Neo-Aortic Root Dilation and Valve Regurgitation Up to 21 Years After Staged Reconstruction for Hypoplastic Left Heart Syndrome

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OBJECTIVES
We sought to assess the prevalence and progression of neo-aortic root dilation and valvar regurgitation after staged reconstruction for hypoplastic left heart syndrome (HLHS).

BACKGROUND
In HLHS, the pulmonary valve functions as the neo-aortic valve. Neo-aortic valve dysfunction has been observed after arterial switch operation and the Ross procedure.

METHODS
Patients with HLHS born before January 1995 who had the Fontan operation and had serial echocardiograms were included. Echocardiograms were reviewed preoperatively, after each surgical reconstruction, and at most recent follow-up for neo-aortic root size and severity of neo-aortic regurgitation (AR). Potential risk factors for neo-aortic valve dysfunction were assessed.

RESULTS
Fifty-three patients met inclusion criteria. Bidirectional superior cavopulmonary anastomosis as an interim procedure was performed in 39 patients (74%). Median duration of follow-up was 9.2 (range 5.1 to 21) years. During follow-up, the neo-aortic root progressively dilated out of proportion to body size over time, with 52 patients (98%) having a Z-score ≥2 at most recent follow-up. Neo-AR was present in 61% of patients at most recent follow-up, with progression over time in 26 patients (49%). However, neo-AR was more than mild in only three patients. Significantly larger neo-aortic root Z-scores were observed in patients with any degree of neo-AR at most recent follow-up. No other anatomic or clinical variables correlated with severity of neo-AR or root dilation.

CONCLUSIONS
After staged reconstruction for HLHS, neo-aortic root dilation and neo-AR progress over time. Early volume unloading does not have a beneficial impact on dilation of the neo-aortic root. These findings raise concerns about neo-aortic valve function into adulthood.

Hypoplastic left heart syndrome (HLHS) was a uniformly fatal cardiac lesion two decades ago. Since then, staged reconstructive surgery has resulted in satisfactory palliation for a growing number of patients (1–3). Improvement in surgical results for HLHS has shifted the emphasis from short- to long-term concerns with regard to performance of the right-sided structures in the systemic circulation. Right ventricular dysfunction and tricuspid regurgitation occur over time in patients with HLHS and may lead to exercise intolerance, arrhythmias, and early death (4,5). The long-term fate of the neo-aortic valve and root complex in HLHS remains unknown.

After palliative reconstruction for HLHS, the pulmonary valve functions as the systemic semilunar (neo-aortic) valve. Macroscopically, the aortic and pulmonary valves are indistinguishable at birth (6,7). By adulthood, the aortic valve develops more collagen and elastin fibers likely in response to the higher shear forces and tensile stresses imparted by systemic blood flow and vascular resistance (6–9). The supportive structures of the semilunar valves differ as well; the aortic root annulus is wedged between the left and right atrioventricular valve annuli and thick left ventricular myocardium whereas the pulmonary valve complex has only slight support from the usually thin right ventricular myocardium (9). Physiologic pulmonary regurgitation is a common echocardiographic finding in normal children, whereas any degree of aortic regurgitation (AR) is generally thought to be abnormal (10,11). These functional differences between the normal aortic and pulmonary valves raise concern about potential deterioration of the neo-aortic valve over time.

The pulmonary valve in HLHS is usually normal in function and architecture at birth (12,13); cases of bicuspid or dysplastic pulmonary valve have been reported (13–15). Previous short-term cross-sectional follow-up studies have shown that neo-AR is common in HLHS but usually not severe enough to require surgical intervention (16–20). No study has addressed progressive changes in the neo-aortic valve complex after staged reconstruction for HLHS.

The purpose of this study was to determine the preva-
ience and progression of neo-aortic root dilation and neo-AR after staged reconstruction for HLHS. We also sought to identify risk factors associated with the development of neo-aortic valve disease.

METHODS

Patients were eligible for inclusion if they were born before January 1995, had HLHS or a variant (e.g., critical aortic stenosis, unbalanced atrioventricular canal), underwent staged reconstruction culminating in a Fontan circulation, and had at least three adequate serial echocardiograms performed at our institution. Patients with a cardiac diagnosis of single left ventricle with systemic outflow obstruction or double-outlet right ventricle with mitral atresia were excluded, as were those patients with an abnormal pulmonary valve at presentation (by cross-sectional and Doppler echocardiography). Medical records were reviewed for perioperative parameters, timing of surgical procedures, interim interventions (e.g., catheter directed dilation of recurrent coarctation of the aorta), and current status.

Echocardiograms were performed using Hewlett-Packard (Andover, Massachusetts) or Acuson (Mountain-view, California) echocardiographic systems with appropriate phased-array transducers for patient size and recorded on half-inch videocassette tape. Echocardiographic studies were assessed at the following intervals: the initial preoperative study, and the first study after each surgical procedure including stage 1 palliation, bidirectional superior cavopulmonary anastomosis (BSCA), if performed, and Fontan operation. The most recent follow-up echocardiogram available was also reviewed. All measurements were made using Image Vue off-line analysis system (Allendale, New Jersey) by two concurrent observers (D.R.V. and W.V.W.) with 20% of random studies being simultaneously reviewed by a senior echocardiographer (M.S.C.).

Anatomy of neo-aortic structures. Echocardiographic assessment of neo-aortic valve size included measurements of the diameter of the pulmonary (neo-aortic) valve annulus, root, and sinotubular junction, made in the subcostal frontal or oblique view or parasternal long-axis view. Two-dimensional measurements were made during three consecutive cardiac cycles, and the average was recorded. The annulus was measured at the hinge points of the valve leaflets in midsystole, the root at the widest point in the sinuses of Valsalva and the sinotubular junction where a change in caliber of the neoaorta was seen (Fig. 1).

Assessment of neo-AR. Because the right ventricular outflow tract is different in geometry than the left, criteria for assessing the severity of AR in the normal pediatric heart could not be used. Therefore, a semiquantitative assessment was made similar to the method of Jenkins et al. (16). The width of the color jet of valve regurgitation was measured at the level of the valve with 0 mm = absent, 1 to 4 mm = mild, 5 to 6 mm = moderate, and >6 mm = severe. Hemodynamically significant neo-AR was confirmed by Doppler evidence of holodiastolic reversal in the distal thoracic descending aorta (after BSCA and Fontan operations only) (21).

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**Figure 1.** Two-dimensional echocardiographic image in parasternal long-axis view of the neo-aortic root in a 11-year-old patient with hypoplastic left heart syndrome at most recent follow-up. Diameter measurements of the valve annulus, root, and sinotubular junction are shown.
Statistical analysis. Data are presented as mean ± SD or median (range). Body surface area (BSA) was calculated from weight and height as follows: BSA = [(weight × height)/3,600]^{1/2}. Z-scores were calculated for the neo-aortic valve annulus, root, and sinotubular junction from normal echocardiographic dimensions of the aortic valve (22). On preoperative studies, the pulmonary valve Z-scores were calculated from both normal pulmonary and aortic valves (no significant differences were identified). For this study, we chose to compare the neo-aortic valve to the normal aortic valve rather than the pulmonary valve. Correlation between continuous variables (e.g., BSA, neo-aortic valve annulus, root, and sinotubular junction) was assessed by linear regression analysis. The significance of changes in Z-scores over time (differences at the four time points) was assessed by analysis of variance, with post-hoc testing using the Bonferroni correction (three comparisons for each time point) when significant differences were detected.

To assess for independent variables that correlated with dimensions of the neo-aortic valve annulus, root, and sinotubular junction, each of these measures was collapsed into a dichotomous categorical variable, with the median value of Z-score for the measure among our cohort used as the threshold for discretion. Thus, patients with neo-aortic valve annulus, root, and sinotubular junction Z-scores higher than the median for the study group were compared against those with Z-scores lower than the median. Chi-square and independent samples t test analysis were used to assess for correlation of categorical and continuous independent variables respectively, with the following outcome measures: neo-AR at most recent follow-up (primary outcome measure) and percentage of patients with a neo-aortic annulus, root, or sinotubular junction Z-score above the median for the study population. Independent variables analyzed included anatomic subtype of HLHS (aortic atresia or aortic stenosis), age at volume unloading surgery (BSCA if performed or Fontan operation if BSCA not performed), dimensions of the neo-aortic root structures, presence of neo-AR or atriointerventricular valve regurgitation at each stage of palliation, and whether a BSCA was performed. Odds ratios are presented with 95% confidence intervals.

RESULTS

Demographics. From January 1984 to December 1994, 697 patients with HLHS or variants thereof underwent stage 1 reconstruction at our institution. Of these, 53 survivors continued to follow-up at our institution and satisfied enrollment criteria for this study. Of the 53 patients, 49 (92%) had a diagnosis of HLHS, 2 had unbalanced atrioventricular canal with severe left ventricular hypoplasia (4%), and 2 had critical aortic stenosis with a failed initial attempt at biventricular repair (4%). Thirty-five patients (66%) had aortic atresia and 18 (34%) had aortic stenosis. There were 29 (55%) males and 24 (45%) females.

Eight patients (15.1%) underwent catheter-directed balloon dilation of recurrent distal arch obstruction (6 after stage 1 palliation and 2 after Fontan operation).

Patients underwent stage 1 reconstruction at a mean age of 7.3 ± 5.8 days. In 39 patients (74%), volume unloading was accomplished with BSCA and in 14 patients (26%) with “single-staged” Fontan. The patients who underwent an interim BSCA were significantly younger at volume unloading surgery than those who proceeded directly from stage 1 to Fontan (9.1 ± 5.3 months vs. 18 ± 4.8 months, p = 0.05). The median duration of follow-up ranged from 5.1 to 21.0 years (median, 9.2 years; mean, 9.8 ± 3.0 years) after stage 1 reconstruction with no significant difference between patients who underwent two-stage versus three-stage surgery.

Dimensions of the neo-aortic valve annulus, root, and sinotubular junction. Adequate preoperative echocardiographic studies were available for 47 patients; postoperative studies were available for 49 patients after stage 1 procedure, all 39 after BSCA, 51 after Fontan operation, and all 53 at most recent follow-up. Each measurement of the diameters of the neo-aortic valve annulus, root, and sinotubular junction is plotted in Figure 2. Diameters of the neo-aortic valve annulus, root, and sinotubular junction each correlated strongly with BSA and with one another by linear regression analysis. The diameters of each of these indices increased relative to normal during the course of follow-up (Fig. 2). Figure 3 shows the data converted to Z-scores for each measurement interval. On average, Z-scores were within the 95% prediction intervals for normal (−1.96 SD ≤ Z-score ≥1.96 SD) before stage 1 palliation relative to both the native pulmonary valve (data not shown) and the native aortic valve of patients with normal hearts. Over time, there were progressive and significant increases in Z-scores of all three indices out of proportion to normal growth (Fig. 3). The most profound enlargement was observed in the neo-aortic root with only one patient having a Z-score in the normal range (<2) at most recent follow-up.

The median values for neo-aortic valve annulus, root, and sinotubular junction Z-scores were 2.8, 4.7, and 2.3, respectively. Independent variables found to correlate with neo-aortic valve annulus, root, and sinotubular junction Z-scores above the median are summarized in Table 1 (because neo-AR at follow-up was analyzed as a dependent variable, as discussed below, it was not entered into this analysis as an independent variable). Patients with interim staging with BSCA had similar Z-scores for valve annulus, root, and sinotubular junction at most recent follow-up compared with those without interim staging (Table 2).

Neo-AR. The prevalence of neo-AR at each stage is shown in Figure 4. Before surgery, 26% of patients had trace-to-mild pulmonary regurgitation. By the most recent follow-up, 61% had at least mild neo-AR. Neo-AR that was more than mild in degree was rare. Overall, only three patients (6%) demonstrated moderate or greater neo-AR at any
Figure 2. The diameters of the neo-aortic valve annulus (left), root (middle), and sinotubular junction (right) are plotted against body surface area (BSA) and compared with the normal distribution (mean with 95% confidence intervals).

Figure 3. Box plots depicting the median value (middle line of box), the 25th and 75th percentiles (upper and lower boundaries of box), and 10th and 90th percentiles (upper and lower error bars) for Z-scores of the neo-aortic valve annulus (left), root (middle), and sinotubular junction (right) in the study population. Significant differences (p < 0.05) by general factorial analysis of variance with the Bonferroni correction for multiple comparisons are indicated by the following symbols: P = differs significantly from the preoperative Z-score; 1 = differs significantly from the stage 1 Z-score; 2 = differs significantly from the bidirectional superior cavopulmonary anastomosis Z-score; F = differs significantly from the Fontan Z-score.
The results of our Neo-aortic valve and root dilation.

**DISCUSSION**

Neo-aortic valve and root dilation. The results of our study show that the neo-aortic valve complex dilates out of proportion to normal growth in children and adolescents with HLHS and that this dilatation is progressive. The median Z-score for all three indices measured at most recent follow-up was significantly larger than normal controls. Although the most profound abnormal growth was seen in the neo-aortic root, the neo-aortic valve annulus and the sinotubular junction followed a similar trend of dilation with age (Fig. 3). The dilation of the neo-aortic structures was not an instantaneous phenomenon; Z-scores for the neo-aortic valve complex fell within normal range after stage 1 reconstruction. However, the mean Z-score for all three measurements was >2 after the volume unloading procedure (i.e., BSCA or Fontan) and continued to progressively dilate on the follow-up studies. The only factors that we could identify that correlated with larger Z-scores of the neo-aortic valve complex at most recent follow-up were the Z-score measurements of the corresponding structure after Fontan operation.

Early volume unloading diminishes the volume of blood that crosses the neo-aortic valve and is known to improve early survival (3,23,24) and exercise performance (25) in patients with HLHS. Although we hypothesized that patients who underwent early volume unloading surgery would have less severe dilation, no beneficial impact was seen. Moreover, patients with recurrent coarctation of the distal neo-aorta (requiring intervention) exhibited similar dilation to those with an unobstructed distal arch. Coarctation of the aorta and subsequently underwent replacement of the neo-aortic valve with a mechanical valve. No other patient had surgical intervention for neo-AR.

Patients with neo-AR had significantly higher Z-scores for the neo-aortic valve annulus, root, and sinotubular junction at most recent follow-up and post-Fontan echocardiographic examinations compared with patients without regurgitation (Table 3). Dimensions of the neo-aortic valve structures at earlier time points did not correlate with neo-AR at follow-up. In addition, patients with neo-AR detected on the post-Fontan echocardiogram were more likely to have neo-AR at follow-up (63% vs. 15%, odds ratio = 9.8 [95% confidence interval = 2.3 to 41], p = 0.001). Neo-AR before Fontan completion, however, did not correlate with regurgitation at most recent follow-up. Other variables that did not correlate with neo-AR at most recent follow-up included anatomic subtype of HLHS, whether a bidirectional superior cavopulmonary anastomosis (BSCA) was performed, age at volume unloading surgery, presence of atrioventricular valve regurgitation at each study interval, and recurrent coarctation of the aorta.

![Table 1. Independent Variables Found to Correlate With Follow-Up Neo-Aortic Valve Annulus, Root, and Sinotubular Junction Z-Scores Above the Median for This Population](image)

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Z-Score Above the Median</th>
<th>Yes</th>
<th>No</th>
<th>p Value</th>
</tr>
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<tr>
<td>Median for annulus = Z-score of 2.8</td>
<td>Post-Fontan neo-aortic valve annulus Z-score</td>
<td>3.0 ± 1.5</td>
<td>1.7 ± 0.9</td>
<td>0.002</td>
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<tr>
<td>Post-Fontan neo-aortic root Z-score</td>
<td>4.6 ± 1.4</td>
<td>3.7 ± 0.8</td>
<td>0.01</td>
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<tr>
<td>Post-Fontan neo-aortic sinotubular junction Z-score</td>
<td>2.8 ± 1.3</td>
<td>1.8 ± 1.0</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Median for root = Z-score of 4.7</td>
<td>Post-Fontan neo-aortic valve annulus Z-score</td>
<td>2.8 ± 1.6</td>
<td>1.9 ± 0.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Post-Fontan neo-aortic root Z-score</td>
<td>4.6 ± 1.4</td>
<td>3.6 ± 0.8</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Post-Fontan neo-aortic sinotubular junction Z-score</td>
<td>2.7 ± 1.4</td>
<td>1.8 ± 1.0</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Median for sinotubular junction Z-score of 2.3</td>
<td>Post-Fontan neo-aortic valve annulus Z-score</td>
<td>2.8 ± 1.5</td>
<td>1.8 ± 0.9</td>
<td>0.01</td>
</tr>
<tr>
<td>Post-Fontan neo-aortic root Z-score</td>
<td>4.6 ± 1.2</td>
<td>3.5 ± 0.9</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Post-Fontan neo-aortic sinotubular junction Z-score</td>
<td>2.9 ± 1.2</td>
<td>1.6 ± 1.0</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Post-BSCA neo-aortic valve annulus Z-score</td>
<td>2.6 ± 1.0</td>
<td>1.7 ± 0.9</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Post-BSCA neo-aortic root Z-score</td>
<td>2.7 ± 0.7</td>
<td>1.8 ± 0.8</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Post-BSCA neo-aortic sinotubular junction Z-score</td>
<td>2.5 ± 0.9</td>
<td>1.8 ± 0.8</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

BSCA = bidirectional superior cavopulmonary anastomosis.
Neo-aortic Root in HLHS

Figure 4. Bar graph depicting the percentage of patients with neo-aortic regurgitation at the various measurement intervals. Solid part of bars = moderate; dotted part of bars = mild; open part of bars = none.

The pulmonary valve functions as the neo-aortic valve after surgical intervention for several congenital heart lesions; neo-aortic root dilation has been observed after these procedures as well. Chin et al. (18) observed that the pulmonary root dilated after stage 1 palliation for HLHS and Damus-Kaye-Stansel operation for other single ventricle with pulmonic stenosis, tetralogy of Fallot, and bicuspid aortic valve. Although HLHS was not included in this histological cohort, an abnormal elastic media may contribute to the dilation seen in our patients.

The impact of neo-AR on neo-aortic root dilation was also assessed. Although our data indicates that a larger neo-aortic root Z-score after Fontan and at most recent follow-up is associated with the presence of neo-AR (Table 3), the cause and effect relationship is unknown because the study design did not allow us to determine precisely when the neo-AR developed.

The common denominator for all surgical interventions where the pulmonary valve becomes the neo-aortic valve is transection of the main pulmonary artery with the neo-aortic root subsequently at systemic pressure. Blood flow to the vessel wall is compromised as a result of this procedure. Murakami et al. (41) observed that the distensibility of the neo-aortic root decreases after arterial switch operation. They attributed this “stiffness” in part, to disruption of the vaso-vasorum blood flow after pulmonary artery transection. Ischemia from disruption of vaso-vasorum blood flow has been associated with the development of medial necrosis of the arterial wall (42) and may be a factor in the development of neo-aortic root dilation. In addition, a recent study by Niwa et al. (43) assessing arterial wall abnormalities in congenital heart disease reported that significant cystic medial necrosis is present in the aorta and pulmonary artery in a variety of heart defects, including transposition of the great arteries, single ventricle with pulmonic stenosis, tetralogy of Fallot, and bicuspid aortic valve. Although HLHS was not included in this histological cohort, an abnormal elastic media may contribute to the dilation seen in our patients.

**Neo-AR.** The majority of patients (61%) in our cohort had neo-AR at most recent follow-up. Neo-AR progressed over time, although moderate or greater neo-AR was rare (two patients) (Fig. 4). The only independent predictors of
dure for aortic valve disease (32–36). In contrast to the pattern of root dilation observed in our study, the neo-aortic root after Ross operation dilates in the immediate postoperative period, followed by a pattern of normal growth over time (32,34,35). Early neo-aortic root dilation after the Ross procedure may be explained by the acute change from pulmonary to systemic pressure (32,35,37). Heath et al. (38) showed that the pulmonary artery maintains an aortic configuration of the medial elastic tissue if pressure remains high early in life as a result of pulmonary hypertension. This phenomenon has also been observed after early pulmonary artery banding (39). Therefore, the immediate postoperative changes observed after the Ross procedure may not occur after stage 1 reconstruction or the arterial switch operation. Moreover, coronary re-implantation, which may affect neo-aortic root size in the immediate postoperative period after arterial switch and Ross procedure, is not a component of the stage 1 reconstruction for HLHS and may, in part, explain the delay in dilation seen in our population (40).

**Table 3. Independent Variables Found to Correlate With Follow-Up Neo-Aortic Regurgitation at Most Recent Follow-Up**

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Present</th>
<th>Absent</th>
<th>p Value</th>
</tr>
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<tbody>
<tr>
<td>Follow-up neo-aortic valve annulus Z-score</td>
<td>4.2 ± 2.8</td>
<td>1.9 ± 1.0</td>
<td>0.003</td>
</tr>
<tr>
<td>Follow-up neo-aortic root Z-score</td>
<td>6.0 ± 2.2</td>
<td>4.0 ± 1.0</td>
<td>0.003</td>
</tr>
<tr>
<td>Follow-up neo-aortic sinotubular junction Z-score</td>
<td>3.0 ± 1.8</td>
<td>1.5 ± 1.2</td>
<td>0.004</td>
</tr>
<tr>
<td>Post-Fontan neo-aortic valve annulus Z-score</td>
<td>3.0 ± 1.7</td>
<td>1.7 ± 0.9</td>
<td>0.01</td>
</tr>
<tr>
<td>Post-Fontan neo-aortic root Z-score</td>
<td>4.7 ± 1.2</td>
<td>3.4 ± 0.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Post-Fontan neo-aortic sinotubular junction Z-score</td>
<td>2.9 ± 1.3</td>
<td>1.6 ± 1.0</td>
<td>0.002</td>
</tr>
</tbody>
</table>
neo-AR at follow-up included larger neo-aortic root size after Fontan procedure and at most recent follow-up (Table 3). Because of the small number of patients with moderate or severe neo-AR, no predictors for this outcome could be determined. However, the potential distortion of the neo-aortic valve at the time of stage 1 reconstruction is not likely to account for the high prevalence of valve regurgitation because there was no significant progression of neo-AR from the preoperative to the post-stage 1 echocardiographic studies (Fig. 4).

Neo-AR has also been previously reported in short-term follow-up studies of patients with HLHS. Studies from the early era of color Doppler echocardiography and surgical reconstruction for HLHS reported that up to 60% of patients had mild neo-AR after stage 1 reconstruction but none required surgical intervention for the neo-aortic valve (16,18,20). Pulmonary artery banding before arterial switch operation or Damus–Kaye–Stansel operation has been associated with the development of neo-AR, likely secondary to changes in loading conditions and/or surgical distortion of the valve leaflets and root (27,44,45). Neo-AR has also been observed after the Ross procedure (33,46). Despite its prevalence, neo-AR is rarely severe enough to cause symptoms or require treatment (16,27,30,31). Although the etiology of neo-AR is unknown, diminished distensibility of the root may affect valve competency. Brewer et al. (47) observed that a rigid aortic root resulted in fatigue stress to the valve leaflets. Because trivial pulmonary regurgitation is a common finding in normal children (10), the finding of neo-AR may simply be a component of the pulmonary valve’s adaptation to the systemic circulation.

For now, at least, neo-aortic root dilation and neo-AR in the setting of HLHS have not had a major impact on outcome; however, close observation of the functional status of the neo-aortic valve into adulthood is warranted. Aortic rupture has been reported in other congenital heart defects with dilation of the ascending aorta (43). It is unclear whether patients with HLHS will be at risk for dissecting aortic aneurysm or rupture as they age. It is unknown whether medical treatment of root dilation (e.g., with beta-blockade) will have beneficial effects in the long term. Significant neo-AR in the setting of HLHS may result in right ventricular dilation and dysfunction as well as compromised coronary perfusion (in patients already at risk for coronary ischemia) (48,49). Moreover, the impact of adult diseases, such as essential hypertension and coronary vascular disease, on neo-aortic valve function after staged reconstruction for HLHS remains to be seen.

Study limitations. The retrospective cohort study design and close association of some of the variables with the era of surgical intervention prevents the determination of some risk factors, such as gradual improvement in technique with regard to neo-aortic root reconstruction, cannulation site, and type of Fontan performed. In addition, some variables that may have had an impact on the development neo-aortic root dilation and neo-AR, including systemic hypertension and medical therapy (i.e., afterload reduction), were not well documented on all patients at the established intervals. In addition, Doppler assessment of neo-AR in HLHS and other lesions remains mostly subjective; no standard method presently exists to determine severity.

Selection bias may have played a role in the findings of our study because the study cohort was small in comparison with the total cohort who underwent surgery for HLHS at our institution (many of the total cohort were followed by outside physicians). It is possible that patients followed at our institution are not similar to those followed elsewhere. Data were not available for the surviving cohort followed elsewhere regarding the prevalence and/or hemodynamic impact of neo-AR and neo-aortic root dilation. In particular, it is unknown whether neo-AR or root dilation contributes to late death after Norwood survival. However, we believe that these abnormal findings are unlikely to contribute to mortality because late death is a rare event beyond the Fontan procedure (3), when neo-AR and root dilation begin to appear.

Conclusions. The neo-aortic valve complex dilates out of proportion to normal growth after staged reconstruction for HLHS and progresses over time. Neo-AR is present in the majority of patients at most recent follow-up but is rarely more than mild. To date, valve failure has not occurred in the majority of children and adolescents with HLHS. Prospective confirmation of our findings and efforts to discover the causes of neo-aortic root dilation and neo-AR will be helpful in the long-term care of patients with HLHS.

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