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● *Original Contribution*

MEASUREMENT OF WAVE VELOCITY IN ARTERIAL WALLS WITH ULTRASOUND TRANSDUCERS

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Abstract—Arterial wall stiffness can be associated with various diseases. The stiffness of an artery can be measured with the pulse wave velocity (PWV) using the "foot-to-foot" method. However, the foot of the pressure pulse is not very clear, due to reflected waves. The blood pressure pulse generated by the heart is a low frequency wave and its time resolution is low. PWV is an average indicator of artery stiffness between the two measuring positions; therefore, it cannot easily identify local stiffness. In this paper, a sinusoidally modulated force with a high frequency is generated noninvasively on the arterial wall by the radiation force of ultrasound (US). The resulting vibration in the artery is measured with an US Doppler transceiver. The wave velocity in the artery is measured from a wave image obtained by scanning the force transducer and fixing the sensor transducer. Because of the high imposed force frequency, the temporal resolution of this method is much higher than the conventional pressure PWV method. Local wave velocity more than a few millimeters can be measured, which is not possible with the PWV method. (E-mail: zhang.xiaoming@mayo.edu) © 2006 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Measurement, Wave velocity, Arterial wall, Ultrasound Doppler.**

INTRODUCTION

According to recent statistics by the American Heart Association, cardiovascular disease (CVD) is the number one killer in the USA (American Heart Association 2003). CVD claims more lives each year than the next five leading causes of death combined: cancer, chronic lower respiratory diseases, accidents, diabetes mellitus and influenza and pneumonia. It has long been recognized that a high percentage of all CVD is associated with stiffening of the arteries or arteriosclerosis (Hallock 1934). Arteriosclerosis involves the build-up of plaques on the insides of the artery walls, which stiffens the arteries, affects circulation and may lead to high blood pressure, angina (chest pain), heart attack, stroke and sudden cardiac death. Arteriosclerosis can be associated with various diseases and aging (Nichols and O'Rourke 1990; Sutton-Tyrrell et al. 2001). Increased stiffness of the arteries has recently gained recognition as a potential risk factor for CVD and many other diseases (O'Rourke et al. 2002; London and Cohn 2002; Laurent et al. 2003).

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Pulse wave velocity (PWV) is widely used for estimating the stiffness of an artery (Steptoe et al. 1976; Nagai et al. 1999). Measurements of PWV in humans have shown that the velocity increases with age, from an average of 4 m/s to 10 m/s for persons from five years of age to seventy years of age (Hallock 1934). Measurement of the PWV using ultrasound (US) has been an area of recent interest (Brands et al. 1998; Meinders et al. 2001; Eriksson et al. 2002).

PWV is defined as the distance between two measurement points divided by the pulse-wave transit time from the two points. The PWV is directly related to the elastic modulus in the circumferential direction of the artery by the well-known Moens-Korteweg equation (Nichols and O'Rourke 1990)

$$c_p = \sqrt{\frac{Eh}{2R\rho}}, \tag{1}$$

where c_p is the PWV, R the radius, E Young's modulus, h the thickness of the artery and ρ mass density of the blood. This equation was modified by Bramwell and Hill (1922):

$$c_p = 3.57/\sqrt{D_p} \tag{2}$$

where $D_p = (dV/V)/d_p$ is the distensibility, which is defined as the relative change in volume (*dV/V*) for a given change in pressure (*dp*).

Despite the simple definition of PWV, some problems still remain that limit the interpretation of the available data and the general applicability of PWV measurement (Xu 2003). Usually, PWV is measured using the "foot-to-foot" method (Nichols and O'Rourke 1990). The "foot" of the pressure wave is not clear, because of reflected waves. In addition, the pressure pulse, produced by the pumping of the heart, is predominately a low-frequency wave. Therefore, it is difficult to measure small time changes from the pulse-wave forms. In other words, the time resolution of the pulse is low; therefore, a relatively large distance is needed for reliable time change measurement. Measurement over a large distance means PWV produces an average value of artery stiffness between the two measuring points. It is, therefore, difficult to identify local stiffness variation of a few millimeters' length. For early diagnosis of arteriosclerosis, a measurement of local stiffness in a few millimeters' length is needed (Chubachi 1994), because, in the early stage of arteriosclerosis, a fibrous spot is several millimeters in diameter and becomes homogeneously hard in the final stage.

Recently, we have developed a novel method for noninvasive estimating elastic properties of arteries (Zhang et al. 2004, 2005a). In this method, a bending wave is generated in an arterial vessel by the radiation force of US, and the wave velocity along the longitudinal direction of the artery is measured with a laser vibrometer. A new wave propagation theory in arteries was developed, from which longitudinal elastic modulus of the artery is estimated accurately from measured wave velocity.

In this paper, the method of using a US Doppler transceiver for measuring the wave propagation in a rubber tube and an excised artery is investigated. This method has been recently applied for *in vivo* noninvasive measurement of local wave velocity in femoral arteries of pigs (Zhang et al. 2005b).

METHOD

Phantom preparation

The measurement techniques are studied first in a rubber tube and then applied to an artery. To prepare a tube phantom, a 24-cm-length of 5-mm outer radius × 3-mm inside radius latex rubber tubing (Kent Elastomer Products, Inc., OH, USA) was secured to rigid connectors at each end and mounted in a three-sided aluminum/acrylic frame. The tube was slightly stretched lengthwise to place it under tension to prevent sagging. The tube was pressurized with normal saline to 60 mmHg. The tube axis was positioned at the center of the frame's 6 × 6-cm cross-section. The two long open sides of the frame were temporarily sealed and a gelatin mixture was poured into the frame, filling it completely. The gelatin mixture had been prepared by dissolving 60*g* of porcine gelatin (Sigma, G2500, 300 bloom, Sigma-Aldrich, Inc., St. Louis, MO, USA) in a 60/40 solution of water and glycerol to make a 1000-mL volume, with 1% potassium sorbate added as a preservative. The phantom was then allowed to rest overnight at room temperature. A fresh porcine femoral artery of 8-cm length was embedded in the gelatin in the same way. The tube or the artery was positioned at the center of the frame, such that it lay approximately 20 mm below the final surface of the gelatin.

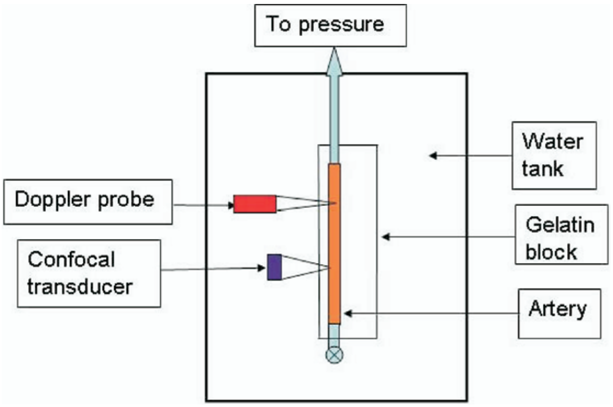

Fig. 1. Schema of the experimental system for measuring the wave velocity in an artery with US transducers.

Wave generation and measurement

The radiation force of US is used to generate a continuous wave (CW) modulated tone-burst of a few hundred Herz in an artery, and the resulting vibration in the artery is measured with a US Doppler transceiver. The experiments were conducted in a water tank. The artery is embedded in a tissue-mimicking gelatin phantom and can be pressurized through the saline inside the artery. A schema of this experimental system is shown in Fig. 1.

The low-frequency CW is generated with a two-element US transducer by modulating its two intersecting CW focused US beams of different frequencies (Zhang et al. 2004, 2005a). A scanning technique is used to measure the wave velocity in the artery in which the US Doppler transceiver is fixed and the US force transducer is moved. A custom-built commercial three-axis scanning system (Brandt Automation, Delano, MN, USA) is used. The scanner can perform linear scans in each of the three axes with a resolution of 2.5 μm and at speeds over 25 cm/s. Scanning motion is controlled by an intelligent servo controller (Galil Motion Control, Rock-