special communication

Age-related changes of human aortic flow wave velocity measured noninvasively by magnetic resonance imaging

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MOHIADDIN, RAAD H., DAVID N. FIRMIN, AND DONALD B. LONGMORE. *Age-related changes of human aortic flow wave velocity measured noninvasively by magnetic resonance imaging.* J. Appl. Physiol. 74(1): 492–497, 1993.—We have used magnetic resonance imaging with cine velocity mapping to measure flow wave velocity in the thoracic aorta of 20 healthy volunteers of different ages. We have also studied the relationship between propagation of flow wave velocity and regional aortic compliance. Aortic flow velocity increased linearly with age ($r = 0.87$), and there was a significant difference between the youngest decade [age 10–19, mean velocity 4.3 ± 0.7 (SD) m/s] and the oldest decade studied (age 50–59, mean velocity 7.2 ± 0.2 m/s). Flow wave velocity (m/s) was negatively correlated with ascending aortic compliance (μl/mmHg) ($r = -0.75$). Magnetic resonance imaging is a noninvasive method for measurement of aortic flow wave velocity that is an important parameter in assessing arterial wall mechanics and blood flow dynamic.

age; aorta; compliance; velocity mapping

WALLS OF BLOOD VESSELS contain a variety of tissues, each with its own characteristic properties. Smooth muscle is a physiologically active element, and by contracting or developing force it can alter the diameter of the vessel or the tension in the wall. The other components include endothelial cells, connective tissue, bands of elastin, and fibers of collagen, which are essentially passive in their mechanical behavior. The compliance of a blood vessel depends on the proportions and interconnections of these materials and on the contractile state of the vascular smooth muscle. The artery is an elastic tube the diameter of which will vary with a pulsating pressure. In addition, it will propagate pressure and flow waves, created by the ejection of blood by the heart, at a certain velocity that is largely determined by the elastic properties of the wall.

Previous workers have measured human arterial compliance from pressure-volume curves of postmortem arteries (1, 12, 14, 26). In vivo estimation of arterial wall compliance is more difficult, however, and has been performed using indirect and invasive techniques, including pulse wave velocity measurements in animals and in humans (5, 10), the pressure-radius relationship using the Peterson transformer coil in animals (27), X-ray contrast angiography in humans (16), and pulsed ultrasound aortography (9). Compliance of the whole arterial system has previously been calculated from the left ventricular stroke volume divided by pulse pressure (7). We have demonstrated that both regional aortic compliance and total arterial compliance can be measured in vivo noninvasively by magnetic resonance imaging, have established normal ranges of aortic compliance with age, and have investigated compliance in athletes, in patients with coronary artery disease (4, 21), and in patients with coarctation of the aorta (25).

Magnetic resonance with velocity mapping can be used to display anatomy of the heart and vessels in high resolution and to measure blood flow and characterize its pattern noninvasively in any plane or direction in large and medium-sized arteries and veins (18, 19, 22).

In this study we have used magnetic resonance imaging with velocity mapping to measure the velocity of propagation of flow wave between two points on the thoracic aorta of healthy volunteers as an index of assessment of global compliance in this vessel. We have also studied the relationship between flow wave velocity and regional aortic compliance measured simultaneously in the thoracic aorta.

It is not essential to consider the formation of magnetic resonance images in detail in this paper; there are many other descriptions of the technique (15). Conventional images represent a map of the amplitude of the radio-frequency signal emitted by sensitive nuclei in the imaging plane under the influence of a static magnetic field, applied magnetic field gradients, and radio-frequency pulses. Like any wave, however, the magnetic resonance signal possesses both phase and amplitude. The phase of the signal is ignored in conventional images, but a phase image may be constructed. It is possible to encode velocity of motion in the phase of the signal so that the phase map becomes a velocity map (6). The encoding of velocity is achieved by a combination of magnetic field gradients that leaves the phase in each pixel of the image proportional to velocity in a chosen direction, either through the image plane or within it. Many other factors, including inhomogeneity of the applied magnetic field

and susceptibility variations within the patient, also lead to phase changes; to compensate for these, two phase images are acquired, one with velocity encoding and one without. Subtraction of one image from the other yields the velocity map. The images are acquired simultaneously by interleaving.

To measure velocity of blood it is necessary to have signal from it; otherwise no phase data are acquired. With use of a spin echo sequence, moving blood gives no signal, and such images are not suitable. The combination of gradient echo imaging with even echo rephasing [the field even echo rephasing (FEER) sequence] gives high signal even from rapidly moving blood and allows accurate flow measurements to be made (23).

We have previously validated the techniques used and have demonstrated that magnetic resonance flow measurements in the aorta and pulmonary artery agree well with each other and with left and right ventricular stroke volumes in normal subjects (2, 3). Good correlation has been shown between magnetic resonance flow measurements of venous return and aortic flow (31) and between magnetic resonance aortic flow measurements and aortic Doppler ultrasound (13, 31). There is also good correlation in vitro ($r = 0.996$) for the FEER technique calibrated against flow phantoms (13).

MATERIALS AND METHODS

Subjects. Twenty healthy volunteers, 12 female and 8 male subjects aged 16–59 yr without symptoms or past history of cardiovascular or renal disease, were examined.

Magnetic resonance imaging. A Vista 2055 magnetic resonance machine (Picker International) operating at 0.5 T was used, with some modifications made to the scanning software and magnetic gradient coils to enable this type of flow measurement. A surface receiver coil and electrocardiographic gating were used in all anatomic and flow studies. The images were constructed on a 256 × 256 matrix from data acquired from the average of 2 × 128 views. Slice thickness was 10 mm, and field of view was 40 cm. Data acquisition was triggered by the R wave of the electrocardiogram and was extended to cover ventricular systole.

Flow wave velocity. A spin echo sequence (TE 40 ms) was used to obtain multislice anatomic sections in transverse and oblique planes through the thoracic aorta. From these images the plane used for flow and compliance measurement was determined at the level of bifurcation of the pulmonary artery (Figs. 1 and 2). A cine FEER sequence was used with velocity encoding in the phase of magnetic resonance signal to record velocity profiles in the midascending and middescending thoracic aorta with a temporal resolution of 10 ms (Fig. 3). At each acquisition the sequence was repeated twice, first to encode velocity in the direction of the slice select gradient and a second time without encoding the velocity. This sequence was done simultaneously by interleaving.

The instantaneous flow (l/s) in the ascending and descending aorta was calculated from aortic cross-sectional area, and the mean velocity within that area was taken at 32 points throughout ventricular systole.

Aortic flow wave velocity (FWV) was calculated in meters per second from the transit time (T) of the foot of the flow wave (Fig. 4) and from the distance (D) between the two points obtained from an oblique sagittal spin echo image. The distance was determined manually on the computer screen by drawing a line in the center of the aorta joining the two points (Fig. 1). The foot of the flow wave was defined by extrapolation of the rapid upstroke of the flow wave to the baseline (Fig. 4)

$$\mathrm{FWV} = \frac{D}{\mathrm{T}}$$

Regional aortic compliance. The lumen of the aorta was outlined manually on the computer screen to measure the change in aortic area (ΔA) between diastole and systole. Regional aortic compliance (C, μl/mmHg) was calculated from the change in volume ($\Delta V = \Delta A \times$ slice thickness) of aortic segment (Figs. 1 and 2) and from aortic pulse pressure (ΔP) measured by a sphygmomanometer (21)

$$\mathrm{C} = \frac{\Delta \mathrm{V}}{\Delta \mathrm{P}}$$

RESULTS

Aortic flow velocity increased linearly with age in the normal subjects ($r = 0.87$), and there was a significant difference between the youngest decade (age 10–19 yr, mean velocity 4.3 ± 0.7 m/s) and the oldest decade studied (age 50–59 yr, mean velocity 7.2 ± 0.2 m/s; Figs. 4 and 5*A*).

FWV (m/s) was negatively correlated ($r = -0.75$) with ascending aortic compliance (μl/mmHg; Fig. 5*B*).

DISCUSSION

The repeated ejection of the blood by the heart generates pressure and flow waves in the aorta and pulmonary artery, and these pulsations are transmitted throughout the arterial tree. The velocity of such waves depends principally on the distensibility of the vessel wall. If the vascular wall tree were completely rigid and the blood were incompressible, the motion of blood in the root of the aorta would be communicated to all of the peripheral vessels instantaneously, creating an infinitely high wave velocity. Blood is indeed incompressible, but the vessels are distensible in varying degrees, and the pulse wave velocity is consequently finite. Flow waves are propagated in much the same way as the pressure wave. The propagation of flow waves has not been studied as extensively as that of pressure waves, partly because, unlike flow, accurate methods of pulsatile pressure measurements have been available for a long time, and partly because the distinction between flow wave velocity and blood velocity has not always been clearly recognized. Blood velocity means the speed of an average drop of blood, whereas flow wave velocity means the speed with which motion is transmitted.

Because the vessel wall is not homogeneous in composition or in the arrangement of its component, it is not surprising that the mechanical properties are not isotropic (the elastic properties of a body are independent of the directions in which force is applied). For this reason,

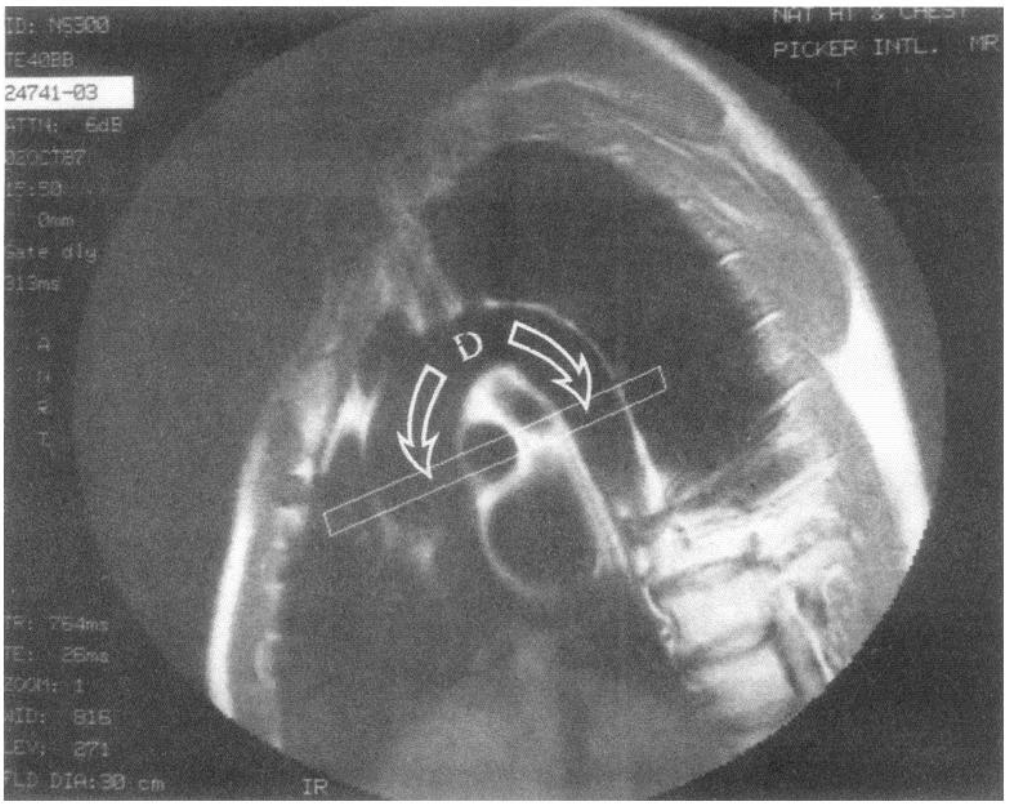

FIG. 1. Spin echo image in an oblique plane, showing whole length of thoracic aorta and illustrating sites where flow wave velocity and regional compliance were measured. D, distance between 2 points where flow wave velocity was measured.

the mechanical properties of arteries are commonly defined in terms of their distensibility or compliance, which in turn is defined as the fractional change in vessel area or volume divided by the distending pressure.

In this study we have described a new noninvasive method of assessing arterial wall compliance in two ways, from measurement of either the volume-pressure relationship or the flow wave velocity between two points on an artery. As expected, our results show a direct relation between age and flow wave velocity and an indirect relation between this and regional aortic compliance (Fig. 5). Although it would be desirable to measure flow wave velocity in the thoracic aorta by simultaneously using magnetic resonance and an alternative method, the difficulty

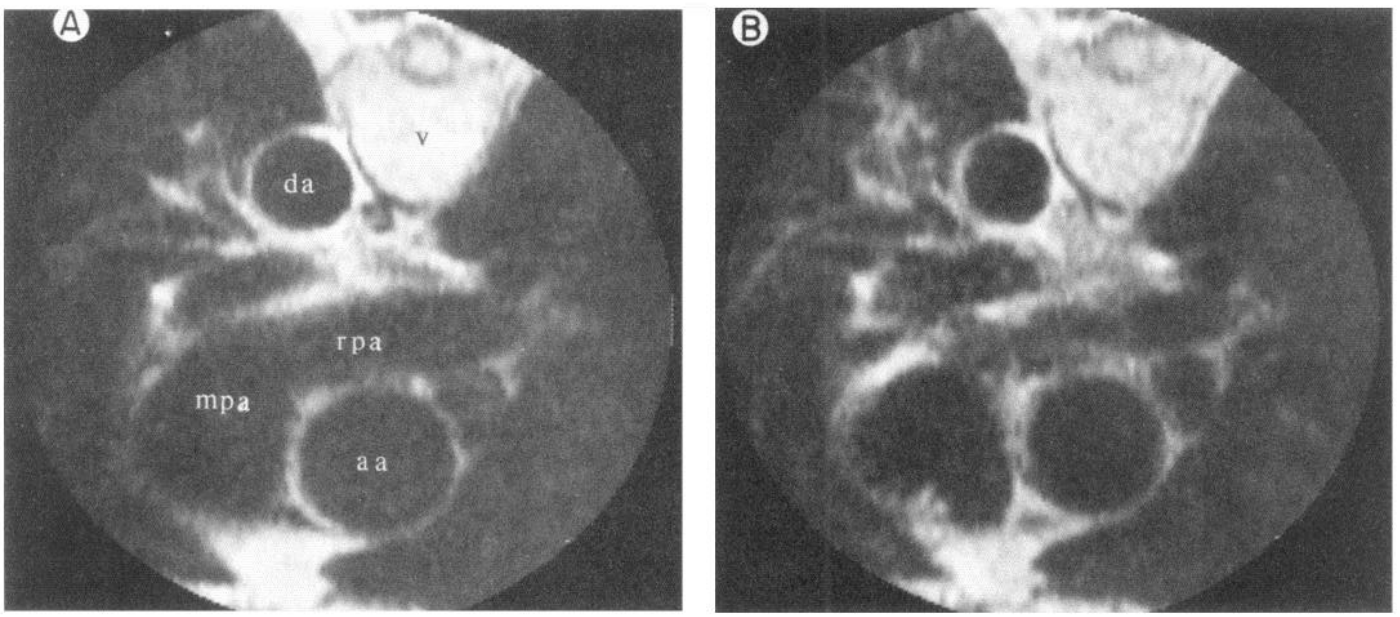

FIG. 2. Systolic (*A*) and diastolic (*B*) images of ascending (aa) and descending aorta (da), showing change in aortic area of a 40-yr-old normal volunteer. mpa, Main pulmonary artery; rpa, right pulmonary artery; v, vertebral body.

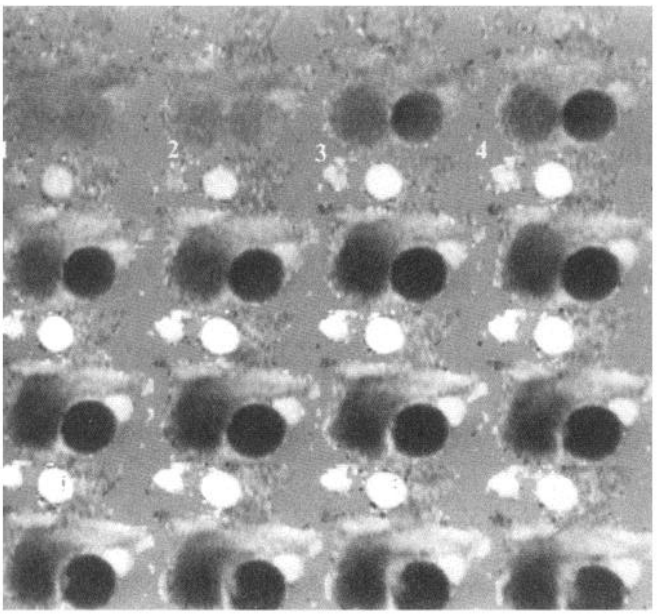

FIG. 3. Representative example of cine velocity mapping in a plane similar to that of Fig. 2. Sixteen of 32 frames acquired at different points on cardiac cycle are presented with a temporal resolution of 10 ms. The 1st frame was acquired 47 ms after R wave of electrocardiogram and represents the very beginning of left ventricular systole. Velocity maps indicate zero velocity as medium gray, caudal velocities (descending aorta) in lighter shades of gray, and cranial velocities (ascending aorta) in darker shades of gray; signal intensity is related to velocity.

of obtaining similar measurements in the thoracic aorta reliably by other noninvasive techniques makes this comparison impractical. Invasive techniques are obviously less desirable. However, we have demonstrated a good correlation between flow wave velocity and regional aortic compliance by use of two different magnetic resonance imaging techniques. In addition, magnetic resonance velocity mapping, as stated earlier, has been extensively validated both in vitro and in vivo.

The limitations of cine magnetic velocity mapping include the relatively long acquisition times, the confined bore of the magnet (making it difficult to image sick patients), and the high cost of the imager. These limitations may become less important with the development of real time magnetic resonance velocity mapping with use of an echo planar technique (8), open access magnets, and cheaper imagers.

Age is an important determinant of arterial elasticity, and it is generally accepted that arterial elasticity tends to decrease with age in humans (14, 21). Furthermore, arterial dilatation, which has been shown to be associated with the aging process in humans both in postmortem aortas (33) and in living subjects (20), could increase its stress-strain modulus by engaging more of the stiff collagen fibers. Systolic blood pressure and pulse pressure are well known to increase with age (11). A fall in arterial compliance may be one factor causing systolic hypertension (24, 28). Decreased compliance may also lead to the decreased baroreceptor sensitivity that has been observed in elderly hypertensive individuals (29). The relationship between blood pressure and compliance is complex, however, inasmuch as hypertension can be a cause as well as a consequence of reduced compliance.

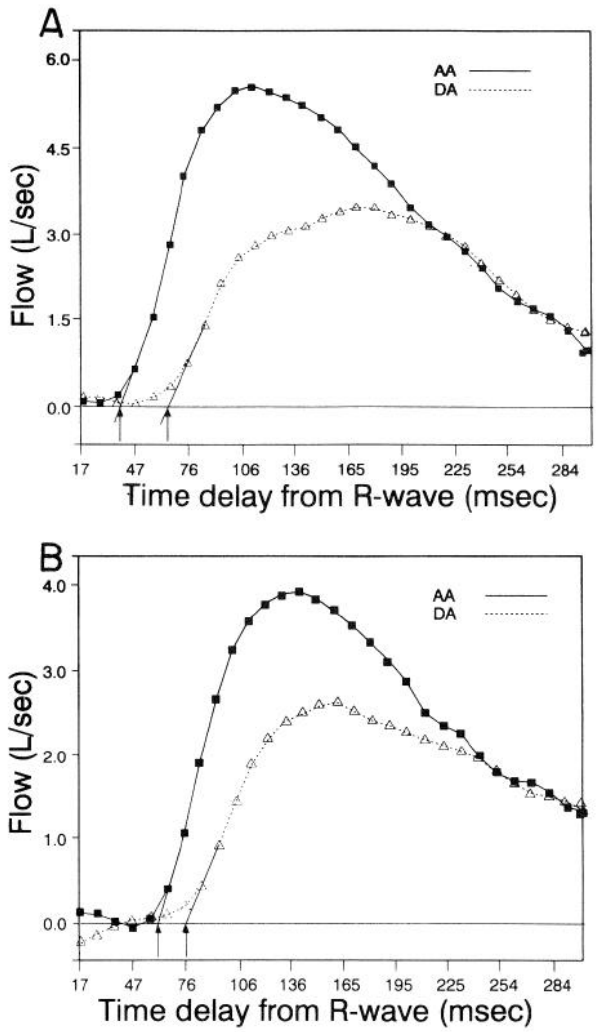

FIG. 4. Foot of flow wave is defined by extrapolation of rapid upstroke of flow wave to baseline. Transit time needed for flow wave to propagate from a point on midascending aorta and a point on middescending thoracic aorta can then be calculated. *A*: data obtained from a young normal subject with good regional aortic compliance. *B*: data obtained from an elderly normal subject with poor compliance, for whom transit time is shorter.

Aortic compliance is an important determinant of left ventricular afterload and, therefore, left ventricular performance (17, 30). The combination of elastic arteries and resistant arterioles constitutes a hydraulic filter, enabling the intermittent cardiac output to be converted to a steady capillary flow. Part of the energy of left ventricular contraction produces forward flow during systole, but the remainder is stored as potential energy in the distended arteries. During diastole, elastic recoil converts this potential energy again into forward flow (windkessel model). A fall in aortic compliance, therefore, increases the impedance to ventricular ejection and decreases capillary blood flow (32).

Relatively few studies of this kind have been reported, and indeed the term "wave velocity" in the literature almost always refers to pressure wave velocity. The development of the noninvasive ultrasonic flowmeter has provided a tool for studying flow wave propagation in human subjects as well as animals (9). Although useful and widely applicable as a simple noninvasive way of record-

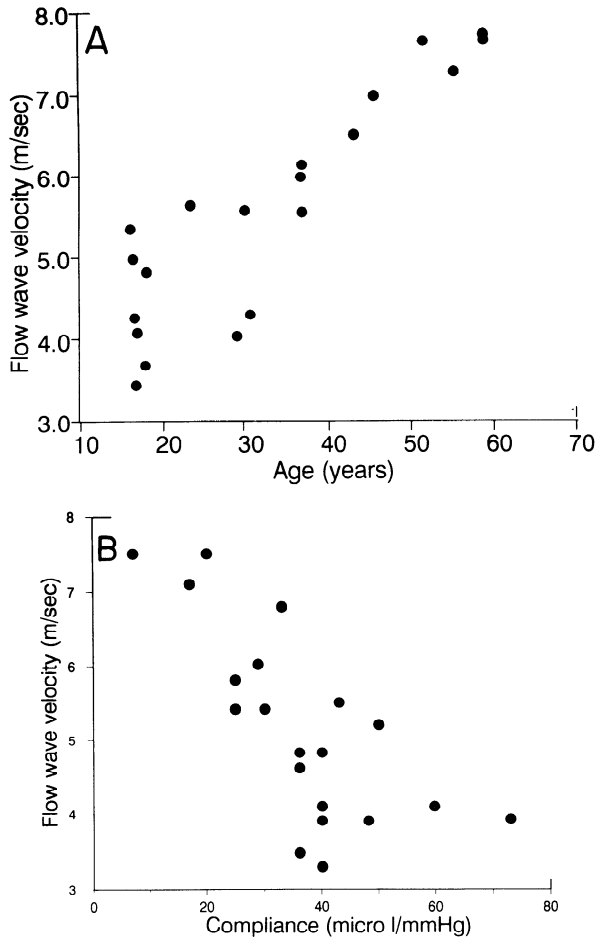

FIG. 5. *A*: flow wave velocity is directly related to age. $y = 0.77x + 2.94$. SEE = 0.101; $t = 7.7$; $r = 0.87$; $P = 0.0001$. *B*: flow wave velocity is inversely related to regional aortic compliance. $y = -0.079x + 7.97$; SEE = 0.016; $t = -4.9$; $r = -0.75$; $P = 0.0001$.

ing flow wave forms from peripheral arteries, this technique has acoustic window limitation that makes access to central arteries more difficult.

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