Comparison of local pulse wave velocity values acquired with EMFi sensor

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Abstract

The purpose of this work is to show the potential of Electromechanical Film (EMFi) sensor in local vascular elasticity studies via pulse wave velocity (PWV) obtained from limbs and radial arteries. ECG and pulse signals from the limbs were recorded from 48 working aged men in sitting position. Duration of the signal components (pulse transit time; PTT) from the foot point and from the peak of the ankle and radial pulse signals according to R wave of the ECG were studied. PWV parameters between left and right wrist and respectively between left and right ankle were compared with Bland-Altman (BA) plots and with Pearson correlation in order to study, whether foot point or peak point from the ankle and radial pulse give consistent information about vascular elasticity in the form of PWV.

Results show that elastic information in the form of PWV is obtainable from the ankle and radial pulse signals having variation which depends from the detected site of the pulse signal. Little more variation was seen in the PWV and Pearson correlation values obtained from the foot point of the signal utilizing PTT with a minimum method. As the differences between the obtained results were relatively small, both locations are at least suitable in PWV determination giving consistent information about vascular elasticity. The variation in the form of the pulse signal due to local elasticity changes may challenge accurate point detection in PWV studies.

Keywords: EMFi, radial and ankle pulse signals

Tiivistelmä

Tämän työn tarkoituksena on osoittaa EMFi anturin mahdollisuudet paikallisessa suonien elastisuustutkimuksessa käyttäen pulssiaallon nopeutta (PWV) raajoista ja rannevaltimosta. EKG ja pulssiaallot äänitettiin 48:sta työikäisestä miehestä EMFi -anturiliuskoilla. Pulssiaaltojen signaalikomponenttien ajalliset kestot ja amplitudit määritettiin ja näistä laskettiin parametreja, jotka kuvaavat suonien elastisuutta. PWV arvoja vasemman ja oikean rannevaltimon ja nilkkojen välillä verrattiin Bland-Altman kuvien ja Pearsonin korrelaation avulla tarkoituksena selvittää, antavatko rannevaltimosta ja nilkasta määritetty PWV yhdenmukaista tietoa suonten elastisuudesta. Tutkittiin lisäksi, antaako pulssiaallon minimi eli 'foot' -kohta yhdenmukaista tietoa pulssiaallon maksimiarvon kanssa suonien elastisuudesta.

Tulokset osoittavat, että rannevaltimosta ja nilkoista on saatavissa elastista tietoa PWV:n muodossa EMFi anturilla. Muutokset PWV:n arvossa riippuvat paikallisesta pulssiaallon havaintopaikasta. Tutkimuksessa havaittiin jonkinverran suurempaa vaihtelevuutta pulssiaallon 'jalan' eli minimikohdasta tapahtuvan pulssin kulkuajan arvojen määrittämisessä verrattuna pulssiaallon huippukohtaan. Koska erot olivat varsin pieniä, molemmat sijainnit ovat joka tapauksessa sopivia PWV:n määrittämiseen antaen yhdenmukaista tietoa suonien elastisuudesta. Paikalliset suonen elastisuuden muutokset voivat vaikuttaa pulssiaallon muotoon ja paikallisen pulssiaallon aallonmuodon kohdan paikallistamiseen ja näinollen PWV:n määrittämiseen.

Avainsanat: Elektromekaaninen kalvo (EMFi), rannevaltimon ja nilkan pulssiaallon signaalit

Introduction

Increased arterial stiffness has been shown to be an early marker of accelerated vascular aging in prediabetic and prehypertensive states in young adults and it has been shown to correlate with coronary risk factors [1,2]. It also correlates with the presence of angiographic coronary artery disease (CAD) [2]. It is an independent predictor for all-cause and cardiovascular mortality in patients with essential hypertension [3]. Arterial compliance reflects the artery expanding and recoiling capability during cardiac contraction and relaxation, stabilizing the fluctuations in arterial pressure and blood flow [4].

The properties of the entire artery system can be evaluated by using pulse wave velocity (PWV), which is directly related to the stiffness of the aorta and its major branches [5]. The PWV measurement is an established measure of central and distal arterial stiffness based on calculation of transit time and transit distance of a pressure waveform, which travels between two arterial sites. It provides a regional measure of arterial stiffness. The carotid-femoral PWV is a marker of central arterial stiffness and aortic wall alterations [6,7]. It is also an independent predictor of coronary heart disease and stroke in healthy subjects, as well as of mortality in the general population and in various patient groups [6]. PWV is inversely related to arterial compliance and elasticity.

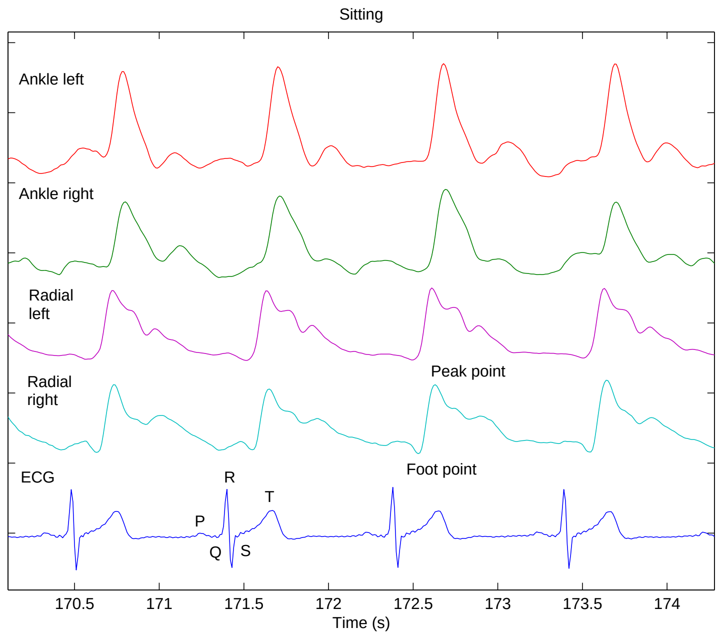

Figure 1. Signals recorded in sitting position (Case 48). Radial and ankle pulse waves are labelled as mentioned in this study. Five channels of seven recorded ones are presented. The foot point of the radial signal was easily detectable due to the clear minimum point in the signal.

During a person's lifetime, as part of the ageing process or as a consequence of hypertension, atherosclerosis and other pathological processes make the aorta to stiffen. In the elderly, the forward pulse wave travels faster, i.e., PWV is high, and the arterial waves reflected from the periphery of the arterial tree return earlier merging with the systolic part of the incident wave causing augmentation of the workload of the heart. Favorable 'tuning' between left ventricle and arterial tree seen with younger is thus progressively lost [8]. The wave reflection of the pulse wave due to increase in PWV also increases with age [9]. This is greatest in the aorta, and least in the upper limb muscular arteries [8]. Aortic PWV is traditionally estimated noninvasively from the delay of pressure wave foot at the femoral site compared to the carotid site and from the distance travelled by the pulse [8].

The form of the pulse wave is defined by the properties of the heart beat, blood pressure (BP) and the properties of the vessel wall. Age and BP affect to the size and form of the aortic pulse wave in adults. The cross-sectional area of the aorta has been shown to double between the ages of 20 to 80 having a considerable effect to the aortic elastic properties in different locations of the aorta [12]. Atherosclerosis contributes to the mechanical properties of the arterial wall which becomes rigid and loses its elasticity [13] having a considerable effect to the form of the local aortic pulse wave.

In this paper a Mobile Physiological Signal Measurement Station has been used as a device, which enables recording of local pulse signals from different locations of the body [10] with EMFi sensors [11]. The main goal of this study is to show, that EMFi sensor can produce elastic information from the vasculature in the form of PWV values obtained from radial and ankle pulse signals. Another objective is to study, if consistent elastic information in the form of PWV is obtained from pulse signals from the left and right wrist and from the left and right ankle measured with EMFi sensor. As arterial properties have an influence on the amplification of the pulse wave, differences in elasticity are expected to have an effect to the form of the pulse wave and thus to the detection of temporal values from the foot or the top point of the pulse signal affecting to the calculated PWV values.

Methods

The EMFi [11] sensor is basically a thin biaxially oriented plastic film coated with electrically conductive layers which are permanently polarized. Changes in the pressure acting on the film generate a charge on its electrically conductive surfaces and this charge can be measured as a current or a voltage signal. It can convert mechanical energy to electrical and vice versa. Thus the EMFi acts as a sensitive movement sensor suitable for ballistocardiographic (BCG) recordings.

Signals from EMFi sensors were recorded with the Mobile Physiological Signal Measurement Station [10] into a notebook computer with a data acquisition card (Daqcard 6036E) and the recordings were made into ASCII format. In the Mobile Physiological Signal Measurement Station an active Butterworth 8. degree low pass filter was used, where the cut-off frequency was 256 Hz. Four EMFi sensor strips (15 cm x 2 cm) were attached to the limbs and ECG trace was used as reference in detecting features from the pressure related signals from EMFi sensors (Fig. 1).

Measurements

In this study we compared PWV values obtained from radial and ankle pulse waves. The recordings were made from 48 middle aged men (age 41 - 65 years) in a sitting position measured with EMFi sensor strips attached on the skin with a tape to the wrists and ankles. The medical history of the measured persons relating to smoking, hypertension, atherosclerotic disease and diabetes was known (Table 1). All the measurements lasted about 3 min and the used sampling frequency was 500 Hz. Just before the measurements the blood pressure and the pulse were meas-ured with Omron M5-I blood pressure monitor device.

Table 1. Population characteristics with the mean value ± standard deviation and the number of patients.

Variable	All
Number of patients (n)	48
Age (years)	58±5.3
Height (cm)	177.8±6.2
Weight (kg)	82.6±12.9
Mean systolic blood pressure (mmHg)[a)]	136±17
Mean diastolic blood pressure (mmHg)[a)]	86±9
Mean heart rate (bpm)[b)]	61±9
Smoking status (present/previous/never) (n)	8/24/16
Hypertension (n)	20
Diabetes mellitus (n)	8
Atherosclerotic disease (CHD, PAD, CVD) (n)	28

W, week; CHD, coronary heart disease; PAD, peripheral artery disease; CVD, cerebrovascular disease. [a)]Values from the Omron M5-I blood pressure monitor device. [b)]Mean values from the ECG's R-R interval (bpm=beats/min).

The PWV recordings were carried out in the morning between 7 and 10.30. Eating and drinking were not allowed 12 hours before the measurement. Informed written consent was obtained from all participants. The study was approved by the ethics committee of Kanta-Häme Hospital district. The measurements were made in Linnan Klinikka, Hämeenlinna, Finland.

Signals were first band pass filtered (0.5–30 Hz FIR, 700 taps, time delay corrected), down sampled into 100 Hz and the analysis was done with 0.5s window length. The index of the R point from the ECG was detected first by differentiating (2 points), squaring and integrating (5 points) and by taking the maximum from the ECG signal. The foot point from the radial and ankle pulse wave was detected by local minimum method and the top of the wave was detected by local maximum method. PWV was calculated by dividing the height of the person (from the foot recording site to the jugulum point added by the distance from jugulum point to carotid artery location) with the median PTT value. Matlab software was used in previous calculations.

The R wave of the ECG was used as a reference in detecting the slopes from the pulse signals. Detected slopes for PTT were also confirmed visually. Bland-Altman plot (BA) and Pearson correlation coefficient were determined in order to estimate similarity of the measurements from radial and ankle pulse signals. All statistical analyses were performed using the SPSS 17.0 program (SPSS Inc.).

Results

Detection of the signal components from ankle and radial pulse signals with minimum and maximum method by using a moving detecting window was successful. Calculated PWV values from the left and the right radial pulse as well as from the left and the right ankle pulse showed variation which depended from the detected site of the pulse signal (peak point or foot point of the signal). Little more variation was seen in the PWV and Pearson correlation values obtained from the foot point of the signal utilizing median PTT with minimum method. Correlation between ankle PWV values was higher when compared to radial values. Figures 2-5 present obtained PWV values between left and right radial pulse and between left and right ankle pulse signals in BA plots.

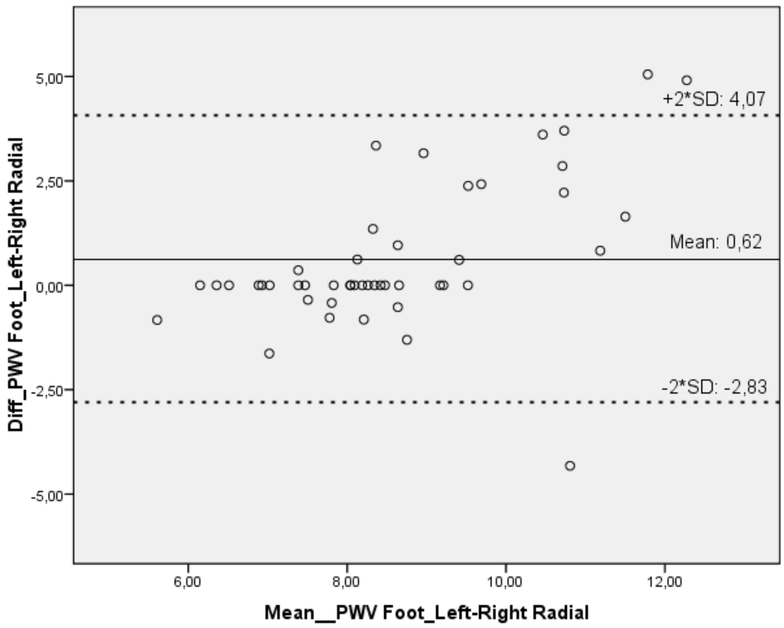

Figure 2. Bland-Altman plot from the PWV calculated from the foot point of the left and right radial pulse signals (in m/s). Pearson correlation coefficient 0.593.

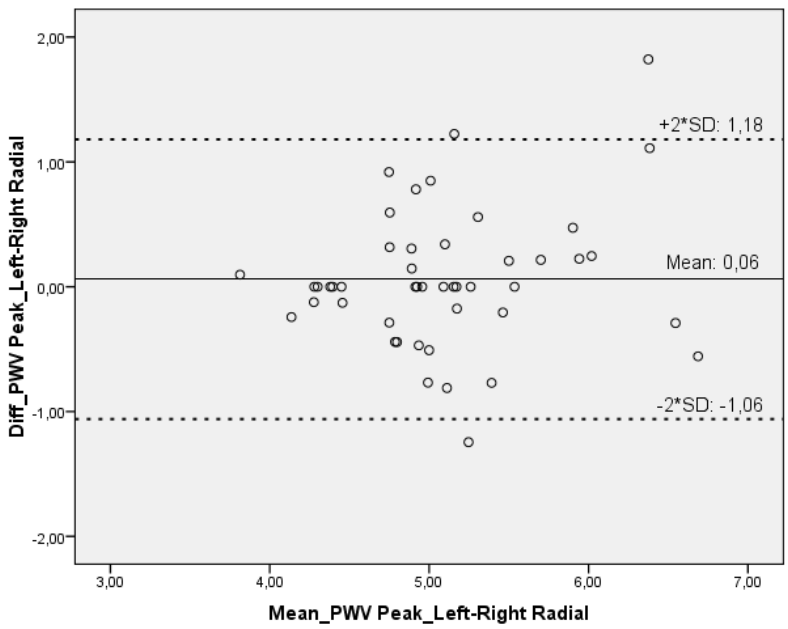

Figure 3. Bland-Altman plot from the PWV calculated from the peak point of the left and right radial pulse signals (in m/s). Pearson correlation coefficient 0.681.

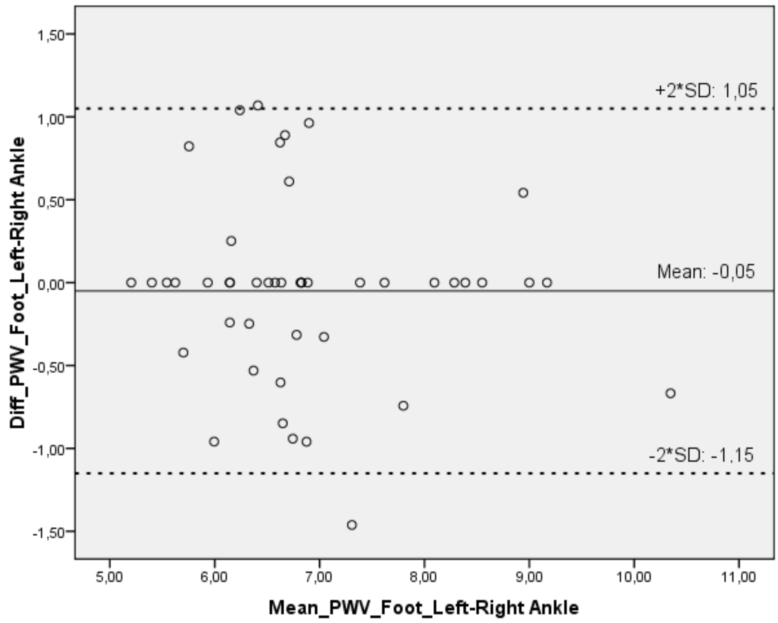

Figure 4. Bland-Altman plot from the PWV calculated from the foot point of the left and right ankle pulse signals (in m/s). Pearson correlation coefficient 0.880.

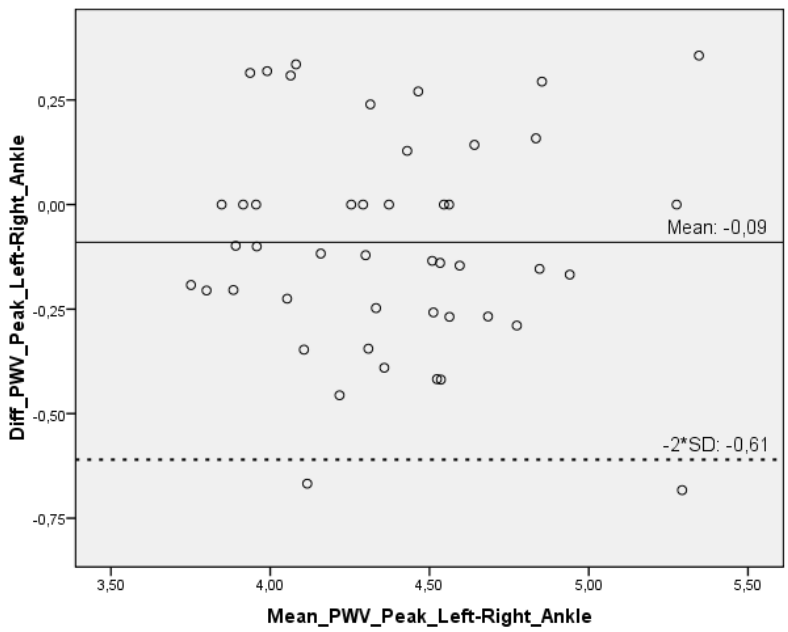

Figure 5. Bland-Altman plot from the PWV calculated from the peak point of the left and right ankle pulse signals (in m/s). Pearson correlation coefficient 0.810.

Discussion

Information from aortic elasticity is obtainable from both ankle and radial pulse signals utilizing EMFi sensors. PTT determination accuracy depends on the method used to detect foot point or peak point from the pulse signal. It is much debated in the literature, which point should be used in PWV determination. In our previous publications PWV determination from the peak of the pulse wave was preferred due to the simplicity of the method. The peak detection method in PTT determination from pulse signals succeeded well and more variation was seen in PWV values obtained with the minimum method from the foot point of the pulse signals. This is due to larger variation in the form of the pulse signal in exact foot point detection depending also from the measured patient population (Table 1), most of them possessing factors exposing to elements which increase aortic calcification. Usually arteries store energy by expanding during systole and contracting during diastole maintaining blood flow. Hardened and calcified arteries store lesser amount of the energy of the pulse wave increasing also systemic blood pressure.

The features of radial and ankle pulse waves clearly differ from each other being also different between different subjects. Therefore the measurement location in proportion to the arterial tree has its own effect to the measurement results. It is known, that the contour of the pulse waveform and systolic BP differ between central and peripheral arteries [14]. When measured from two different locations of the arterial tree, the form of the pulse wave is influenced by the local reflections, BP and measurement position.

Spreading of the obtained values in BA plots between radial PWV values obtained from the foot point of the pulse signal may also indicate possible inadequate foot point detection of the pulse wave. In this study, the foot of the pulse wave was detected by local minimum method. Minimum method in foot point detection may fail, as some fluctuation in the signal may happen before the main ejection of the heart placing the detected point before the actual start of ejection. Therefore, the intersecting tangent algorithm would be worth of study. However in foot point detection from the ankle the deviation was smaller when compared to radial foot point detection. The pulse-alike waveform in the ankle makes detection of the foot as well as the peak point easier and hardened arteries even advance this development by forming the pulse wave even more to pulse-shaped.

Usually, the pulse transit time has been taken from the foot of the pressure waveform. In this work, the transit time has been calculated also from the peak of the pressure waveform producing larger temporal values and thus, smaller PWV values than in the literature. If the transit time has been taken from the foot of the pressure waveform, PWV increase is about 2 m/s when compared to peak value. In an earlier study, the aortic PWV ranged from 5 (age 20 years [15]) to 7,5 m/s in healthy persons and was almost always increased in coronary patients (7,5 -12,5 m/s) [16] and is typically 12m/s in a 80 year old person [15]. Results in Fig. 4 match well to abovementioned ranges. The wave speed in peripheral arteries is higher than in central arteries, since peripheral arteries are smaller, they have relatively larger wall thickness and they are stiffer [17]. Therefore when local stiffness is studied, the recording location should be described accurately. Moreover in transit time calculations the form of the signal should be taken into account when choosing the right detection method.

This study shows that elastic information is obtainable from both ankle and radial pulse signals with EMFi sensors. However, the information obtained from radial pulse differs from that obtained from ankle pulse due to different recording site and due to pulse amplification as the pulse wave propagates along the arterial tree. Hence in scientific publications the methodology of the measurement of local arterial elasticity should be conclusively described.

In this study the differences between the foot point and the peak point of the left and right radial and ankle pulse waves were relatively small judged by BA plots and Pearson correlation showing, that consistent information about vascular elasticity is obtainable from both locations. The measuring method used, as well as the measuring site and patient population have their own effect to the measuring results. Local elasticity changes may challenge accurate foot point detection of the pulse wave in PWV studies.

Acknowledgments

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References

[1] Martin H, Hu J, Gennser G, Norman M. Impaired endothelial function and increased carotid stiffness in 9-year old children with low birthweight. Circulation. 2000;102:2739-2744.

[2] Chirinos JA, Zambrano JP, et al. Aortic pressure augmentation predicts adverse cardiovascular events in patients with estabilished coronary artery disease. Hypertension. 2005;45:980-985.

[3] Laurent S, Boutoyrie P, et al. Aortic stiffness is an independent predictor of all-cause and car-diovascular mortality in hypertensive patients. Hypertension. 2001;37:1236-1241.

[4] Nichols WW, O'Rourke MF (eds.). McDonald's blood flow in arteries: Theoretical, experi-mental and clinical principles, 5 th edition. UK: Butler & Tanner Ltd; 2005.

[5] Cohn JN. New approaches to screening for vascular and cardiac risk. Am. J. Hypertens. 2001;14:218-220.

[6] Najjar SS, Scuteri A, et al. Pulse wave velocity is an independent predictor of the longitudinal increase in systolic blood pressure and of incident hypertension in the baltimore longitudinal study of aging. Am Coll Cardiol. 2008;51:1377-1383.

[7] Protogerou A, Blacher J, et al. Blood pressure response under antihypertensive drug therapy. The role of aortic stiffness in the REASON study. J Am Coll Cardiol. 2009;53:445-451.

[8] O'Rourke MF, Hashimoto J. Mechanical factors in arterial aging. JACC. 2007:50(1);1-13.

[9] Segers P, Rietzschel ER, etc. Nonivasive (input) impedance, pulse wave velocity, and wave reflection in healthy middle-aged men and women. Hypertension. 2007; 49:1248-1255.

[10] Alametsä J, Värri A, Viik J, Hyttinen J, Palomäki A. Ballistocardiographic Studies with Acceleration and EMFi Sensors. Medical Engineering & Physics . 2009:31:1154-1165.

[11] Kirjavainen K. 'Electromechanical film and procedure for manufacturing same'. U.S. Patent no. 4654546'. Manufacturer of EMFi: Emfitech Ltd, Vaajakoski, Finland; 1987. http://www.emfit.com

[12] Towfiq B, et al. Effect of age and blood pressure on aortic size and stroke distance. Br Heart J 1986;55:560-568.

[13] Chlebus H. Early Diagnosis of Arterial Atherosclerosis by Means of Resonance Electro-sphygmography, in Bibliotheca Cardiologica 30: Hemodynamic Stress and Relief of the Heart. Juznic G, Editor. Karger S. Basel; 1973,. p. 9-25.

[14] Millasseau SC, et al. Pressure Wave Reflection Assessed From the Peripheral Pulse – Is a Transfer Function Necessary? Hypertension 2003;41:1016-1020.

[15] O'Rourke MF, Hashimoto J. Mechanical factors in arterial aging. JACC.50(1):1-13. 2007.

[16] Chlebus H. Early diagnosis of arterial atherosclerosis by means of resonance electrosphymography. (Karger, Basel 1973).Bibl. Cardiol.30:9-25.

[17] Westerhof N, Stergiopulos N, and Noble MIM. Snapshots of Hemodynamics: An Aid for Clinical Research and Graduate Education. Boston. Springer, 2005, Vol. 18. pp.100-103.