The Evaluation of Methods in Determination of the Arterial Compliance for Real-Time Application

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Abstract

The objective of this study is to evaluate a method that could be used in real-time arterial compliance estimation while measure blood pressure noninvasively. The noninvasive pressure waveform at carotid artery and pressure volume relation (PVR) at brachial artery were first evaluated to assert the consistency of compliance calculation. The arterial pressure waveform was acquired using oscillometric method. The result was checked against the data calculated using invasive pressure waveforms at aortic root and brachial artery that were acquired simultaneously. The result showed that the relaxation constant could be used to reveal stiffness of artery. The index could be assessed using pulse waveform acquired oscillometric method.

1. Introduction

In general, there were two models that were accepted in exploring arterial functional and structural correlation of pulsatile hemodynamics [1-4]. One was to model the arterial system using circuit theory, the Windkessel model. Two models may describe the relation between the aortic inflow and arterial pressure. These models provided important insight into the arterial system. Yet, these models have limitations.

The arterial system could be modeled as circuitry using 2, 3, or 4 compartments or elements. The system, then, could be described with a dominated relaxation constant and with other parameters. The Windkessel model could not satisfied in describing the brisk upstroke of pressure in early systole and the presence of secondary pressure wave peaks. It could not explain the transmission delay of pressure wave in the arterial system. The Transmission delays along the aorta or arterial system are measured at various points along the arterial tree. This fact could not be explained by the assumption of infinite PWV using Windkessel model.

The other model was assuming the arterial system using a transmission line theory. This was a distributed, propagated models based on finite wave velocity. This model was account for a transmission delays, the wave reflection in the system, and a spatial and temporal pressure gradients within the arterial system. Then, the index of pulse wave velocity (PWV) would be the determination of the arterial stiffness. In tube model, the tube properties are determined by PWV and impedance (Z_c) of the aorta and arterial system. The amplitude forward traveling pressure wave is determined by the flow and local impedance of the tube impedance, Z_c. And, the small arteries provide a substantial component of total arterial compliance (TAC). The model implies that central pressure augmentation will increase monotonically with increasing aortic stiffness and PWV. Yet, the amplitude of forward wave could not explain the nonlinear change in augmentation index.

In comparison the indexes of arterial stiffness such as pulse wave velocity (PWV) and the arterial system relaxation constant using Windkessel's model, the compliance is a common dominator of two models. The higher number of PWV is signifying a stiff arterial system with less compliance. With the Windkessel model, the smaller number of a relaxation constant is representing that the artery need more time to reach the resting point. This meant that the artery was having stress with less compliance. Thus, to accurate evaluation of arterial compliance is importance in its common index for the determination the arterial stiffness.

There were two locations that were generally used to acquire the blood pressure waveform noninvasively. One is at carotid artery with the tonometry device or at the brachial artery with pressure volume relation method. The measured blood pressure waveform at carotid artery was said to be more prominent similar to aortic blood pressure than the pressure waveform at brachial artery.

In this study, we would like to demonstrate a close correlation of TAC calculated from invasive pressure waveform and noninvasive blood pressure waveform using the oscillometric method. This could help us analyze the methodology in accessing the index of arterial stiffness noninvasively. And, using the arterial system relaxation constant with the Windkessels model to index the arterial stiffness may simplify the procedure.

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2. Method and material

In this section, we will be discussing the subject and data collection, methods compliance calculation and the data analysis.

2.1. Subject and data collection

Subjects referred for diagnostic catheterization for coronary anatomy through radial approach were potential candidates of the study. The study protocol adhered to the principles of the Declaration of Helsinki and was approved by the Institutional Review Board at Taipei Veterans General Hospital. Informed consent was obtained from all patients.

We will first evaluate arterial compliance from previously collected non-invasive data. The blood pressure waveform examined were tonometry pressure waveform at carotid artery and pressure volume relation at brachial artery from 581 subjects.

A dual-sensor micro manometer-tipped catheter was used to acquire blood pressure waveform at aortic root and brachial artery. A number of 15 patients (age range 30-84 years) who were satisfied the inclusion and exclusion criteria were completed the study without any complications.

2F dual-sensor, high-fidelity micro manometer-tipped catheters (model SSD-1059, Millar Instruments Inc., U.S.A.) with the first sensor located at the tip and the second sensor at 60, 61, or 65 cm from the tip were manufactured for the present study.

The micro manometers had a flat frequency response from 0 to 1000 Hz. The frequency range of our catheterization laboratory amplifier was 0-400 Hz for pressure measurement (-50~400 mmHg) with the accuracy of ± 1 mmHg or ± 3% exclusive of the pressure transducer. All signals were digitized instantaneously at a sampling frequency of 500 Hz for off-line analysis.

The non-invasive blood pressure waveform was acquired using oscillometric method (Colin VP1000) and invasive pressure waveform at aortic root were acquired (mean age 63.2±12.7 years). Their pulse wave velocities were acquired at same the sitting (Colin VP1000).

Invasive high-fidelity right brachial and central aortic pressure waveforms were obtained during cardiac catheterization. Individual and central aortic pressure waveforms and the brachial Pressure Volume Relation waveform (PVR) were obtained and recorded simultaneously. The brachial PVR was acquired using fix cuff pressure at 60 mmHg while recording PWV pressure waveform from brachial and femoral artery at the same situation.

2.2. Compliance calculation

There were two methods of calculating the compliance. One was using the area proportion under pressure waveform. And, the other method could be using the formulas of arterial system relaxation constant. Both methods have assumed a hypothetical stoke volume and using a mean arterial pressure. These are the common methods for assessing the compliance of the aorta or artery. The area method calculates the area ratio cover by systolic waveform and diastolic pressure waveform. And, the compliance will be the proportion of assumed stroke volume and pressure difference between incisura pressure and the diastolic pressure that multiplied by the reciprocal ratio of diastolic area and total area [5].

To assess global arterial stiffness, the Total Arterial Compliance (TAC) is computed by analyzing the contour of the diastolic pressure decay, the latter half or two-thirds of diastole [6-8]. That is, to calculate the relaxation constant of the Windkessel's model, that the lowest pressure point was marked before the R-peak of ECG signal as the diastolic pressure (DBP) point. The segment of data analyzed was starting from the minimum of down slope of pressure waveform to the DBP point [5].

Both invasive data and noninvasive data were evaluated in this study. The relaxation constant of the aortic pressure waveform was calculated the same as brachial relaxation constant. These data were the indicator of the arterial stiffness index or compliance index. The same indicators that were assessed using invasive aortic and brachial pressure waveform by area method were also calculated.

3. Result

The previous acquired pressure waveform at carotid artery and brachial artery were analyzed. This was to assess the consistence of compliance calculation using pressure waveforms from two separated location and using two different methodologies. The evaluation of invasive data was to assert the assumption that the compliance of arterial system could be easily estimated at brachial artery. And, the presentation of data will easily leading to a conclusion that the estimation of arterial compliance could be accessed noninvasively and in real time.

3.1. The analysis of noninvasive data

The compliance of carotid artery calculated using area method was 1.41±0.548. And, the compliance using relaxation constant was 1.41±0.527. The correlation was

0.8 and the R^2 was 0.7. For brachial artery, the compliance calculated from area proportion was 1.14±0.4288. And, the compliance calculated using relaxation constant was 0.97±0.36. The correlation of compliance was 0.76 and R^2 was 0.82. The correlation of compliance between two pressure locations was 0.64 and R^2 was 0.68 using area proportional methods. The correlation of compliance using relaxation constant was 0.5 and R^2 was 0.58. The correlation of compliance at both locations and the methods of calculation were high. This result means that the measurement of compliance could be carried out at brachial artery with a simpler instrument such as using oscillometric blood pressure measurement method.

3.2. The analysis of invasive data

The invasive pressure waveform was acquired using Millar dual-sensor micro manometer-tipped catheter. The blood pressure waveforms were acquired at aortic root and at brachial artery of the right arm. The noninvasive blood pressure waveform and the brachial Pressure Volume Relation waveform (PVR) were acquired using oscillometric method and recorded simultaneously. This example data was shown in Figure 1. The figure was showing a full blood pressure measurement recording of oscillometric method.

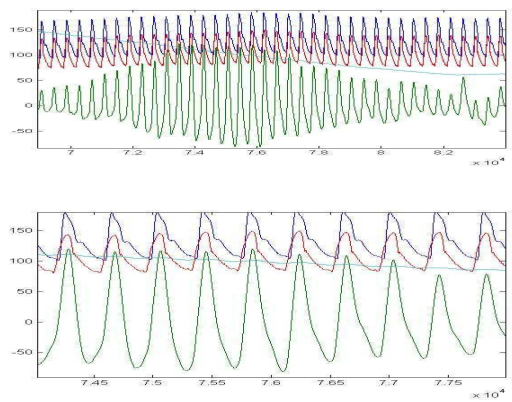

Figure 1. The upper panel was signal traces of data recording. The lower panel was showing a section of the detail blood pressure traces. The blue line was showing the invasive brachial blood pressure recording. The red line was showing the blood pressure recording at aortic root. The green line was showing noninvasive blood pressure recording using oscillometric method. The line in cyan color was showing the cuff's pressure during the measurement. The horizontal axis was the timing scale in sampling data point. The vertical axis was the pressure in mmHg.

The compliances at aortic root and at brachial artery were calculated using two difference methods. The results of invasive data were compared by methods of calculation and location of measurements. The noninvasive and invasive compliance at brachial artery was also compared shown in Figure 2. In this figure, the upper two panels, the results of compliance calculation were illustrating a good correlation of compliance calculation using two different methodologies. The lower panel, at the left, the figure was showing the correlation of compliance calculation of noninvasive data using two different methods. It was also showing a good relationship despite of calculation methodology. This meant that the method of calculation was not the factor. We have further evaluated and compared the compliance at aortic root and brachial artery. The data was also showing excellent correlation. This meant that for the same patient, the compliance did not showing dramatic variation. The relationship and correlation of compliance at brachial arteries using noninvasive blood pressure data and invasive pressure waveform was illustrated in the lower right panel.

To access the arterial compliance in real-time, the pulse waveform of each heart beat during the oscillometric blood pressure measurement were evaluated. The noninvasive blood pressure volume relation waveform was acquired using oscillometric method at left arm. The invasive blood pressures were acquired at aortic root and brachial artery at right arm simultaneously. The compliance of each waveform was accessed using Windkessel model. The results of compliance calculation were showing in Figure 3. The magnitude of oscillometric pulse waveform was showing in purple dot. The peak of purple line was indicating the timing of the mean arterial pressure in the oscillometric measurement. The red and cyan dots were the relaxation constant of noninvasive during oscillometric measurement. The blue and green dots were the relaxation constant of invasive data. In this figure, the relaxation constant for the noninvasive data have a very large range of variation before mean arterial pressure point in oscillometric measurement. However, the relaxation constants were relatively held constant after the mean arterial pressure point. This result indicated that the compliance of brachial artery could be accessed using oscillometric method.

4. Conclusion

The objective of this abstract was to accessing a method that could be used in acquiring arterial compliance or pressure relaxation constant in real-time while using oscillometric method to measure the blood pressure. We have acquired invasive blood pressure at aortic root and brachial artery using dual headed Millar pressure sensors while the pressure volume relation waveform was acquired using oscillometric method simultaneously. We have shown that the methods of compliance calculation were having a good correlation. The compliances of noninvasive and invasive data were also having a good correlation. The relaxation constant of each pressure waveforms was calculated and plotted with the magnitude the pulse pressure waveform. The result showing the relaxation constant was held with very little variation after the timing point of mean arterial pressure during oscillometric measurement. Therefore, we concluded that the arterial compliance or relaxation constant of artery could be evaluated in real-time during the noninvasive blood pressure measurement.

Acknowledgements

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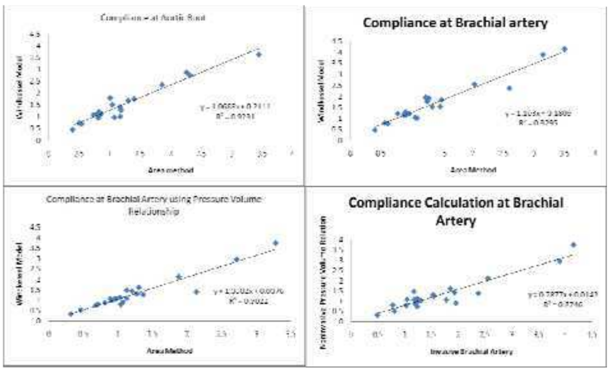

Figure 2. The correlation of compliance. Upper panel, the figure were illustrating the methodologies of compliance calculation using invasive data. The noninvasive compliance calculation was showing at lower panel, at left. The correlation of compliance of noninvasive data and invasive data was showing at right of lower panel.

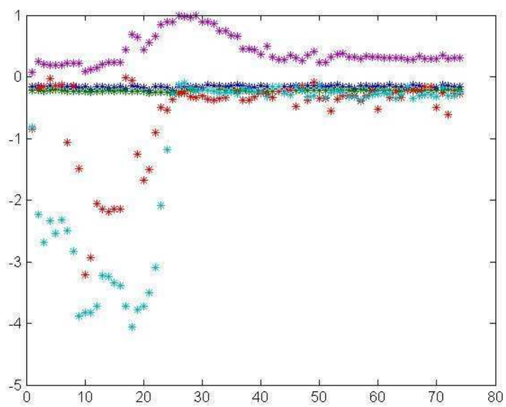

Figure 3. The illustration of complaince for every heart beat during the oscillometric measurement. The purple dots was illustrating pulse pressure. The peak of pulse pressure was the mean arterial pressure (MAP). The blue line and green dots were complainces of invasive data. The red and cyan dots were compliances of noninvasive data.