The Growth of the Normal Aorta and of the Anastomotic Site in Infants Following Surgical Resection of Coarctation of the Aorta


Observations were made on the growth of the anastomotic site 2 to 4 years after surgical resection of coarctation of the aorta in 5 infants who were less than 2 years of age at the time of surgery. Aortic measurements were made from biplane angiocardiograms. The physiologic adequacy of the anastomotic site was demonstrated by absence of a gradient in direct pressure measurements between the upper and lower extremities. Additional observations on the normal growth of the descending thoracic aorta were made from studies in 154 subjects with other forms of heart disease. They ranged in age from 2 days to 74 years.

In 1945 a major milestone in the development of cardiovascular surgery was reached when Crafoord and Gross independently demonstrated that it was possible to correct coarctation of the aorta in human subjects. Since that time aortic resection for this condition has become one of the least hazardous of present day cardiovascular surgical endeavors. Although a number of brilliant studies concerning the physiologic effects of aortic block, the technic of repair, the choice of suture material, and the growth of the anastomotic site have furthered considerably our knowledge of this condition, certain problems continue to exist.

Of particular importance in the selection of candidates for surgery is the question of growth of the suture line following aortic anastomosis. The many divergent views expressed in the literature concerning the optimal age for operative intervention attest to the significance of this issue. Although this question has been studied extensively in animals, the hazards of extrapolating information obtained from animal observations are well known. This risk is especially true of problems relating to coarctation of the aorta, since, depending upon the species of animal, an appreciable difference may exist in the rate of body growth, the ultimate body size, the development of collateral circulation, the degree of vascular fragility, and the pressure in the aorta.

![Diagram showing the actual diameter (A) at the anastomotic site as opposed to the "expected diameter," (B).](image)

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GROWTH OF NORMAL AORTA

FIG. 2. Relationship of aortic diameter to age for 3 types of physiologic abnormalities. No difference is apparent.

FIG. 3. Relationship of aortic diameter to age. A straight line fitted to these points has the formula

\[ d = 3.5 (t + 8) .31 \]

where \( d \) is the aortic diameter in millimeters and \( t \) is the age in months.

FIG. 4A. Case 1. Anteroposterior and lateral angiograms after surgery.

FIG. 4B. Anteroposterior and lateral diameters of the aorta in the region of the anastomosis.

MATERIAL AND METHODS

As a prerequisite for the critical interpretation of observations on the growth of the anastomotic site following resection of the coarctation, a pre-
liminary investigation was undertaken in which the growth of the descending aorta from birth to maturity was determined. This phase of the study consisted of recording measurements of the aortic diameter as projected on angiocardiograms in 154 patients ranging from 2 days to 74 years of age. The majority had some type of cardiovascular disorder, either congenital or acquired. The angiocardiography was of the high-speed biplane type, allowing visualization of the aorta in 2 planes as well as during both systole and diastole. However, since blood vessels are normally tubular in configuration, the diameter in only 1 plane was measured. Correction was made for distortion due to x-ray tube distance with the use of the ratio of the actual and projected size of the cardiac catheter as a basis. In each case the measurement was made with a Vernier caliper to the nearest millimeter at the level of the diaphragm.

The diaphragm was chosen as the level of measurement primarily because it offered a reasonably constant anatomic site. Also, it was believed that at this distance from the heart the influence of cardiac disease upon the size of the thoracic aorta would be minimal. This hypothesis was tested by classifying the patients into 3 groups, in each of which a different physiologic effect upon the size of the aorta might have been exerted: right-to-left cardiac shunt, left-to-right cardiac shunt, and no cardiac shunt. The presence or absence of a shunt was established in all cases by cardiac catheterization.

The second phase of the study consisted of observations in 5 infants who had been treated surgically for coarctation of the aorta. Operation had been performed early in life because of cardiac failure or pronounced cardiomegaly. Their ages at the time of surgery ranged from 18 days to 22 months. In each case the ductus arteriosus was observed to be patent. Its mouth was located opposite the site of constriction in 2 patients (cases 2 and 3), distal to it in 2 (cases 1 and 4), and proximal to it in 1 (case 5). Aortic obstruction was limited in all subjects to the area distal to the left subclavian artery. The operation routinely consisted of aortic resection and end-to-end anastomosis with 5-0 silk suture material. The vessel ends were approximated by a continuous suture in 2 of the patients (cases 1 and 5) and an interrupted suture in 3 (cases 2, 3, and 4).

\*Surgery was performed by Dr. J. V. Maloney, Jr. (cases 1, 2, and 4), Dr. W. H. Muller, Jr. (case 5), and Dr. William P. Longmire, Jr. (case 3).
GROWTH OF NORMAL AORTA

All of the infants were re-evaluated approximately 2 to 4 years postoperatively. The studies at that time consisted principally of right heart catheterization, intrabrachial and intrafemoral pressure determinations, and high-speed biplane, selective angiocardiography. These were carried out with the patient in a state of basal anesthesia. The peripheral blood pressures were measured by surgically exposing a brachial and femoral artery and cannulating them with a no. 20 hypodermic needle. Two P23D Statham strain gages were used, and the impulses were recorded simultaneously by an Offner multichannel direct recorder. The measurements of the aortic lumen were made in the same manner as previously described for the normal studies. However, for this portion of the study both the anteroposterior and lateral diameters were measured, since the cylindrical form of the vessel had been altered by the effects of surgery. The average of the 2 values obtained at any given location was accepted as the inner diame- ter of the aorta at that particular level. Measurements were made at half centimeter inter-

vals along the entire thoracic length of the descending portion of the vessel. By correlating the angiocardiogram with the electrocardiogram, satisfactory diameter determinations could be made during diastole as well as during systole in 2 of the patients.

The growth of the anastomotic ring was evaluated by comparing its measured diameter to the so-called “expected diameter.” The latter was estimated by measuring the distance between 2 peripheral lines drawn from a point 1 cm. above the suture site to a point 1 cm. below (fig. 1). This estimate was assumed to represent the maximum intraluminal diameter that could be expected under the most favorable conditions.

RESULTS

Growth of the Descending Aorta. The aortic diameter during systole was demonstrated to be, on the average, 1.3 mm. greater than that during diastole. Therefore only the systolic measurements were analyzed. Statistical study revealed that aortic growth correlated better with age or surface area than with weight, and that surface area was slightly superior to age. However, the difference between the latter 2 was so small that, for all practical purposes, either could be used. Therefore the more familiar index of age was selected.

The influence of cardiac disease upon the diameter of the aorta at the level of the diaphragm is demonstrated in figure 2. The lack of uniformity of the relative course of the 3
curves indicates that there is no appreciable effect. The relationship of the diameter to age, irrespective, then, of cardiovascular abnormality, is presented in figure 3. In view of the foregoing, this curve may be assumed to represent the growth curve of the aorta in normal individuals. The growth curve is represented very closely by a straight line when time is computed from birth minus 8 months and both time and aortic diameter are expressed in logarithmic units. The equation for this relationship is \( d = 3.5(t + 8)^{0.31} \) where \( d \) represents the aortic diameter in millimeters and \( t \) is the age in months. This equation permits a reasonably accurate derivation of the inner diameter of the aorta at the diaphragm for any desired age.* In fact, only 5 per cent of the 154 observed cases deviated more than 45 per cent above or 30 per cent below the diameters derived, which are shown in table 1. It is to be noted that the rate of aortic growth decreases progressively with increasing age.

_Growth of the Suture Line Following Aortic Resection._ The angiocardiograms made in the 5 postoperative patients are reproduced in figures 4 to 8. All show evidence of poststenotic dilatation and 4 demonstrate a clearly detectable constriction at the anastomotic site, suggesting that varying degrees of growth deficit did occur. The extent of these aberrations is presented graphically for each patient. Figure 9 shows the behavior of the anastomotic ring in relation to the growth of each patient as measured by surface area. A deficiency in growth at the suture line occurred in all but 1 patient; however, the lack of a constant relationship between the anastomotic ring and body size supports the contention that the aortic diameter at the anastomotic site does not remain stationary. Additional

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*The extreme right point plotted in figure 3 is somewhat arbitrarily located at 400 months and represents all patients over the age of 15 years.
Evidence for this conclusion is the finding in the 2 patients (cases 4 and 5) that the diameter was 1 mm. larger in systole than in diastole, indicating that the anastomotic ring is distensible. In table 2 the degree of growth retardation is quantitatively expressed as the percentage of the "expected diameter"; in no case was this less than 55 per cent.

**Hemodynamic Effects of Various Degrees of Aortic Obstruction.** Results of the physiologic studies made in the 5 surgically treated infants are presented in table 3. In the 4 in whom comparative measurements were made of blood pressures of upper and lower extremities, the relationships were normal. An incidental finding was the presence of pulmonary hypertension, which occurred in various degrees of severity in 4 patients. The 1 patient in whom it was most pronounced was discovered to have an interventricular septal defect.

The pulse propagation times and the brachial and femoral intra-arterial pressure ratios are presented in table 3. These figures were well enough within the normal range to preclude functional obstruction of the aorta. The values in the table representing the normal range were compiled from data published by other investigators.7, 11-13, 65, 66
TABLE 1.—Computed Average Normal Diameter of the Aorta at the Level of the Diaphragm for Various Ages

<table>
<thead>
<tr>
<th>Age (yrs.)</th>
<th>Diameter (mm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birth</td>
<td>6.8</td>
</tr>
<tr>
<td>1/12</td>
<td>6.9</td>
</tr>
<tr>
<td>2/12</td>
<td>7.2</td>
</tr>
<tr>
<td>3/12</td>
<td>7.4</td>
</tr>
<tr>
<td>4/12</td>
<td>7.6</td>
</tr>
<tr>
<td>5/12</td>
<td>7.8</td>
</tr>
<tr>
<td>6/12</td>
<td>8.1</td>
</tr>
<tr>
<td>7/12</td>
<td>8.3</td>
</tr>
<tr>
<td>8/12</td>
<td>8.3</td>
</tr>
<tr>
<td>9/12</td>
<td>8.5</td>
</tr>
<tr>
<td>10/12</td>
<td>8.7</td>
</tr>
<tr>
<td>11/12</td>
<td>8.9</td>
</tr>
<tr>
<td>1</td>
<td>8.9</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
</tr>
<tr>
<td>3</td>
<td>11.5</td>
</tr>
<tr>
<td>4</td>
<td>12.3</td>
</tr>
<tr>
<td>5</td>
<td>13.2</td>
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<tr>
<td>6</td>
<td>13.8</td>
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<td>7</td>
<td>14.4</td>
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<tr>
<td>8</td>
<td>15.1</td>
</tr>
<tr>
<td>9</td>
<td>15.5</td>
</tr>
<tr>
<td>10</td>
<td>15.8</td>
</tr>
<tr>
<td>11</td>
<td>16.6</td>
</tr>
<tr>
<td>12</td>
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<td>13</td>
<td>17.4</td>
</tr>
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<td>14</td>
<td>17.8</td>
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<tr>
<td>15</td>
<td>17.8</td>
</tr>
<tr>
<td>Over 15</td>
<td>20.9</td>
</tr>
</tbody>
</table>

TABLE 2.—Diameter Measurements and Estimated Growth of the Suture Line Following Aortic Resection and End-to-End Anastomosis

<table>
<thead>
<tr>
<th>Case</th>
<th>Age at surgery (mos.)</th>
<th>Interval since surgery (mos.)</th>
<th>Diameter at suture line (mm.)</th>
<th>Expected diameter (mm.)</th>
<th>Growth attained*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>22</td>
<td>11.5</td>
<td>11.5</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>30</td>
<td>8.0</td>
<td>9.5</td>
<td>84</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>23</td>
<td>5.5</td>
<td>7.5</td>
<td>73</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>21</td>
<td>5.5</td>
<td>10.0</td>
<td>55</td>
</tr>
<tr>
<td>5</td>
<td>1/2</td>
<td>49</td>
<td>5.5</td>
<td>10.0</td>
<td>55</td>
</tr>
</tbody>
</table>

*Expressed as percentage of expected diameter.

DISCUSSION

The observations reported here suggest that growth of the suture line following aortic anastomosis in infants is frequently deficient. However, the data also indicate that the anastomotic ring is readily distensible and therefore probably capable of future growth. It is probable, then, that the suture site does not remain absolutely stationary. Experimental evidence recorded in the literature favors this view.29, 30, 33, 35

Results of the present study permit some interesting speculation concerning the optimal age for surgery. It was found, for example, that from birth to maturity the diameter of the descending aorta undergoes about a 3-fold increase. The growth increment proceeds at a more rapid rate earlier in life than later, so that at 3 years of age the diameter is about 55 per cent of that in an adult. It has

TABLE 3.—Postoperative Hemodynamic Data in Five Patients Following Surgery

<table>
<thead>
<tr>
<th>Case</th>
<th>Age at surgery (mos.)</th>
<th>Months since surgery</th>
<th>Blood pressure (mm. Hg)</th>
<th>Ratio femoral : brachial Systolic pressure</th>
<th>Delay in onset of femoral pulse (sec.)</th>
<th>Build-up time of femoral pulse (sec.)</th>
<th>Evidence of shunt</th>
<th>Pulmonary hypertension (mm. Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>22</td>
<td>121/80</td>
<td>1.02</td>
<td>1.14</td>
<td>0.0</td>
<td>0.13</td>
<td>+75/17</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>30</td>
<td>100/65</td>
<td>1.02</td>
<td>1.14</td>
<td>0.0</td>
<td>0.16</td>
<td>+36/21</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>23</td>
<td>120/93</td>
<td>1.03</td>
<td>1.78</td>
<td>0.01</td>
<td>0.16</td>
<td>+42/18</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>21</td>
<td>129/66</td>
<td>1.00</td>
<td>0.79</td>
<td>0.0</td>
<td>0.16</td>
<td>+50/25</td>
</tr>
<tr>
<td>5</td>
<td>1/2</td>
<td>49</td>
<td>94/64</td>
<td>1.02</td>
<td>1.07</td>
<td>0.0</td>
<td>0.14</td>
<td>—</td>
</tr>
</tbody>
</table>

Range of normal 0.91-1.06 0.82-1.20 —0.01+0.02 0.13-0.18

*Interval between onset of upstroke of brachial pulse and onset of upstroke of femoral pulse wave.
†Interventricular septal defect.
been demonstrated in dogs that the passage of blood through a stenotic orifice is not interfered with unless the intraluminal diameter is reduced to about 50 per cent. That this figure probably applies to man also is suggested by the absence of physiologic evidence of aortic obstruction in our studies, even though the diameter was reduced to 55 per cent of the “expected diameter.” On the basis of these limited observations, then, it would appear that after 3 years of age the risk is indeed slight of recurrence of aortic constriction of a significant degree. The earlier the anastomosis is performed prior to this age the greater is the amount of aortic growth that is required to ensure an adequate lumen. Even at the age of 1 month, however, retardation of future growth would have to exceed 65 per cent to result in a physiologically significant obstruction.

In deriving these conclusions, 2 basic principles are taken for granted: that the surgeon completely excise the constricted area and that the lumen of the vessel not be compressed in creating the anastomosis. The significance of these prerequisites is reflected in the data presented in figure 10. The patient was an infant who at the age of 2 weeks had been treated surgically for coarctation of the aorta with excellent clinical results. At the time

**Fig. 10.** Aortogram and aortic blood pressure withdrawal tracing obtained in an 8-week-old infant who had been treated surgically at the age of 2 weeks for coarctation of the aorta. The patient had a significant degree of anatomic and physiologic obstruction, suggesting that the aortic lumen had not been completely restored at surgery.
of restudy, however, only 6 weeks later, the anastomotic diameter was but 35 per cent of the "expected diameter" and there was physiologic evidence of severe aortic obstruction. The aortic lumen obviously had not been completely restored at the time of surgery.

The demonstration of an elevated pulmonary artery pressure in 4 of the 5 subjects studied postoperatively merits some discussion. Only 1 of these patients had an associated malformation that could account for this finding. Although the occasional development of pulmonary hypertension in patients with coarctation of the aorta and a patent ductus arteriosus is well known,18, 60, 61, 68-71 no studies have been reported concerning its fate following surgical correction of the underlying abnormalities. It is of considerable interest as well as of some concern that we found pulmonary hypertension of some degree as long as 2 to 3 years after operation.

**Summary**

Observations were made in 5 infants on the growth of the anastomotic site approximately 2 to 4 years after surgical correction of coarctation of the aorta. At the time of surgery, 4 patients were under 9 months of age, the youngest being 18 days and the oldest being 22 months. Observations were also made on 154 subjects from 2 days to 74 years of age to establish the average normal growth of the descending aorta. Systolic and diastolic measurements were made from biplane angiograms in both groups. In the postoperative patients the physiologic adequacy of the suture site was determined by intra-arterial blood pressure and pulse measurements.

These studies demonstrate that from birth to maturity the diameter of the aorta at the level of the diaphragm increases about 3-fold. At 3 years of age it is about 55 per cent that of an adult. In the subjects studied postoperatively, anatomic stenosis of the aorta occurred in 4, but no physiologic obstruction could be demonstrated.

Since physiologic obstruction was not apparent with an aortic diameter of 55 per cent of the expected normal and since the average diameter in children 3 years of age is about 55 per cent that of an adult, it was concluded that anastomoses performed at this age should remain functionally patent regardless of future growth. Even if surgery were performed at 1 month of age, retardation of growth would have to exceed 65 per cent to result in a physiologically significant obstruction.

**Summario in Interlingua**

Esseva facite observationes in 5 infantes con respecto al crescencia del sito anastomotic aproximativamente 2 a 4 annos post le correccion chirurgic de coarctation del aorta. Al tempore del operation, 4 del patientes habeva minus que 9 menses de etate. Le etate del plus juveme esseva 18 dies, illo del plus avantiate 22 menses. Esseva etiam facite observaciones in 154 subjectos de etates de inter 2 dies e 74 annos pro establir le normal crescentia medie del aorta descendente. Mesurationes systolic e diastolic esseva facite ab angiocardiogrammas biplan in ambe gruppos. In le patientes postoperatori, le adequatia physiologic del suturas esseva determinate per mesurationes del pulso e del tension de sanguine intra-arterial.

Iste studios demonstra que ab le nascentia usque al maturitate le diametro del aorta al nivello del diaphragma es augmentate circa tripemente. Al etate de 3 annos, illo es circa 55 pro cento de illo de un adulto. Inter le subjectos studiate post le operation, 4 monstrava stenosis anatomic del aorta, sed nulle obstruction physiologic poteva esser identificate.

Viste que nulle obstruction physiologic esseva apparente quando le diametro aortic amontava a solmente 55 pro cento del expec- tate valor normal e viste que le diametro medie in juveniles de 3 annos de etate es circa 55 pro cento de illo trovate in adultos il esseva concludite que anastomoses effectu ate a iste etate remane functionalmente pa- tente, sin reguardo al crescentia futur. Mesmo si le operation es effectuate al etate de 1 mense, le retardation dei crescentia futur debe exceder 65 pro cento pro resultar in un obstruction de signification physiologic.
REFERENCES
29. Hurwitt, E. S., and Altman, S. F.: Obser-


Pre-Harveian Doubts of Galenic Doctrine

In the course of his description and after remarking that the right ventricle of the heart transmits its blood to the left ventricle, he adds, "not through the middle wall of the heart, as is commonly believed, but by a very ingenious arrangement . . . by a long course through the lungs." This, Servetus remarks, represents "a truth which was unknown to Galen." This statement is correct if by it we understand Servetus to refer merely to a difference in emphasis, since Galen had, in fact, presented the fundamental information necessary for the discovery and description. Here let us remember that Servetus has revealed himself as a confirmed and literal student of Galen.—CHARLES D. O'MALLEY. The Complementary Careers of Michael Servetus: Theologian and Physician. History of Medicine and Allied Sciences. 8: 387, 1953.
The Growth of the Normal Aorta and of the Anastomotic Site in Infants Following Surgical Resection of Coarctation of the Aorta

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