Coarctation of the Aorta: Midterm Outcomes of Resection With Extended End-to-End Anastomosis

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Background. We began using the technique of resection with extended end-to-end anastomosis for infants and children with coarctation of the aorta in 1991. The purpose of this review is to evaluate the midterm outcomes of this technique, specifically determining the incidence of and risk factors for transcatheter or surgical reintervention.

Methods. A retrospective analysis of the cardiac surgery database was performed to identify all patients who had a diagnosis of coarctation of the aorta with or without ventricular septal defect and had resection with extended end-to-end anastomosis from 1991 to 2007. Perioperative course and follow-up with physical examination, echocardiogram, and cardiology evaluation were obtained.

Results. From 1991 through 2007, 201 patients had repair of coarctation of the aorta with resection with extended end-to-end anastomosis. The median age was 23 days, and the median weight was 4.0 kg. Surgical approach was by left thoracotomy in 157 patients (78%) with a mean cross-clamp time of 18 ± 4 minutes. Median sternotomy approach was used in 44 patients (22%) to repair a hypoplastic transverse aortic arch (n = 16) or because of associated ventricular septal defect (n = 28) with a mean circulatory arrest time of 14 ± 9 minutes. Early mortality occurred in 4 patients (2.0%). Three patients (1.5%) required early arch revision: 2 intraoperatively and 1 on postoperative day 1. Follow-up data were available for 182 patients (91%) with a mean follow-up of 5.0 ± 4.3 years (908 patient-years). Reinterventions (n = 8; 4.0%) included three balloon angioplasties and five reoperations; 75% of the reinterventions occurred in the first postoperative year. Hypoplastic transverse aortic arch was not a risk factor for reintervention (p = 0.36), but was a risk factor for mortality (p = 0.039). Aberrant right subclavian artery was the only risk factor for recoarctation (p = 0.007).

Conclusions. Repair of coarctation of the aorta with resection with extended end-to-end anastomosis has a low early mortality, effectively addresses transverse arch hypoplasia, and at midterm follow-up has a low rate of reintervention for recurrent coarctation.

(Ann Thorac Surg 2009;88:1932–8)

The surgical repair of coarctation of the aorta (CoAo) has evolved considerably during the past 60 years since the first description of this operation in 1945 [1, 2]. Initially, the surgical repair addressed only the coarctation site itself. Now the surgical repair has incorporated the issues of transverse aortic arch hypoplasia and residual ductal tissue to reduce the incidence of recoarctation. Of the many techniques described for CoAo, resection with extended end-to-end anastomosis (REEEA) offers the greatest potential to correct transverse aortic arch hypoplasia and ductal tissue extension [3–5]. We began using this technique in 1991 and published our initial results with 55 infants in 1998 [6]. The purpose of the current study is to update our surgical experience with REEEA and evaluate risk factors for midterm outcomes with this surgical technique, particularly regarding the need for reintervention or medical treatment of hypertension.

Material and Methods

Patients and Procedures

The Institutional Review Board at Children's Memorial Hospital, Chicago, IL, approved this review as a retrospective study and granted a waiver of informed consent. Retrospective review of the Children's Memorial Hospital cardiothoracic surgical database identified patients who underwent CoAo repair with REEEA. We included patients with simple CoAo repair or CoAo repair with ventricular septal defect (VSD) closure (simultaneous or later). We excluded patients with more complex associated intracardiac anomalies such as transposition of the great arteries, double-outlet right ventricle, and complete atrioventricular canal. Chart review and the database were used to determine demographics, operative details, perioperative events, and complications. Midterm follow-up was obtained from a combination of the cardiovascular surgery database, the Children's Memorial Hospital electronic medical record, the cardiology charts, and the echocardiogram database.

Accepted for publication Aug 13, 2009.

Presented at the Poster Session of the Forty-fifth Annual Meeting of The Society of Thoracic Surgeons, San Francisco, CA, Jan 26–28, 2009.

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Published by Elsevier Inc

0003-4975/09/$36.00
doi:10.1016/j.athoracsur.2009.08.035

Table 1. Patient Characteristics

Characteristics	Number (%) n = 201
Age (days)	
Mean	304 ± 724
Median	23
Range	1–4,053
Neonate	106 (53%)
Sex	
Male	126 (63%)
Female	75 (37%)
Median weight (kg)	4
Genetic syndrome or other anomaly	30 (15%)
Preoperative prostaglandin E_1	90 (45%)
Preoperative shock	41 (20%)

Surgical Technique

Our technique of REEEA reconstruction has been previously described [6, 7]. The two main technical issues pertain to proximal extension of the anastomosis and complete coarctation and ductal excision. In 157 patients the approach was through a left thoracotomy. Through the fourth intercostal space, the aortic arch including the head vessels, descending thoracic aorta, and ductus arteriosus were dissected and fully mobilized. The ductus arteriosus was doubly ligated. The aorta was clamped proximal to the left subclavian artery (in many cases proximal to the left carotid artery) and distal to the ductus arteriosus. All coarctation and ductal tissue was resected. One to three sets of intercostal collateral arteries were ligated and divided. The anastomosis was extended proximally by incising the undersurface of the transverse aortic arch with a mirror-image counter incision in the descending thoracic aorta. Anastomosis was performed using continuous 7-0 polypropylene suture (8-0 in babies weighing < 1.5 kg). In 44 patients a median sternotomy approach with cardiopulmonary bypass and hypothermic circulatory arrest was used. The coarctation site and ductal tissue were resected and a similar anastomosis was constructed. In recent years modified cerebral perfusion has been used in a few patients.

Table 2. Intraoperative Factors

Characteristics	Number (%) n = 201
Left thoracotomy	157 (78%)
Median sternotomy	44 (22%)
Intracardiac repair	28
Isolated transverse arch hypoplasia	16
Cross-clamp time (min)	
Mean	18 ± 4
Median	17
Range	10–41
Deep hypothermic circulatory arrest time (min)	
Mean	14 ± 9
Median	16
Range	Up to 30

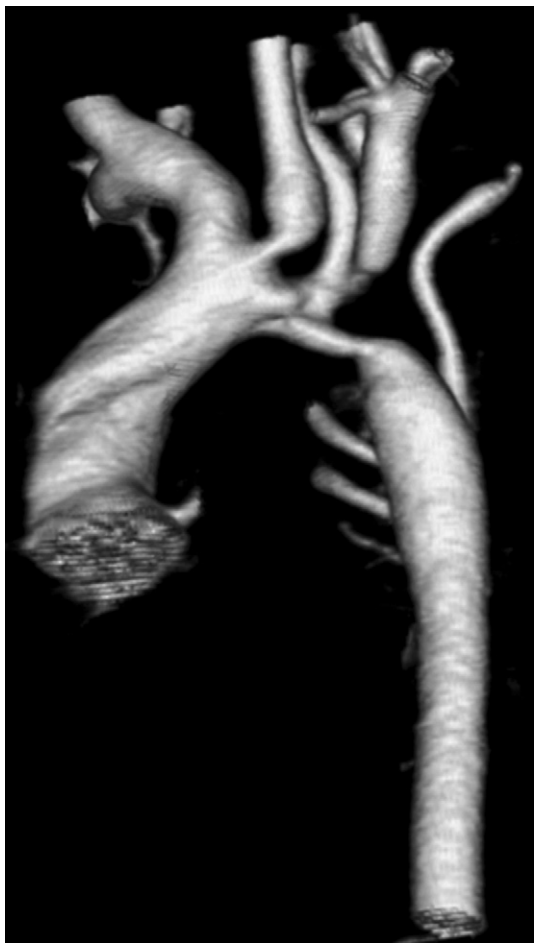

Fig 1. Three-dimensional computed tomographic reconstruction of a newborn with coarctation of the aorta. By echocardiographic analysis adequate visualization of the transverse aortic arch could not be obtained. Because of the computed tomography angiogram showing complex hypoplasia of the transverse aortic arch and stenosis of the origin of three of four cervical vessels, repair was electively performed through a sternotomy with modified cerebral perfusion.

Hypoplastic transverse aortic arch was defined as a transverse aortic arch dimension measured in millimeters that was less than the weight of the patient in kilograms plus one [8].

Statistical Analysis

Statistical analysis was performed with a commercially available statistical program using χ^2 test and Student's *t* test as appropriate. Estimated rates of survival and freedom from recoarctation were determined by the Kaplan-Meier product-limit method with 95% confidence intervals. Predictors of death and reintervention were examined in univariate analyses using Cox proportional hazard modeling. For these univariate analyses, separate models were fit for each possible predictor variable. Multiple regression and model selection were not considered because of the limited sample size.

Table 3. Postoperative Results

Characteristics	Number (%)
Early mortality	
Yes	4 (2.0%)
No	197 (98%)
Reoperations (in 30 days)	
Yes	3 (1.5%)
No	198 (98.5%)
Complications	
Septicemia	8 (4%)
Recurrent laryngeal temporary paresis	6 (3%)
Chylothorax	5 (3%)
Pulmonary hypertensive crisis	2 (1%)
Seizures	3 (1.5%)
Length of stay (days)	
Mean	13.8 ± 15
Median	7
Range	3–169

Results

Patient Characteristics and Intraoperative Factors

During the 16 years of this study, 201 patients underwent REEEA. Patient characteristics and intraoperative factors that were assessed are presented in Tables 1 and 2. The median age of the patients was 23 days; 37% were girls and 63% were boys. The median weight was 4 kg. One hundred six patients (53%) were neonates. Preoperative shock occurred in 41 patients (20%), and 90 patients (45%) were managed with preoperative prostaglandin E_1 therapy.

All of the patients in this series had repair with REEEA as patients with patch augmentation of the arch were excluded. A left thoracotomy was performed in 157 patients (78%) with a mean cross-clamp time of 18 ± 4 minutes (range, 10 to 41 minutes). Three neonatal patients had residual arch hypoplasia after the initial repair. All underwent a reverse subclavian flap [9]: 2 during the same operation and 1 on postoperative day 1 to further augment the aortic arch. A median sternotomy approach was used in 44 patients. The indication for this approach was the need for a concomitant intracardiac repair of a VSD in 28 patients. The other 16 patients had a hypoplastic transverse aortic arch not amenable to repair from a thoracotomy approach based on an individual surgeon decision. An example of this is shown in Figure 1. Other anatomic issues that favored a sternotomy approach were a common brachiocephalic trunk and aberrant distal thoracic aortic origin of the right subclavian artery. The mean deep hypothermic circulatory arrest time was 14 ± 9 minutes (range, up to 30

Table 4. Early and Late Mortality

Year	Weight (kg)	Preoperative Inotropic Drugs	Operative Procedure	Approach	Age at Operation (days)	Complication and Cause of Death	Postoperative Interval (days)
Early							
1994	3.3	++	REEEA + VSD Preoperative ECMO (meconium aspiration)	Sternotomy	7	NEC, renal failure	26
1997	3.2	++	REEEA after diaphragmatic hernia repair	Thoracotomy	7	Pulmonary hypertension	4
1998	2.6	++	REEEA + multiple VSD High-frequency oscillator for respiratory failure preoperatively	Sternotomy	22	Multiorgan failure	20
1998	3.5	++	REEEA + Multiple VSD ECMO for RSV on POD 3	Sternotomy	58	Necrotizing pneumonia (RSV)	4
Late							
1993	3.2	−	REEEA + VSD	Sternotomy	225	Respiratory infection	3,570
1995	3.6	−	REEEA + VSD + ASD + Turner's syndrome	Sternotomy	3	IVH at 3 days and 18 months Recurrent coarctation Balloon dilatation ×2	566
2001	2.4	+	REEEA + PAB for VSD Reimplanted aberrant RSA Operation at 6 months for VSD + subaortic membrane	Thoracotomy	10	Sepsis	932
2007	2.9	−	REEEA + Multiple VSD + repair aberrant RSA + ASD	Sternotomy	11	Respiratory infection	137

ASD = atrial septal defect; ECMO = extracorporeal membrane oxygenation; IVH = intraventricular hemorrhage; NEC = necrotizing enterocolitis; PAB = pulmonary artery banding; POD = postoperative day; REEEA = resection with extended end-to-end anastomosis; RSA = right subclavian artery; RSV = respiratory syncytial virus; VSD = ventricular septal defect.

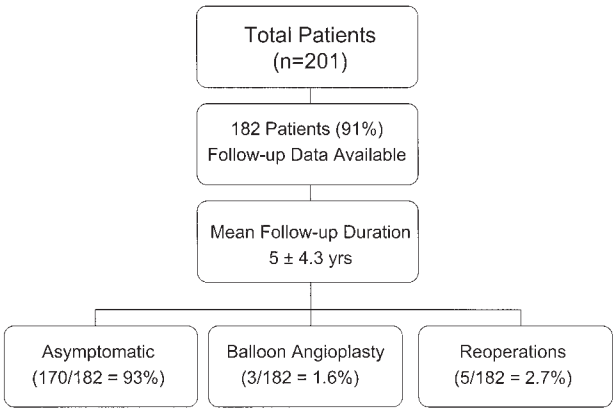

Fig 2. Follow-up data in 201 patients who underwent resection with extended end-to-end anastomosis for repair of coarctation of the aorta from 1991 to 2007 at Children's Memorial Hospital.

minutes). Two patients had modified cerebral perfusion with a mean time of 25 minutes.

Early Outcomes

There were 4 early deaths resulting in an early mortality rate of 2% (Tables 3, 4). All of the deaths occurred in infants with significant comorbidities from 4 to 26 days after the coarctation repair. One patient was receiving extracorporeal membrane oxygenation preoperatively for meconium aspiration. A second patient required extracorporeal membrane oxygenation postoperatively for respiratory syncytial virus pneumonia. A third patient had a diaphragmatic hernia repair before the coarctation surgery, and the fourth patient was on an oscillator preoperatively. Two patients required immediate arch revision during the initial repair with a reverse subclavian flap in the operating room after REEEA. One patient required reoperation the next day for an increased gradient across the transverse arch and anastomosis site, and underwent a successful reverse subclavian flap to augment the arch. Of these 3 patients, 1 had an aberrant right subclavian artery. There were no patients who experienced paraplegia. Three patients undergoing deep hypothermic circulatory arrest had postoperative seizures, but during the last decade, there have been no postoperative seizures reported. The most common complications were septicemia in 8 patients (4%), temporary recurrent laryngeal nerve paresis in 6 patients (3%), chylothorax in 5 patients (3%), and pulmonary hypertensive crisis in 2 patients (1%). Three patients (2%) required reoperations for VSD closure, mediastinitis, and delayed sternal closure. The median postoperative length of stay was 7 days.

Late Outcomes

Follow-up data were obtained from the cardiovascular surgery database, cardiology charts, hospital electronic medical record, and the echocardiogram database. Follow-up data were obtained in 182 patients (91%; Fig 2). Mean duration of follow-up was 5.0 ± 4.3 years. This totals 908 patient years of follow-up out of a potential 1,293 patient years of follow-up. One hundred seventy patients (93%)

Table 5. Patients With Recoarctation

Year	Operative Procedure	Technique	Age at Surgery (days)	LOS (days)	Weight at Surgery (kg)	Intervention	Interval to Intervention (y)	Hypoplastic Arch	Other
1994	REEEA	Thoracotomy	16	4	3.2	Balloon angioplasty ×2	11.0	No	Aberrant RSA
2006	REEEA	Thoracotomy	6	22	3.7	Balloon angioplasty ×2	0.25	Yes	
2007	REEEA + multiple VSD + ASD	Sternotomy	11	12	2.9	Balloon angioplasty ×2	0.20	No	Aberrant RSA Died
1994	REEEA	Thoracotomy	1,361	4	13.0	Transverse arch repair (Hemashield)	9.33	Yes	
1997	REEEA	Thoracotomy	18	7	3.1	Repeat REEEA	0.75	Yes	
2001	REEEA + VSD	Sternotomy	34	9	3.5	Transverse arch repair with pulmonary homograft patch	0.25	Yes	
2004	REEEA	Thoracotomy	15	12	3.2	Transverse arch repair with pulmonary homograft patch	0.25	Yes	Common brachiocephalic trunk
2006	REEEA	Thoracotomy (right), PAB	10	12	3.0	Transverse arch repair with pulmonary homograft patch + VSD	0.25	Yes	Right arch, aberrant RSA

ASD = atrial septal defect; LOS = length of stay; PAB = pulmonary artery banding; REEEA = resection with extended end-to-end anastomosis; RSA = right subclavian artery; VSD = ventricular septal defect.

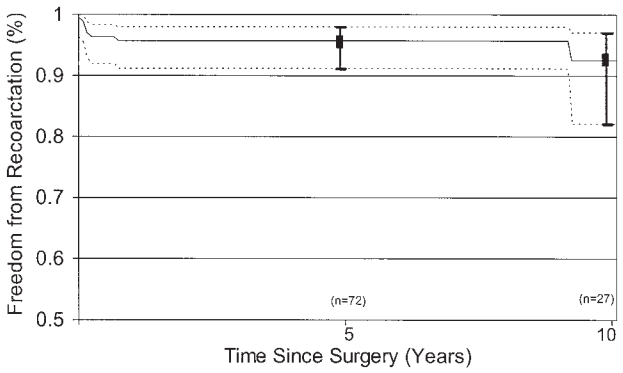

Fig 3. Kaplan-Meier curve indicating freedom from recoarctation 10 years postoperatively. Confidence intervals are indicated by the dotted lines.

had no residual aortic arch obstruction as defined by an echocardiogram gradient or systolic blood pressure gradient greater than 20 mm Hg. These 170 patients were also not receiving any antihypertensive medications. There were 4 late deaths (2.0%), 2 as a result of respiratory infections, 1 as a result of interventricular hemorrhage, and 1 as a result of sepsis (Table 4). None of the patients who died had aortic arch obstruction.

Eight patients had an intervention because of residual or recurrent aortic arch gradients, which resulted in an overall reintervention rate of 4% (Table 5). Six of these 8 patients (75%) had reintervention within the first year postoperatively. Three patients had balloon angioplasty and five patients had a reoperation. The time interval from initial repair to reintervention was 3 to 132 months (mean, 41 ± 52 months). All 3 patients who had balloon angioplasty required a second balloon angioplasty, and none of them have redeveloped another coarctation. Fifteen other patients had postcoarctation cardiac catheterization for various indications. All of these patients had peak systolic gradients across the aortic arch of less than 20 mm Hg. The 5 patients who underwent reoperations all had successful relief, with 4 requiring transverse arch repair with homograft patch augmentation and 1 requiring repeat REEEA.

The calculated freedom from reintervention at 10 years for the entire group was 93% (95% confidence interval, 82% to 97%; Fig 3). Univariate analysis using Cox proportional hazard modeling indicated that aberrant right subclavian artery was a risk factor for recoarctation ($p = 0.007$), and none of the other factors examined, which included weight less than 2.5 kg, VSD repair, sternotomy approach, hypoplastic arch, preoperative inotropic drug support, or aberrant right subclavian artery, were associated with recoarctation (all $p > 0.3$; Table 6). Univariate analysis revealed that the presence of a VSD ($p = 0.0021$), sternotomy approach ($p = 0.0028$), preoperative inotropic drugs ($p = 0.036$), and hypoplastic transverse aortic arch ($p = 0.039$) were all associated with a higher probability of death (Table 6). Survival was not associated with age, weight, or sex (all $p > 0.5$).

Comment

Many different surgical techniques have evolved during the last half-century for the correction of CoAo. These techniques include simple end-to-end anastomosis, [1, 2] subclavian flap aortoplasty [10], and prosthetic patch aortoplasty [11, 12]. Owing to higher than anticipated recurrence rates of these other surgical techniques [13], we began using the REEEA technique in 1991 [6]. We now use this technique not only in neonates but in all infants and in most younger children with coarctation. The advantages of this technique include complete resection of all coarctation and ductal tissue, a wide anastomosis that addresses transverse arch hypoplasia, and growth potential of the repair. Many other centers have reported successful use of the REEEA technique (Table 7). However, some centers still recommend subclavian flap aortoplasty [18, 19], and one center stresses repair of most coarctations from a sternotomy approach with cardiopulmonary bypass [20]. Others have

Table 6. Predictors of Death and Reintervention After Surgery for Coarctation

Outcome	Variable	*p* Value	HR	95% CI
Death	Weight < 2.5 kg	0.81	0.77	0.09–6.4
	VSD repair	0.0021[a]	12.6	2.5–62.9
	Sternotomy	0.0028[a]	11.6	2.3–57.9
	Preoperative inotropic drugs	0.0036[a]	22.5	2.8–183.5
	Hypoplastic transverse aortic arch	0.039[a]	4.5	1.1–18.9
	Aberrant right subclavian	0.47	2.2	0.26–18.1
Reintervention	Weight < 2.5 kg	0.99	NA	NA
	VSD repair	0.63	1.5	0.30–7.5
	Sternotomy	0.71	1.4	0.27–6.8
	Preoperative inotropic drugs	0.95	0.95	0.19–4.7
	Hypoplastic transverse arch	0.36	2.0	0.46–8.3
	Aberrant right subclavian	0.007[a]	7.4	1.7–31.7

[a] $p < 0.05$.

CI = confidence interval; HR = hazard ratio; NA = not available; VSD = ventricular septal defect.

Table 7. Results of Resection With Extended End-to-End Anastomosis

Author	Age	Year	Patients	Operative Mortality	Recoarctation
van Son et al [14]	<1 month	1997	25	0	1 (4%)
Backer et al [6]	<6 months	1997	55	1 (2%)	2 (4%)
Wood et al [15]	<1 year	2004	181	1	4 (2.2%)
Wright et al [16]	≤1 year	2005	83	2 (2%)	4 (5%)
Thomson et al [17]	<1 year	2005	191	9 (5%)	7 (4.2%)
Totals			535	13 (2.3%)	18 (3.4%)

recommended the use of an end-to-side anastomosis [21, 22].

Our current study confirms the low early mortality (2%) and low recoarctation rate (4%) we previously reported and extends our follow-up to demonstrate excellent midterm results. These updated results also confirm the excellent results of other recently published surgical series (Table 7). A collection of five other surgical series leads to a total of 535 reported patients undergoing REEEA for CoAo with an overall mortality rate of 2.3% and a recoarctation rate of 3.4%. By univariate analysis, we determined that the presence of a VSD, a sternotomy approach, use of preoperative inotropic drugs, and a hypoplastic transverse aortic arch were all associated with a higher mortality rate. These associated mortality risk factors reflect the fact that these patients are more complex. All patients who had early mortality in our series had significant medical or surgical comorbidities such as preoperative or postoperative extracorporeal membrane oxygenation, respiratory syncytial virus, operation after diaphragmatic hernia repair, and others. In contrast to patients with complex coarctation, these findings emphasize that the mortality after repair of isolated CoAo is minimal with low morbidity.

In our series, the freedom from reintervention to the aortic arch was 92% in the patients in whom we have follow-up at 10 years. By univariate analysis aberrant right subclavian artery was a risk factor for recoarctation. Of the 3 patients who required early arch revision, 1 had aberrant right subclavian artery. Of the 8 patients who had late reintervention for recoarctation, 3 had aberrant right subclavian artery. Hence, 4 of 11 patients (36%) who required an arch reintervention had an aberrant right subclavian artery. None of the other risk factors analyzed—weight of the patient, hypoplastic transverse aortic arch, VSD repair, sternotomy, or preoperative inotropic drugs—were a risk factor for recoarctation. The reason for this association may involve a more difficult anastomosis owing to the added complexity of the aberrant right subclavian artery arising from the descending thoracic aorta and limiting mobility of the anastomosis. A second explanation is that it is more difficult to place the proximal clamp without an innominate artery because there is no site to ascertain that the ascending aorta is not occluded as a result of no right radial arterial catheter monitoring. A third explanation is that the transverse arch may be more hypoplastic because the aberrant right subclavian artery arises from the descending thoracic aorta instead of contributing to the blood flow through the ascending aorta.

Our surgical results are similar to those reported by other studies [16, 23], but differ from two studies that reported that the anatomy of the hypoplastic transverse aortic arch is critical [24] and that the risk of recoarctation is higher in low birth weight infants [25]. McElhinney and colleagues [24] reported that a smaller absolute transverse arch diameter and younger age were independent predictors of shorter time to arch reintervention. Bacha and associates [25] reported that the risk of recoarctation was higher in the very low birth weight infants. In our analysis weight less than 2.5 kg (n = 11) was not a risk factor for recoarctation. We only had 4 patients weighing less than 2 kg, and none required reintervention. Our results support the notion that an extended end-to-end repair creates a widely patent anastomosis despite the presence of hypoplasia of the transverse aortic arch. The only risk factor for recoarctation or arch revision in our series was aberrant right subclavian artery. Even though a possible limitation of our series is the 5-year mean follow-up, we noticed that the majority of coarctation recurrences in our series occurred within the first year after the initial repair and thus our surgical follow-up should have captured all potential recurrences. Other series similarly report that the majority of restenoses after coarctation repair, regardless of technique, occur early after repair [26, 27]. This finding may reflect the fact that the somatic growth may be highest in the first year after initial repair, especially in neonatal patients.

There are several technical modifications of the REEEA repair that may be useful for patients who have complex transverse arch anatomy. Elliott [28] described a technique of using a partial occlusion clamp on the innominate artery and thus performing a more radical extended end-to-end anastomosis. This surgical approach resulted in excellent freedom from recoarctation. We rarely use this radical approach, but frequently extend the anastomosis to a site opposite the left carotid artery. In patients with a hypoplastic transverse aortic arch, we still use the REEEA repair to augment the arch but do the repair from a sternotomy approach. Fraser and colleagues [20] have also successfully used this strategy. Our observation that an aberrant right subclavian artery increases the risk of recoarctation leads us to favor recommending a sternotomy approach if there is an aberrant right subclavian artery. Other authors have recommended this if there is a common brachiocephalic trunk [14].

We now routinely perform reconstructive computed tomography angiographic scans to assist in the surgical repair of patients when there is any concern about the anatomy of

the arch on the preoperative echocardiogram. We believe that this enhanced analysis of aortic arch anatomy provides the necessary information to develop the operative strategy (Fig 1). A key determinant for the operative strategy is defining whether the aortic arch is hypoplastic. We have used a formula that defines the aortic arch to be hypoplastic if the smallest arch dimension is less than the weight of the patient plus one (in millimeters), similar to the method reported by Karl and associates [8]. If the transverse arch is hypoplastic, then we have used a median sternotomy approach. Using these criteria we have a low rate of initial recurrence with only three early arch reconstructions in the postoperative period (one with aberrant right subclavian artery). Even though we may have a certain selection bias with our patients, other studies and our experience emphasize that the REEEA repair technique is an excellent one for patients with coarctation and hypoplasia of the transverse aortic arch.

Our study has several limitations. One limitation of this study is the duration of follow-up data. The mean follow-up time is 5 ± 4.3 years. Mitigating against this limitation is the fact that most recurrences observed in our series (75%) are noted in the first year after the procedure. Other studies have noticed this observation as well [26, 27]. Although the current results appear excellent, it will be important to continue to examine the endurance of this repair for a longer time.

This series of more than 200 patients undergoing coarctation repair demonstrates that REEEA repair can be performed with a low operative mortality and complication rate. The repair can be performed both by median sternotomy or a left thoracotomy approach. The repair effectively addresses arch hypoplasia. Aberrant origin of the right subclavian artery was a risk factor for recoarctation and should be considered a potential reason to repair the defect with a sternotomy approach. Midterm follow-up demonstrates the recoarctation rate is low and makes this our procedure of choice for CoAo in all neonates, infants, and younger children.

We would like to thank our statistician, Christine Sullivan, MS.

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