Growth of the Aortic Anastomosis, Annulus, and Root After the Arterial Switch Procedure Performed in Infancy

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Background. We investigated the size and growth potential of the neoaortic root and aortic anastomosis after the arterial switch operation (ASO) for D-transposition of the great arteries (D-TGA) performed in infants. Circumferential suture lines connecting the great arteries and extensive surgery on the arterial roots to transplant the coronary arteries are essential parts of the ASO. However, little is known about the growth of the aortic anastomosis, the neoaortic root, and the neoaortic annulus after the ASO performed in infancy.

Methods and Results. Serial echocardiograms on 50 patients with D-TGA who underwent ASO in infancy at our institution were reviewed, and the size of the aortic anastomosis, the neoaortic root, and the neoaortic annulus were compared with similar structures in a group of 312 control subjects. Before surgery, the native pulmonary root (future neoaortic root) was 1.59 SD larger (P<.001) and the native pulmonary annulus (future neoaortic annulus) was 1.4 SD larger (P<.001) in infants with D-TGA than the aortic root and annulus of control patients. At a mean of 22 months (12 months to 6½ years) after surgery, the diameter of the aorta at the anastomosis was 0.45 SD smaller than the ascending aorta of control subjects (P<.001). The neoaortic root was 2.9 SD larger (P<.001) and the neoaortic annulus was 1.6 SD larger (P<.001) than the comparable structures in the control population. Most important, growth of the aortic anastomosis was commensurate with somatic growth, but the dilation of the neoaortic root appeared to be progressive over time. The neoaortic root was significantly more dilated in patients with a history of pulmonary artery banding (P<.001) and in patients with neoaortic regurgitation (P<.001). The presence of a ventricular septal defect was not significantly related to postoperative neoaortic root size.

Conclusions. This study underlines the importance of continued acquisition and examination of the data regarding the long-term outcome of the arterial switch operation performed in infancy. (Circulation 1993;88:615-620)

KEY WORDS • arterial switch operation • transposition • anastomosis, aortic • neoaortic root

At many institutions, the arterial switch operation (ASO) is now the surgical procedure of choice for infants with D-transposition of the great arteries (D-TGA).1-4 This operation involves transection and reanastomosis of both great arteries above the sinuses of Valsalva and transplantation of the coronary arteries. After the ASO, the pulmonary valve and root function in the systemic circulation. The long-term success of this operation depends partly upon adequate growth of the circumferential anastomoses of the great arteries and the capability of the native pulmonary valve and root to function in the systemic circulation.

We used echocardiography to investigate the aortic anastomosis, neoaortic root, and neoaortic annulus in patients who underwent an ASO in infancy. Serial measurements were made of all three structures to determine growth, and the sizes of these structures were compared with those of normal control subjects.

Methods

Patients

The study population comprised all patients with D-TGA who underwent an ASO at Children's Hospital, Boston, before 6 months of age between January 1983 and December 1989 and who had two or more postoperative echocardiograms at least 12 months apart as of December 1989. Patients in whom the echocardiographic images of the aortic anastomosis were inadequate for measurement were excluded.

The control population consisted of 312 normal patients who had undergone an echocardiogram at Boston Children's Hospital between June of 1986 and February of 1991 in whom acquired and congenital heart disease had been excluded.

Data Collection

Echocardiograms were performed with a phased-array sector scanner (Hewlett-Packard 77020 or Acuson 128) with either a 3.5- or 5.0-MHz transducer and were

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recorded on half-inch videotape. Height and weight were recorded at the time of each echocardiogram, and body surface area (BSA) was calculated using the formula of Haycock.5

One author (M.H.) reviewed one preoperative echocardiogram and two to five serial postoperative echocardiograms for each patient. Still frames were printed of images of the native pulmonary annulus and the native pulmonary root on the preoperative studies and the aortic annomosis, the neo-aortic annulus, and the neoaortic root from each postoperative echocardiogram. These images were taken from the parasternal long-axis view whenever possible. When images from this view were inadequate, the subxiphoid long-axis view was used. The images were taken as close to midsystole as possible.

The internal diameter of the aortic annomosis was measured at the suture line when it was obvious and just above the aortic root if the suture line was no longer evident (Fig 1). The internal diameter of the arterial root was measured at the widest point in the sinuses of Valsalva, and the diameter of the valve annulus was measured at the hinge points of the valve leaflets.

The most recent echocardiogram on each patient was reviewed to quantify the degree of neoaortic regurgitation (neo-AR). A four-point scale based on the proximal width of the regurgitant jet on Doppler color flow mapping was used (0 mm, absent; 1 to 3 mm, mild; 4 to 6 mm, moderate; >6 mm, severe). The echocardiograms of the control population were also reviewed by one author (U.M.), and the diameter of the aortic annulus, aortic root, and ascending aorta were measured using a similar technique.

To assess interobserver variability, a random sample of 9% of the echocardiograms was reviewed and measurements were made by a second author (S.P.S.). These measurements were compared with those made by the first reviewer.

When image quality permitted, measurements were made from both the parasternal long-axis and the subxiphoid long-axis views for comparison.

Data Analysis

To account for growth-related changes in the size of cardiac structures, all echocardiographic measurements are expressed as Z scores relative to the normal population. The normal relation between each variable and BSA was determined in the control population; then, the position of each measurement for the study patients was determined within the normal distribution and expressed as a Z score (normal deviate6), or number of standard deviations from the expected normal mean value, where the mean and standard deviation are BSA dependent. Thus, a measurement at the expected nor-
mal mean for BSA has a Z score of 0, and measurements at the upper and lower 95% confidence limits have Z scores of 1.96 and −1.96, respectively.

The mean Z score for each structure measured before surgery (native pulmonary root and annulus) and each structure measured after surgery (neoaortic root, annulus, and anastomosis) was compared with zero using a single-sample t test.

One-way ANOVA was used to determine the relation between the Z scores and the presence or absence of a ventricular septal defect (VSD), the amount of neo-AR present on the most recent echocardiogram, and a history of pulmonary artery banding (PAB).

As an index of growth, the rate of change in Z score per year was calculated for each structure. To determine statistical significance, these rates of change were compared with zero using a single-sample t test. For illustration purposes, growth of the three structures was also calculated as δdiameter/ΔBSA.

The measurements made by two reviewers were compared using linear regression analysis, as were the measurements made from subxiphoid and parasternal images. For all statistical analyses, a value of P < .05 was considered significant.

Results

Patients

Of the 309 patients who underwent ASO at our institution during the study period, 50 patients met the inclusion criteria for this study. The mean age at ASO was 32 days, and the median age was 8 days. The male to female ratio was 2.3 to 1. Thirty-two patients had an intact ventricular septum and underwent an ASO as the primary surgical procedure. Fifteen patients had a VSD that was repaired surgically at the time of ASO. Six patients underwent PAB before the ASO. In three cases, the band was placed to "prepare" a left ventricle functioning at low pressure for an ASO. The band was left in place an average of 14 days before ASO. PAB was performed as palliation in three patients with transposition of the great arteries and a large VSD and remained in place an average of 87 days before ASO. Three patients underwent surgical repair of coarctation of the aorta.

The control population comprised 312 subjects, age 1 week to 19 years (172 male subjects, 140 female subjects), with BSA of 0.2 m² to 2.11 m².

Of the 50 study patients, 44 had preoperative studies from this institution available for review. One study did not have adequate image quality for measurements. Therefore, 43 of the 50 study patients had preoperative echocardiograms reviewed and measurements made. Preoperative echocardiograms were performed at a mean age of 24 days and a median age of 4 days. Preoperative measurements were available of the native pulmonary valve annulus in 43 patients and of the native pulmonary root in 41 patients.

One hundred thirty-two postoperative echocardiograms were reviewed on these 50 patients. In 8 of these 132 studies, the image quality was not adequate for measurements. Therefore, 124 postoperative echocardiograms provided measurements for the study population. Postoperative echocardiograms were performed between 1 day and 6½ years after the ASO at a mean of 22 months after surgery.

Serial postoperative measurements of the aortic anastomosis were available in all 50 study patients, of the aortic root in 35, and of the aortic annulus in 29. Of the 312 control patients, 215 had measurements made of the aortic annulus, 185 of the aortic root, and 141 of the proximal ascending aorta.

Preoperative Studies

Annulus. The mean Z score for the native pulmonary annulus diameter before surgery was 1.4, indicating that in patients with D-TGA at a median age of 4 days, the mean diameter of the native pulmonary annulus (the future neoaortic annulus) was 1.4 SD larger than the mean native aortic annulus diameter in normal subjects. This difference is highly significant (P < .0001) and represents a 21%, or, on average, a 1.6-mm difference. The Z score for the pulmonary annulus diameter among patients with a VSD (Z = 2.3) was significantly larger (P = .01) than the Z score among patients with no VSD (Z = 0.94). In both groups, the annulus was significantly larger than the native aortic annulus in the control population.

Root. The mean Z score for the preoperative pulmonary root diameter was 1.59, showing that in patients with D-TGA at a median age of 4 days, the mean diameter of the native pulmonary root (future neoaortic root) was 1.59 SD larger than the native aortic root diameter in normal subjects. This difference was also highly significant (P < .0001) and represents on average a 25%, or 2.3-mm difference in size. The Z scores for the preoperative root measurements were not significantly related to the presence or absence of a VSD.

Postoperative Studies

Fig 2 demonstrates the relation between the size of the three structures studied after surgery and the square root of the BSA in the study and control populations.

Anastomosis. The mean Z score for the aortic anastomosis in the study population was −0.45, indicating that the anastomosis after ASO was smaller than the normal ascending aorta. Although this difference was highly significant (P < .0001), the average difference in diameter was only 16%, or 2 mm.

Annulus. The mean Z score for the neoaortic annulus in the ASO patients was 1.6, indicating that the neoaortic annulus after ASO was significantly larger (P < .0001) than the aortic annulus in control subjects. This represents an average difference in diameter of 7 mm, or 50%.

Root. The mean Z score for the neoaortic root in the ASO patients was 2.9, indicating that the neoaortic root after ASO was significantly larger than the aortic root in control subjects (P < .0001). This represents an average difference in diameter of 16 mm, or 90%.

Pulmonary artery band. The mean Z score for the neoaortic annulus in patients with no history of PAB (Z = 1.7) was significantly larger (P = .002) than the Z score for the neoaortic annulus in patients who had undergone prior PAB (Z = −0.7). The neoaortic annulus was significantly larger than the aortic annulus of control subjects only in patients with no history of PAB.
The mean Z score for the neoaortic root in the patients with no history of PAB (Z = 2.7) was significantly smaller (P = .0003) than the mean Z score for the neoaortic root in patients with a history of PAB (Z = 4.5). The neoaortic root in both groups was significantly larger than the aortic root of the control group. The Z scores for the measurement of the aortic anastomosis were not related to a history of PAB.

**Neoaortic regurgitation.** Thirty-three of the 50 study patients (66%) had no neo-AR on the most recent echocardiogram, 16 (32%) had mild regurgitation, 1 (2%) had moderate regurgitation, and no patient had severe regurgitation. Therefore, reliable statistical comparisons could only be made between those with no neo-AR and those with mild neo-AR.

The mean Z score for the aortic anastomosis measurement in patients with mild neo-AR (Z = −0.07) was significantly larger (P = .0015) than the mean Z score for the aortic anastomosis in patients with no neo-AR (Z = −0.77). The aortic anastomosis was significantly smaller than the ascending aorta of control subjects only in patients with no neo-AR.

The mean Z score for the neoaortic root in patients with mild neo-AR (Z = 3.3) was also significantly larger (P = .023) than the mean Z score for the neoaortic root in patients with no neo-AR (Z = 2.6). The neoaortic root was significantly larger than the native aortic root of control subjects in both groups. The Z scores for the neoaortic annulus diameter were not related to the presence of neo-AR.

**Ventricular septal defect.** The Z scores for none of the postoperative measurements were related significantly to a history of VSD.

**Growth.** The rate of change in size for the aortic anastomosis was 0.29 ± 1.45 SD per year; for the neoaortic root, 0.58 ± 1.12 SD per year; and for the neoaortic annulus, 0.22 ± 1.05 SD per year (Fig 3). All three structures tended to increase in size in excess of that expected for normal somatic growth, although this was statistically significant only for the aortic root (P = .002). The rates of change in Z scores for all three structures were unrelated to neo-AR or the presence of VSD before surgery.

**Measurement Variability**

The interobserver variability was low for all measurements. The values obtained by the two observers were

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**Figure 2.** Scatterplots: Postoperative measurements of the aortic anastomosis (graph A), the neoaortic annulus (graph B), and the neoaortic root (graph C) are plotted vs the square root of body surface area (BSA). The solid line and small dashed lines represent the mean and 95% confidence intervals, respectively, for the study patients. The large dashed line and shaded area represent the mean and 95% confidence intervals, respectively, for comparable structures in the control population. Patients with a ventricular septal defect (VSD) are shown as open circles, patients with intact ventricular septum (IVS) as open squares, and patients with a pulmonary artery band (PAB) as solid squares.

**Figure 3.** Plot of growth rate of the neoaortic annulus and root and of the aortic anastomosis after the arterial switch operation shown in relation to somatic growth and expressed as increment in diameter per increment in the square root of body surface area (BSA). Open circles indicate growth rates for individual patients with ventricular septal defect; open squares, patients with intact ventricular septum; solid squares, patients with pulmonary artery band. Solid circles and vertical bars indicate group mean and standard deviation, respectively. Horizontal bars represent the mean growth rate for the control population.
highly correlated \((r=.94)\), with a standard error of the estimate of 1.9 mm. The measurements made from the parasternal long-axis view and those made from the subxiphoid long-axis view were also highly correlated \((r=.94)\), with a standard error of the estimate of 1.4 mm.

**Discussion**

**Aortic Anastomosis**

Although the diameter of the aortic anastomosis in our patients was statistically smaller than the diameter of the ascending aorta in the control population, the absolute difference in size was small (2 mm, or 16% of the lumen diameter). Previous studies in patients with coarctation of the aorta indicate that a reduction in lumen diameter of at least 50% is required to create a pressure gradient.\(^9\) Therefore, the difference in diameter that we found at the anastomosis is unlikely to be of physiological significance. More important, we did find that the size of the anastomosis increased with time since repair at a rate commensurate with somatic growth.

Our data on the aortic anastomosis are in contrast to those of Arensman et al.,\(^9\) who reported an angiographic study in 25 patients that demonstrated no significant difference between the size of the aortic anastomosis in patients after ASO and the ascending aorta of control subjects at a mean of 18.8 months after surgery. However, all of the patients in that study were 9 months of age or older at the time of surgery and all either had a large VSD or aorticopulmonary window or had undergone PAB. To our knowledge, there are no other reports of the size and growth of the aortic anastomosis after primary ASO performed in infants.

Long-term follow-up of infants and children who have undergone repair of coarctation of the aorta\(^10\) and experimental data in animals\(^11-13\) suggest that circumferential anastomoses do not always grow normally. On this basis, many have voiced concern about the growth potential of the aortic anastomosis created in the ASO.\(^14-16\) Our data are reassuring regarding the growth of the aortic anastomosis created during the ASO performed in infancy. However, the longer-term growth potential of this anastomosis after ASO remains to be determined and warrants continued study.

**Neoaortic Root and Annulus**

The dilation of the neoaortic root and annulus in our patients before and after ASO was surprising. Before ASO, the native pulmonary root and annulus (future neoaortic root and annulus) were significantly larger in patients with transposition of the great arteries than the native aortic root and annulus in infants of comparable size with normally related great arteries. After ASO, the dilation of the neoaortic root and annulus persisted at a mean of 22 months (range, 12 months to 61/2 years) after surgery.

Our study also indicates that the dilation of the neoaortic root after ASO is progressive, whereas the dilation of the neoaortic annulus is not. It is difficult to postulate a cause for this isolated progressive root dilation. One possibility is that manipulations unique to this root during the ASO, such as the reimplantation of coronary arteries, somehow predispose the root to progressive dilation over time. Another possibility is a structural difference between the walls of the two arterial roots. Sievers et al.\(^17\) have reported fragmentation and shortening of the elastic fibers in the pulmonary root after banding in preparation for ASO. The progressive root dilation is not due to excess influence from the patients with VSD because the rate of growth of the neoaortic root did not differ significantly between patients with VSD and those with an intact ventricular septum.

Prior reports have not found the native pulmonary root to be dilated before banding or ASO\(^18-19\), but have documented dilation after banding.\(^9,17,18\) and after ASO.\(^17,18\) All of the patients in these reports were older at the time of ASO (mean age >2 years) and all either had a large VSD or aorticopulmonary window or had undergone PAB. In contrast to our data, prior reports of aortic root growth,\(^9,17,18\) have not indicated progression of the root dilation, although data are available in fewer than 20 patients, most of whom had undergone PAB. Klautz et al.\(^19\) reported findings similar to ours regarding aortic root growth in 11 or 12 patients, some with VSD and some with an intact septum, with surgery performed in the neonatal period. Other investigators reporting follow-up of primary ASO performed in infants did not find aortic root dilation,\(^20,21\) but root dimensions and the method used to determine root size were not presented.

**Neoaortic Regurgitation**

Although the number of study patients with neo-AR was small (17 of 50) and the degree of regurgitation was only mild in all except one patient, neo-AR was significantly related to the diameter of the neoaortic root. Whether this valvar regurgitation is a cause or an effect of the dilated root and whether it is progressive with time is unclear and also warrants further study. Several recent series have demonstrated a significant incidence of neo-AR in patients after ASO.\(^22-29\) Our results support the concerns about the native pulmonary valve in the systemic circulation and emphasize the need for continuing follow-up to determine if mild neo-AR will be progressive.

**Pulmonary Artery Banding**

The number of patients in our study with a history of PAB before ASO was small, and although the effects were statistically significant, it is difficult to draw any firm conclusions regarding the effect of this procedure on the growth of the neoaortic root or annulus. One could postulate that annulus diameter is primarily a function of flow volume across the orifice, whereas root size is more related to wall tension and shear forces acting on the walls. By reducing pulmonary blood flow, PAB limits annulus diameter. However, the increased wall tension proximal to the band could lead to root dilation. The fact that before ASO, the native pulmonary annulus diameter but not the root diameter was influenced by the presence or absence of a VSD supports this hypothesis.

**Summary**

It is reassuring that growth of the aortic anastomosis after ASO in infancy is commensurate with somatic growth and that a nearly normal ascending aortic diameter is attained. However, the implications of our find-
ings of significantly dilated neoaortic root and annulus after ASO, even in patients with intact ventricular septum operated on in infancy, are not clear. The tendency for the neoaortic root dilatation to progress with time after repair raises some concerns and underlines the importance of continued acquisition and examination of data regarding the long-term outcome of the ASO.

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References

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