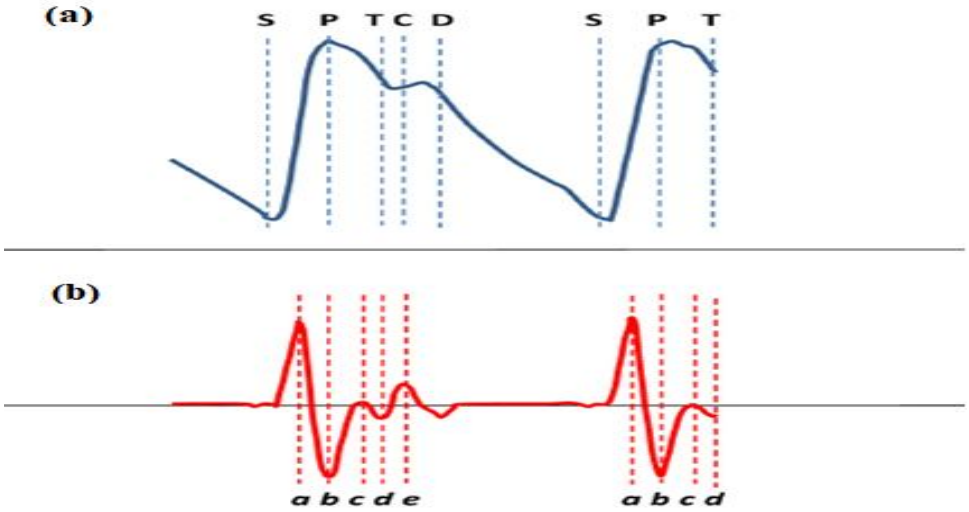

Fig 1. Illustration of a typical PPG and SDPPG waveform. (a) Raw photoplethysmogram and (b) its second derivative. S = starting point of systole; P = peak of percussion wave; T = tidal wave; C = Incisura wave; D = Dicrotic wave (from von Wowern et al. [6]).

Several publications have carried out statistical analysis of the relationship between cardiovascular risk factors and the normalized amplitude values of the second derivative of PPG [8–10]. The SDPPG normalized amplitudes and AI can be considered as capable indicators for a screening method to sense increased arterial stiffness [11]. Millasseau et al. in their study described the detection of wave amplitudes by processing the SDPPG signals [12]. It is assumed that, for subjects that are healthy, over short periods of time there are no changes in the cardiovascular system. Additionally, peaks detected in the first and third periods are attributed to the beginning of systolic phase of the PPG waveform compared to the second and fourth periods. Due to this, the amplitudes of distinguished peaks in successive periods depict different phase of the PPG signal and AI values are evidently different[1].

II. METHODOLOGY

A. Subjects

The study was performed on healthy subjects and diabetic patients. Consent was taken from all the subjects to extract and analyse the PPG signals for the study. The PPG signals were recorded from 15 healthy and 15 diabetic subjects. The subjects ranged from 20 years to 60 years in age. Since PPG varies with age, the subjects were further classified into three distinct age groups, that is, 20-25 years, 35-40 years and 55-60 years. Each group comprised of five healthy subjects and five diabetic subjects. The healthy subjects were not on any permanent medications.

B. Instrumentation and Data Processing

A device to record PPG was built using an IR LED (940nm) and a light intensity sensor (OPT101), all the necessary filters to record PPG waveform and eliminate the noise were also included. All the signal processing steps were carried out in MATLAB. The sampling frequency was 500Hz. The data was recorded for the duration of a minute from the index finger while the subjects were at resting position. The subjects were at resting position for at least five minutes before the recording began. The room temperature was maintained at 28 degrees Celsius during the recordings. Even though the signals were recorded for the duration of a minute, only a partial amount of that duration, about 6 to 8 seconds, was selected for analysis of the SDPPG.

The PPG signal and the SDPPG of a healthy subject of age 36 years are shown in Fig. 2 and Fig. 3respectively.

The SDPPG waveforms comprise of a, b, c, d and e waves. The ‘a’ wave is the early positive wave, ‘b’ wave is the initial negative wave, ‘c’ wave is the second positive wave, ‘d’ wave is the late negative wave and ‘e’ wave is the diastolic up sloping wave. The peak amplitude of each wave is considered as the value of that particular wave. The SDPPG waveform outline is established by the magnitudes of the ‘b’, ‘c’, ‘d’ and ‘e’ waves to the ‘a’ wave [13].

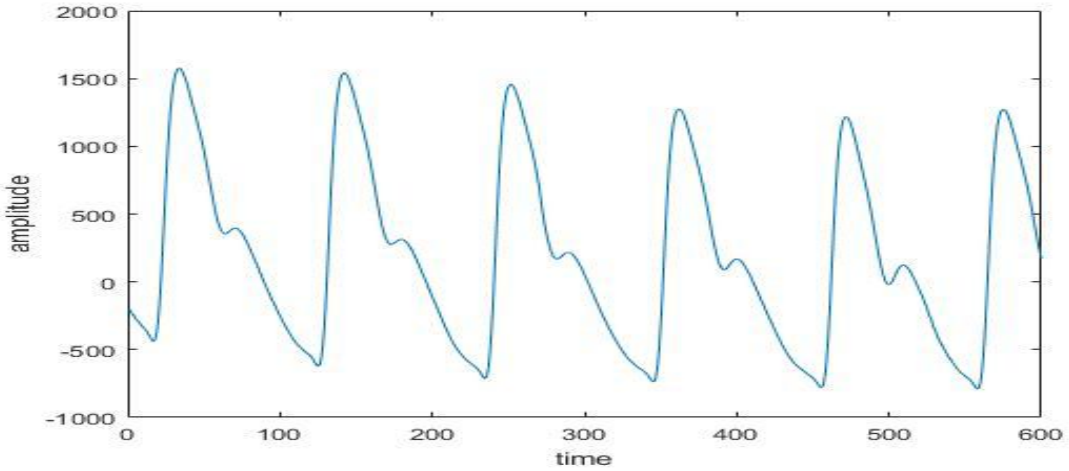

Fig. 2 PPG signal of a healthy 36 years old subject.

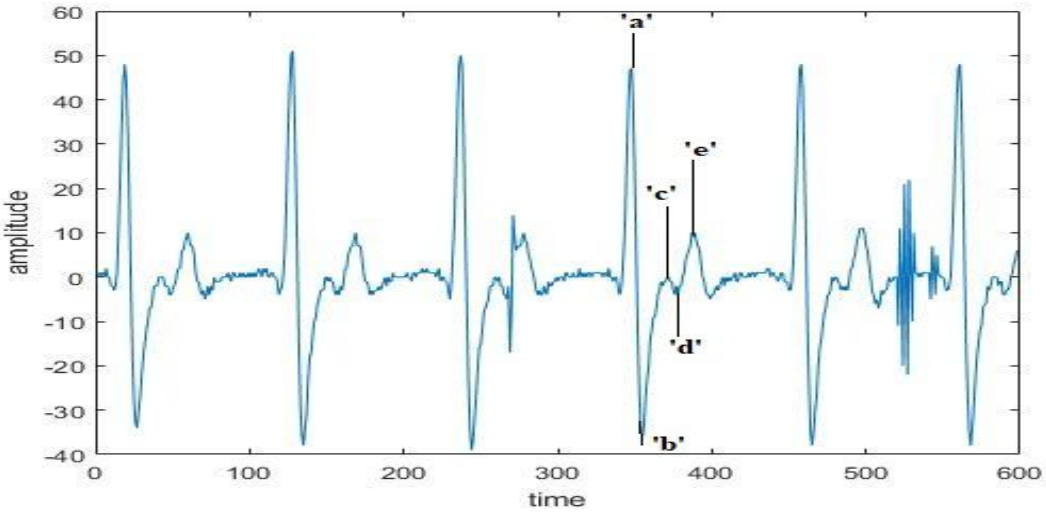

Fig. 3 SDPPG of a healthy 36 years old subject.

Similarly, the PPG signal and the SDPPG of a diabetic patient aged 38 years are shown in Fig. 4 and Fig. 5 respectively.

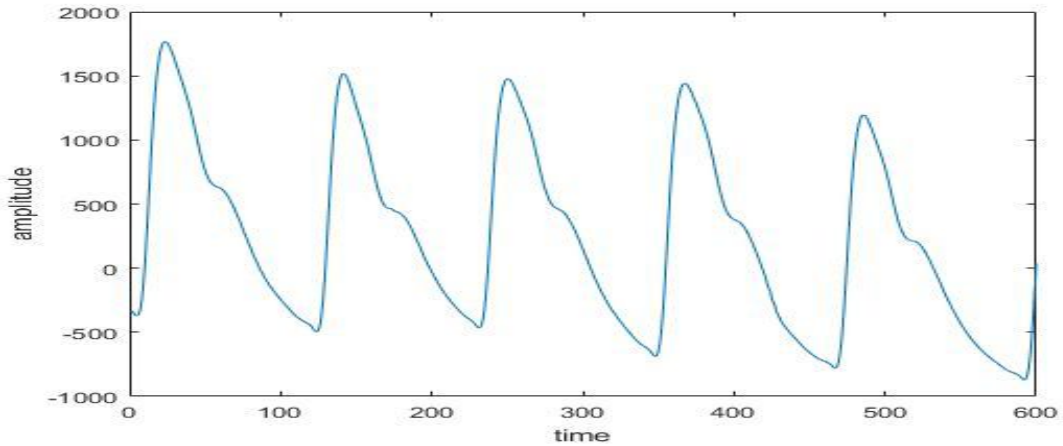

Fig. 4 PPG signal of a 38 years old diabetic subject.

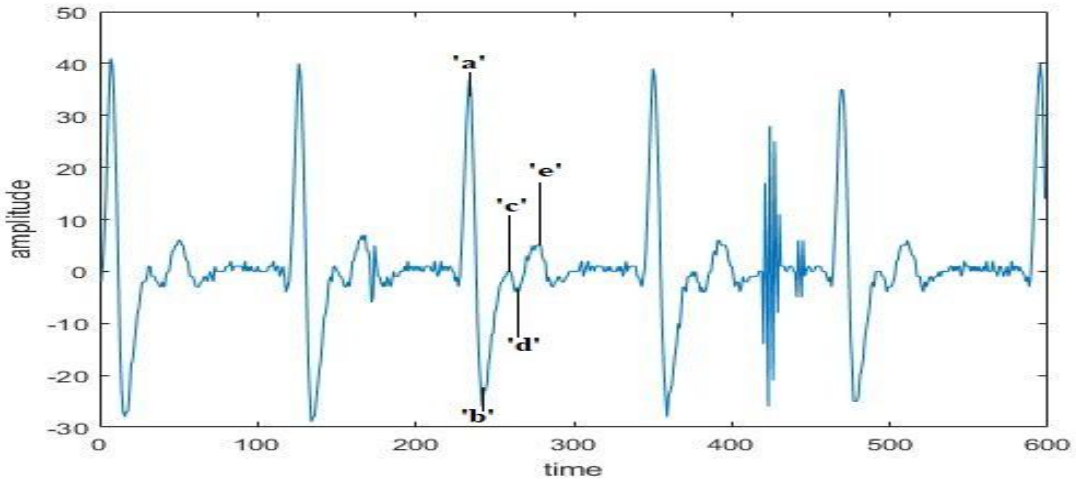

Fig. 5 SDPPG signal of a 38 years old diabetic subject.

III. RESULTS

The aging index from the SDPPG waveform can be calculated by using equation (1),

$$AI = \frac{(b - c - d - e)}{a} \quad (1)$$

Even though the SDPPG waveforms resemble each other, their gradient of each period (b wave to e wave interval) is entirely reliant on the vessel health of the particular subject [13]. Therefore, it is very important to make sure that the values are recorded accurately to calculate the aging index.

The results obtained after calculating aging index (AI) for all the 30 subjects are tabulated in Table I, II&III and Table IV shows the mean and standard deviation values of each group selected.

TABLE I: AI VALUES FOR AGE GROUP 20-25

SUBJECTS	AGE	AI
HEALTHY	20	-1.26
	23	-1.14
	23	-1.15
	24	-1.21
	25	-1.19
DIABETIC	23	-0.86
	24	-0.75
	25	-0.92
	25	-0.75
	25	-0.84

TABLE II: AI VALUES FOR AGE GROUP 35-40

SUBJECTS	AGE	AI
HEALTHY	36	-0.88
	36	-0.91
	38	-0.84
	39	-0.86
	40	-0.75
	37	-0.55

DIABETIC	37	-0.58
	38	-0.56
	39	-0.49
	39	-0.47

TABLE III: AI VALUES FOR AGE GROUP 55-60

SUBJECTS	AGE	AI
HEALTHY	55	-0.64
	56	-0.52
	55	-0.61
	58	-0.48
	59	-0.56
DIABETIC	59	-0.15
	57	-0.23
	59	-0.19
	60	-0.11
	60	-0.14

Fig. 6 The AI values differences between the age groups selected.

TABLE IV: MEAN AND STANDARD DEVIATION OF AGE GROUP AND AI

SUBJECTS	AGE MEAN ± S.D	AGING INDEX (AI) MEAN ± S.D
HEALTHY	23 ± 1.87	-1.19 ± 0.04
	37.8 ± 1.78	-0.848 ± 0.06
	56.6 ± 1.81	-0.562 ± 0.064
DIABETIC	24.4 ± 0.89	-0.824 ± 0.07
	38 ± 1.00	-0.53 ± 0.04
	59 ± 1.22	-0.164 ± 0.046

*S.D: STANDARD DEVIATION

The difference between the AI values of healthy subjects and diabetic patients as seen in Table IV is illustrated in Fig. 6. As it can be observed, the healthy subjects in the age groups selected have lower AI values than that of the AI values of diabetic patients in their respective age group.

IV. CONCLUSION

In conclusion, it can be said that the aging index (AI) values obtained from the SDPPG waveform offer a way to estimate arterial stiffness of individual subjects. It can be observed that the subjects with diabetes have prominently higher AI values, which are due to an increase in the arterial stiffness. Due to this, the subjects having increased arterial stiffness can be differentiated with more efficiency from healthy subjects and hence cardiovascular disease risks can be determined. In future studies, more complex models and test parameters must be taken into account in order to improve the differentiation of the healthy subjects from patients with increased arterial stiffness by including additional physiological factors for testing. Also, the results of this study should be compared with the results of other available arterial stiffness estimation reference methods in order to truly understand the validity of the obtained results.

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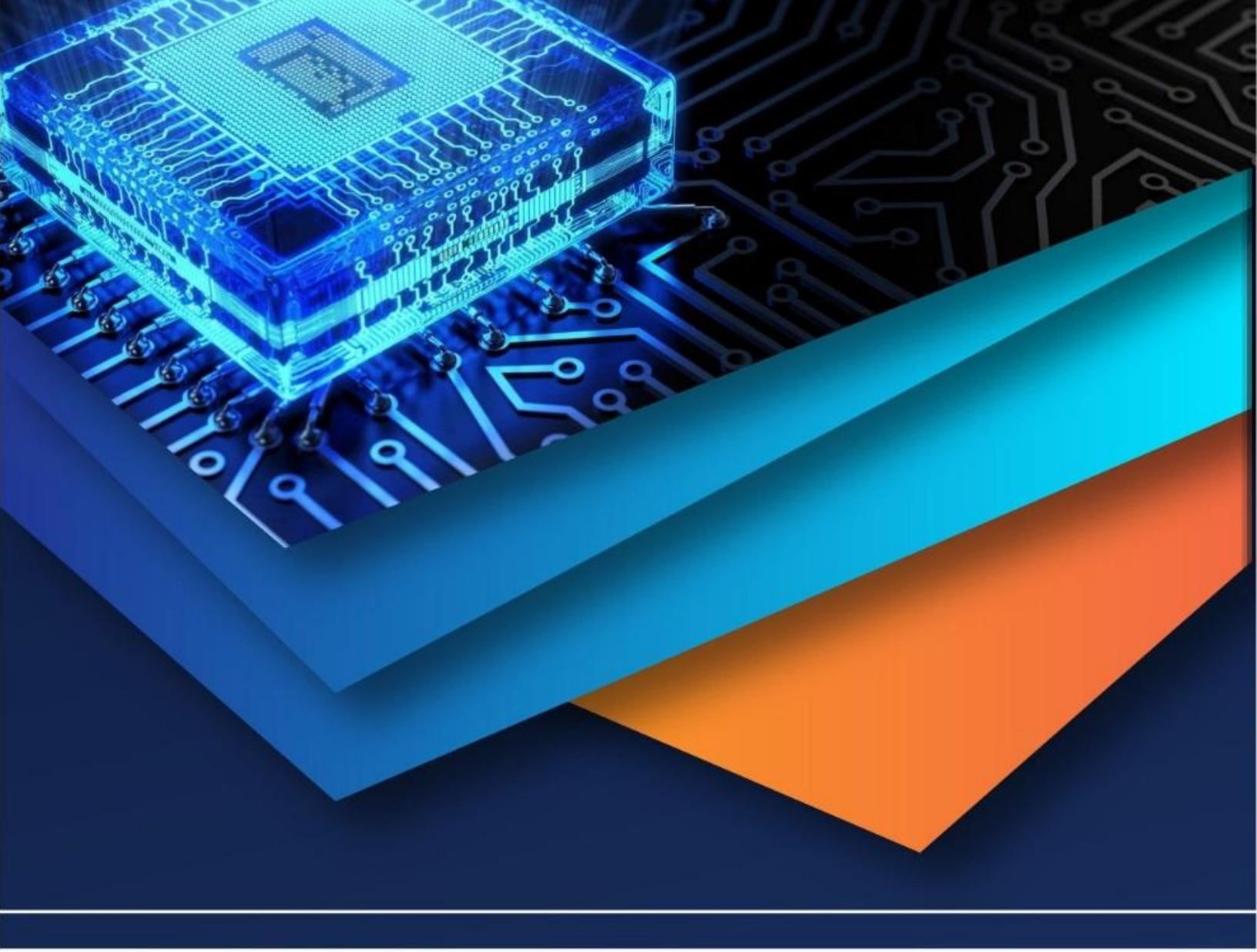

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