THE USE OF ULTRASOUND IMAGING IN THE *IN VIVO* DETERMINATION OF NORMAL HUMAN ARTERIAL COMPLIANCE

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ABSTRACT

Elastic properties of major arteries were measured in vivo in ten normal volunteers, age 26 to 44 years (mean = 32 years). A B-mode ultrasound imager was used to noninvasively measure mean diameter and pulsatile diameter change at five locations along the main arteries in the abdomen and the lower extremities. Together with pulsatile pressure (measured by the auscultatory method), strain (ε), compliance (C) and the pressure-strain elastic modulus (Ep = 1/C) were calculated. Ep increased significantly along the arterial tree; mean values ($\times 10^5$ N/m^{-2}) were: 0.99 aorta, 1.21 common iliac artery (CIA), 1.43 common femoral artery (CFA), 1.57 superficial femoral artery (SFA), and 1.56 popliteal (POP) artery.

INTRODUCTION

Arteriosclerosis causes structural changes in all layers of the arterial wall [1]. These changes alter the elastic properties of the vessel. A simple, noninvasive procedure that could measure these elastic properties would be helpful to physicians and physiologists.

The properties of the arterial wall, like those of any material, can be described in terms of the relationship between stress and strain. Strain, in this case, is equivalent to the ratio of diameter change to mean diameter. In a circular cylinder, such as an artery, strain is defined as:

$$\varepsilon = \frac{dc}{c} \qquad (1)$$

where c is circumference, $c = \pi D$

Substituting for compliance in terms of diameter yields:

$$\varepsilon = \frac{d(D)}{D} \qquad (2)$$

which is the form used in this study. This value is used in the calculation of compliance which is given by:

$$C = \frac{1}{\delta P} \frac{\delta D}{D_0} \qquad (3)$$

where δD is the maximum change in arterial diameter (m)
δP is the pulse pressure (N)
D_0 is the mean arterial diameter (m)

A related quantity is the pressure-strain elastic modulus (Ep). It is the inverse of compliance as defined by Eqn. 3.

Volume changes, which are a result of pressure changes, may be expressed in terms of compliance. The volume of a circular cylinder is :

$$V = \frac{\pi}{4} D^2 \, l \qquad (4)$$

where V = volume (l)
D = diameter (m)
l = vessel length (m)

The change in volume becomes:

$$dV = \frac{\pi}{4} 2 \, D \, l \, dD \qquad (5)$$

Dividing by volume and pressure change yields:

$$\frac{dV}{dP \, V} = \frac{2 \, dD}{dP \, D} \qquad (6)$$

which is two times the compliance, as defined by Eqn. (3).

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$$\frac{dV}{dP\ V} = 2C \qquad (7)$$

The purpose of this study was to develop a noninvasive method for determining arterial elastic properties *in vivo*. These findings are intended for use in the development of an analytical and experimental model of the human arterial system.

MATERIALS AND METHODS

A B-mode ultrasonic imager (Hewlett-Packard model #7702A) was utilized to obtain pulsatile and mean diameter measurements from the arteries of 10 normal volunteers, 5 women and 5 men with an age range of 26 to 44 years. Elastic properties were calculated for the aorta, common iliac, common femoral, superficial femoral and popliteal arteries.

Each subject was tested in a supine position. The aorta was scanned 3-5 cm. distal to the origin of the superior mesenteric artery. Measurements were taken from the common iliac artery about 3 cm. distal to the aortic bifurcation. The common femoral artery was imaged just proximal to the origin of the profunda femoris. The superficial femoral artery was scanned approximately 10 cm. distal to the origin of the profunda. Finally, the popliteal artery was scanned approximately 10 cm. proximal to the trifurcation of the peroneal, anterior tibial and posterior tibial arteries.

The aorta was scanned using a 3.5 MHz imaging transducer; all other vessels were imaged using a 5 MHz probe. The 3.5 MHz probe provided the necessary penetration for imaging the aorta. Acoustic gel was placed on the surface of the skin over the approximate location of the artery to provide coupling between the ultrasound probe and the skin. While monitoring the video screen, an optimal image of the artery was obtained. Vessel movement over 5-10 cardiac cycles was recorded on video tape.

To determine the pulsatile diameter change and mean diameter, the video recording was analyzed frame-by-frame over five cardiac cycles. Built-in electronic calipers were used to make the diameter measurements.

Brachial blood pressures were determined for each subject by the auscultatory method. The difference between systolic and diastolic pressure measurements was used as the pulsatile pressure change, δP, in calculating Ep.

Calculations

Arterial compliance was calculated using Eqn. (3). The mean diameter, D_o, was determined from the mean of the measured diameter values for one cardiac cycle. The pulsatile diameter change was estimated to be 1.8 times the standard deviation of the diameter values for the cardiac cycle. This estimation was used because the diameter records contained moderate experimental error. Ensemble averaging was not possible since there was no time reference available. The correlation between standard deviation and total excursion was obtained from analysis of volume pulse recordings which have a similar morphology to diameter pulses [2,3]. The relationship is similar to that for a sine wave which has a proportionality constant of 1.414.

The mean diameter and pulsatile diameter change were used to calculate compliance as well as Ep. Five values of Ep were determined for each vessel scanned on each volunteer.

RESULTS

In all volunteers, Ep increased with distance (distally) along the arterial tree (Fig. 1). A significant difference ($p<0.05$) was noted between the values of Ep at locations other than adjacent sites (Table 1).

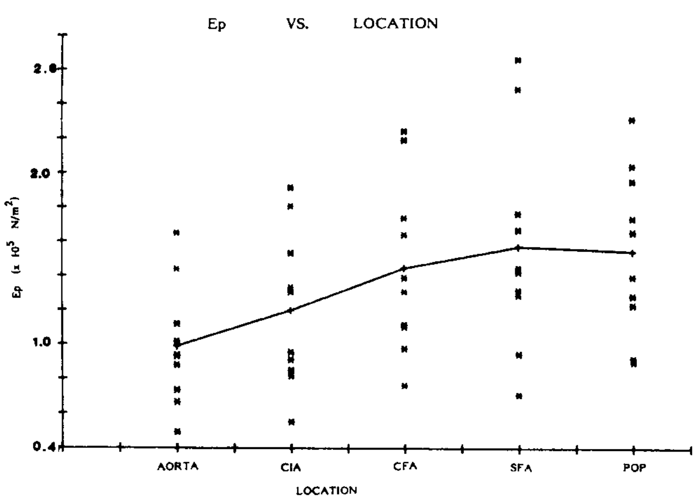

Figure 1: Ep vs. Location

TABLE 1

Arteries	Significance
Aorta vs. CIA	NS
Aorta vs. CFA	0.0595
Aorta vs. SFA	0.0074
Aorta vs. POP	0.0010
CIA vs. CFA	NS
CIA vs. SFA	0.0046
CIA vs. POP	0.0307
CFA vs. SFA	NS
CFA vs. POP	NS
SFA vs. POP	NS

Table 2 summarizes the mean pressure-strain elastic modulus values obtained for each vessel segment.

TABLE 2

Artery	Ep ($x10^5$ N/m^{-2})
Aorta	0.99
CIA	1.20
CFA	1.45
SFA	1.57
POP	1.55

DISCUSSION

This study employed B-mode ultrasonic imaging to provide an estimate of the *in vivo* compliance of normal human arteries at several locations. Ep, the inverse of compliance, was calculated from three parameters: pulsatile diameter change, mean diameter and pulsatile pressure change.

Previous canine and *in vitro* studies have documented that Ep increases with distance from the heart [1]. The present study is the first to confirm these findings *in vivo* in humans.

A recently published study employed a similar noninvasive method to obtain Ep for the aorta [3]. Values of 0.99 and 1.57 ($x10^5$ N/m^{-2}) were obtained in normal subjects with a mean age of 25 and 46 years, respectively. In the present study, Ep was equal to 0.99 ($x10^5$ N/m^{-2}) in 10 normal volunteers with a mean age of 32 years.

Improvements to this procedure that will increase the accuracy and resolution of these compliance measurements are now feasible. New B-mode ultrasound imagers have been recently developed that incorporate echo-tracking capability. The echo-tracking unit can be used to track the motion of the arterial walls. This eliminates the measurement error due to manual cursor placement. The echo-tracking systems also reduce the amount of time required for data analysis. The manual procedure used in the present study was too time consuming for routine use.

Advances are being made in the quality of ultrasound instruments which improve image resolution. The machine used in this study had a resolution of 0.01 cm [4]. This resolution is adequate for measurements of diameter changes in the arteries of young normal volunteers, but may not be sufficient for reliable compliance measurements in older people or in patients with vascular disease.

In summary, this study introduces a procedure which can be used to noninvasively determine arterial elastic properties *in vivo*. Ep was measured at five locations in the arteries of ten young, normal volunteers and was shown to increase with distance along the arterial tree. With improvements in image quality and resolution this technique can provide a simple noninvasive, *in vivo* measure of compliance in the main arteries.

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