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● *Review*

PHYSICAL PROPERTIES OF TISSUES RELEVANT TO ARTERIAL ULTRASOUND IMAGING AND BLOOD VELOCITY MEASUREMENT

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Abstract—A review was undertaken of physical phenomena and the values of associated physical quantities relevant to arterial ultrasound imaging and measurement. Arteries are multilayered anisotropic structures. However, the requirement to obtain elasticity measurements from the data available using ultrasound imaging necessitates the use of highly simplified constitutive models involving Young's modulus, E. Values of E are reported for healthy arteries and for the constituents of diseased arteries. It is widely assumed that arterial blood flow is Newtonian. However, recent studies suggest that non-Newtonian behavior has a strong influence on arterial flow, and the balance of published evidence suggests that non-Newtonian behavior is associated primarily with red cell deformation rather than with aggregation. Hence, modeling studies should account for red cell deformation and the shear thinning effect that this produces. Published literature in healthy adults gives an average hematocrit and high-shear viscosity of 0.44 ± 0.03 and 3.9 ± 0.6 mPa.s, respectively. Published data on the acoustic properties of arteries and blood is sufficiently consistent between papers to allow compilation and derivation of best-fit equations summarizing the behavior across a wide frequency range, which then may be used in future modeling studies. Best-fit equations were derived for the attenuation coefficient *vs.* frequency in whole arteries (R^2 = 0.995), plasma (R^2 = 0.963) and blood with hematocrit near 45% (R^2 = 0.999), and for the backscatter coefficient *vs.* frequency from blood with hematocrit near 45% (R^2 = 0.958). (E-mail: P.Hoskins@ed.ac.uk) © 2007 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Artery, Attenuation coefficient, Backscatter coefficient, Blood flow, Blood viscosity, Doppler ultrasound, Elastic modulus, Non-Newtonian, Red cell aggregation, Red cell deformation, Speed of sound, Young's modulus.**

INTRODUCTION

A wide variety of measurements are made using ultrasound systems, related to arterial blood flow and wall motion, which are then used in clinical research studies or in clinical diagnosis. The image formation process in ultrasound is linked to key acoustic and mechanical properties of tissues within the beam. In the case of arterial ultrasound, the properties of the artery and of blood are of utmost importance. These properties will directly influence B-mode, spectral Doppler and color flow images, hence, an understanding of relevant physical phenomena is important in interpreting arterial ultrasound images and measurements. In turn, some of these physical properties, such as elasticity, are of interest as diagnostic indices so that a specification of values in disease and in health is of interest to compare against values measured using ultrasound. For interpretation of ultrasound image data and as a platform for developing new ultrasound methods, models of the ultrasound measurement process may be used. Such models can be computational (Oung and Forsberg 1996; Thompson et al. 2004a, 2004b; Khoshniat et al. 2005) or experimental (Ramnarine et al. 2001; Baldewsing et al. 2005), but for both types, knowledge of the relevant physical properties of tissues is needed. The aim of this article is to review the physical phenomena relevant to arterial ultrasound imaging and blood flow, and to compile data on the values of physical properties applicable to these phenomena.

MECHANICAL PROPERTIES OF ARTERIES

The three layers of an artery are the intima, media and adventitia. The intima consists of the endothelium, which is a single-cell layer next to the blood, and associated connective tissue. The media consists of layers of

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smooth muscle cells and fibers composed of elastin, along with collagen fibers. The adventitia is composed mostly of collagen fibers. Arteries are multilayered anisotropic structures, demonstrate a nonlinear stress-strain relationship and are pre-stressed both longitudinally and circumferentially. In addition to radial wall motion, there is both longitudinal motion and twisting. The relationship between the applied forces and the resulting displacements in materials is summarized mathematically by the "constitutive equations," which are tensor equations relating the stress field to the strain field. Such equations have 36 components, of which 21 are independent for a generalized material, reducing to two components (Young's modulus and Poisson ratio) in an isotropic linear elastic material. Prof. Y. C. Fung has been instrumental in the development of constitutive equations for arteries, of which the equations described in the paper Chuong and Fung (1983), containing seven material parameters, are used widely in computational modeling of blood flow and wall dynamics. This complex area is discussed in detail by Fung (1993) and Humphrey (1995, 2001, 2003). Humphrey's paper (1995), in which more than 500 references are detailed, concludes that there is a need for 3-D constitutive models of elastic behavior. These models are now being developed and used in simulation studies (Holzapfel et al. 2002, 2004). In time it may be possible to obtain sufficient information from medical imaging to enable multiple parameters of constitutive equations to be specified for the individual patient. However, the approach taken to date in ultrasound imaging has been to radically simplify the nature of the assumed physical model of arterial mechanics to obtain estimates of mechanical properties from the data available from ultrasound imaging. This

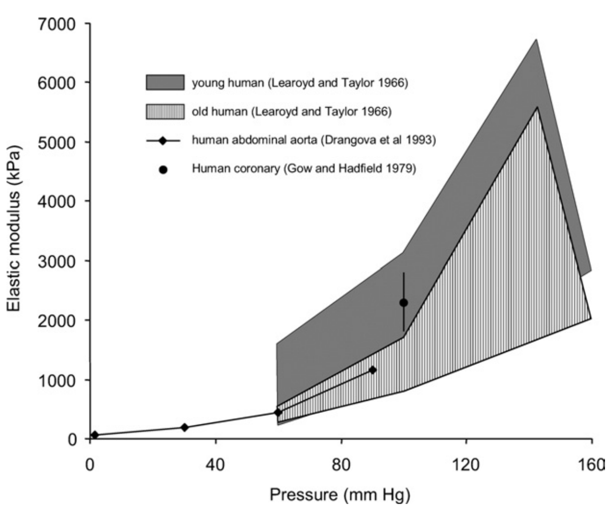

Fig. 1. Static Young's modulus in human arteries. (Reprinted from Ryan LK, Foster FS. Tissue equivalent vessel phantoms for intravascular ultrasound. Ultrasound Med Biol 1997;23:261–273.)

Table 1. Abdominal aorta and abdominal aortic aneurysm (AAA) component tissue stiffness for elastin (Ee) and collagen (Ec) (from Raghavan et al 1996). Arterial segments were stretched in a tensile testing machine. Ee and Ec were derived from the slope of the stress-strain curve at low and high strains respectively.

Artery	Ee (MPa)	Ec (MPa)
AAA (longitudinal)	0.421 ± 0.06	4.08 ± 0.68
AAA (circumferential)	0.556 ± 0.11	5.39 ± 0.89
Normal (longitudinal)	0.453 ± 0.16	4.68 ± 1.1

approach has relied on the traditional "Hookean" description of elastic behavior, as detailed below.

A "Hookean" solid is one in which stress and strain are linearly related, and the constitutive equations that relate stress to strain are completely characterized by the Young's modulus, E, and the Poisson ratio, σ (Fung 1993). The latter term is related to compressibility, and is taken as 0.5 in arteries on the basis that they are incompressible. A viscoelastic solid requires the specification of relaxation times, which describe the time lag between stress and strain. This simplified approach enables elastic (Gamble et al. 1994) and viscoelastic (Shau et al. 1999; Armentano et al. 1995) behavior to be measured in arteries using data available from ultrasound imaging. The stress strain behavior of arteries is nonlinear, hence the slope of the stress/strain curve, called the "incremental Young's modulus," may be measured at a specific distending pressure or as a function of distending pressure. However, most published data on the elastic properties of arteries refers to a different quantity, the pressure-strain elastic modulus, Ep (Nicholls and O'Rourke 2005). This quantity was introduced by Peterson et al. (1960) as a measure of elasticity that could be calculated, which did not require knowledge of wall thickness, and which has been used in ultrasound studies (Wilson et al. 2003; Lanne et al. 1994). Hayashi (1993) distinguished between indices of "structural stiffness," which describe the behavior of the artery as a whole, of which Ep is an example, and indices of "material stiffness" which are true material properties, primarily Young's modulus. The relationship between E and Ep is discussed by Reneman et al. (1996), from which eqn (1) can be derived.

Table 2. Abdominal aortic aneurysm intraluminal thrombus stiffness indices (from Wang et al 2001). Thrombus was stretched in a tensile testing machine.

Region and orientation	Stiffness (MPa)
Luminal layer—longitudinal	0.54 ± 0.07
Luminal layer—circumferential	0.57 ± 0.07
Medial layer—longitudinal	0.33 ± 0.07
Medial layer—circumferential	0.27 ± 0.04