Selective management of the left ventricular outflow tract for repair of interrupted aortic arch with ventricular septal defect: Management of left ventricular outflow tract obstruction

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Objective: Left ventricular outflow tract obstruction remains an early and late complication after repair of interrupted aortic arch and ventricular septal defect. We reviewed our experience with the selective management of the infundibular septum during primary repair to address left ventricular outflow tract obstruction.

Methods: From 1991 through 2001, all 27 patients presenting with interrupted aortic arch/ventricular septal defect and posterior deviation of the infundibular septum were analyzed. Fifteen patients with the smallest subaortic areas underwent myectomy or myotomy of the infundibular septum concomitant with interrupted aortic arch/ventricular septal defect repair.

Results: Patients undergoing myectomy-myotomy (Group 1) had significantly smaller subaortic diameter indexes ($0.83 \pm 0.16 \text{ cm/m}^2$) when compared with those who had only interrupted aortic arch/ventricular septal defect repair (group 2: $0.99 \pm 0.13 \text{ cm/m}^2$, $P = .012$). Two hospital deaths occurred in group 1, and 1 occurred in group 2. No late deaths occurred. No patient in group 2 required reoperation. Six group 1 patients required 9 reoperations for left ventricular outflow tract obstruction. Five patients underwent resection of a new subaortic membrane. Only 1 patient had recurrent muscular left ventricular outflow tract obstruction. Three patients required a second reoperation, primarily related to aortic valve stenosis.

Conclusions: Interrupted aortic arch/ventricular septal defect with posterior malalignment of the infundibular septum can be repaired with low mortality in the neonatal period. Tailored to the degree of subaortic narrowing, resection or incision of the infundibular septum at the time of primary repair was very effective in preventing or prolonging the interval to recurrent left ventricular outflow tract obstruction compared with the published data. However, reoperation for left ventricular outflow tract obstruction, often related to the development of a new and discrete subaortic membrane or valvar stenosis, is still required in a subset of patients.

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Although the results of primary repair of interrupted aortic arch (IAA) and ventricular septal defect (VSD) have significantly improved during recent years, left ventricular outflow tract obstruction (LVOTO) continues to be identified as a major risk factor for morbidity and mortality and a significant

Abbreviations and Acronyms

BSA	= body surface area
CHSS	= Congenital Heart Surgeons Society
CPB	= cardiopulmonary bypass
IAA	= interrupted aortic arch
LVOT	= left ventricular outflow tract
LVOTO	= left ventricular outflow tract obstruction
VSD	= ventricular septal defect

complication after repair.¹ Because there are multiple anatomic causes of LVOTO, the surgical management is often complex. The most common cause is posterior deviation of the infundibular septum. We reviewed our experience to assess the results of selective management of the infundibular septum during primary repair as a means of addressing LVOTO.

Patients and Methods**Patients**

From November 1991 through November 2001, 50 consecutive neonates with IAA and VSD underwent primary repair at C.S. Mott Children's Hospital, the University of Michigan Medical Center. Excluded from this study were 15 patients whose aortic valve was believed not to be adequate in size or structure. These patients underwent a modified Damus-Kaye-Stansel anastomosis with baffling of the VSD to both great arteries combined with a valved conduit between the right ventricle and pulmonary artery bifurcation. The patients with a subarterial VSD (5 patients) or a noncommitted VSD (3 patients) were also excluded because this study was focused on the effect of the deviated infundibular septum on operative management of the left ventricular outflow tract (LVOT). A review of the remaining 27 neonates undergoing primary repair for IAA and an isolated malalignment-type VSD was undertaken. As is commonly seen with IAA and a malalignment-type VSD, all patients had some degree of posterior deviation of the infundibular septum. Patients were retrospectively divided into 2 clinical groups based on the effect this posterior deviation and the resultant narrowing of the subaortic area had on operative management. Fifteen of these patients with the smallest subaortic areas were believed to be at risk for early and late postrepair subaortic obstruction. No specific objective criteria were applied, and these 15 patients were selected on the basis of the subjective opinion of the operating surgeon. Consequently, these patients underwent transatrial myectomy or myotomy of the infundibular septum concomitant with the VSD closure and IAA repair (group 1). The remaining 12 patients underwent solely VSD closure and IAA repair (group 2). The diagnosis of LVOTO was made on the basis of echocardiography or intraoperative findings in all patients. Echocardiographic measurements of the dimensions of the left heart–aorta complex were recorded preoperatively and postoperatively before discharge. All echocardiographic measurements were retrospectively performed by a single cardiologist to minimize interoperator variation. The diameters of the aortic annulus were standardized to z values,² and subaortic diameters were indexed to

body surface area (BSA). All measurements were taken from a parasternal long-axis view. The interval between the preoperative echocardiogram and discharge echocardiogram ranged from 5 to 25 days (median, 10 days).

All hospital survivors have been followed up for a median of 5.4 years (range, 0.4–12.1 years). The sources of follow-up information are the hospital medical records and information obtained by means of telephone calls and correspondence with the referring pediatric cardiologists.

Operative Techniques

The operation was performed through a median sternotomy by using cardiopulmonary bypass (CPB) and deep hypothermic circulatory arrest. During the period of these operations, circulatory arrest was used for both arch repair and VSD closure. Currently, the trend is to perform the arch repair during hypothermic circulatory arrest and the VSD closure during CPB. The ascending aorta and the main pulmonary trunk were both cannulated. Cold blood cardioplegia and topical cooling were used for myocardial protection. Mean CPB time was 75 ± 20 minutes, aortic crossclamp time was 48.6 ± 9.4 minutes, and circulatory arrest time was 45.1 ± 13 minutes. Primary repair consisting of aortic arch reconstruction and VSD closure was performed in all 27 patients. Of these 27 patients, 15 (group 1) underwent concomitant transatrial excision or incision of the infundibular septum to enlarge the subaortic area, which has been previously described.³ In all patients aortic arch reconstruction was accomplished by means of primary anastomosis of the postductal descending aorta to the ascending aorta or aortic arch by using a continuous monofilament absorbable or nonabsorbable suture. An anomalous right subclavian artery was divided when arch mobilization appeared to be difficult or retroesophageal compression was believed to be an issue. The VSD was patch closed with a running monofilament suture. No difficulty was encountered in attaching the superior aspect of the patch to the infundibular septum in the setting of a myectomy-myotomy.

Statistical Analysis

Statistical analysis was performed with SPSS software (SPSS, Inc, Chicago, Ill). Data were expressed as means $\pm$ standard deviation. The Student t test or Mann-Whitney U test was used to distinguish demographic differences between the groups.

Results

Age and body weight at the time of the operation ranged from 3 to 24 days (median, 8 days) and 1.2 to 4.3 kg (median, 3.2 kg), respectively. There were 17 male and 10 female patients. Six patients had type A IAA, and 21 had type B IAA. An anomalous right subclavian artery with retroesophageal course was noted in 6 patients with type B IAA. Associated cardiac anomalies were atrial septal defect in 14 patients and valvular pulmonary stenosis in 1 patient. A bicuspid aortic valve was noted in 18 patients. DiGeorge syndrome was present in 8 patients. A comparison of patient characteristics is described in Table 1. There was no difference in the mean age or body weight at the time of the operation between groups. There was no difference in the mean CPB time or aortic crossclamp time. Mean circulatory

TABLE 1. Comparison of patient characteristics

	Group 1 (n = 15)	Group 2 (n = 12)	P value
Age (d)	8.4 ± 3.9	10.1 ± 5.8	.3951
Body weight (kg)	3.0 ± 0.8	3.2 ± 0.3	.5568
BSA (m ²)	0.199 ± 0.032	0.204 ± 0.016	.5899
CPB time (min)	77 ± 23.5	72.5 ± 15.2	.05836
Aortic crossclamp time (min)	51.8 ± 10.1	44.8 ± 7.3	.059
Circulatory arrest time (min)	49.8 ± 11.2	39.7 ± 13.2	.0454
IAA type			
Type A	4	2	
Type B	11	10	.6618
Type B with aberrant RSCA	2	4	.3575
Bicuspid aortic valve	10	8	>.999
DiGeorge syndrome	4	4	>.999
Associated cardiac anomaly			
ASD	9	5	.4495
Valvular PS	1	0	>.999

BSA, Body surface area; CPB, cardiopulmonary bypass; IAA, interrupted aortic arch; RSCA, right subclavian artery; ASD, atrial septal defect; PS, pulmonary stenosis.

arrest time was shorter in the group 2 patients (group 1, 49.8 ± 11.2 minutes; group 2, 39.7 ± 13.2 minutes; $P = .0454$). There was no difference in distribution of other anatomic features between groups.

Varying degrees of posterior malalignment of the infundibular septum were present preoperatively in all patients. Those patients undergoing myectomy-myotomy (group 1) had significantly smaller subaortic diameters (3.7 ± 0.9 mm) when compared with those who had only IAA/VSD repair (group 2, 4.5 ± 0.7 mm; $P = .0231$). This remained significant when indexed to BSA (0.83 ± 0.16 vs 0.99 ± 0.13 cm/[BSA]^{0.5}, $P = .012$).⁴ There was no significant difference in the mean aortic z value between the groups

(group 1, -4.1 ± 1.9 ; group 2, -5.1 ± 1.4 ; $P = .1581$). By contrast, there was no difference in the echocardiographic measurements of the subaortic diameters, subaortic diameter index, and aortic annulus z value at the time of discharge after surgical intervention between the groups (Table 2).

There were 2 hospital deaths in group 1 (13.3%) and 1 in group 2 (8.3%). One 1.3-kg group 1 patient also underwent an open aortic valvotomy for a thickened abnormal valve, resulting in moderate-to-severe aortic insufficiency that led to ventricular failure. One patient with respiratory distress caused by meconium aspiration syndrome could not be weaned from CPB, and another patient in group 2 died from sepsis. No late deaths occurred.

Six (22.2%) of the 27 patients required 9 reoperations for LVOTO (Table 3). All of those patients were in group 1, and no patient in group 2 required reoperation. Five of these patients underwent resection of a new subaortic membrane. One of those 5 patients also underwent combined open commissurotomy of the aortic valve. Only 1 patient required muscle resection for recurrent muscular LVOTO. The mean interval between the initial operation and the first reoperation was 3.7 ± 4.1 years (range, 0.5-9.6 years). Three patients required a second reoperation related to aortic valve stenosis. Of these, 1 patient underwent aortic root replacement with an aortic homograft 11 months after the initial reoperation. Two patients underwent the Ross operation combined with aortic arch augmentation at 13 months and 14 months after the initial reoperation, respectively. One of those 2 patients required the combined Konno procedure to relieve recurrent muscular LVOTO. This patient was the same patient who required muscle resection for recurrent muscular LVOTO at the initial reoperation.

There were no differences in the preoperative and postoperative echocardiographic measurements of subaortic diameters, subaortic diameter index, and aortic annulus z value between those who required reoperation for LVOTO ($n = 6$) and those who did not ($n = 21$, Table 4). The residual peak systolic LVOT gradient after the operation, as

TABLE 2. Echocardiographic measurements of the dimensions of the various levels in the left heart–aorta complex (group 1 vs group 2)

	Subaortic diameter, mm (mean ± SD; range)	Subaortic diameter index, cm/[BSA] ^{0.5} (mean ± SD; range)	Aortic annulus z score (mean ± SD; range)
Before the operation			
Group 1 (n = 15)	3.7 ± 0.9; 2.4~5.0	0.83 ± 0.16; 0.61~0.98	-4.1 ± 1.9; -7.5~-1.3
Group 2 (n = 12)	4.5 ± 0.7; 3.2~5.3	0.99 ± 0.13; 0.83~1.16	-5.1 ± 1.4; -6.6~-2.6
P value	.0231	.012	.1581
At discharge			
Group 1 (n = 15)	6.4 ± 2.2; 4.2~9.7	1.43 ± 0.44; 0.99~2.17	-2.0 ± 1.2; -6.3~-0.3
Group 2 (n = 12)	6.7 ± 1.8; 4.9~9.7	1.47 ± 0.4; 1.08~2.12	-3.1 ± 0.9; -5.0~-2.0
P value	.775	.8611	.052

SD, Standard deviation; BSA, body surface area.

TABLE 3. Reoperations for postrepair left ventricular outflow tract obstruction

Patient	First reoperation (interval from initial operation)	Second reoperation (interval from first reoperation)
1	Resection of subaortic membrane (2.25 y)	None
2	Resection of subaortic membrane and commissurotomy of aortic valve (8 y)	None
3	Resection of subaortic membrane (9.5 y)	None
4	Resection of subaortic membrane (6 mo)	Ross operation and aortic arch augmentation (14 mo)
5	Myectomy (8 mo)	Ross/Konno operation and aortic arch augmentation (13 mo)
6	Resection of subaortic membrane (10 mo)	Aortic root replacement with aortic homograft (11 mo)

determined by using discharge Doppler echocardiography, was 17.8 ± 9.1 mm Hg (range, 0–32 mm Hg) in group 1 and 15.2 ± 9.6 mm Hg (range, 0–30 mm Hg) in group 2 ($P = .5427$). At a median follow-up of 5.4 years, LVOT gradients from the most recent studies were 13.6 ± 9.6 in group 1 and 21.8 ± 14.9 in group 2, excluding the 5 patients undergoing reoperation.

Discussion

Although the results of primary repair of IAA/VSD have significantly improved during recent years, LVOTO continues to be identified as a major risk factor for morbidity and mortality, as well as for the need for reoperation.^{1,5} The Congenital Heart Surgeons Society (CHSS) demonstrated that reinterventions for LVOTO were less prevalent in patients undergoing 1-stage repair when a concomitant (myotomy-myectomy) procedure was performed and that failure to perform a myotomy-myectomy for significant subaortic narrowing was an incremental risk factor for reintervention.¹ Interestingly, the CHSS also demonstrated that concomitant myotomy-myectomy was a procedural risk factor for death after repair. Thus the optimal management would seem to be a myotomy-myectomy to minimize recurrence in the setting of an acceptable mortality. Our experience demonstrates that IAA/VSD with posterior malalignment of the infundibular septum can be repaired with acceptable mortality in the neonatal period. The overall mortality in this

cohort was 11.1%. In patients undergoing myectomy or myotomy of the infundibular septum, early mortality was 13.3%, with no late deaths. The mortality rate in this group of patients is relatively high but compares favorably with the mortality reported by the CHSS, in which the short- and long-term mortality after myectomy-myotomy was 47%.¹ Serraf and colleagues⁶ also reported a high mortality (80%) after myectomy of the infundibular septum.

Regarding recurrent LVOTO, Apfel and associates⁷ demonstrated a high incidence (39%) of significant recurrent LVOTO in patients who underwent primary repair of IAA without myotomy or myectomy, with all of the recurrent LVOTO developing within 1 year after the initial operation. Although 6 (22.2%) patients required reoperation for LVOTO in this study, only 3 patients required reoperation within 1 year after the initial operation. These 3 patients required aortic root replacement as a second reoperation, primarily related to aortic valve stenosis. The other 3 patients underwent resection of a new subaortic membrane at 2.25, 8, and 9.5 years after the initial operation, respectively. Salem and coworkers⁸ demonstrated that the most important predictor of subsequent LVOTO is a smaller aortic valve annulus after primary repair of IAA/VSD, even with placing the VSD patch on the left side of the infundibular septum to draw the septum in an anterior direction and away from the subaortic area.⁹ Similar to the current results, they found that 29% of patient undergoing primary repair had clinically significant obstruction and re-

TABLE 4. Echocardiographic measurements of the dimensions of the various levels in the left heart–aorta complex (reoperation required vs no reoperation required)

	Subaortic diameter, mm (mean $\pm$ SD; range)	Subaortic diameter index, cm/(BSA) ^{0.5} (mean $\pm$ SD; range)	Aortic annulus z score (mean $\pm$ SD; range)
Before the operation			
Reoperation required (n = 6)	3.9 ± 0.7 ; 3.0–5.0	0.84 ± 0.11 ; 0.67–0.98	-3.9 ± 1.8 ; -6.5–-1.3
No reoperation required (n = 21)	4.1 ± 0.9 ; 2.4–5.3	0.92 ± 0.18 ; 0.61–1.16	-4.7 ± 1.7 ; -7.5–-2.0
P value	.6708	.3247	.2616
At discharge			
Reoperation required (n = 6)	6.8 ± 2.4 ; 4.2–9.7	1.47 ± 0.47 ; 1.08–2.0	-1.7 ± 0.2 ; -6.3–-0.3
No reoperation required (n = 21)	6.5 ± 1.9 ; 4.9–9.7	1.45 ± 0.41 ; 0.99–2.17	-2.8 ± 1.2 ; -5.0–-2.0
P value	.7645	.9349	.0859

SD, Standard deviation; BSA, body surface area.

quired reoperation, although the mean time to reintervention of 9.4 months (range, 2-14 months) was shorter than the current experience. In our study aortic annular size was not a predictor of subsequent reoperation for LVOTO; however, aortic valve stenosis or a dysplastic valve seemed to be related to early development of subsequent LVOTO and requirement of further reoperation for aortic valve stenosis. Our study suggested that tailored to the degree of subaortic narrowing, resection or incision of the infundibular septum at the time of primary repair was very effective in preventing or prolonging the interval to recurrent LVOTO compared with the published data.

In the current cohort 15 (55%) patients with the narrowest subaortic areas were believed to be at risk for early and late postrepair subaortic obstruction. This percentage is in contrast to the estimate from the CHSS study of only 21% (33/159) of patients with “functionally significant” subaortic stenosis, leading to the potential suggestion that in the current study the use of myectomy-myotomy was overly aggressive. However, several differences are apparent between the 2 studies, making direct comparison difficult. The CHSS study was not able to evaluate 13% of the study population for LVOTO, raising the possibility of selection bias. In addition, the CHSS article notes that some patients had suboptimal or no echocardiograms and that the definition of “functional significance” was based on an arbitrary 0- to 5-point estimate, with greater than 2 points being defined as significant. Although the current study defines significance by using an equally arbitrary measure, all estimates were made on the basis of high-quality echocardiograms. However, perhaps the most significant factor is likely the fact that the subjects in the current study were preselected with the inclusion criterion of a malalignment-type VSD, a requirement not applied to the CHSS study. This criterion would be expected to increase the prevalence of significant subaortic stenosis.

In this subgroup of 15 patients with the smallest subaortic region, we performed transatrial excision or incision of the infundibular septum concomitant with the VSD closure and IAA repair. The minimum size of the subaortic area below which patients undergoing standard repair might be at increased risk for postrepair LVOTO has long since been a matter of controversy. Apfel and associates⁷ analyzed preoperative echocardiograms retrospectively and demonstrated that the cross-sectional area of the LVOT index, the subaortic diameter index, and the subaortic diameter *z* value were sensitive predictors of postoperative LVOTO after standard repair of IAA. They demonstrated that those patients with significant postrepair LVOTO had significantly smaller subaortic diameter indexes ($0.83 \pm 0.1 \text{ cm}/[\text{BSA}]^{0.5}$) when compared with those with a good result ($0.99 \pm 0.16 \text{ cm}/[\text{BSA}]^{0.5}$). Goldmintz and colleagues¹⁰ recommended that primary repair of IAA should only be attempted when the absolute subaortic diameter was larger than 4 mm,

regardless of patient size. In our retrospective study patients requiring myectomy-myotomy had significantly smaller subaortic diameters ($3.7 \pm 0.9 \text{ mm}$) when compared with those who had only IAA/VSD repair ($4.5 \pm 0.7 \text{ mm}$). This remained significant when indexed to BSA (0.83 ± 0.16 vs $0.99 \pm 0.13 \text{ cm}/[\text{BSA}]^{0.5}$). There were 2 patients in our non-myectomy-myotomy series whose preoperative measurement of subaortic diameter or subaortic diameter index was less than 4 mm or $0.9 \text{ cm}/(\text{BSA})^{0.5}$. Although they have not required reoperation, their peak systolic gradients across the LVOT were 30 and 40 mm Hg during their follow-up period. In this retrospective study it is difficult to address the absolute subaortic diameter that requires operative intervention at the initial operation for an optimal result. However, our results demonstrated that our judgment on whether to perform concomitant myectomy-myotomy seemed retrospectively to coincide with the previous report. A subaortic diameter of less than 4 mm or a subaortic diameter index of less than $0.9 \text{ cm}/(\text{BSA})^{0.5}$ seemed to correspond retrospectively to the surgeon's judgment of significant narrowing and might be considered a selection criteria for concomitant resection or incision of the infundibular septum at the time of primary repair.

The minimum size of the aortic annulus below which standard repair is not possible has also long been a matter of controversy. The smallest aortic annulus in our series was 3.7 mm, or -7.5 in *z* value, and this patient has not required reoperation for aortic valve stenosis. The preoperative aortic annulus of the 3 patients requiring subsequent aortic root replacement for aortic valve stenosis ranged from 4.6 to 5.4 mm (-4 to -6.5 *z* value). Although the minimum acceptable diameter or *z* value for standard repair has yet to be defined and cannot be determined from this study, we have used the Damus-Kaye-Stansel anastomosis/Rastelli or Ross/Konno procedure for the patients whose aortic valves were believed objectively not to be adequate in size or structure. On the basis of our experience, when the aortic valve annulus is clinically believed to be adequate in size (roughly more than -6.5 in *z* value), the valve leaflets are normal, and deviation of the infundibular septum is the main cause of the subaortic stenosis, transatrial excision or incision of the infundibular septum is the procedure of choice to relieve LVOTO.

In conclusion, IAA/VSD with posterior malalignment of the infundibular septum can be repaired with low mortality in the neonatal period. Tailored to the degree of subaortic narrowing, resection or incision of the infundibular septum at the time of primary repair was very effective in preventing or prolonging the interval to recurrent LVOTO compared with historical data. However, reoperation for LVOTO, often related to the development of a new and discrete subaortic membrane or valvar aortic stenosis, is still required in a subset of patients.

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