

Virtual Instrumentation based Non-Invasive Assessment of Arterial Stiffness Using Finger Photoplethysmographic Signal

A.Ramsrinivas¹, Sikkandar Mohamed Yacin²

Abstract—Cardiovascular disease (CVD) is currently the biggest single cause of mortality in the world; hence, the early detection of its onset is vital for effective prevention therapies. Arterial Stiffness (AS) has proved to be a direct indicator for CVD. In this study, a non-invasive method for assessing AS using Finger Photoplethysmographic (PPG) Signal is proposed. Virtual Instrumentation (VI) software was used for developing the front panel of the proposed system to estimate the clinical parameters of AS like Augmentation Index (AI), Arterial Stiffness Index (ASI) and pulse rate. AI is the measure of AS derived from the ascending Aortic waveform, ASI indicates degree of arterial elasticity and Pulse rate is the number of pulses per minute. All the 3 parameters are estimated by the proposed algorithm using LabVIEW. PPG signal data is collected for 10 adult volunteers and 15 aged volunteers using the proposed system. Further analysis was done using the developed virtual instrumentation front panel. The results show that the clinical parameters are estimated with good accuracy and repeatability.

Index Terms— Cardiovascular disease (CVD), Arterial Stiffness (AS), Photoplethysmographic Signal (PPG), Virtual Instrumentation (VI), Augmentation Index (AI) Arterial Stiffness Index (ASI), Pulse rate.

I. INTRODUCTION

CARDIOVASCULAR disease (CVD) is the leading cause of mortality in the developed world. An estimated 17 million people die every year from CVD (mainly from myocardial infarction and stroke; source: World Health Organization). Established risk factors for CVD include age, sex, cigarette smoking, high blood pressure (hypertension), serum cholesterol and the presence or absence of diabetes mellitus [1]. Cardiovascular disease occurs principally as a result of atherosclerosis and arteriosclerosis, inflammatory and degenerative conditions of the arterial wall. Therefore it is important to determine the cardiac risk of a patient in advance to prevent premature death [2]. The analysis of peripheral pulse volume helps us to understand arterial pathologies, a major contributor to cardiovascular diseases, which is a common cause of death in modern society. The risk factor for CVD is associated with the increasing stiffness of the arterial wall. Furthermore,

arterial stiffness has also been shown to be a useful predictor of all-cause cardiovascular mortality in subjects with end stage renal disease [2].

Ultrasonography and pulse wave velocity (PWV) tests are the main diagnostic approaches used to assess the degree of arteriosclerosis or atherosclerosis. The ultrasonography approach involves measurement of the intima-media thickness and checking for abnormal changes in the carotid artery. Because this artery is one site where atherosclerosis occurs early on, the diagnostic result is regarded as a surrogate marker of systemic atherosclerosis. The advantage of ultrasonography is its high degree of diagnostic accuracy. However, this method is suitable for determining atherosclerosis once an abnormal structure has already developed. Therefore, it has become important to develop tests for checking excessive arterial stiffness in the very early stages of arteriosclerosis [3]-[4].

The velocity of the pulse wave (PWV) has been used as a marker of arterial stiffness [3]. The pulse wave results from displacement of the skin surface caused by intravascular pressure arising from contraction of the heart [5]. PWV is easily measured by applying cuffs to the extremities. In independent theoretical studies, Moens and Korteweg noted that PWV appears to be proportional to the square root of the young's modulus of the arterial wall. In fact, PWV values measured in arteriosclerosis patients were higher than those in age-matched normal control subjects [4]. However, PWV efficacy is not as good because PWV is directly or indirectly influenced by all of the factors that influence blood pressure. Moreover, the method does not make full use of an enormous amount of information included in the pulse wave besides its velocity. Therefore, a more precise method for screening arterial stiffness is required [4]-[6].

Therefore, we need to go for some alternative and easy to measure indices for measuring arterial stiffness. Here the two indices we use are, Augmentation Index (AI) and Arterial Stiffness Index (ASI) [10]. Augmentation Index is an important factor of cardiovascular risk. Augmentation Index is the measure of Arterial Stiffness derived from the Ascending Aortic Waveform [11]. The augmentation index is defined as the ratio of augmented ascending aortic pressure and pulse pressure [7]. Arterial stiffness index is an important non-dimensional parameter which represents the degree of blood vessel stiffness [8].

In the section II, we will see about Pulse Wave Analysis i.e. Pulse Propagation along the Arterial tree and Photoplethysmograph and Various indices of Arterial Stiffness. In the section III, we will see about the Front Panel developed

1. A.Ramsrinivas, Research scholar

Rajalakshmi Engineering College

2. Sikkandar Mohamed Yacin, Professor

Rajalakshmi Engineering College

in LabVIEW and implementation of software with a real time PPG signal acquired from the subject. In the section IV we will see about the Future works and Conclusions.

II. PULSE WAVE ANALYSIS AND PLETHYSMOGRAPH

Arterial pressure pulses are generated at the onset of left-Ventricular ejection: after an initial period of isovolumetric contraction, the ventricular pressure exceeds arterial pressure, and forces the aortic valve to open [12]. The sudden rise of aortic pressure distends the elastic walls of the ascending aorta, thus, creating a pressure pulse that propagates through the walls of the entire arterial tree [5].

A. Pulse Propagation: Anatomy of the Arterial Tree

Fig. 1 provides an overview of the arterial segments propagating a pressure pulse before reaching the sternum. After leaving the left ventricle, the pressure pulse propagates through the aorta and moves forward to the brachiocephalic trunk [13]. Up to this point, the propagation is performed through elastic arteries only and at relatively low velocities.

From the brachiocephalic trunk, the pressure pulse accelerates while propagating through the internal thoracic artery (a large muscular artery, similar to the radial artery before reaching the heterogeneous subcutaneous vascular bed covering the sternum manubrium [14]. Note that because pressure-pulse propagation at the sternum vascular bed is performed at high velocities (Moens–Korteweg equation applied to arterioles geometry), the influence of arteriolar autoregulation to the total transit time can be neglected [5]-[15]

B. Photoplethysmograph (PPG)

The word Plethysmograph is a combination of two ancient Greek words ‘plethysmos’ which means increase and ‘graph’ which is the word for write [16], and is an instrument mainly used to determine and register the variations in blood volume or blood flow in the body which occur with each heartbeat [9],[14]. Various types of Plethysmograph exist, and each of them measures the changes in blood volume in a different manner. With a specific transducer and has certain applications. The general Plethysmograph types are: water, air, strain gauge, impedance, and photoelectric [9]-[17]. Photoelectric plethysmography, also known as photoplethysmography and its acronym in some literature, is (PTG/PPG) and when it is called digital volume pulse, the acronym is (DVP). In this paper, the abbreviation PPG is going to be used. [2], [9].

PPG is easy to set up, convenient, simple and economically efficient compared to the other types of plethysmograph. It uses a probe which contains a light source and a detector to detect cardio-vascular pulse wave that propagates through the body [18].

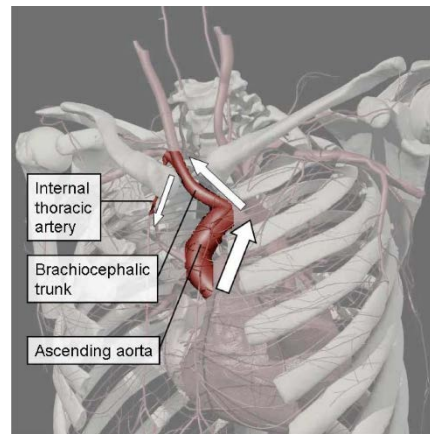


Fig. 1. Overview of the arterial segments involved in the propagation of pressure pulse from the left ventricle to the vascular bed at the upper region the sternum. 3-D model courtesy and copyright from Primal Pictures, Ltd.

The PPG signal reflects the blood movement in the vessel, which goes from the heart to the fingertips and toes through the blood vessels in a wave-like motion [9]. It is an optical measurement technique that uses an invisible infrared light sent into the tissue and the amount of the backscattered light corresponds with the variation of the blood volume [25]. Hertzman was the first to find a relationship between the intensity of backscattered light and blood volume in 1938.

The low-cost and simplicity of this optical based technology could offer significant benefits to healthcare (e.g. in primary care where noninvasive, accurate and simple-to-use diagnostic techniques are desirable) [19]. Further development of PPG could place this methodology among other tools used in the management of vascular disease.

The fingertip PPG signal reflects the blood movement in the vessel, which goes from the centre (heart) to the end (fingertips) in a wave-like motion [20]. It is affected by the heartbeat, the haemodynamics and the physiological condition caused by the change in the properties of an arteriole [23], [25]. The effects can be observed as distortions in the wave profiles. A typical Photoplethysmographic signal obtained from index finger is shown below in Fig.2 where Systolic peak, Diastolic peak and Dicrotic Notch (Inflection Point) is marked. Here the systolic peak is denoted as ‘x’ and Diastolic peak is denoted as ‘y’.

C. Indices of Arterial Stiffness

There are several ways of quantifying the degree of Arterial Stiffness. Index is a term given for quantifying any Physical quantity or process. There are several indices of quantifying Arterial Stiffness which we will see in the following paragraphs.

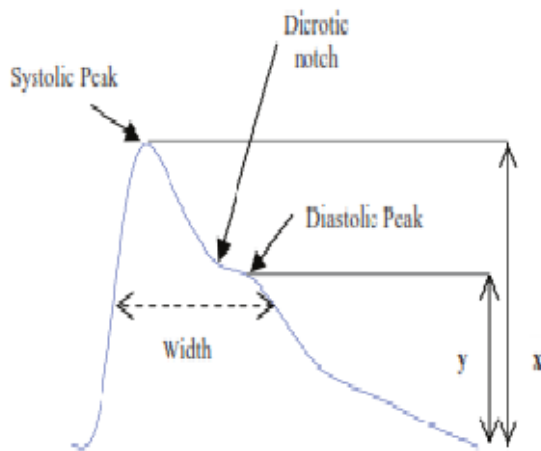


Fig.2 A typical PPG Waveform and its characteristic parameters, whereas the amplitudes of the systolic peaks is x while the amplitude of the diastolic peak is y

1. Augmentation Index

The augmentation index is a ratio calculated from the blood pressure waveform, it is a measure of wave reflection and arterial stiffness. Augmentation index is commonly accepted as a measure of the enhancement (augmentation) of central aortic pressure by a reflected pulse wave (shown in green in the Fig.3) [8]. Augmentation index is a sensitive marker of arterial status: Augmentation index 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. Augmentation index can distinguish between the effects of different vasoactive medications when upper arm blood pressure and pulse wave velocity do not [8]. Some evidence suggests that the timing of the reflected wave is related to the dimensions of the body. In shorter individuals, a shortened return time for reflected waves leads to an increase in central pressure augmentation [13]. As augmentation index is a ratio, variations in the arm, cuff or artery do not significantly affect the measurement. The AI is below 0.70 for patients with elastic arteries and above 0.70 for patients with stiffer arteries.

The equation for Calculating Augmentation Index is:

$$\frac{\rho_s - \rho_i}{\rho_s - \rho_d}$$

Where ρ_s is Systolic Pressure, ρ_i is Inflection Point and ρ_d is Diastolic pressure. Augmentation index is good indicator of Arterial Stiffness, but it is not an ultimate indicator to indicate the stiffening of the Arteries, after this you have to confirm it with some other tests to confirm the stiffening of arteries.

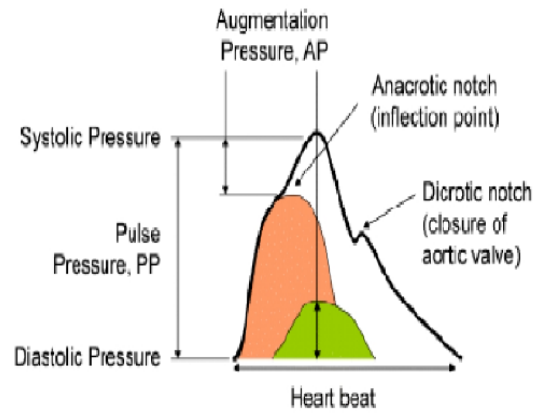


Fig.3 PPG waveform with all the necessary parameters needed for measuring Augmentation Index .Courtesy: Pulsecor Pvt Ltd.

2. Arterial Stiffness Index

The Arterial Stiffness Index (ASI), the ASI is a number that correlates with arteriosclerosis. Because arteriosclerosis reduces flexibility in arteries, the higher the ASI, the more likely someone is to have hardening of the arteries, the lower the number, the less likely [8]. Consequently, the ASI can be viewed as another cardiovascular “risk factor”, just like high blood pressure or a cholesterol level above 40. Additionally, we think that the ASI can be used to follow cholesterol lowering therapy and other “risk factor” changes. A high to very high ASI value indicates a high to very high risk of coronary artery disease. When added to other risk factors it will help the physician make a decision as to what future tests should be done [8]-[15].

In the measurement of ASI, the maximum peak of the whole pulse wave is obtained firstly, namely the MAP of the pulse wave. Secondly, we need to find out two peaks of pulse wave whose values are the most approach to 80% of the maximum. The difference of two cuff pressures corresponding to the two peaks multiplies a special factor to get ASI. Let $P_1 = P_{max}$ and $P_2 = .8 * P_{max}$

The expression for finding ASI is:

$$ASI = K * (P_1 - P_2)$$

Where K is the correction factor which is relate to the particular case of tester, such as smoking, sex, age, and health.

3. Pulse Rate

The pulse is a decidedly low tech-high yield and antiquated term still useful at the bedside in an age of computational analysis of cardiac performance [16]. The pulse is an expedient tactile method of determination of systolic blood pressure to a trained observer. Diastolic blood pressure is non-palpable and unobservable by tactile methods, occurring between heartbeats [17]. Pressure waves generated by the heart in systole moves the arterial walls. Forward movement of blood occurs when the

boundaries are pliable and compliant. These properties form enough to create a palpable pressure wave. The heart rate may be greater or lesser than the pulse rate depending upon physiologic demand. In this case, the heart rate is determined by auscultation or audible sounds at the heart apex, in which case it is not the pulse [18]-[19]. The pulse deficit (difference between heart beats and pulsations at the periphery) is determined by simultaneous palpation at the radial artery and auscultation at the heart apex [20]. It may be present in case of premature beats or atrial fibrillation. The rate of the pulse is observed and measured by tactile or visual means on the outside of an artery and is recorded as beats per minute or BPM [21]. The pulse may be further indirectly observed under light absorbances of varying wavelengths with assigned and inexpensively reproduced mathematical ratios [22], [25]. Applied capture of variances of light signal from the blood component hemoglobin under oxygenated vs. deoxygenated conditions allows the technology of pulse oximetry [24].

III.RESULTS AND DISCUSSION

The Photoplethysmograph (PPG) signals are acquired from the index finger of the subject through BIOPAC MP36R Data Acquisition system and PPG transducer SS4LA and it is given to the software developed for finding cardiovascular dynamic parameters.

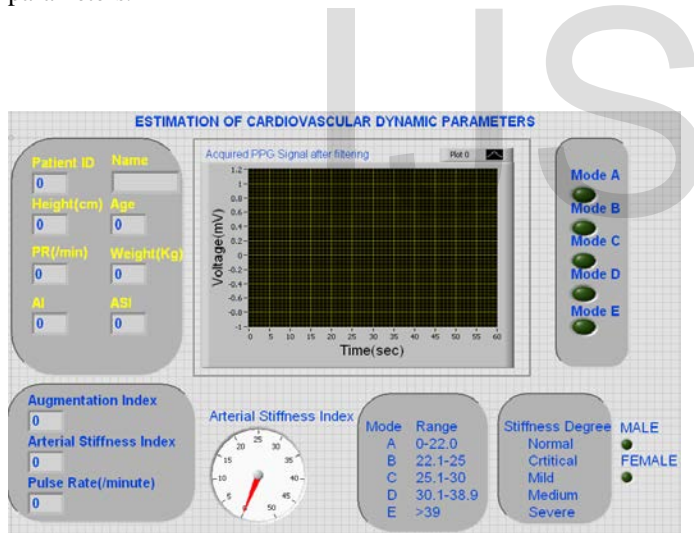


Fig.4 Front panel of the Cardiovascular Dynamic software

The above front panel is developed for real time signals obtained using BIOPAC. For each Patient's we can enter Name, Patient ID, Gender and Age. Then we can store the data in separate Database so that we can reuse the data later. According to the ASI values range 5 modes are distinguished: Normal, Critical, Mild, Medium and Severe; This is classified as Mode A, Mode B, Mode C, Mode D, Mode E . And each mode has specific range of values, which are mentioned in the software's front panel. The signal is passed detrended to remove the base line interference and passed through an equi-ripple High Pass Filter to remove the low frequency noises in the PPG signal.

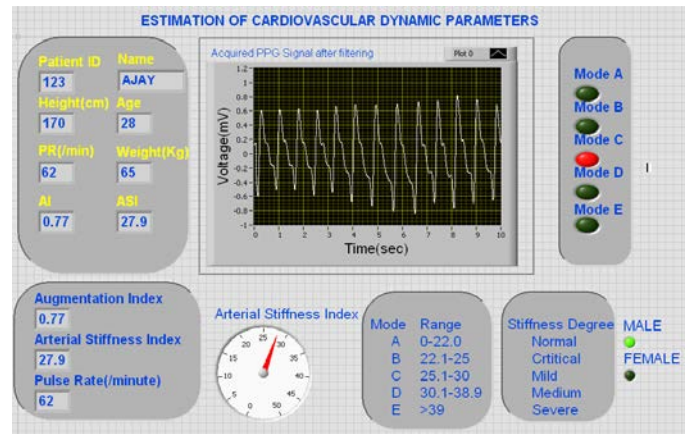


Fig.5 Front panel showing a Subject's PPG signal after Filtering

For the above subject, the PPG signal is acquired using BIOPAC PPG transducer SS4LA under room temperature. For the above Patient even though his weight is normal his Arterial Stiffness degree comes under 'Mild' Category because of other factors such as Stress, Lack of physical activity . So he needs to do lot of Physical activity and Yoga to keep his mind and body fit.

IV. CONCLUSIONS

The Photoplethysmographic (PPG) signal is a very useful indicator for Diagnostic purposes of Cardiac Health. The Proposed system was found to be good in extraction of arterial parameters .The future Work involves design of good filter to counter motion Artifacts and to find out some more cardiovascular parameters in addition to the parameters found out in the software.

REFERENCES

- [1] Stephen.R.Alt et al., "Predicting Arterial Stiffness from the Digital Volume Pulse Waveform" - IEEE Trans. on Biomed. Eng., vol. 54, Issue no. 12, pp. 2268-2275, 2007.
- [2] Sanjeev Kumar et al., "Estimation of Arterial Stiffness by using PPG Signal: A Review" - IJCTT, vol. 4, Issue 5, pp.1362-1365, 2013.
- [3] Masashi Saito et al., "Noninvasive Assessment of Arterial Stiffness by Pulse Wave Analysis" - IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control, vol. 59, no. 11, 2012.
- [4] Jayaraj Joseph, V.Jayashankar, "A Virtual Instrument for automated measurement of Arterial Compliance", - Transactions of the ASME, Journal of Medical Devices, and doi: 10.1115/1.4002493, vol. 4, 2010.
- [5] Josep Sola et al., "Chest Pulse Wave Velocity: A Novel Approach to assess Arterial Stiffness", IEEE Trans. on Biomed. Eng, vol.58, no.1, pp: 215-223, 2011
- [6] Raymond R. Townsend and Stephanie S. DeLoach, "Vascular Stiffness: Its Measurement and Significance for Epidemiologic and Outcome Studies" - Clin J Am Soc Nephrol, vol.3, 2008.
- [7] Delpha et al., "Analysis of pulse wave to determine cardiac risk" - International journal of Advanced Scientific and Technical Research, vol.1, Issue. 2, pp. 30-40, 2012.

- [8] Wei He et al., "Practical Applications and Solutions using LabVIEW software".
- [9] Mohamed Elgendi, "On the Analysis of Fingertip Photoplethysmogram Signals"-Current Cardiology Reviews, Vol.8, pp-14-25, 2012.
- [10] Charalambos Vlachopoulos et al., "Prediction of Cardiovascular Events and All-Cause Mortality with Arterial Stiffness" - Journal of American College of Cardiology, vol.55, no.13, 2010.
- [11] Ching-ChuanWei et al., "Developing an Effective Arterial Stiffness Monitoring System using the Spring Constant Method and Photoplethysmography", - IEEE Transactions on Biomedical Engineering, vol.60, Issue No.1, pp. 151-154, 2013.
- [12] Dae-Geun Jang et al., "A Knowledge-Based Approach to Arterial Stiffness Estimation Using the Digital Volume Pulse" - IEEE Transactions on biomedical Circuits and systems, vol. 6, issue no. 4, pp. 366-374, 2012.
- [13] Dariusz Prokop et al., "Monitoring of the arterial blood waveforms with a multisensor System" - Proc. Eurosensors XXVI, vol.47, pp. 422-425, 2012
- [14] S. Mohamed Yacin, M. Manivannan and V. Srinivasa Chakravarthy, Reconstruction of Gastric Slow wave from Finger Photoplethysmographic Signal using Radial Basis Function Neural Network, Medical Biological Engineering and Computing, Volume 49, Number 11, 1241-1247, 2011.
- [15] Depari et al., "Portable multi-sensor system for non-invasive measurement of Biometrical data" - Eurosensors XXVI, vol.47, pp. 1323-1326, 2012.
- [16] Hsein-Tsai Wu et al., "Arterial Stiffness Using Radial Arterial Waveforms Measured at the Wrist as an Indicator of Diabetic Control in the Elderly" - IEEE Transactions on Biomedical engineering, vol. 58, issue no 2, pp. 243-252, 2011.
- [17] James F. Greenleaf and Xiaoming Zhang, "The Stiffening of Arteries by the Tissue - Mimicking Gelatin" - IEEE Transactions on ultrasonics, ferroelectrics, and frequency Control, vol. 53, issue no. 8, pp. 1534-1539, 2006.
- [18] Lei Wang et al., "Multichannel Reflective PPG Earpiece Sensor with Passive Motion Cancellation IEEE Transactions on biomedical circuits and systems vol. 1, no. 4, pp 235-241,2007
- [19] S. Mohamed Yacin and M. Manivannan, V.S. Chakravarthy, Effect of gastric myoelectric activity on Pulse Rate Variability in fasting and postprandial conditions, International Journal of Healthcare Technology and Management, Vol. 12, No.5/6 pp. 434 – 446, 2011.
- [20] Nenad Popovich and Shahariar Kabir, "A Human Brachial Artery System Prototype Controller Calibration (Static Model)" - Int. J. Emerg. Sci. ISSN: 2222-4254, pp. 706- 722, 2011.
- [21] Nozomi Matsumoto and Sho Onodera, "The Relationship between Arterial Stiffness and Under Water Blood Pressure in Middle-aged and Elderly Women" – Kawasaki Journal of Medical Welfare, vol. 17, no. 1, pp. 29-36, 2011
- [22] Xiao-Fei Teng and Yuan-Ting Zhang, "Theoretical Study on the Effect of Sensor Contact Force on Pulse Transit Time", - IEEE Transactions on Biomedical Engineering, vol. 54, issue no. 8, pp. 1490-1498, 2007
- [23] Kang-Ming Chang and Keng-Ming Chang, " Pulse rate derivation and its correlation with Heart rate "-Journal of Medical and Biological Engineering,vol.29,issue.3,pp-132-137,2008.
- [24] Maria Pauline et al., "Non Invasive Measurement of Systolic Blood Pressure in Rats: A Simple Technique" Al Ameen J Med Sci, Vol.4, issue.4, pp-365-369, 2011.
- [25] S. Mohamed Yacin, M. Manivannan, V. Srinivasa Chakravarthy, On non-invasive measurement of Gastric motility from finger photoplethysmographic signal, Annals of Biomedical Engineering, vol 38, no 12, 3744-3755, 2010.