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Arteries Become Stiffer with Increasing Blood Pressure: Agreement Between Computer Simulation and Clinical Measurement

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Abstract

Arteries are naturally elastic and able to respond to different and changing pressure conditions. If these changes could be characterized and quantified, this would be clinically useful. This study investigated arterial property changes with changes in arterial pressure using computer simulations and clinical measurements.

Three elastic tube models (ideal elastic model, stretching elastic model and physiological elastic model) were simulated to give the detailed relationships between arterial pressure (P) and arterial volume compliance (C) and pulse propagation time.

Clinical measurements were performed in 8 subjects by positioning the arm to induce different arterial pressures. The changes in arm pulse propagation time, determined by subtracting ear pulse propagation time from finger pulse propagation time, were analyzed.

Experimental results showed that both arm pulse propagation time and arterial volume compliance changes were inversely related to arterial pressure changes, which provided evidence that the characteristics of the physiological elastic model provide an understanding of how arterial properties change with arterial pressure.

1. Clinical importance of arterial compliance

Arteries are naturally elastic and able to respond to different and changing pressure conditions. When arteries become stiff, their function is impaired, as shown in figure 1. Arterial wall function changes are associated with increased cardiovascular disease. If these changes could be quantified, it would provide useful information for clinical diagnosis and therapy assessment, and provide an early risk marker for cardiovascular disease.

2. Latest research in clinical measurement of arterial compliance

Arterial volume compliance is a classic quantitative measure of arterial properties. It is defined as a change in arterial blood volume in response to a given change in arterial transmural pressure, normally to a given change in arterial blood pressure [1]. Both arterial pressure change and its corresponding blood volume change can be recorded directly by invasive techniques. It can also be estimated indirectly and non-invasively based mainly on analysis of pulse wave velocity and pulse contour [2-4]. But to date there is no generally agreed gold standard to estimate arterial volume compliance in clinical practice. As a result there is little quantitative understanding of how arterial properties change with changes in arterial pressure. The aim of this study was to investigate the relationship between arterial properties and arterial pressure using computer simulations and clinical measurements.

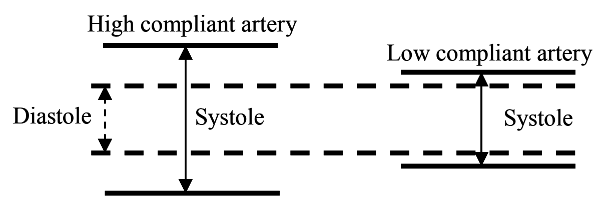

Figure 1. Arterial function in high and low compliant artery.

3. Computer model of arterial compliance

3.1. Tube behaviour under a distending lumen pressure

In a tube with cylindrical cross section, the circumferential lengthening is caused by the distending lumen pressure or transmural pressure, and the applied force is the circumferential force in the wall, which is related to wall tension (T). Laplace's Law ($T = P \cdot R$, where R is tube radius) states that for a given tube radius, the tube carrying a higher pressure (P) has a higher wall tension.

Then, by applying Laplace's Law to the definition of circumferential elastic modulus and volume compliance, the relationship between circumferential elastic modulus and volume compliance can be derived [5].

3.2. Wave propagation in a cylindrical tube

The speed with which the wave propagates down the tube depends on the elasticity of the tube. Pulse wave velocity (PWV) is approximated by the Bramwell and Hill equation [6]:

$$PWV = \sqrt{\frac{V \cdot \Delta P}{\rho \cdot \Delta V}} = \sqrt{\frac{V}{\rho \cdot C}}$$

(where V is fluid volume in a certain length of tube, ρ is density of liquid in tube, C is volume compliance)

This equation defines the relationship between pulse wave velocity and volume compliance. Because the pulse propagation time is the time it takes the pulse to propagate through a tube, for a tube with a known length, the relationship between pulse propagation time and volume compliance can be easily obtained.

3.3. Three different elastic tube models

By applying the tube behaviour to human arteries, the detailed relationships between arterial pressure and arterial volume compliance and pulse propagation time are described based on three different elastic tube models:

(1). Ideal elastic model. The circumferential elastic modulus in this model keeps constant with different arterial pressures, equivalent to unstressed circumferential elastic modulus (E_o).

(2). Stretching elastic model. Because of constant wall volume, the circumferential elastic modulus becomes less with the increase of arterial pressure.

(3). Physiological elastic model. It was proposed by Hardy *et al* [7] and Forster *et al* [8]. Its circumferential elastic modulus is a function of arterial pressure, unstressed and maximum blood volumes, and unstressed arterial volume compliance. It increases with the increase of arterial pressure.

3.4. Model parameters

Next, the different circumferential elastic modulus properties from the three elastic tube models were applied to the relationship between circumferential elastic modulus and volume compliance, pulse wave velocity and pulse propagation time for simulation. And the following model parameters are chosen.

The artery length for modeling was considered as 0.5 m, which is equivalent to the approximate artery segment length between the aorta and finger.

Regarding brachial arteries, 1.53 mm unstressed brachial internal artery radius, 2.25 mm maximum internal artery radius at high arterial pressure and 0.46 mm wall thickness [9] were used in the simulations. So the unstressed and maximum blood volumes for a 0.5 m artery are 3.7 ml and 8.0 ml.

Because E_o of brachial arteries measured in vivo ranges from about 16 to 360 kPa [9-10], the artery with E_o=100 kPa was used in this initial simulations. Its corresponding unstressed arterial volume compliance for a 0.5 m artery is 32 ul/mmHg.

3.5. Simulation results

Figure 2 shows the relationship between arterial pressure and arterial volume compliance for the three elastic tube models. With the increase in arterial pressure, arterial volume compliance increases in the ideal and stretching elastic models, but the rate of increase is different. It is larger in the stretching elastic model. However, in the physiological elastic model, arterial volume compliance decreases with arterial pressure.

For the relationship between arterial pressure and pulse propagation time, as shown in figure 3, the direction changes are similar to those for arterial volume compliance.

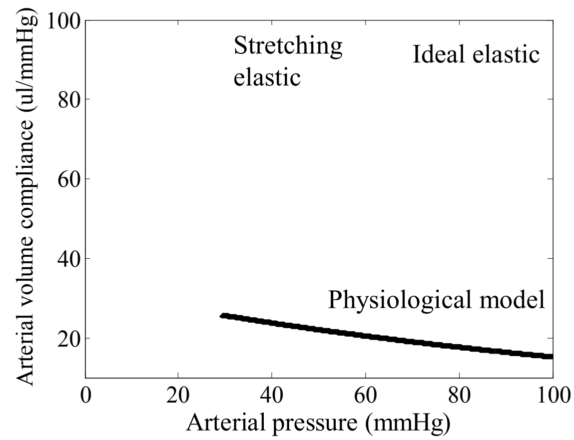

Figure 2. The simulated relationships between arterial pressure and arterial volume compliance for the artery with 100 kPa unstressed circumferential elastic modulus.

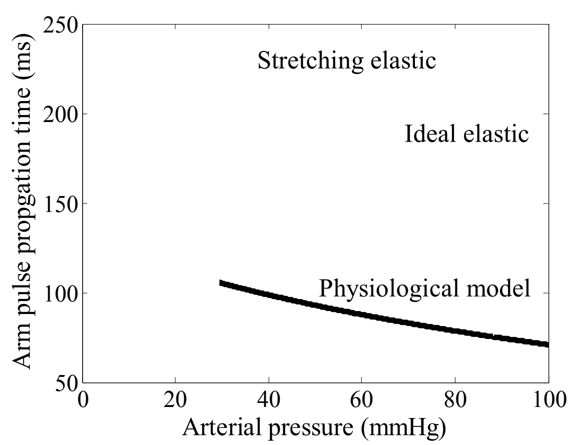

Figure 3. The simulated relationships between arterial pressure and pulse propagation time for the artery with 100 kPa unstressed circumferential elastic modulus.

4. Clinical measurement of arterial compliance

Clinical measurements were next performed to provide evidence for selecting the realistic model.

4.1. Subjects and experimental protocol

Eight healthy volunteers with no history of cardiovascular disease were studied. For each study on a subject, a series of three separate tests were performed with the right arm at different positions (-90°, horizontal level, and 90° to horizontal level).

In each test, the electrocardiogram (ECG), finger and ear photoplethysmogram (PPG) from the right index finger and right earlobe were recorded simultaneously for 2 min. At the end of each test, the systolic blood pressure, diastolic blood pressure and mean arterial pressure were acquired using an automatic oscillometric monitor.

4.2. Pulse wave analysis and data statistics

Arm pulse propagation time was calculated by subtracting the ear pulse propagation time from the finger pulse propagation time in order to eliminate the pre-ejection time. The overall means of arterial pressure and arm pulse propagation time changes referred to those with the arm at the horizontal level were calculated from all subjects. All differences were for paired values in each subject, and all statistical t-tests were performed on paired data.

4.3. Results

4.3.1. Inverse relationship between arm pulse propagation time and arterial pressure

The overall mean arm pulse propagation time with the arm at the above three positions were 53, 59 and 88 ms. Figure 4(A) gives their changes with arterial pressure changes referred to those obtained with the arm at horizontal level. By raising the arm to perpendicular, the decrease in brachial arterial pressure was associated with longer arm pulse propagation times (with the mean value of 30 ms). Conversely, if the arm was placed 90° below the horizontal level, the arm pulse propagation time decreased by a mean value of 6 ms. Statistically, with the increase in arterial pressure, the arm pulse propagation time decreased significantly ($P<0.01$).

4.3.2. Inverse relationship between arterial compliance and arterial pressure

Figure 4(B) shows the calculated relative arterial volume compliance changes against the recorded brachial arterial pressure changes referred to horizontal values. The inverse relationship between arterial pressure and arterial volume compliance was also confirmed.

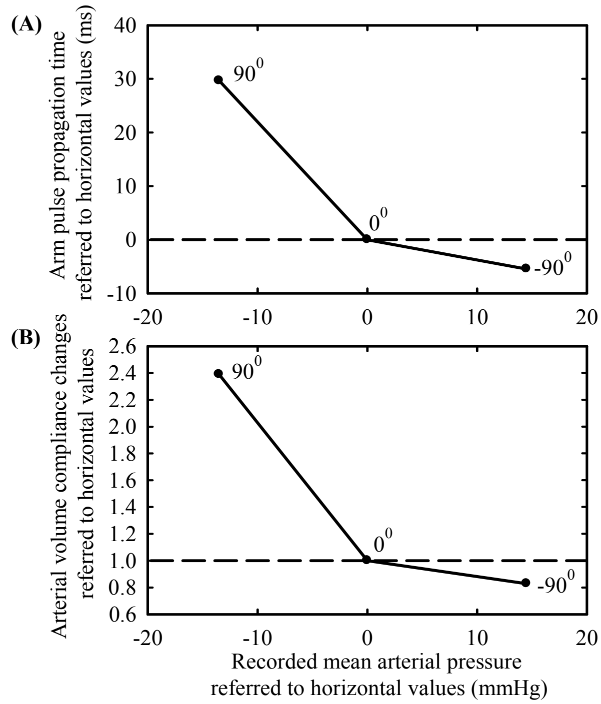

Figure 4. Experimental results for the relationship between recorded arterial pressure changes and arm pulse propagation time changes (A) and arterial volume compliance changes (B), which were referred to horizontal values.

5. Comparison between computer simulation and clinical measurement

It was observed that the experimental results in figure 4 demonstrated the same changing trend as the simulation results from the physiological elastic model, but not the ideal or stretching elastic model. It confirmed that, with more arterial pressure on the artery, the less compliant or stiffer the artery is, which leads to shorter arm pulse propagation times.

By simulating different values of maximal arterial volume compliance in the physiological elastic model, it was found that with the maximal arterial volume compliance of 110 ul/mmHg, equivalent to 30 kPa unstressed circumferential elastic modulus, the simulation value of arm pulse propagation time at the recorded overall mean arterial pressure with the arm at the horizontal level (85 mmHg) was the same as the experimental value of 59 ms. And the corresponding simulation value of circumferential elastic modulus at the recorded overall mean arterial pressure with the arm at the horizontal level is 750 kPa, which was within the normal range from 500 to 2000 kPa [9, 11-13].

6. Discussion and conclusions

The inverse relationship between arterial volume compliance and arterial pressure has been experimentally detected by arm pulse propagation time. It was consistent with the simulation results based on the physiological elastic model, which provided evidence that the simulation used for the physiological elastic model is useful for understanding how arterial properties change with arterial pressure.

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