The relation between the aortic diameter and the intravascular pressure has been studied by several workers in intact experimental animals and in the isolated human aorta. However, no simultaneous direct measurements of the instantaneous aortic diameter and pressure in the living human subject are available. This information would be important for the following reasons: (1) It is possible to measure the instantaneous blood velocity in the intact human aorta by the pressure gradient technique. However, in order to compute the phasic blood flow, a knowledge of the vessel diameter at every instant in the cardiac cycle is needed. If a simple relation can be established between pressure and diameter, then the intravascular pressure may be used to predict the vessel diameter. (2) The mathematics describing pulsatile flow in blood vessels is strongly influenced by the motions and geometry of vascular-fluid boundaries. Some idea of these boundary conditions can be obtained from measuring the diameter continuously during the cardiac cycle. (3) Finally, an estimate of the elastic behavior of the vessel wall can be obtained from the pressure-diameter relationship.

The relation between the pressure and the diameter of the aorta must be evaluated in a living subject, since these measurements are altered significantly by death of the patient or excision of the vessel. Therefore, the purpose of this investigation was to measure simultaneously the lateral intravascular pressure and the diameter in the ascending aorta of man.

Methods

The study was carried out in 10 patients undergoing open-heart surgery. The clinical information describing these patients is listed in table 1. Preanesthetic medications included meperidine (25 to 75 mg.), scopoline (0.1 to 0.4 mg.), and promethazine (15 to 50 mg.). After intravenous thioental induction, all patients were maintained under light general anesthesia with nitrous oxide, oxygen, and a muscle relaxant, either succinylcholine or d-tubocurarine. The surgical approach to the heart was through a midsternal incision which exposed the ascending aorta. This study was carried out immediately after the pericardium was opened and before the cardiac surgery was performed so as not to disturb grossly the normal tethering of the aorta.

Changes in the aortic diameter were estimated with an electrical strain-gauge caliper, shown in figure 1. The legs of the caliper were sutured to the wall of the aorta as near to the true diameter of the vessel as possible. Displacement of one leg of the caliper with respect to the other results in a proportional change in electrical resistance of the strain gauges. The characteristics of this instrument have been described elsewhere and are felt to be adequate for the purpose of this study. The caliper was connected to a Sanborn no. 350 strain-gauge amplifier. The calibration of the instrument against known increments of displacement was essentially linear for the range of displacements encountered.

Lateral intravascular pressure was measured directly under the caliper using a short beveled 22-gauge needle connected directly to a Statham P23Db strain gauge (fig. 1). The frequency response of the pressure recording system was uniform (± 5 per cent) to 20 c.p.s. Recording of data was carried out on an Electronics-for-Medicine eight-channel optical recorder. In two patients, following control studies, an intravenous dose of 1.0 μg. of l-norepinephrine was given and the pressure and diameter recorded.

In evaluating the data of each patient, the mean value of 10 consecutive pressure and diameter complexes was used. For convenience, all measurements of diameter were converted to radius. The values of the greatest change in radius (ΔR) and the pulse pressure (ΔP) were obtained, and the ratio (ΔR/ΔP) calculated. Circumferential extensibility was calculated by the following formula:

$$\text{circumferential extensibility} = \frac{\Delta R \times 100}{R_d \times \Delta P} \%$$

where $R_d$ is the diastolic radius. The per cent...
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FIGURE 1

Drawing of the ascending aorta, showing the caliper (b.) sutured to the diameter of the vessel, and the pressure transducer (a.) in place.

change in aortic area during a cardiac cycle was also calculated.

Results

The results are listed in table 1. The mean value for $\Delta R/\Delta P \times 10^3$ was 1.82 cm. per cm. H$_2$O (± S.D. 0.80 ± S.E.M. 0.30). The mean value for circumferential extensibility was 0.14 per cent per cm. H$_2$O (± S.D. 0.06 ± S.E.M. 0.02). The maximum change in aortic area during systole ranged from 5.4 to 16.8 per cent of the diastolic value, and the mean value was 11 per cent. In general, the cir-

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FIGURE 2

Curve of lateral pressure and radius obtained during the control state and following administration of 1.0 μg. of l-norepinephrine.

FIGURE 3

Comparison of the radial wall velocity with a typical blood velocity curve obtained in a normal man by the pressure gradient technique.
cumferential extensibility decreased with a rise in the mean aortic pressure. In two patients, the injection of 1.0 µg of L-norepinephrine was followed by an increase in the pressure and the diastolic radius and a decrease in the circumferential extensibility. No definite relation was found between the age, height, or weight of the patients and either the circumferential extensibility or AR/ΔP. An 11 per cent change in cross sectional area of the aorta during systole was greater than has been previously estimated by angiographic techniques. The change in cross sectional area of the ascending aorta during systole was greater than has been previously estimated by angiographic techniques. It is of note that the value for the change in cross sectional area of about 11 per cent was more consistent than either circumferential extensibility or AR/ΔP. An 11 per cent change in cross sectional area during a cardiac cycle appears to be of sufficient magnitude that for certain applications, such as a mathematical treatment of the pulsatile flow, the assumption that the aorta behaves as a rigid tube must be accepted with reservations.

In figure 2, both pressure and radius curves in the control state and following 1.0 µg of L-norepinephrine are shown. The time derivative of a radius curve computed numerically is shown in figure 3. In this figure, a typical aortic blood velocity curve is also included for comparison.

**Discussion**

In general, the configuration of the lateral intravascular pressure and radius curves in the ascending aorta are similar, but (fig. 2) differences can be noted which are probably related to the tethering of the vessel, the longitudinal transmitted stress, and to the inertial and viscous properties of the vessel wall. However, this dissimilarity is not enough to negate the use of the expression ΔR/ΔP to estimate change in radius during a cardiac cycle in a given subject. Unfortunately, the values for ΔR/ΔP were too widely scattered to justify the use of the mean value of ΔR/ΔP to predict instantaneous changes in diameter from the pressure curve. Also, from the data presented, no indirect method of computing the diastolic radius of the aorta could be formulated.

The change in cross sectional area of the ascending aorta during systole was greater than has been previously estimated by angiographic techniques. It is of note that the value for the change in cross sectional area of about 11 per cent was more consistent than either circumferential extensibility or ΔR/ΔP. An 11 per cent change in cross sectional area during a cardiac cycle appears to be of sufficient magnitude that for certain applications, such as a mathematical treatment of the pulsatile flow, the assumption that the aorta behaves as a rigid tube must be accepted with reservations.

In figure 3, the time derivative of a radius curve representing radial wall velocity is compared to a typical blood velocity curve ob-

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**Table 1**

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Weight (Kg.)</th>
<th>Height (cm.)</th>
<th>Age (years)</th>
<th>Condition</th>
<th>Diagnosis*</th>
<th>Diastolic pressure (mm Hg)</th>
<th>Mean pressure (mm Hg)</th>
<th>Systolic pressure (mm Hg)</th>
<th>AR/AP</th>
<th>ΔR/ΔP</th>
<th>ΔR/ΔP</th>
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<td>ASD</td>
<td>206/117</td>
<td>147</td>
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<td>0.56</td>
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<td>46.8</td>
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<td>TOF</td>
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<td>101</td>
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<td>0.159</td>
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<td>AS</td>
<td>178/135</td>
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<td>1.26</td>
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</tr>
</tbody>
</table>

*Abbreviations used in the diagnosis column are: ASD = atrial septal defect; TOF = tetralogy of Fallot; AS = aortic stenosis; AM = atrial myxoma; VSD = ventricular septal defect.

†Abbreviations used in the condition column are: C = control; NE = L-norepinephrine.

Circ. ext. = Circumferential extensibility.
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obtained from a normal subject by the pressure gradient technique. As can be seen, the velocity of blood flow is quite large when compared to the vessel wall velocity.

The elasticity of the vessel wall was expressed by the circumferential extensibility. Although this is a small series, it is of interest that no relation between the age of the patient and the circumferential extensibility was found. In the studies of Hallock and Benson on the isolated aorta, a definite decrease in elasticity of the vessel with age was shown. In general, the circumferential extensibility did decrease as the pressure increased. In the two patients in which l-norepinephrine was administered, the circumferential extensibility decreased markedly. This effect may have been due to increasing pressure and/or to a direct effect of the drug on the vessel wall.

Summary

The pressure-diameter relationship in the ascending aorta of man was estimated directly in 10 patients undergoing open-heart surgery. The diameter was measured by means of an electrical strain-gauge caliper sutured to the vessel wall. The lateral intra-vascular pressure was measured using a 22-gauge needle connected directly to a Statham P23Db strain gauge. The results indicate: (1) a gross similarity between the pressure and diameter curves; (2) the mean value for ratio of change in radius to change in pressure (ΔR/ΔP) was $1.82 \times 10^{-3}$ cm. per cm. H$_2$O (± S.D. 0.80); (3) the mean value for circumferential extensibility was 0.14 per cent change in radius per cm. H$_2$O (± S.D. 0.06); and (4) the change in cross sectional area during an average cardiac cycle was 11 per cent of the diastolic value.

Acknowledgment

The authors wish to express their gratitude to the surgical staff of the National Heart Institute, particularly to Drs. Andrew O. Morrow, Joseph W. Gilbert, Nina S. Braunwald, J. Roland Folsa, James L. Talbert, and Paul A. Ebert, without whose cooperation this study would not have been possible.

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Relation Between Pressure and Diameter in the Ascending Aorta of Man
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Circ Res. 1962;10:778-781
doi: 10.1161/01.RES.10.5.778
Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

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