JACC Vol. 26, No. 4
October 1995:1008–15

Early Changes in Ventricular Septal Defect Size and Ventricular Geometry in the Single Left Ventricle After Volume-Unloading Surgery

MARY T. DONOFRIO, MD, MARSHALL L. JACOBS, MD, WILLIAM I. NORWOOD, MD, PhD, FACC, JACK RYCHIK, MD, FACC

Philadelphia, Pennsylvania

Objectives. **This study investigated the phenomenon of, and the relation between, alterations in ventricular geometry after acute surgical volume unloading of the ventricle and the development of subaortic stenosis in patients with a single ventricle and ventricular septal defect–dependent systemic flow.**

Background. **Subaortic outflow obstruction has been observed to occur in patients with a single left ventricle after placement of a pulmonary artery band. The timing and etiology of this phenomenon are not well defined.**

Methods. **The preoperative and postoperative echocardiograms of 18 patients 14.9 ± 22.8 months old (mean ± SD) with a diagnosis of single left ventricle who underwent pulmonary artery banding or cavopulmonary connection were reviewed. Postoperative studies were performed a mean of 7.0 ± 6.5 days after operation. The ventricular septal defect diameter was measured in two orthogonal views and the area calculated using the formula for an ellipse. Interventricular septal and posterior wall thickness and left ventricular diameter and length were also measured.**

Results. **Mean ventricular septal defect area indexed to body surface area diminished by 36 ± 23% (3.1 ± 2.7 to 2.0 ± 1.8 cm^2/m^2, $p < 0.01$). Mean interventricular septal and posterior wall thickness increased significantly, and left ventricular diameter and length decreased significantly. A greater diminution in ventricular septal defect area was noted after cavopulmonary connection (41 ± 19%, $p < 0.01$) than after pulmonary artery banding (25 ± 28%, $p = 0.22$).**

Conclusions. **In the single left ventricle, diminution in ventricular septal defect size occurs early and is related to an acute alteration in ventricular geometry that accompanies the decrease in ventricular volume. Ventricular septal defect diminution was greater after volume unloading of the ventricle after cavopulmonary connection than after pulmonary artery banding.**

(J Am Coll Cardiol 1995;26:1008–15)

Subaortic obstruction may occur naturally or after surgical intervention in patients with complex congenital heart disease consisting of a single left ventricle and transposition of the great arteries. In such lesions, the pulmonary artery originates from the left ventricular chamber, and the aorta from a diminutive right ventricular outflow chamber with no atrioventricular (AV) valve inlet. In the absence of pulmonic stenosis, pulmonary blood flow is unrestricted and usually results in pulmonary overcirculation and congestive heart failure. Systemic outflow is dependent on the size of the communication between the left ventricle and the outflow chamber (i.e., ventricular septal defect or bulboventricular foramen), which, if smaller than the aortic annulus, will be restrictive to outflow. In some patients initially perceived to have a large, unrestrictive interventricular communication, obstruction at the level of the ventricular septal defect has been observed after placement of a pulmonary artery band. The timing and etiology of this phenomenon are not well established.

Freedom et al. (1–4) and others (5–9) have suggested that subaortic obstruction occurs as the ventricular septal defect orifice diminishes in size as a result of ventricular muscle hypertrophy brought about by increased afterload on the ventricle after pulmonary artery banding. We hypothesize that early diminution in ventricular septal defect size and the development of subaortic stenosis after pulmonary artery banding is a phenomenon that results from an immediate change in ventricular geometry (change in cavity dimensions and wall thickness) brought about by diminished pulmonary blood flow and diminished ventricular cavity filling, whereas changes in afterload are more likely to cause chronic hypertrophy and later progression of subaortic stenosis. Because myocardial muscle mass remains constant in the short term, any immediate decrease in ventricular filling volume produces a decrease in cavity dimensions and an increase in wall thickness, resulting in closer apposition of the internal myocardial surfaces. Contraction of the ventricular cavity and increase in myocardial wall thickness result in ventricular septal defect orifice diminution and the development of subaortic obstruction.

Changes in ventricular geometry and ventricular septal defect size should therefore be evident early after any form of

From the Divisions of Cardiology and Cardiothoracic Surgery, The Children's Hospital of Philadelphia and Departments of Pediatrics and Surgery, The University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania.

Manuscript received November 23, 1994; revised manuscript received April 28, 1995, accepted May 3, 1995.

Address for correspondence: Dr. Jack Rychik, The Non-Invasive Cardiovascular Laboratories, Division of Cardiology, The Children's Hospital of Philadelphia, 34th and Civic Center Boulevard, Philadelphia, Pennsylvania 19104.

0735-1097/95/$9.50
0735-1097(95)00241-U

volume reduction surgery, including both banding of the pulmonary artery and cavopulmonary connection. To test our hypothesis, we investigated the immediate postoperative changes that occur in ventricular cavity dimensions, ventricular wall thickness and ventricular septal defect area in the single left ventricle with transposition of the great arteries after various forms of volume reduction surgery.

Methods

Study patients. The hospital medical records as well as the data base of the Non-Invasive Cardiovascular Laboratories of the Children's Hospital of Philadelphia were searched. Infants and children with a diagnosis of L-looped, single left ventricle and transposition of the great arteries {S,L,L}, or D-looped, single left ventricle with tricuspid atresia and transposition of the great arteries {S,D,D} admitted to the Children's Hospital of Philadelphia between 1987 and 1993 for either pulmonary artery band placement, partial cavopulmonary connection (the bidirectional Glenn or hemi-Fontan operation [10]), or complete cavopulmonary connection (the Fontan operation [11]) were identified. Patients were included in the study if a two-dimensional echocardiogram was obtained before and within 1 month of surgery and if studies were of good quality such that cardiac structures could be adequately visualized in at least two orthogonal planes for measurement. Patients with greater than mild AV valve insufficiency or significant pericardial effusion were excluded.

Patient data. Eighteen patients with a single left ventricle were identified: 1) 14 had a single left ventricle {S,L,L} and either a double-inlet AV connection (n = 8) or a hypoplastic/atretic left-sided tricuspid valve (n = 6); and 2) 4 had tricuspid atresia {S,D,D}. A rudimentary right ventricular outflow chamber giving rise to the aorta and communicating with the left ventricle through a ventricular septal defect was present in all. Eleven patients initially had coexistent coarctation of the aorta or aortic arch hypoplasia. Analysis of the anatomic type of ventricular septal defect present in each patient revealed 11 muscular, 6 malalignment and 1 AV canal type.

Before volume-unloading surgery, 11 patients had other surgical procedures performed. Eight patients had early neonatal evidence of natural restriction to aortic outflow (dimensions of ventricular septal defect smaller than dimensions of aortic annulus) and therefore underwent a modified Norwood-type palliation (12). Two patients had evidence of impediment to pulmonary blood flow and had placement of a systemic to pulmonary artery shunt. Four patients had repair of coarctation of the aorta or arch augmentation.

The mean (±SD) age at volume-unloading surgery was 15 ± 23 months (median 7, range 0.1 to 84). Mean body surface area at the time of the echocardiogram was 0.38 ± 0.20 m^2. Echocardiography was performed a mean of 7.0 ± 6.5 days after operation (median 5.5, range 1 to 27). No patient received inotropic support at the time of postoperative study.

Of the 18 patients, 12 underwent cavopulmonary connection (66%) (11 hemi-Fontan, 1 primary Fontan) and 6 pulmonary artery band placement (33%). The mean age of the patients who had a cavopulmonary connection was 21.6 ± 25.5 months (median 8.9, range 5.3 to 84); mean body surface area 0.47 ± 0.19 m^2. The mean age of the patients who had placement of a pulmonary artery band was 1.4 ± 6.7 months (median 0.4, range 0.1 to 6.7); mean body surface area 0.2 ± 0.03 m^2.

Echocardiographic measurements. Two-dimensional echocardiograms obtained before and after surgical volume unloading were retrospectively reviewed. Studies were performed using either a Hewlett-Packard Sonos 1000 or Sonos 1500 unit or an Acuson 128 XP10 imaging system, using either a 3.5- or 5.0-MHz transducer where appropriate, and were recorded on 0.5-in. VHS videotape. Measurements were made using a commercially available off-line digital analysis package (Digisonics) interfaced with a Summagraphics digitizing tablet and a personal computer. Measurements were made three times, and the average was used for analysis. Interobserver variability was assayed for by repeat measurements in nine patients by two independent observers (M.D., J.R.). The following were measured in each patient before and after operation. 1) The *ventricular septal defect* was visualized in two orthogonal planes (the subcostal frontal and sagittal views) (Fig. 1), and the diameters of the orifice were measured from the side of the left ventricular surface at end-diastole. Ventricular septal defect area was calculated assuming the shape of an ellipse: A = F/2 × S/2 × pi, where F = ventricular septal defect diameter in the frontal projection; and S = ventricular septal defect diameter in the sagittal projection. Ventricular septal defect area (cm^2) was then indexed to body surface area (m^2). 2) The *left ventricular short-axis internal cavity diameter, left ventricular posterior wall thickness and interventricular septal wall thickness* were measured in the subcostal sagittal view at end-diastole. Measurements were taken at the high level of the papillary muscles. 3) The *left ventricular long-axis length* was measured in the apical four-chamber view at end-diastole. The length recorded was the maximal distance from the plane of the AV valve annulus to the apex of the heart.

Data analysis and statistics. All results are expressed as the mean value ± SD. For all tests $p < 0.05$ was considered significant. Measurements before and after operation were compared using a Wilcoxon signed-rank test. To determine whether a change in wall thickness/volume ratio occurred after operation, four indexes of the ratio of wall thickness to internal cavity dimension were recorded for each patient before and after operation (interventricular septal thickness divided by ventricular cavity short-axis diameter or long-axis length and posterior wall thickness divided by ventricular cavity short-axis diameter or long-axis length). The changes in these indexes, reflecting the geometric change of the ventricle, were correlated with the change in ventricular septal defect area. Regression analysis was used to identify a relation between the degree of geometric change and change in ventricular septal defect size.

Patients were classified into two groups according to the type of volume reduction surgery performed: pulmonary artery

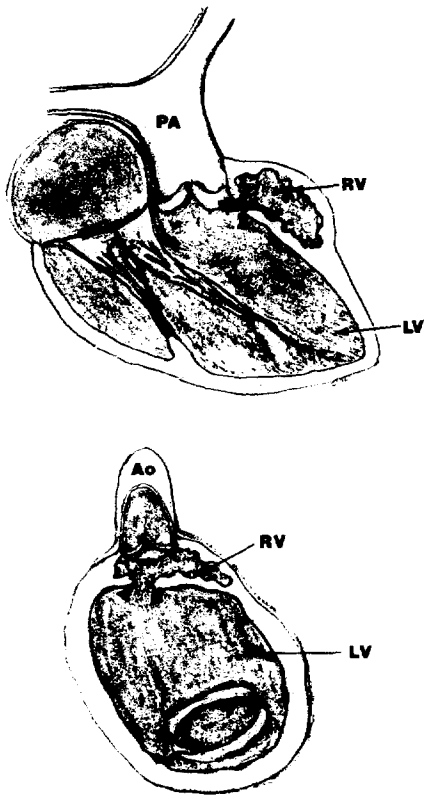


Figure 1. Schematic representation of tomographic cuts through the ventricular septal defect in the single left ventricle (LV) in two orthogonal echocardiographic planes: subcostal frontal (**top**) and sagittal (**bottom**). The aorta (Ao) is not visualized in the **top panel** but can be seen originating from the right ventricular outlet chamber (RV) in the **bottom panel. Arrowheads** indicate the borders of the ventricular septal defect. PA = pulmonary artery.

band or cavopulmonary connection (either hemi-Fontan [10] or primary Fontan [11]). Results from these subgroups were compared using the Mann-Whitney rank sum test.

Factors that potentially influence the degree of ventricular geometric change were studied. Cardiac catheterization hemodynamic variables were analyzed to determine whether a relationship exists between the ratio of pulmonary to systemic flow and the degree of change in ventricular septal defect area or ventricular geometry. The pulmonary/systemic flow ratio was calculated using oximetry and the Fick principle, where the flow ratio equals aortic saturation minus superior vena cava saturation divided by pulmonary venous saturation minus pulmonary artery saturation.

Interobserver variability was tested by performance of regression analysis to determine correlation between two observers. Intraobserver variability was tested by using analysis of variance between the measured samples for each variable.

Results

Change in ventricular septal defect area and ventricular dimensions after operation. Age, body surface area and measurements of calculated ventricular septal defect area, left ventricular posterior wall thickness, interventricular septal wall thickness, left ventricular short-axis diameter and left ventricular long-axis length for all patients before and after operation are shown in Table 1. Ventricular septal defect area diminished following surgery in all patients except for one (Patient 3) (Fig. 2). Mean percent decrement in ventricular septal defect area was 36 ± 23%, and mean ventricular septal defect area indexed to body surface area was significantly reduced

Table 1. Measurements Before and After Operation

Pt No./Op	BSA (m^2)	Age at Op (mo)	Postop Echo (days)	VSD (cm^2/m^2)		IVS (cm)		PW (cm)		LVSAd (cm)		LVLAl (cm)	
				Preop	Postop	Preop	Postop	Preop	Postop	Preop	Postop	Preop	Postop
1/PAB	0.21	0.23	9	5.57	4.44	0.27	0.49	0.35	0.50	1.84	1.66	3.26	2.98
2/PAB	0.16	0.67	3	2.08	1.59	0.40	0.43	0.40	0.45	1.71	1.41	3.05	3.04
3/PAB	0.20	0.63	5	1.65	1.98	0.43	0.46	0.48	0.49	2.04	2.49	2.43	2.47
4/PAB	0.21	6.73	4	12.02	6.92	0.51	0.57	0.63	0.63	3.22	3.19	3.49	3.10
5/PAB	0.25	0.20	27	2.65	2.14	0.37	0.50	0.44	0.54	2.25	2.15	3.86	3.87
6/PAB	0.16	0.10	20	3.30	1.23	0.35	0.36	0.30	0.38	1.44	1.21	2.64	2.68
7/Hemi	0.36	5.30	4	5.43	5.26	0.42	0.52	0.50	0.51	2.52	1.80	4.02	4.03
8/Hemi	0.77	61.00	3	1.74	0.72	1.18	1.20	1.14	1.27	3.60	3.61	6.97	5.87
9/Hemi	0.51	8.30	3	0.26	0.21	0.55	0.50	0.57	0.53	2.56	2.51	4.01	4.29
10/Hemi	0.38	8.87	6	0.85	0.60	0.54	0.56	0.57	0.60	2.84	3.07	4.26	4.14
11/Hemi	0.34	7.27	6	1.14	0.46	0.56	0.65	0.63	0.65	2.69	2.36	4.03	3.81
12/Hemi	0.37	9.00	3	5.11	2.75	0.77	0.78	0.71	0.83	2.35	1.75	4.22	3.65
13/Hemi	0.26	5.93	8	1.84	0.72	0.85	0.83	0.76	0.79	2.40	2.12	4.16	3.26
14/Hemi	0.38	9.33	7	1.43	1.01	0.72	0.71	0.70	0.68	3.09	2.85	4.46	4.25
15/Hemi	0.9	84.23	8	4.28	2.31	0.81	1.14	0.98	1.22	6.22	4.64	7.06	5.34
16/Hemi	0.45	20.00	2	1.26	0.50	0.59	0.84	0.58	0.95	2.52	1.56	4.49	4.40
17/Hemi	0.37	7.30	1	2.14	0.97	0.57	0.69	0.53	0.71	3.23	2.95	4.46	3.82
18/Font	0.59	33.00	7	3.08	2.22	0.71	0.76	0.66	0.67	2.95	2.35	4.47	4.58

BSA = body surface area; Echo = echocardiogram; Font = Fontan procedure; Hemi = hemi-Fontan procedure; IVS = interventricular septum; LVSAd = left ventricular short-axis diameter; LVLAl = left ventricular long-axis length; Op = operation; PAB = pulmonary artery band; Postop = postoperative; Preop = preoperative; Pt = patient; PW = posterior wall; VSD = ventricular septal defect.

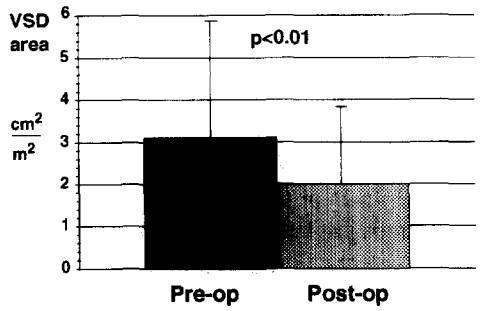


Figure 2. Ventricular septal defect (VSD) area indexed to body surface area (cm^2/m^2) before (Pre-op) and after (Post-op) volume-unloading surgery. Note the significant decrease in ventricular septal defect area. Data shown are mean value (**columns**) ± SD (**vertical bars**).

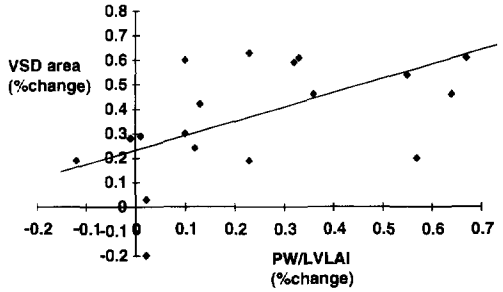


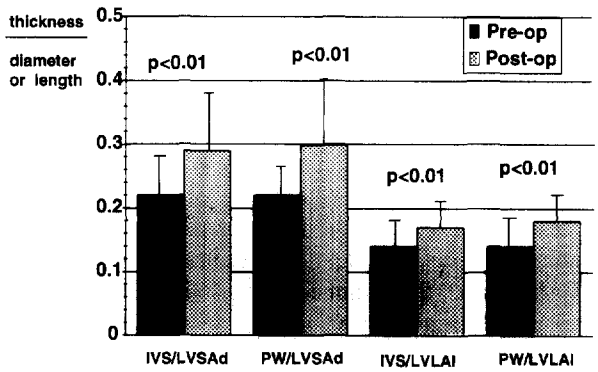
Figure 4. Percent change in ventricular geometric dimensions versus ventricular septal defect (VSD) area (cm^2/m^2) after volume-unloading surgery (r = 0.52, p = 0.03). Other abbreviations as in Figure 3. **Diamonds** = individual patient data; **diagonal line** = regression line.

from 3.1 ± 2.7 cm^2/m^2 before to 2.0 ± 1.8 cm^2/m^2 after operation ($p < 0.01$).

Ventricular wall thickness increased significantly after operation. Interventricular septal wall thickness increased by a mean of 16%, from 0.59 ± 0.22 to 0.67 ± 0.23 cm ($p < 0.01$), and posterior wall thickness increased by a mean of 15%, from 0.61 ± 0.21 to 0.69 ± 0.25 cm ($p < 0.01$). Ventricular cavity dimensions decreased significantly after operation. Left ventricular short-axis diameter decreased by a mean of 11% (from 2.75 ± 1.03 to 2.43 ± 0.86 cm, $p < 0.01$) and left ventricular long-axis length decreased by a mean of 6% (from 4.19 ± 1.20 to 3.87 ± 0.88 cm, $p < 0.02$).

All mean geometric indexes of ventricular wall thickness/cavity dimension ratio increased significantly after operation (Fig. 3). In Patient 3, the interventricular septum divided by the left ventricular short-axis diameter and the posterior wall divided by the left ventricular short-axis diameter decreased, whereas the other two wall thickness/cavity dimension ratios remained unchanged. For the total group, the mean indexes were as follows: interventricular septum divided by the left ventricular short-axis diameter increased 35% (from 0.22 ± 0.06 to 0.29 ± 0.09 cm, $p < 0.01$); posterior wall divided by the left ventricular short-axis diameter increased 34% (from 0.22 ± 0.05 to 0.30 ± 0.10, $p < 0.01$); interventricular septum divided by the left ventricular long-axis length increased 25% (from 0.14 ± 0.03 to 0.17 ± 0.04, $p < 0.01$), and posterior wall divided by the left ventricular long-axis length increased 24% (from 0.14 ± 0.03 to 0.18 ± 0.04, $p < 0.01$). Thus, for the whole group, mean ventricular septal defect area decreased significantly with a concomitant increase in all linear estimates of the wall thickness/volume ratios.

Figure 3. Linear estimates of wall thickness/volume ratios before (Pre-op) and after (Post-op) volume-unloading surgery. All wall thickness/volume ratios increased significantly. IVS = interventricular septum; LVSAd = left ventricular short-axis diameter; LVLAI = left ventricular long-axis length; PW = posterior wall. Data shown are mean value (**columns**) ± SD (**vertical bars**).



Relation between change in ventricular septal defect area and ventricular geometry. Correlation of percent change in ventricular septal defect area before and after operation with percent change of all four geometric indexes (interventricular septum or posterior wall divided by left ventricular short-axis diameter or long-axis length) revealed similar trends, indicating that the greater the increase in wall thickness/cavity dimension ratio after operation, the greater the decrease in ventricular septal defect area. However, the only statistically significant correlation was between percent change in ventricular septal defect area and percent change in the posterior wall divided by the left ventricular long-axis length ($r = 0.51$, $p < 0.05$) (Fig. 4).

Comparison of change in ventricular septal defect area and ventricular geometry: pulmonary artery band versus cavopulmonary connection. In the cavopulmonary connection group ($n = 12$), the ventricular septal defect area decreased from 2.4 ± 1.7 to 1.5 ± 1.5 cm^2/m^2, a mean decrimental change of 41 ± 19% ($p < 0.01$). In the group undergoing pulmonary artery banding ($n = 6$), the ventricular septal defect area decreased from 4.6 ± 3.9 to 3.1 ± 2.2 cm^2/m^2, a change of 25 ± 28% ($p = 0.06$) (Fig. 5). A greater reduction in ventricular septal defect area for the cavopulmonary connection group versus the pulmonary artery band group (41% vs. 25%) was observed ($p = 0.22$).

In both surgical subgroups a similar trend in geometric change was observed after operation (Fig. 6). In the cavopulmonary connection group, all ratios of ventricular wall thickness to cavity dimensions increased significantly. The interventricular septum divided by the short-axis diameter increased from 0.23 ± 0.07 to 0.31 ± 0.11 ($p < 0.05$); the posterior wall

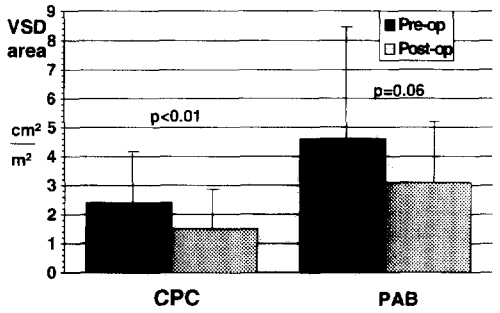
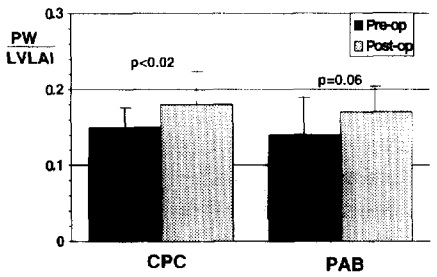


Figure 5. Ventricular septal defect (VSD) area indexed to body surface area (cm^2/m^2) before (Pre-op) and after (Post-op) either cavopulmonary connection (CPC) or pulmonary artery banding (PAB). Ventricular septal defect area decreased significantly in the cavopulmonary connection group, and there was a trend toward a decrease in the pulmonary artery band group. Data shown are mean value **(columns)** ± SD **(vertical bars)**.

divided by the short-axis diameter increased from 0.23 ± 0.05 to 0.32 ± 0.12 ($p < 0.01$); the interventricular septum divided by the long-axis length increased from 0.15 ± 0.03 to 0.18 ± 0.04 ($p < 0.01$); and the posterior wall divided by the long-axis length increased from 0.15 ± 0.02 to 0.18 ± 0.04 ($p < 0.02$). In the pulmonary artery band group, the interventricular septum divided by the short-axis diameter increased from 0.19 ± 0.04 to 0.25 ± 0.06 ($p = 0.10$); the posterior wall divided by the short-axis diameter increased from 0.21 ± 0.02 to 0.26 ± 0.06 ($p > 0.10$); the interventricular septum divided by the long-axis length increased from 0.13 ± 0.03 to 0.16 ± 0.03 ($p = 0.06$); and the posterior wall divided by the long-axis length increased from 0.14 ± 0.04 to 0.17 ± 0.03 ($p = 0.06$).

When the degree of geometric change in each of the surgical subgroups, as reflected by the percent change in indexes of ventricular wall thickness to cavity dimension, were compared, no significant difference in percent change was noted between patients who underwent cavopulmonary connection versus pulmonary artery banding (interventricular septum divided by short-axis diameter 36% ± 42% vs. 32% ± 37%, $p = 0.96$; posterior wall divided by short-axis diameter

Figure 6. Posterior wall divided by left ventricular long-axis length (PW/LVLAI) before (Pre-op) and after (Post-op) either cavopulmonary connection (CPC) or pulmonary artery banding (PAB). In both surgical subgroups there was a decrease in ventricular septal defect area and an increase in the linear estimate of the wall thickness/volume ratio. Data shown are mean value **(columns)** ± SD **(vertical bars)**.



38% ± 46% vs. 26% ± 28%, $p = 0.96$; interventricular septum divided by long-axis length 23% ± 25% vs. 29% ± 36%, $p = 0.93$; posterior wall divided by long-axis length 25% ± 27% vs. 22% ± 19%, $p = 1.0$).

Factors that may influence degree of change in ventricular geometry after surgical volume removal. *Pulmonary/systemic blood flow ratio.* In 15 of the 18 patients, cardiac catheterization was performed just before surgical volume reduction, and the pulmonary/systemic flow ratio was calculated (mean 3.9 ± 4.3, median 2.0, range 0.9 to 14). No significant relation was noted between the pulmonary/systemic flow ratio and percent change in ventricular septal defect area ($r = 0.25$, $p = 0.36$) or any of the other indexes of ventricular geometry (interventricular septum divided by short-axis diameter, $r = 0.35$, $p = 0.20$; interventricular septum divided by long-axis length, $r = 0.22$, $p = 0.42$; posterior wall divided by short-axis diameter, $r = 0.29$, $p = 0.29$; posterior wall divided by long-axis length, $r = 0.22$, $p = 0.43$).

Other factors. When the patient population was separated according to ventricular septal defect type (i.e., muscular [n = 11] vs. nonmuscular [n = 7]), initial ventricular septal defect size before operation (≥1 vs. <1 cm^2/m^2), patient age at the time of operation (>6 months [n = 10] vs. ≤6 months [n = 8]) and anatomic subtype (single left ventricle {S,L,L} vs. tricuspid atresia {S,D,D}), no significant differences were noted in percent change of ventricular septal defect area or indexes of ventricular geometry between the groups.

Interobserver and intraobserver variability testing. In nine patients ventricular septal defect dimensions were measured by two independent observers. The correlation coefficient for the calculated area was 0.99 ($p < 0.001$) for preoperative measurements and 0.95 ($p < 0.001$) for postoperative measurements. When analysis of variance was used to test for differences within the three measurements made by a single observer for each patient, values were found not to be significantly different from each other ($p = 0.94$ to $p = 0.99$).

Discussion

Physiology of volume-unloading surgery. The univentricular heart naturally exists in a physiologically volume-loaded state. With each stroke of the cardiac cycle, the single ventricle must do the work of delivering both pulmonary and systemic outputs. In diastole, ventricular filling is composed of flow returning from multiple sources: the systemic circulation through the superior and inferior vena cavae in addition to the pulmonary circulation through the pulmonary veins. Under these conditions, the ventricle is maximally volume loaded. By placing a band on the pulmonary artery, pulmonary blood flow is limited to the degree of restriction from the band, and the pulmonary component of the ventricular output is decreased. Pulmonary venous flow, and thus ventricular filling, is also diminished, and the volume load of the left ventricle is decreased, although not eliminated. In the single ventricle after cavopulmonary connection surgery, the ventricular stroke

work of each cardiac cycle is reduced from the combined pulmonary and systemic output to the systemic output alone. Ventricular filling is from the systemic venous return alone. Hence, the ventricle is volume unloaded to a greater degree than after pulmonary artery banding.

Subaortic obstruction and theory of ventricular contraction after volume unloading. Many published reports have described the development of subaortic obstruction in patients with a single left ventricle and systemic output dependent on a ventricular septal defect. Obstruction to systemic outflow typically occurs at the site of the ventricular septal defect and can be present at birth; it may be related to the type of ventricular septal defect (13) or develop spontaneously (14,15) or after surgical intervention. Freedom et al. (1–4) and others (5–9) have reported cases in which subaortic stenosis has developed after pulmonary artery band placement. They suggest that the etiology of this phenomenon is related to an increased afterload placed on the ventricle as a result of banding of the pulmonary artery, resulting in muscular hypertrophy and subsequent subaortic obstruction. There have also been reports of the development of subaortic stenosis in the single ventricle after a Fontan anastomosis (5,6,16,17), an operation not directly known to result in increased ventricular afterload.

Afterload or, more exactly, systolic wall stress is defined by LaPlace's law, which states that the force against contraction is directly related to the arterial pressure and ventricular cavity radius and inversely related to the myocardial wall thickness. Preoperatively the single left ventricle has a high wall stress caused by a dilated ventricular cavity from an increased volume load. This stress leads to myocardial hypertrophy and an increase in muscle mass. With volume reduction surgery, there is an immediate decrease in cavity size. Because there is a constant muscle mass in the short term, myocardial wall thickness increases, and there is an obligate mass/volume mismatch. It is likely that the decrease in cavity size and increase in wall thickness outweigh any change in arterial blood pressure postoperatively, especially in those patients who have a greater reduction in volume after cavopulmonary connection. Thus, according to LaPlace's law, patients who undergo either cavopulmonary connection or pulmonary artery banding will have a decrease in wall stress with the cavity contraction that accompanies volume reduction. However, the long-term effects of wall stress are less clear, and there may be an ultimate increase in afterload from the creation of subaortic narrowing, which develops immediately.

As an alternative to the concept of increased afterload leading to progressive muscular hypertrophy, we propose a different hypothesis with greater universal applicability. Common to both pulmonary artery banding and a cavopulmonary connection is the physiologic reduction of ventricular filling and volume load. In the short term, before any theoretic stimulus to hypertrophy may take effect, an immediate reduction in the filling of the ventricle results in a reduction in heart size and ventricular cavity contraction and an obligatory increase in myocardial wall thickness. Closer apposition of the internal myocardial borders secondary to this reduction in ventricular cavity size results in the development of ventricular septal defect orifice diminution and subaortic obstruction. Ventricular cavity contraction with an increase in wall thickness has been reported previously after ventricular septal defect closure (18), after a Rastelli-type operation for transposition of the great arteries with pulmonic stenosis, double-outlet right ventricle or subaortic stenosis (19) and after a hemi-Fontan or Fontan operation for hypoplastic left heart syndrome (20) or single left ventricle (18,20).

Published reports (1–9) of changes in ventricular septal defect size after pulmonary artery band placement have described results gathered over a variable period of time, up to years after operation. In this time frame, chronic muscle hypertrophy from long-term changes in wall stress or afterload as well as spontaneous (natural) ventricular septal defect orifice diminution may occur, thus obstructing aortic outflow. To our knowledge, no studies to date have addressed the possible changes in ventricular septal defect size that occur immediately after the operation, before the theoretic effects of chronic hypertrophy. We postulated that because patients with a single left ventricle and transposition of the great arteries are physiologically volume loaded, early changes in ventricular septal defect orifice size as well as changes in wall thickness and cavity dimensions may be seen after any operation that diminishes the volume load, either pulmonary artery banding or cavopulmonary connection (hemi-Fontan or Fontan procedure).

Our results. In the single left ventricle, echocardiographic imaging of the ventricular septal defect orifice in two orthogonal planes and the calculated ventricular septal defect orifice area based on the equation of a regular ellipse has correlated well with ventricular septal defect orifice area obtained at the time of autopsy (5,8). We retrospectively reviewed echocardiographic images to calculate ventricular septal defect area in our patients both before and after volume-unloading surgery. Subjects were limited to those with echocardiographic studies that were performed early after operation, most within 5 to 7 days after operation, to reduce the chance that significant ventricular septal defect diminution could result from chronic muscle hypertrophy with changes in afterload.

We found that diminution of ventricular septal defect area (by 36%) occurred early, after all forms of volume-unloading surgery, and coincided with an acute alteration in ventricular geometry, as represented by an increase in ventricular myocardial wall thickness and a decrease in cavity dimensions. In addition, the trend in ventricular septal defect diminution was greatest after volume unloading of the ventricle after cavopulmonary connection surgery (41%) versus pulmonary artery banding (25%). Comparison with the hemi-Fontan and Fontan procedures in which a more predictable and absolute reduction in ventricular filling can be expected, pulmonary artery banding results in a variable diminution in volume load because it is dependent on the degree of restriction at the site of banding. Because there is variability in volume reduction, the degree of ventricular septal defect orifice diminution and geometric change may be less predictable and less dramatic in the

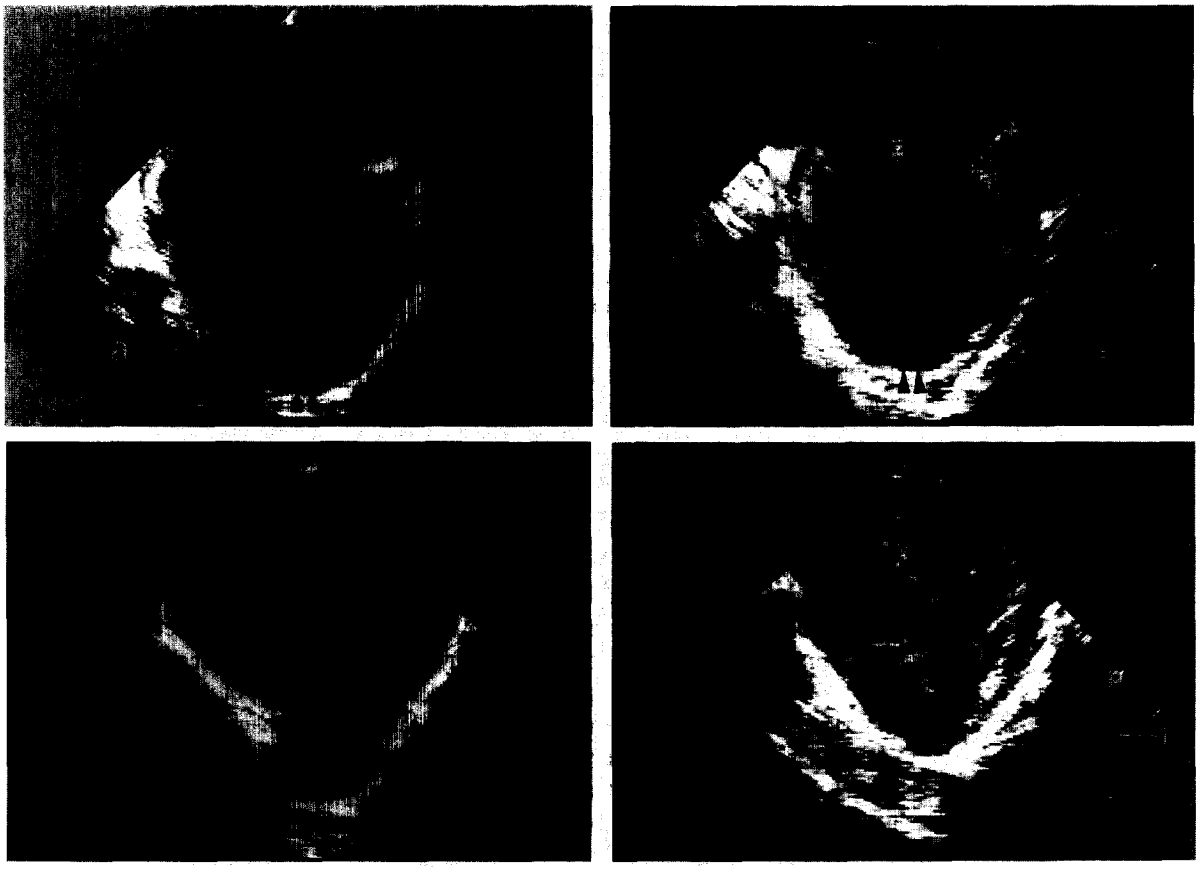


Figure 7. Transesophageal echocardiographic images before and immediately after the hemi-Fontan procedure in a patient with a single left ventricle (SLV). Transverse four-chamber view before (**a**) and after (**b**) operation and transverse short-axis view before (**c**) and after (**d**) operation. Note the decrease in ventricular cavity dimension and increase in wall thickness after operation. Ventricular septal defect diameter decreased by 27%. **Arrowheads** indicate posterior wall thickness (**a** and **b**) and borders of ventricular septal defect (**c** and **d**). a = anterior; Ao = aorta; AVV = atrioventricular valves; l = left; p = posterior; r = right.

pulmonary artery band group relative to the cavopulmonary group.

Of our 18 patients studied, only 1 (Patient 3) had an increase in ventricular septal defect area, this after pulmonary artery band placement. Of note, he was also the only patient to have an increase in ventricular dimensions without a significant change in wall thickness after operation, further supporting the hypothesis of a distinct relation between ventricular geometric change and alteration in ventricular septal defect area after volume unloading. Preoperatively, this patient was calculated to have a very large pulmonary/systemic flow ratio (14:1) and had placement of a pulmonary artery band at a very early age (3 weeks) after development of pulmonary overcirculation and congestive heart failure. Yet, despite the presence of massive volume overload before banding, ventricular contraction and ventricular septal defect diminution did not occur. Review of the preoperative hemodynamic variables in 15 of the 18 patients also revealed no relation between pulmonary/systemic flow ratio and degree of geometric change in the ventricle after volume unloading. The factors influencing degree of geometric change and ventricular septal defect diminution are therefore multiple and most likely interrelated. A lack of significant geometric change in a patient undergoing volume reduction at a very early age could possibly be accounted for by the different histologic composition of the myocardium at this age (i.e., collagen content) compared with the more mature heart (21). Factors other than age, such as duration of volume overload, and surgical variables, such as circulatory arrest time, may play a role but were not analyzed in our study.

Study limitations. It was not the purpose of our study to define the absolute dimensions of a ventricular septal defect that is likely to become obstructive. Matitiau et al. (5) recently reported that patients with an initial ventricular septal defect area <2 cm^2/m^2 are at high risk of developing obstruction. Others (7,9) have reported similar findings. It has also been observed (6,7,22) that patients who present with any evidence of aortic arch obstruction (coarctation, arch hypoplasia or interruption) are likely to develop obstruction later even if it is not present on initial evaluation. Our study goals were not to address any of these issues but rather to document the phenomenon of an early change that occurs in ventricular septal defect dimension and ventricular geometry after volume reduction surgery. In fact, many of our patients were already perceived to have a ventricular septal defect restrictive to aortic outflow and received stage I Norwood palliation in

infancy. Analysis of the physiologic consequences of the change in ventricular septal defect dimension, such as a possible gradient by either postoperative cardiac catheterization or echocardiographic Doppler assessment, was therefore not feasible.

In addition, our purpose was not (nor were we able) to measure wall stress changes after volume reduction. We believe that wall stress affects the potential for chronic progression of ventricular septal defect diminution and does not have an effect on any changes that might occur immediately after operation.

Because this was a retrospective analysis, there are many variables that could not be controlled. For instance, the patient population was preselected as to which surgical procedure was performed according to the clinical presentation. Younger and smaller infants had placement of a pulmonary artery band if they were symptomatic, whereas children >4 to 6 months were considered for cavopulmonary connection. This approach to patient management is reflected in the difference in patient age and size between the two surgical subgroups. Despite this selection bias, the results of our analysis were not affected, because the echocardiographic measurements of the ventricular septal defect were corrected for patient size, and thus age, by indexing to the body surface area. In addition, the interval of time after operation at which the echocardiogram was obtained could not be planned. Prospectively, we have thus far analyzed two patients using intraoperative transesophogeal echocardiography during the hemi-Fontan operation and have observed dramatic changes in ventricular septal defect size and ventricular geometry (Fig. 7) immediately after operation.

Conclusions. Early development of subaortic stenosis in patients with a single left ventricle is secondary to diminution in ventricular septal defect size related to alterations in ventricular volume. The early diminution in ventricular septal defect size is seen in conjunction with an acute alteration in ventricular geometry after pulmonary artery banding and hemi-Fontan and primary Fontan procedures, surgical interventions that entail a decrease in ventricular volume. Ventricular septal defect diminution is greatest after volume unloading after cavopulmonary connection surgery. Thus, in planning the surgical management of this diverse group of patients, consideration must be given to the possibility of early changes in ventricular septal defect size as a predictor for the potential to develop hemodynamically significant subaortic obstruction at a later date. Specific factors that influence the degree of ventricular geometric change and ventricular septal defect diminution are yet to be determined.

We express our gratitude to Renee Adams Bornemeier, MD for artwork.

References

1. Freedom RM, Sondheimer H, Dische MR, Rowe RD. Development of "subaortic stenosis" after pulmonary arterial banding for common ventricle. Am J Cardiol 1977;39:78–83.
2. Freedom RM, Dische MR, Rowe RD. Pathologic anatomy of subaortic stenosis and atresia in the first year of life. Am J Cardiol 1977;39:1035–44.
3. Freedom RM, Benson LN, Smallhorn JF, Williams WG, Trusler GA, Rowe RD. Subaortic stenosis, the univentricular heart, and banding of the pulmonary artery: an analysis of the course of 43 patients with univentricular heart palliated by pulmonary artery banding. Circulation 1986;73:758–64.
4. Freedom RM. The dinosaur and banding of the main pulmonary trunk in the heart with functionally one ventricle and transposition of the great arteries: a saga of evolution and caution. J Am Coll Cardiol 1987;10:427–9.
5. Matitiau A, Geva T, Colan SD, et al. Bulboventricular foramen size in infants with double-inlet left ventricle or tricuspid atresia with transposed great arteries: Influence on initial palliative operation and rate of growth. J Am Coll Cardiol 1992;19:142–8.
6. Penkoske PA, Freedom RA, Williams WG, Trusler GA, Rowe RD. Surgical palliation of subaortic stenosis in the univentricular heart. J Thorac Cardiovasc Surg 1984;87:767–81.
7. Franklin RC, Sullivan ID, Anderson RH, Shinebourne EA, Deanfield JE. Is banding of the pulmonary trunk obsolete for infants with tricuspid atresia and double inlet ventricle with a discordant ventriculoarterial connection? Role of aortic arch obstruction and subaortic stenosis. J Am Coll Cardiol 1990;16:1455–64.
8. Shiraishi H, Silverman NH. Echocardiographic spectrum of double inlet ventricle: evaluation of the interventricular communication. J Am Coll Cardiol 1990;15:1401–8.
9. Lin AE, Laks H, Barber G, Chin AJ, Williams RG. Subaortic obstruction in complex congenital heart disease: management by proximal artery to ascending aorta end to side anastomosis. J Am Coll Cardiol 1986;7: 617–24.
10. Norwood WI, Jacobs ML, Murphy JD. Fontan procedure for hypoplastic left heart syndrome. Ann Thorac Surg 1992;54(6):1025–9.
11. Farrell PE, Chang AC, Murdison KA, Baffa JM, Norwood WI, Murphy JD. Outcome and assessment after the modified Fontan procedure for hypoplastic left heart syndrome. Circulation 1992;85:116–20.
12. Rychik J, Murdison KA, Chin AJ, Norwood WI. Surgical management of severe aortic outflow obstruction in lesions other than hypoplastic left heart syndrome: use of a pulmonary artery to aorta anastomosis. J Am Coll Cardiol 1991;18:809–16.
13. Bevilacqua M, Sanders SP, VanPraagh SV, Colan SD, Parness I. Double-inlet single left ventricle: echocardiographic anatomy with emphasis on the morphology of the atrioventricular valves and ventricular septal defect. J Am Coll Cardiol 1991;18:559–68.
14. Freedom RA, Rowe RD. Morphological and topographical variations of the outlet chamber in complex congenital heart disease: angiocardiographic study. Cathet Cardiovasc Diagn 1978;4:345–71.
15. Rao PS. Further observations on the spontaneous closure of physiologically advantageous ventricular septal defects in tricuspid atresia: surgical implications. Ann Thorac Surg 1983;35:121–31.
16. Rothman A, Lang P, Lock JE, Jonas RA, Mayer JE, Casteneda AR. Surgical management of subaortic obstruction in single left ventricle and tricuspid atresia. J Am Coll Cardiol 1987;10:421–6.
17. Razzouk AJ, Freedom RA, Cohen AJ, et al. The recognition, identification of morphologic substrate, and treatment of subaortic stenosis after a Fontan operation. J Thorac Cardiovasc Surg 1992;104:938–44.
18. Rychik J, Jacobs ML, Norwood WI. Acute changes in left ventricular geometry after volume reduction surgery. Ann Thorac Surg. In press.
19. Rychik J, Jacobs ML, Norwood WI. Early changes in ventricular geometry and ventricular septal defect size following Rastelli operation or intraventricular baffle repair for conotruncal anomaly: a cause for development of subaortic stenosis. Circulation 1994;90 Suppl II:II-13–9.
20. Chin AJ, Franklin WH, Andrews BA, Norwood WI. Changes in ventricular geometry early after Fontan operation. Ann Thorac Surg 1993;56:1359–65.
21. Marijianowski MM, van der Loos CM, Mohrschladt MF, Becker AE. The neonatal heart has a relatively high content of total collagen and type 1 collagen, a condition that may explain the less compliant state. J Am Coll Cardiol 1994;23:1204–8.
22. Jonas RA, Castenada AR, Lang P. Single ventricle (single- or double-inlet) complicated by subaortic stenosis: surgical options in infancy. Ann Thorac Surg 1985;39:361–6.