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Comparative Study of Arterial Compliance Using Invasive and Noninvasive Blood Pressure Waveform

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Abstract Most of the epidemiological studies have shown a good relationship between blood pressure and manifestation of cardiovascular diseases (CVD). CVD has become a very common health condition that exhibits significant changes in distensibility, compliance, and elastic modulus of the arterial vascular system. The main causes of this disease are the spreading of fats and cholesterols which initiate the damaging of endothelium, decreasing wall buffering capacity, and hardening of the arteries eventually leading to severe narrowing. We compared data from invasive and non-invasive blood pressure wave form. Using the Windkessel model, to estimate the arterial compliance as vascular index, we used data after the aortic valve closed to the end-diastolic point of blood pressure waveforms, utilized Bland-Altman difference plot, T-test, box whisker plot and scatter diagram. We analyzed physiological real data and investigated the correlation between the non-invasive and invasive blood pressure wave form. Non-invasive compressive pulse waveforms can be used to assess the total compliance of the arterial blood pressure waveforms of the invasive aorta that indicates the buffering of muscle and adipose tissue.

Keywords: *cardiovascular disease, arterial compliance, Windkessel model, non-invasive blood pressure waveform*

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1. Introduction

In current times, cardiovascular diseases (CVD) have become the foremost component of mortality statistics in the world [1,2]. It is estimated that approximately 78% of deaths and 86% morbidity are caused because of CVD worldwide. Reports suggest that CVD will be the global health burden by 2020 [3,4]. This disease follows an asymptomatic phase of development which builds up in the body silently over a period of time without any major sign on an individual's health [5]. Many recent studies demonstrated the relationship between biological aging and arteriosclerosis towards the risk of cardiovascular diseases, such as hypertension, hypercholesterolemia, and end-stage renal failure. With aging, the arterial wall thickness and dilation, lengthening become less compliant and increases pulse wave velocity which result in wave reflections [6,7]. The extensive changes in the inner wall of the artery, affects the elasticity of fibers which are responsible for vessel distensiblility. The rising curiosity of non-invasive arterial compliance detection led many researchers to work in the field and put forth methods to estimate the arterial compliance. Prior research of cardiovascular structure and function is based on invasive intra-arterial cannulation to get the arterial pulse wave [8]. The change in arterial pulse wave is a passive consequence of increase in the blood pressure. In physiology, compliance (C) = dV/dP (Ratio of the change in volume (dV) resulting from change in pressure (dP)). Compliance represents the slope of the pressure-volume relationship [9,10]. In the context of an electric circuit, this is analog as to the Windkessel model that simulates blood pressure dynamics in the systemic arteries [11]. When stiffness occur then wide pulse pressure, systolic hypertension, and increased cardiovascular risk increase, because wide pulse pressure and systolic hypertension are late indicators of the arteriosclerotic process. There is important attention to develop more sensitive compliance measurements that can determine premature vascular stiffening at an earlier stage [12]. In this work, we aimed to scrutinize a method of evaluating arterial compliance using non-invasive blood pressure waveform which could be a prevailing method for medical science. Here, we used a dataset which is examined under the supervision of a physician on standardized conditions and we subsequently implemented a mathematical approach. This research work proved that a noninvasive method for the detection of blood pressure is significantly and more precise, compared for the invasive approach.

2. Method

The overall framework in this paper has been majorly grouped into various categories, namely, Study population, data extraction, algorithm implementation, waveform computation and experimental architecture.

2.1. Study Population

All study protocols are approved by the Institutional Review Board of Taipei Veterans General Hospital (IRB) and adhered to the principles of the Declaration of Helsinki [Table 1].

Table 1. Physiological Data

Characteristics	Subjects(n=15)	
L-brachial(cm)	47.73±4.22	
blood pressures,(mmHg)	NTG before	NTG after
Systolic Blood pressure	134.6±18.55	123.13±13.37
Mean Blood Pressure	88.33±10.56	85.33±10.19
Diastolic Blood Pressure	76.4±9.65	72.47±8.73
Heart rate (BPM)	58.33±15.99	50.93±11.43

2.2. Data Extraction

In this step, we extracted data from a non-invasive vascular screening device (Colin VP2000, Omron, Japan) (Figure 1) that measures non-invasively blood pressure [13] which supports early detection and diagnosis of arteriosclerosis.

Figure 1. Non-invasive Vascular Screening Device, (Colin VP2000, Omron, Japan): This device provides indices of PWV (pulse wave velocity) and pulse waveforms, which is applicable for detection and diagnosis of arteriosclerosis. The conditions of patients must the Circumference of arm 16 - 38 cm

In case of invasive blood pressure data acquisition, we used a Millar catheter (Figure 2) which consists of a dual pressure sensor [14]. This device can capture invasive blood pressure waveform of two arterial positions simultaneously.

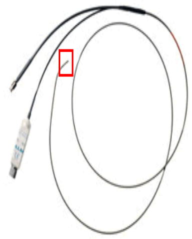

Figure 2. Invasive blood pressure data acquisition (Millar catheter): There is dual pressure sensor. This device captures two different arterial position of the invasive blood pressure waveform.

2.3. Algorithm Implementation

We use the Windkessel model to estimate the arterial compliance (decay constant) as a vascular index using data after aortic valve close to the end diastolic point of blood pressure waveforms [11]

$$P(t) = P(t_0) \times e^{-\frac{t}{RC}} = P(t_0) e^{-\alpha t} \qquad \text{(i)}$$

P (t): Blood pressure value at time (t), P (t0): Blood pressure value at time (t0), t: time (t); R: Resistance of the blood vessel; C: compliance; α: Decay constant

2.4. Waveform Computation

We used an algorithm (equation (i)) to calculate blood pressure wave data. We have already used noninvasive data from Oscillometer and pulse volume recording (PVR); invasive data was taken from aorta and bronchial artery (Figure 3). After getting data, we propose invasive and non-invasive degree of arterial compliance using a Bland-Altman difference plot [15], t-test [16], box whisker plot [17] and scatter diagram [18].

2.5. Experimental Architecture

We took a group of 15 patients for this experiment; the purpose of this study was explained and written consent was taken from them. After that we measured simultaneously invasive and non-invasive blood pressure waveform signal with Oscillometer and Millar catheter, before and after applying nitro-glycerin drug (NTG).

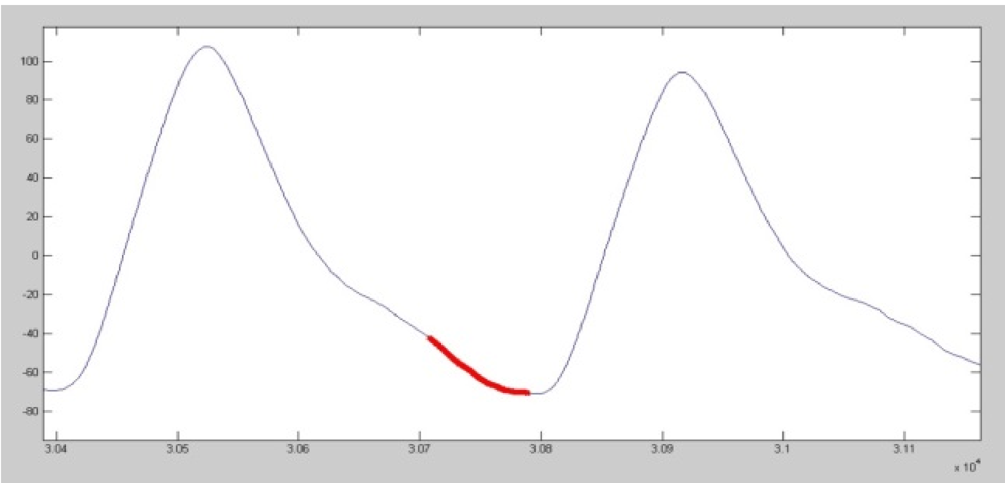

Figure 3. Assessment section for invasive and noninvasive: In this graph blue line represents the blood pressure waveform and red line is the assessment section (Condition is aortic valve closed) that is decay constant α

3. Results

3.1. Estimation of Decay Constant

We evaluated the time decay constant for arterial compliance of the aorta and the upper arm artery at the time end of the diastolic blood pressure using pulsator. The relationship is compared between arterial compliance and times constants. By using invasive and non-invasive waveforms, we analyze arterial compliance index, which is used to assess the degree of compliance (Figure 4, Table 3).

The arterial compliance of invasive and non-invasive type of blood pressure waveform was evaluated before and after taking NTG [Table 2].

NTG is a coronary dilator that expands the coronary artery to improve the blood flow, oxygen supply and reduce the heart load [19]. Firstly, it is assumed that the arterial compliance can be estimated through the invasive aortic blood pressure waveform; when we estimated blood pressure waveform using pulsator, then it reflects the arterial compliance [Figure 5].

The characteristics of the invasive blood pressure waveform can be used to replace the invasive blood pressure waveform that estimates arterial compliance. If both previous hypotheses are considered true, it can be prove that the arterial compliance estimated using a non-invasive cuff waveform, can be used as a predictor of hardening arteries.

Correlation evaluation between Invasive and Non-invasive data:

The arterial compliance of the invasive brachial blood pressure waveform is highly correlated with the arterial compliance of the invasive aortic blood pressure waveform (R^2 = 0.8351, P <0.0001), the invasive upper arm arterial blood pressure waveform can be replace to invasive aortic blood pressure waveform (R^2 = 0.1235, R^2= 0.1076, P <0.0001), noninvasive and invasive aortic blood pressure waveforms, brachial arterial blood pressure waveforms are also shown significant correlation (Table 4).

Table 2. This table exhibits mean time decay constant for arterial compliance of blood pressure waveforms

Waveform\C_{Decay}	NTG before mean±SD	NTG after mean±SD
Aortic	-0.6070±0.1297	-0.5378±0.1246
Brachial	-0.5811±0.1106	-0.5275±0.0773
artcuff	-0.1892±0.0685	-0.15227±0.0792

Table 3. Mean time decay constant for arterial compliance of blood pressure waveforms

Waveform\C_{Decay}	NTG before mean±SD	NTG after mean±SD
Aortic	-0.6070±0.1237	-0.5378±0.1214
Brachial	-0.5811±0.1039	-0.5275±0.0736
Artcuff	-0.1892±0.0446	-0.1523±0.0640

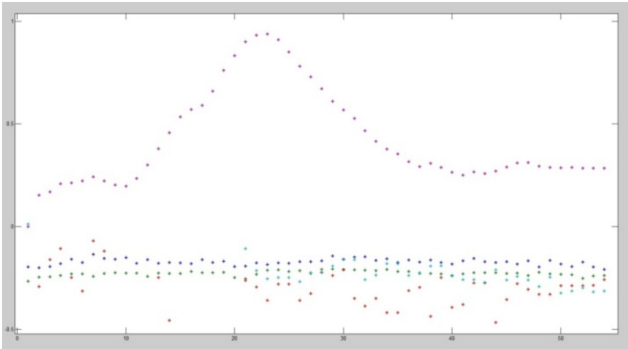

Figure 4. Evaluation of Decay constant: This graph is plotted magnitude vs time which is X and Y axis respectively. The peak of waveform is mean arterial pressure (MAP), before MAP 50% of magnitude is called time for finding systolic blood pressure, After MAP 80% magnitude time for finding diastolic pressure. Blue color waveform is aortic time decay constant, green is brachial artery decay constant and red color waveform is the non-invasive decay constant

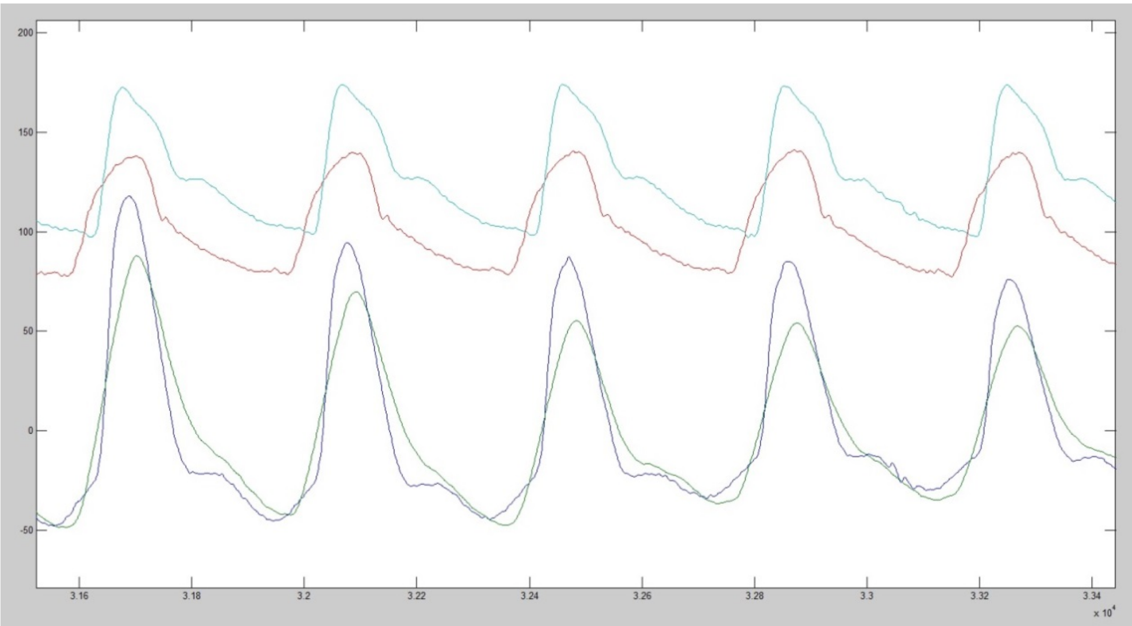

Figure 5. Comparison between invasive and non-invasive wave form: In this graph, green colour is showing brachial, red is aortic which is invasive. In non-invasive, we used two different filter for getting pressure waveform which is Blue and brown colour line. After MAP 80% magnitude time, we took noninvasive waveform, selected 5 waveform for the calculation of decay constant and 75 points from each signals of 15 patients

Table 4. The correlation coefficient is for noninvasive vs invasive arterial compliance of blood pressure waveforms.

Waveform\R^2	NTG before	NTG after
Aortic vs Brachial	0.8351	0.7586
Aortic vs non invasive	0.1235	0.0337
Brachial vs noninvasive	0.1076	0.0961

4. Discussion

Arterial compliance is the primary determining factor of aortic input impedance. It has been shown that increase in oxygen consumption, leads to the development of left ventricular hypertrophy and increasing ventricular after load. It directly affects the amplitude of the incident pressure wave and the timing of wave reflections [20,21].

Previous studies suggest that assessing of the arterial compliance using invasive way was more precise [25]. Most of the methods have been used to estimate compliance, but to date there are no longitudinal studies that relate abnormal compliance [24]. According to clinical data, arterial compliance was estimated by in-vitro methods using excised arteries. In-vivo (invasive) methods of determining compliance frequently use pulse contour analysis and require catheterization [22].

The other invasive technique for estimating compliance was intravascular ultrasound. With this technique, pressure and area are considered simultaneously. Pulse wave velocity (PWV) uses the concept that hard arteries and produce faster pulse wave transmission. While transcutaneous ultrasound techniques are limited by the ability of the ultrasound method to accurately image the anterior and posterior arterial wall. Each technique has own limitations; but in this study we performed analysis with physiological real data and find a better correlation to the non-invasive and invasive blood pressure wave form [23,24,25].

The arterial compliance was estimated by using the invasive brachial arterial blood pressure waveform and non-invasive pressure pulse waveform which is helpful to estimate the invasive aorta and invasive upper arm artery blood pressure waveform arterial compliance.

It can be seen that the arterial compliance estimated by the invasive brachial arterial blood pressure waveform is very close to the total arterial compliance estimated by using the invasive aortic blood pressure waveform [25,26]. In this experiment, we selected the end of the diastolic waveform which is invasive aorta, brachial artery blood pressure waveform. There are two waveforms in the diastolic performance which are almost parallel, indicating that the two end of the diastolic waveform were similar. We found a high correlation of arterial compliance [Table 4] [Figure 5].

The arterial compliance estimated by using non-invasive pulsator waveforms is lower than the values estimated by the other two waveforms because the non-invasive pulsator waveform is captured using a cuff that contains a buffer of the performance such as compliance [Figure 5] [25].

And there are other tissues between the arteries and the cuff, so the non-invasive blood pressure waveform in the diastolic performance should include the superior arm artery arterial compliance, muscle and adipose tissue buffer, and the airbag itself compliance [25].

In contrast to the performance of the NTG drug, the effects of the drug itself on the blood vessels, as shown. We used the exponential decay constant of the blood pressure waveform in the exponential linear function. Non-invasive compressive pulse waveforms can be used to assess the total compliance of the arterial blood pressure waveforms of the invasive aorta to indicate non-invasive vasculature waveforms, contain the buffering of muscle and adipose tissue [25,26]. An arterial algorithm can be used directly on the electronic sphygmomanometer, so that subjects can measure arterial compliance immediately, and doctors can get the patient's daily condition so it has a great potential in homecare or domestic applications.

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