Effect of age and blood pressure on aortic size and stroke distance

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SUMMARY The diameters of the ascending and descending aorta at the level of the carina were measured from computerised tomograms in 200 adults without cardiac or aortic disease. At all ages the ascending aorta had a greater cross sectional area than the descending aorta, and both areas increased significantly with age. The increase was proportionately greater in the descending than in the ascending aorta and the percentage changes were similar in males and females, the latter having a smaller mean descending aortic diameter. The extent of the increase in cross sectional area of the aorta is sufficient to explain the observed fall of stroke distance that occurs with age. The effect of changing blood pressure on aortic cross sectional area, and hence the relation between stroke distance and stroke volume, was calculated from published data on aortic compliance at different ages. Assuming constant peripheral resistance, stroke distance would change by 34, 82, and 94% for a 100% change of stroke volume at age 20, 50, and 80 respectively. At age 80 the aorta behaves like a rigid pipe but at age 20 its elasticity is such that constancy of aortic size cannot be assumed.

Volumetric cardiac output may be measured non-invasively by means of echocardiography to measure aortic diameter and Doppler ultrasound to measure aortic blood velocity.¹⁻⁴ Left ventricular stroke volume is calculated as the product of aortic cross sectional area and the systolic velocity integral or aortic blood flow. The measurement of velocity is simple and highly reproducible,⁵⁻⁷ but measurement of aortic cross sectional area is technically difficult and is the least reproducible part of the procedure.⁸⁻¹⁰ In intervention studies it would therefore be simpler to make a single measurement of aortic diameter and assume that it is constant.^{3,11} We have gone further and have suggested that the measurement may be dispensed with entirely and velocity measurements used by themselves to measure linear, as opposed to volumetric, cardiac output.^{12,13} The systolic velocity integral is then known as stroke distance and its product with heart rate as minute distance. These are analogous to stroke volume and cardiac output respectively. An aortic cross sectional area that is reasonably constant is a prerequisite for the

use of stroke distance either as an absolute measure of cardiac output or for measuring serial changes.

In normal adults peak aortic blood velocity, stroke distance, and minute distance decline with age.^{13,14} This could result from a reduction of volumetric cardiac output or an increase in aortic cross sectional area, and the relative importance of these two factors is not clear. We have therefore measured the diameters of the ascending and descending aorta in 200 adult patients in order to determine the effect of age on aortic cross sectional area and to see whether any increase in size with age is sufficient to account for the observed fall of aortic blood velocity.

In the short term, blood pressure is an obvious factor that might affect aortic size and hence aortic blood velocity. In 1937, long before Doppler ultrasound was used, Hallock and Benson studied the pressure-volume relation of segments of thoracic aortas from subjects of different ages,¹⁵ and raw data from their work are published in reference 16. From these data we have calculated the effect of changes of blood pressure on aortic blood velocity and stroke distance at different ages. In 1967, Bader published a similar though more comprehensive study using complete thoracic aortas, with a detailed statistical analysis.¹⁷ The information in his paper makes

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Fig. 1 A computerised tomogram of the chest showing the horizontal level of the carina.

Fig. 2 Computerised tomogram of the chest at the level of the carina looking cephalad. The bifurcation of the trachea is seen posterior to cursor 2. The external diameter of the ascending aorta is obtained from the distance between the cursors which mark its anterior and posterior boundaries. The descending aorta is seen to the left of the patient's spine.

Fig. 3 Representative pressure-volume curves for the thoracic aorta at various ages, redrawn from Bader.¹

possible the computation of the general relations between age, blood pressure, and aortic blood velocity.

In this paper, blood pressure measured *in vivo* refers to the mean pressure during ejection, and has a value intermediate between systolic and mean blood pressure.

Patients and methods

MEASUREMENT OF AORTIC DIAMETERS

A retrospective examination was undertaken of computerised tomograms of the chest from 200 consecutive patients aged 20–82, most of whom had been referred for the investigation of malignancy. Tomograms from patients in whom tumour masses caused distortion of the aortic anatomy were rejected, as were data from those with known hypertension or congenital or valvar cardiac disease. The images were taken in full inspiration with a scan speed of approximately 10 s and a slice thickness of 12 mm. The horizontal cut at the level of the carina was selected (Fig. 1), because the carina provided an easily recognisable and anatomically reliable landmark. Figure 2 shows a typical image at this level. We used electronic callipers to measure the external diameters of the ascending and descending aorta to the nearest millimetre and we calculated the cross sectional areas by assuming the cross sections to be circular.

EFFECT OF BLOOD PRESSURE ON AORTIC VOLUME

Bader constructed pressure-volume curves from 27 whole human thoracic aortas from subjects aged 22–85 years.¹⁷ Figure 3 shows six representative curves that have been redrawn. Hallock and Benson studied the pressure-volume relation in 18 thoracic aorta segments from subjects aged 20–78,¹⁵ and mean volumes at 10 pressures in five age groups are given.¹⁶ The general appearance of the curves is similar to that in Fig. 3.

Results

AORTIC CROSS SECTIONAL AREA

Mean (SD) cross sectional areas of the ascending and descending aorta are given in the Table. In most

Table Mean (SD) cross sectional area (cm^2) of ascending and descending aorta in men and women. Areas have been calculated from external diameters, and values at ages 20 and 80 have been obtained from the regression equations given in the text

	Men	Women	All
No	133	67	200
Mean age	58.8 (13.7)	58.7 (13.4)	58.8 (13.6)
Cross sectional area of ascending aorta			
Age 20	5.71 (1.59)	5.30 (2.41)	5.57 (1.84)
Age 80	11.44 (1.55)	11.32 (2.32)	11.40 (1.82)
Mean	9.41 (2.01)	9.18 (2.61)	9.33 (2.23)
Cross sectional area of descending aorta			
Age 20	3.21 (1.23)	2.16 (1.40)	2.86 (1.31)
Age 80	7.40 (1.20)	6.73 (1.34)	7.17 (1.29)
Mean	5.92 (1.52)	5.10 (1.64)	5.64 (1.61)

Fig. 4 Cross sectional area of ascending aorta at various ages. The regression line is shown together with its 95% confidence limits.

cases the ascending aorta was larger than the descending aorta, the mean ratio of the two areas being 1.7. Both sections of the aorta were larger in males than in females. Cross sectional areas of both the ascending and descending aorta increased with age ($r=0.59$, $p<0.001$ and $r=0.61$, $p<0.001$), the regression equations being respectively $y=3.63+0.097x$, and $y=1.42+0.072x$ (Figs. 4 and 5). Between the ages of 20 and 80 the ascending aorta increased in area by 105% and the descending aorta increased by 151%.

Fig. 5 Cross sectional area of descending aorta at various ages. The regression line is shown together with its 95% confidence limits.

Fig. 6 Calculated effect of mean blood pressure on cross sectional area of thoracic aorta in various age groups, raw data from Hallock and Benson.^{15 16}

EFFECT OF BLOOD PRESSURE ON AORTIC CROSS SECTIONAL AREA—DATA FROM HALLOCK AND BENSON^{15 16}

When an increasing transmural pressure difference causes an elastic tube to expand, it increases in length (l) as well as in cross sectional area (CSA). If the percentage increase in radius equals the per-

Fig. 7 Calculated effect of mean blood pressure on stroke distance in various age groups, raw data from Hallock and Benson.^{15 16}

Fig. 8 Calculated effect of concomitant change of mean blood pressure and stroke volume on stroke distance with constant peripheral resistance in various age groups. On the abscissa 100% represents a mean blood pressure of 100 mm Hg. Raw data from Hallock and Benson.^{15 16}

centage increase in length then:

$$\delta \text{ volume } \%^{2/3} = \delta \text{ CSA } \%$$

In an elastic tube, however, the longitudinal wall stress is half the tangential wall stress, and in the human aorta the tangential elastic modulus (E_t) is 1.2 times the longitudinal elastic modulus (E_l).¹⁷ Therefore,

$$(1 + \delta) \text{ volume} = \pi (r(1 + \delta))^2 \times l(1 + 0.6 (\delta))$$

We used this equation in an iterative computer method to apportion the increase in volume between cross sectional area and length. Figure 6 shows the calculated effect of blood pressure on cross sectional area. The inflection in the curves is less marked than that in the pressure-volume curves seen in Fig. 3. The cross sectional area at zero pressure increases with age, but at high pressure, except for those from the 71-78 age group, the younger aortas are more distensible and there is a negative relation between age and cross sectional area.

Assuming a flat velocity profile:

$$\text{Stroke volume} = \text{CSA} \times \text{stroke distance} \quad (1)$$

Hence, stroke distance is proportional to the reciprocal of cross sectional area, enabling the effect of blood pressure on stroke distance to be calculated, as shown in Fig. 7. There is a steep rise in stroke distance corresponding to the rapid fall of cross sectional area at low pressures. This occurred at about 125 mm Hg in the youngest group (age 20-24), 100

mm Hg in the middle aged, and 50 mm Hg in the group aged 71-78.

It would be an unusual clinical situation for blood pressure to alter widely without an accompanying change of cardiac output, so Fig. 8 shows the calculated effect on stroke distance of variation of both blood pressure and stroke volume. A constant value of peripheral resistance is assumed, with 100% on the abscissa representing a mean blood pressure of 100 mm Hg and a stroke volume of 100%, and 50% indicating that both variables are halved in value. There is a virtual straight line relation between stroke volume and stroke distance in the oldest age group, with the aorta behaving like a rigid pipe. In the middle age groups there is displacement of the curves upwards but they then run approximately parallel to the line of the oldest group. In the youngest age group there is a pronounced inflection below 100 mm Hg, whereas above this pressure the relation is approximately linear, though with a less steep slope than that in the older age groups.

GENERAL RELATION BETWEEN AGE, BLOOD PRESSURE, CROSS SECTIONAL AREA, AND STROKE DISTANCE—DATA FROM BADER¹⁷

The volume of the aorta at zero pressure rises with age (A) as the internal radius (R_0) and length (l) increase. The regression equation for the internal radius at zero pressure is:

$$R_0 = 5 + 0.064 \times A \quad (2)$$

As pressure rises there is a rapid increase of volume until an inflection is reached when the slope of the curve lessens. The pressure (P_i) at the point of inflection is given by

$$P_i = 106 - 32 \times A$$

which means that $P_i = 0$ and the inflection disappears at about the age of 80.

The percentage increase in aortic volume at a pressure of 100 mm Hg compared with the volume at zero pressure is given by

$$\delta \text{ volume } \% = 234 - 2.27 \times A \quad (3)$$

From (2) and (3) the radius at a pressure of 100 mm Hg (R_{100}) is calculated by iteration as before. Tangential stress in the aortic wall at pressure P is

$$S = 0.04 \times P - 0.00035 \times A \times P + 0.01 \times A - 0.9 \quad (4)$$

and when $P = 100$ mm Hg

$$S_{100} = 3.1 - 0.025 \times A \quad (5)$$

The tangential elastic modulus for pressures around 100 mm Hg is given by

$$E_t = A/2 \quad (6)$$

The radius at pressure P is

$$R_P = R_{100} + (S - S_{100}) \times R_{100}/E_t \quad (7)$$

Fig. 9 Computer plot of effect of mean blood pressure on stroke distance at various ages. Raw data from Bader.¹⁷ Compare with Fig. 7.

Hence, using (1) and (4-7), aortic cross sectional area and stroke distance may be calculated for any age, mean blood pressure, and cardiac output. The prediction becomes less reliable as the pressure departs from 100 mm Hg because the simple relation between E_t and age only holds exactly at that

Fig. 10 Computer plot of effect of concomitant change of mean blood pressure and stroke volume on stroke distance with constant peripheral resistance. On the abscissa 100% represents a mean blood pressure of 100 mm Hg. Raw data from Bader.¹⁷ Compare with Fig. 8.

Fig. 11 The effect of age on the slope of the relation between stroke distance and stroke volume, measured at a mean blood pressure of 100 mm Hg and assuming constant peripheral resistance.

pressure.

Assuming constant stroke volume, the predicted relation between mean blood pressure and stroke distance for blood pressures between 0 and 225 mm Hg and ages 20-80 is seen in Fig. 9, which is essentially similar to that observed in Fig. 7.

In Fig. 10 constant peripheral resistance is assumed and the relation between stroke volume and stroke distance is predicted for the same range of blood pressures and ages. The overall pattern is very similar to that observed in Fig. 8 and the anomalous relation between stroke volume and stroke distance at age 20 is shown in both figures. As age rises the relation becomes more linear and the slope at a mean blood pressure of 100 mm Hg increases, until at age 80 it is 94%. At this age the aorta behaves as an almost rigid pipe, and a change of stroke volume of 100% would be reflected in a change of blood velocity of 94%. At lower ages, when the aorta is more distensible, the slope is reduced, reaching its lowest value of 34% at age 20. Figure 11 shows the effect of age on the slope of the relation between stroke distance and stroke volume, measured at a mean blood pressure of 100 mm Hg and assuming constant peripheral resistance.

Discussion

EFFECT OF AGE ON AORTIC CROSS SECTIONAL AREA

In the arch of the aorta, blood velocity and the mea-

surements derived from it decrease with age.¹⁴⁻¹⁸ From their respective regression equations against age it may be estimated that at age 80, peak aortic blood velocity, stroke distance, and minute distance are 47, 39, and 47% of their values at age 20. This could result from reduction of volumetric cardiac output or an increase in aortic cross sectional area. In this paper we show that between the ages of 20 and 80 the cross sectional areas of the ascending and descending aorta increase by 105% and 151% respectively. In the arch of the aorta, roughly midway between these sites, the increase of cross sectional area may be estimated to have an intermediate value of 128%. Since there is no reason to believe that there is any major change in the thickness of the aortic wall with age, the percentage increase in cross sectional area of the lumen is almost certainly greater than this estimate which is based on measurement of external aortic diameters. If the aortic wall thickness is assumed to be 1.5 mm at all ages, then the increase in the area of the lumen of the arch is about 156%, sufficient to cause a fall of stroke distance to 39% of its initial value, which is exactly the fall observed.

From the regression equation given by Bader for the radius of the descending aorta at different ages, the increase in cross sectional area between age 20-80 is 159%, close to the value of 151% that we obtained.

Strehler and Schmid describe a nomogram for prediction of the external diameter of the aortic knuckle measured from a chest x ray,¹⁹ but the number of measurements on which it is based is not given. At age 58, the mean age of our series, the predicted cross sectional area midway between ascending and descending aortic sections is 7.8 cm² compared with our estimate of 7.4 cm². The nomogram predicts an increase of cross sectional area of 101% between the ages of 20 and 80, somewhat less than the value of 128% that we estimated for this site.

Furakawa *et al* measured the diameter of the aortic root in 130 patients by angiography and echocardiography.²⁰ Though they show an increase in diameter with age, details of the regression are not given, but the cross sectional area of the aortic root appears to increase by about 74% between ages 20-80.

There is therefore good evidence that in adults aortic size increases with age; the more proximal the measurement the less the increase. Aortic blood velocity measured in the proximal aorta would therefore be expected to be less age dependent than in the arch or descending aorta. Hatle and Angelsen reported maximal velocities in the ascending aorta in 30 normal children aged 1-16 and in 40 adults aged

18-72.²¹ Although they comment that in adults velocities were lower in older patients, no details are given. Wilson *et al* report modal peak velocity measurements from the ascending and descending aorta in 110 normal subjects age 14 days to 35 years (mean 11.6 years).²² There was no significant relation at either site between velocity and age, but this is probably because there were too few adults in the series. In the aortic arch, the decline in velocity with age is only recognisable after the age of 20, and in our data did not achieve statistical significance in adults under 35.¹⁴ Peak aortic blood velocity and stroke distance are remarkably constant throughout childhood.²³

An alternative mechanism for the reduction of aortic blood velocity with age is a fall of volumetric cardiac output. Support for this is given by Brandfonbrener *et al* who measured cardiac output by dye dilution in 67 men aged 19-86.²⁴ There was a very highly significant reduction of cardiac output with age so that the value at age 80 was 53% of that at age 20. A series of 17 patients studied by Cournand *et al* showed a similar rate of fall of cardiac output with age, though the regression was not significant.²⁵ In 111 subjects in whom cardiac output was measured by the now discredited acetylene method there was a significant decline of cardiac output with age.²⁶ If indeed there is reduction of volumetric cardiac output as well as dilatation of the aorta with age, the question posed is not why aortic blood velocity falls, but rather why it does not fall more than has been observed.

If stroke and minute distance are to be useful absolute measures of cardiac output, allowance must be made for the increase of aortic cross sectional area with age. This may be done quite simply by establishing the normal range of measurements at different ages, enabling comparisons to be adjusted for age.¹³

ELASTICITY OF AORTA

Greenfield and Patel studied the dynamic relation between pressure and diameter in the ascending aorta in 10 patients aged 14-55 (mean 28) undergoing operation.²⁷ The mean circumferential extensibility was 0.19%/1 mm Hg pressure change. A rise of pressure from 67 to 133 mm Hg would result in a 27% increase in cross sectional area, corresponding closely to the value of 30% that we predict for age 30. There is therefore a close agreement between prediction based on the static measurements by Bader and the observed dynamic measurements of Greenfield and Patel, though in the small number of patients that they studied the expected influence of age on circumferential extensibility did not achieve statistical significance ($r = -0.51$, NS). Static and

dynamic elastic moduli are similar in vessels such as the aorta that owe their elasticity predominantly to elastin and collagen and do not have an important muscular component.²⁸ Thus, the theoretical relations between age, mean blood pressure, and stroke distance shown in Fig. 10 are matched by the static pressure-volume measurements of Hallock and Benson from which Fig. 8 is derived, and the dynamic measurements of Greenfield and Patel.

If serial stroke distance measurements are to be used to detect changes of volumetric cardiac output then a linear relation between them is desirable. An approximately linear relation between stroke distance and stroke volume is predicted for all ages above 30, and even at age 20 the departure from exact linearity would have little practical importance. More disadvantageous to this method of measurement is the buffering effect of the highly elastic aorta at age 20, so that only 34% of a change of stroke volume is reflected in a change of stroke distance, reducing the ability of the method to detect a change of flow rate. There are, however, two mitigating points. At age 20, mean blood pressure is normally about 90 mm Hg and at this pressure the curve is somewhat steeper, and it is steeper still in the clinically important region where blood pressure is below normal. Secondly, this degree of flattening of the slope relating stroke distance and stroke volume assumes constant peripheral resistance and therefore a proportionate fall of mean blood pressure and cardiac output. In reality, blood pressure is likely to fall less than cardiac output because the former is under tighter homeostatic control than the latter.²⁹

In an artificial circulation that included a pig aorta we showed that the graph of minute distance against blood flow rate had a slope of 84%, which was comparable to that predicted in humans at age 50.⁷ Besides the slope of the relation between stroke distance and stroke volume, the ability of Doppler measurement of blood velocity to detect a change of flow rate depends on the reproducibility of the measurement.³⁰ In this respect the method performed as well as the best thermodilution equipment tested, and the overall performance in vitro was comparable despite the adverse effect on the elasticity of the aorta.

CONCLUSIONS

For stroke distance to be a useful measure of cardiac output, aortic cross sectional area must be reasonably constant, or else change in a predictable way. The most important factors affecting aortic size in adults are age and blood pressure. The cross sectional area of the aorta more than doubles between the ages of 20 and 80, and this is sufficient to explain the observed fall of stroke distance with age which

necessitates adjustment of the results for age. At age 20, the elasticity of the aorta causes considerable dampening of the blood velocity change resulting from a change of cardiac output if there is concomitant alteration of mean blood pressure. Above this age, elasticity is less and change of aortic size with blood pressure does not constitute a major problem.

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