Early and long-term results of the surgical treatment of tetralogy of Fallot with pulmonary atresia, with or without major aortopulmonary collateral arteries

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Objective: We sought to determine the results of surgical treatment of patients with tetralogy of Fallot and pulmonary atresia with or without major aortopulmonary collateral arteries, to clarify variables affecting early and late mortality, and to expose late, nonfatal events affecting surgical patients.

Methods: The records of 495 patients operated on from 1977 to 1999 were reviewed. Patients were separated into those who did not undergo complete repair (group A) and those who did (group B).

Results: Group A consisted of 160 patients. Eighty-one (51%) had palliative procedures, 45 (28%) had preliminary surgical stages (unifocalization and right ventricular outflow tract reconstruction) as initial operations, and 34 (21%) had all surgical stages but were rejected for complete repair. Early and late mortality were 16.3% (n = 26) and 23.1% (n = 31), respectively. Mean follow-up was 72.3 months. The presence of major aortopulmonary collateral arteries was a risk factor for late mortality ($P = .0182$). Group B consisted of 335 patients. Mean age at complete repair was 11.3 years (SD, 9.2). One hundred three (30%) patients had single-stage complete repair, whereas 232 (69%) had staged reconstruction. Twenty-two (6.6%) patients underwent reopening of the ventricular septal defect for high right ventricular pressure. Early and late mortality were 4.5% (n = 15). Risk factors were a peak right ventricular/left ventricular pressure ratio of greater than 0.7 and reopening of the ventricular septal defect ($P \leq .05$). Late mortality was 16% (n = 51). Mean follow-up was 11.4 years (SD, 7.5). Risk factors included male sex, nonconfluent central pulmonary arteries, reopening of the ventricular septal defect, and postrepair conduit exchange (n = 137). Ten- and 20-year results were an actuarial survival of 86% and 75% and freedom from reoperation of 55% and 29%, respectively.

Conclusions: Surgical repair of patients with simple or complex forms of tetralogy of Fallot with pulmonary atresia can be achieved with low early mortality. Late mortality and need for reoperation, especially conduit replacement, continue to affect the long-term well-being of these patients.

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Patients with tetralogy of Fallot and pulmonary atresia exhibit the extreme form of the malformation, with its associated anomalies affecting the pulmonary arterial circulation. The morphologic features of this anomaly have been reported previously.¹⁻³ A characteristic of these patients is the presence of complex abnormalities of the pulmonary arterial tree⁴ and the presence of major aortopulmonary arterial collateral arteries connecting the systemic with the pulmonary circulations. The clinical presentation of these patients is variable, depending on the magnitude of the pulmonary blood flow, which allows some patients to maintain an excellent functional status for many years.⁵ Nevertheless, the great majority of patients require surgical treatment for stabilization of their clinical condition.⁶ To this date, few reports have dealt with the long-term results of the surgical treatment of this complex group of patients.

We sought to determine the early and late results of surgical treatment and to identify variables that may influence mortality and the occurrence of late, nonfatal events affecting the clinical course of patients with tetralogy of Fallot and pulmonary atresia.

Methods

Palliative procedures were those designed to improve patient symptomatology; most of these were systemic-pulmonary artery shunts.

Reconstructive procedures were those designed to modify the pulmonary arterial morphology and circulation so as to prepare the patient for complete repair. Right ventricular outflow reconstruction by means of establishment of right ventricle-pulmonary artery continuity with a valveless conduit, leaving the ventricular septal defect open, was used to induce enlargement of hypoplastic, confluent central pulmonary arteries by exposing them to the wide pulse pressure resulting from the absence of the valve in the connecting conduit. Unifocalization procedures, designed to correct the arborization abnormalities associated with the presence of major aortopulmonary arterial collaterals, were used to eliminate multiple, extracardiac sources of pulmonary arterial blood flow while creating a single source that could be accessed at the time of complete repair.

Complete repair was defined as closure of septal defects (atrial and ventricular), establishment of unrestricted continuity between the right ventricle and as many of the pulmonary arterial segments as possible, and elimination of extracardiac sources of pulmonary arterial blood flow. Patients who underwent an attempt at complete repair but had their ventricular septal defect reopened because of excessively high right ventricular pressure were not considered to have had complete biventricular repair. Except for a few exceptions during the early part of our experience, a valved conduit was used to establish continuity between the right ventricle and the pulmonary arteries at the time of complete repair. Conduits used included porcine valved composite Dacron conduits and cryopreserved aortic or pulmonary valve homografts. Complete repair was accomplished with standard techniques of hypothermic cardiopul-

monary bypass. Myocardial protection during periods of aortic crossclamping was achieved with infusion of cold blood cardioplegic solution. Short periods of circulatory arrest were often used during complex reconstruction of the pulmonary arteries.

The techniques and management protocols used in the surgical treatment of patients with tetralogy of Fallot and pulmonary atresia have evolved over the course of the past 3 decades. For most patients, complete repair by means of closure of the septal defects and establishment of continuity between the right ventricle and the largest number of pulmonary arterial segments with a valved conduit constitutes the ultimate objective of the surgical treatment of these patients. This goal was achieved during a single surgical stage when all significant malformations affecting the pulmonary arterial circulation could be corrected with a median sternotomy approach and cardiopulmonary bypass. Patients selected for this approach had relatively simple pulmonary arterial anatomy. Multiple surgical stages were used when the central pulmonary arteries were absent, in the presence of significant hypoplasia of the pulmonary arterial confluence (<50% of normal for the central pulmonary arterial area), when the most proximal portion of the pulmonary arterial tree could not be accessed easily through the median sternotomy approach, and/or in the presence of major arborization abnormalities of the pulmonary arteries associated with major aortopulmonary arterial collaterals. Surgical stages used before complete repair included reconstruction of the right ventricular outflow tract, unifocalization procedures, or both. When staged surgical interventions were used to prepare the patient for complete repair, postoperative cardiac catheterization and angiography were performed to ascertain the success or failure of the procedure before proceeding with the next surgical stage, complete repair, or both. After completion of all preliminary surgical stages, patients selected for complete repair were those in whom final right ventricular outflow reconstruction would incorporate at least 14 pulmonary arterial segments, those with a predominant left-to-right intracardiac shunt, and those with significant but repairable residual stenotic areas in the pulmonary arterial tree. Finally, the relation of the right ventricular to the left ventricular systolic pressures (peak right ventricular/left ventricular [PRV/LV] systolic pressure ratio) at the conclusion of the repair was measured intraoperatively by means of direct needle puncture. If the ratio was found to be higher than 0.85, the ventricular septal defect was reopened immediately.

In recent years, we have pursued complete repair in a selected group of infants and small children with favorable pulmonary arterial anatomy. For this approach, we have selected patients with good-sized central pulmonary arteries whose major aortopulmonary arterial collaterals are accessible through the median sternotomy approach for complete unifocalization.

Population

The records of 499 patients with tetralogy of Fallot and pulmonary atresia with or without major aortopulmonary arterial collaterals who had at least one surgical intervention at the Mayo Clinic from January 1, 1977, to January 1, 2000, were reviewed. Four patients did not authorize inclusion in the study and were eliminated from further analysis. Also excluded from this study were patients with pulmonary atresia associated with other cardiac abnormalities, such as univentricular heart, atrioventricular septal defect, hypo-

Figure 1. Distribution of the patient population: group A, patients who underwent palliative procedures, reconstructive procedures, or both but had not undergone complete repair; group B, patients who underwent complete repair in a single surgical stage or after previous surgical stages. TOF, Tetralogy of Fallot; PA, pulmonary atresia; MAPCA, major aortopulmonary collateral artery; systemic-PA, systemic-pulmonary artery; RVOT, right ventricular outflow tract reconstruction; Uni, unifocalization procedures.

plastic right or left ventricle, and discordant atrioventricular or ventriculoarterial connection.

The patient population was divided into 2 groups. Group A is composed of 160 patients who have not undergone complete biventricular repair but have undergone palliative or reconstructive procedures and may be waiting for complete repair or further surgical stages or were assessed and rejected for complete repair. Group B includes 335 patients who have undergone complete repair in a single surgical stage (96 patients) or after previous reconstructive procedures (239 patients).

Demographic, morphologic, and surgical data were obtained from hospital records and entered into the SAS system (SAS Institute, Inc, Cary, NC). Recent cross-sectional follow-up (94.6%) was obtained through the Mayo Survey Research Center by means of telephone calls and written correspondence. Twenty-seven patients were lost to follow-up, and their last observed episode was used for calculation purposes.

Statistical Analysis

Survival probabilities and 95% confidence intervals were computed with the Kaplan-Meier method. The prognostic significance of factors was tested in a univariate model by using the log rank statistic for categorical covariates and by using the Cox proportional hazards model for continuous and time-dependent covariates. The Cox proportional hazards model was also used to test the prognostic significance of factors in a multivariate model. Relationships of factors to perioperative death were evaluated with the χ^2 test, the Fisher exact test, and the Wilcoxon rank sum test.

Results

The study population is summarized in Figure 1. Group A is composed of 160 patients who underwent palliative or reconstructive procedures but had yet to undergo or had been rejected for complete repair. This group includes 81 patients who had palliative procedures; 45 patients who had palliative procedures, reconstructive procedures, or both but had

not yet been assessed for complete repair; and 34 patients who completed all preliminary surgical stages and were assessed and rejected for complete repair because of persistent uncorrected abnormalities of the pulmonary arterial tree, pulmonary vascular obstructive disease, or both. There were 81 male (50.6%) and 79 female (49.4%) patients. Morphologic characteristics of these patients are shown in Table 1. One hundred forty-six (91.5%) patients had major aortopulmonary collateral arteries. Twenty-three (14.4%) patients had confluent normal-sized pulmonary arteries. The surgical procedures and catheter interventional procedures performed in these patients are shown in Table 2. The reconstructive procedures included right ventricular outflow tract reconstruction (98 procedures) and unifocalization operations (98 procedures). Hospital mortality in group A patients was 16.3% (26 patients). The surgical mortality improved with increasing surgical experience, as shown in Figure 2. Causes of early death are shown in Table 3. Follow-up of these patients from their first surgical procedure, which may have occurred before 1977, ranged from 1 to 369 months (mean, 8.0 years; SD, 6.7). Mortality during the follow-up period included 31 (23.1%) of 134 survivors. Actuarial survival in this group is depicted in Figure 3. Survival at 5, 10, 15, and 20 years of follow-up was 83%, 73%, 61%, and 61%, respectively. Univariate analysis of selected prognostic factors for early and late mortality are listed in Table 4. Perioperative mortality was higher in patients aged 5 years or younger at the time of the last surgical procedure ($P = .04$). Late mortality appeared to be more common in patients with major aortopulmonary collateral arteries ($P = .0182$).

Group B is composed of 335 patients who underwent complete repair during a single surgical stage or after mul-

TABLE 1. Group A: Morphologic characteristics

Morphology Patients	No. (%)
Central PAs	
Absent	23 (14.4)
Confluent, normal sized	1 (0.6)
Confluent, hypoplastic	101 (63.1)
Nonconfluent	33 (20.6)
Single	2 (1.3)
MAPCAs	
Present	146 (91.2)
Absent	14 (8.8)
Other sources of pulmonary blood flow	
Ductus arteriosus	16 (10)
Coronary-PA fistula	4 (2.5)
Ventricular septal defect	
Single	155 (96.9)
Multiple	5 (3.1)

PA, Pulmonary artery; MAPCA, major aortopulmonary collateral artery.

tiple reconstructive procedures. Age at the time of complete repair ranged from 1 day to 54.6 years (mean, 11.3 years; SD, 9.23). Twenty-four patients underwent complete repair during the first year of life. There were 2 (8.3%) surgical deaths in this group. There were 160 male (47.8%) and 175 female (52.2%) patients. Ninety-six (28.6%) patients underwent complete repair during a single surgical stage (mean age at complete repair, 10.2 years; SD, 10.0; range, 1 day-43.77 years). The remaining 239 (71.3%) additional patients in group B required a mean of 1.5 surgical procedures before undergoing complete repair. In this latter group mean age at the initial operation was 5.5 years (SD, 6.7; range, 1 day-34.1 years); mean age at complete repair was 11.8 years (SD, 8.9; range, 1 day-54.6 years). Some of the preliminary surgical stages were done at other institutions before the first Mayo Clinic visit and may have occurred before the onset of the study. Morphologic features of the pulmonary arterial tree for all patients in group B is shown in Table 5. Twelve (3.6%) patients had no central pulmonary arteries, and 223 (66.5%) patients had major aortopulmonary collateral arteries. Preliminary surgical procedures are summarized in Table 6. One hundred sixty-eight patients underwent a total of 198 systemic-pulmonary artery shunts before complete repair. The median time interval between initial shunt placement and complete repair was 4.5 years (SD, 7). Eighty-nine patients underwent right ventricular outflow tract reconstruction before complete repair. One hundred twenty-three unifocalization procedures were performed in 81 patients before complete repair, and 19 unifocalization procedures were performed in 19 patients during complete repair. At the time of complete repair, 146 patients underwent surgical interruption of residual major aortopulmonary arterial collaterals. At the end of complete repair, the mean PRV/LV systolic pressure ratio for the entire group was 0.66 (SD, 0.180). There was a significant

TABLE 2. Group A: Surgical and catheter interventions

Interventions	No.
Palliative procedures	81
RVOT reconstruction	98
Unifocalization	98
ASD closure	3
Pulmonary arterial confluence graft	14
Surgical interruption of MAPCAs	64
PA dilatation-stenting	4
PA dilation-stenting	13
Aortic valve replacement	14

RVOT, Right ventricular outflow tract; ASD, atrial septal defect; MAPCA, major aortopulmonary collateral artery; PA, pulmonary artery.

TABLE 3. Group A: Causes of surgical mortality

Cause	No. (%)
Cardiac	
Low cardiac output	11 (6.9)
Arrhythmia	4 (2.5)
Myocardial infarction	2 (1.25)
Noncardiac	
Bronchospasm-respiratory failure	7 (4.4)
Neurologic	2 (1.25)
Total	26 (16.3)

correlation between age at the time of complete repair and resulting mean PRV/LV systolic pressure ratio ($P = .007$). This difference did not appear to be clinically significant because less than 3% of the variation in the PRV/LV systolic ratio was explained by age. Reopening of the ventricular septal defect during complete repair was performed in 22 patients who were found to have excessively high right ventricular pressures (PRV/LV systolic pressure ratio, >0.85).

Surgical mortality (30-day) for all group B patients was 4.5% (15 patients). Three of the early deaths occurred in the group of patients who had their ventricular septal defects reopened. Causes for early mortality are shown in Table 7. Mortality in patients who underwent single-stage complete repair was 7.8% versus 3% in those who had preliminary surgical stages. Perioperative morbidity is shown in Table 8. Respiratory failure requiring prolonged mechanical ventilation was the most common postoperative complication, occurring in 46 (66%) patients. Mean follow-up from complete repair was 11.4 years (SD, 7.5; range, 1 month-23 years). Fifty-two (16.3%) of 320 operative survivors died during the follow-up period. Causes of late death are shown in Table 9, with cardiac failure and reactive airway disease being the most common causes. Actuarial survival is shown in Figure 4. Five-, 10-, 15-, and 20-year survival is shown in Table 10. Univariate analysis of selected factors for late

Figure 2. Surgical mortality for group A patients grouped under different time periods shows improvement in results with time.

Figure 3. Kaplan-Meier actuarial survival for patients in group A after last surgical procedure.

mortality is shown in Table 11. Statistically significant factors included reopening of the ventricular septal defect, a PRV/LV systolic pressure ratio of greater than 0.7, male sex, the need for a pulmonary artery confluence graft, and late reoperation for extracardiac conduit replacement. Table 11 shows multivariate analysis for possible factors predictive of death after complete repair. Reopening of the ventricular septal defect was the single significant factor ($P = .0004$). Freedom from reoperation is shown in Figure 5. Late surgical and catheter interventions are shown in Table 12. One hundred sixteen patients have required surgical revision of the right ventricular outflow tract during the

follow-up period. Four (3.4%) patients died during conduit replacement at other institutions. The mean interval from complete repair to the first revision of the right ventricular outflow tract was 9.8 years (SD, 5.9). Twenty-one patients of this group required more than one conduit replacement. Twenty patients have required aortic valve repair or replacement for progressive aortic insufficiency, and 29 patients underwent closure of residual ventricular septal defect; 10 of these closures were in patients whose ventricular septal defects had been reopened at the time of complete repair.

An effort was made to determine whether elevation of the right ventricular pressure independent of conduit ob-

TABLE 4. Group A: Selected variables for early mortality univariate analysis

Variable	No. (%)	P value
Female sex	13 (16.5)	.94*
Confluent PAs	17 (16.7)	.40*
Coronary to PA fistula	1 (25)	.51*
Age at last operation		.04†

PA, Pulmonary artery.

*Statistical testing with the Fisher exact test comparing patient characteristics within each respective group.

†Statistical testing with Wilcoxon rank sum test.

TABLE 5. Group B: Morphologic characteristics

Morphology	Single-stage repair (n = 96), No. (%)	Multistage repair (n = 239), No. (%)	Total (n = 335), No. (%)
	No. (%)	No. (%)	No. (%)
Central PAs			
Confluent, normal size	22 (22.9)	28 (11.7)	50 (14.9)
Confluent, hypoplastic	58 (60.4)	162 (67.7)	220 (65.7)
Nonconfluent	11 (11.4)	39 (16.3)	50 (14.9)
Single	3 (3.1)		3 (0.9)
MAPCAs			
Present	69 (71.8)	174 (72.8)	243 (72.5)
Absent	27 (28.1)	65 (27.1)	92 (27.5)
Other sources Q_p			
Ductus arteriosus	37 (38.5)	35 (14.6)	72 (21.5)
Diffuse SCAs	9 (9.3)		9 (2.6)
Coronary-PA fistula	8 (8.3)	3 (1.2)	11 (3.3)
Single VSD	92 (95.8)	235 (98.3)	327 (97.6)

PA, Pulmonary artery; MAPCA, major aortopulmonary collateral artery; SCA, systemic collateral artery; Q_p , pulmonary blood flow; VSD, ventricular septal defect.

TABLE 6. Group B (n = 335): Preliminary surgical procedures before complete repair

Procedure	No.
Systemic-PA shunt	198
Potts	8
Waterston	60
Blalock-Taussig (classic)	41
Blalock-Taussig (modified)	82
BDCPA	2
Mee procedure	5
RVOT reconstruction	89
Unifocalization	161
Before complete repair	142
At the time of complete repair	19
Pulmonary confluence prosthesis	52
Interruption of MAPCAs	156
Surgical	146
Coil embolization	10
Reopened VSD	22

BDCPA, Bidirectional cavopulmonary anastomosis; RVOT, right ventricular outflow reconstruction; MAPCA, major aortopulmonary arterial collateral artery; VSD, ventricular septal defect.

TABLE 7. Group B (n = 335): Causes of early mortality

Cause	No. (%)
Cardiac	
Low cardiac output	10 (3.0)
Arrhythmia	2 (0.6)
Noncardiac	
Bronchospasm	1 (0.3)
Neurologic	2 (0.6)
Total	15 (4.5)

TABLE 8. Group B (700 operations): Perioperative morbidity

Complication	No. of events (%)
Neurologic	5 (0.71)
Phrenic nerve injury	2 (0.28)
Reoperation for bleeding	21 (3.0)
Sepsis	36 (5.1)
Heart block (pacemaker)	4 (0.57)
Prolonged mechanical ventilation*	46 (6.6)
Pulmonary infarct	3 (0.42)
Tracheotomy	9 (1.3)

*More than 48 hours.

TABLE 9. Group B: Causes of late death (320 survivors of complete repair)

Cause	No. (%)
Cardiac	
Cardiac failure	13 (4.0)
Arrhythmia	10 (3.1)
Noncardiac	
Bronchospasm	8 (2.5)
Neurologic	1 (0.3)
Other*	5 (1.6)
Unknown	15 (4.7)
Total	52 (16.3)

*One patient died in a motor vehicle accident, one patient died of bleeding at reoperation, one patient died in hepatic-renal failure, one patient died of trauma, and one patient died suddenly while asleep.

struction occurs in these patients after complete repair. Such a change would reflect an increase in pulmonary arterial resistance. Table 13 compares right ventricular pressure measured intraoperatively after complete repair with that measured after the first extracardiac conduit replacement. These measurements would be independent of conduit obstruction. There was no significant change in right ventricular pressure.

Discussion

The surgical management of patients with tetralogy of Fallot and pulmonary atresia remains controversial and in a

Figure 4. Kaplan-Meier actuarial survival for patients in group B after complete repair.

TABLE 10. Group B: Long-term survival

	Survival (%)	Confidence interval
5 y	92	89–95
10 y	86	82–90
15 y	83	78–88
20 y	75	67–82

TABLE 11. Group B: Final multivariate (Cox model) assessment of prognostic factors in mortality in patients undergoing complete repair

Variable	Risk ratio	95% confidence interval	P value
Male sex	1.772	1.011–3.104	.0456
Reopening VSD	5.613	2.149–14.661	.0004*
Age at complete repair	1.028	1.001–1.055	.0449

VSD, Ventricular septal defect.

*Statistical significance, $P < .001$.

state of evolution. At the Mayo Clinic the focus has been on the search for surgical techniques that would allow reconstitution of the right ventricular outflow tract and closure of the ventricular septal defect (complete repair). Such goals are easily reached when the pulmonary arterial size and architecture are well preserved, as in the simple forms of the anomaly.⁷ In our practice conditions for complete repair have included a central pulmonary arterial area at least 50% of normal size, the potential for incorporating at least 14 pulmonary segments to the right ventricular tract, a predominant left-to-right shunt, and correctable stenotic lesions in the pulmonary arterial tree. For patients with hypoplastic pulmonary arteries, establishment of continuity between the right ventricle and the hypoplastic pulmonary arterial confluence with a nonvalved rigid conduit, leaving the ventricular septal defect open, has been shown to induce pulmo-

nary arterial growth-dilatation, allowing for subsequent closure of the ventricular septal defect in many patients, particularly those without major arborization abnormalities.^{8–11} For neonates and infants with hypoplastic central pulmonary arteries, we have preferred direct anastomosis of the hypoplastic main pulmonary artery to the ascending aorta, as proposed by Watterson and colleagues.¹² For those patients with pulmonary arterial arborization abnormalities and multiple major aortopulmonary collateral arteries, incorporation of an adequate number of pulmonary arterial segments to the right ventricle has required ingenious surgical maneuvers grouped under the term *unifocalization procedures*. Such interventions have met with varied success in improving the candidacy of patients for the final intracardiac repair.^{13–16}

The relative lack of symptoms and long survival seen in some patients with these anomalies demand justification for the need of aggressive and complex surgical procedures.¹⁷ In general terms a low surgical risk is mandatory to justify interference with the natural history of the anomaly. Clearly, surgical intervention is warranted in those symptomatic patients with increasing cyanosis resulting from reduced pulmonary blood flow. It is also indicated in those patients with congestive heart failure caused by excessive pulmonary blood flow. It is frequently indicated in those at risk of losing pulmonary arterial segments because of progressive obstruction of major aortopulmonary collateral arteries and in those whose morphologic characteristics expose them to pulmonary vascular obstructive disease. In such circumstances palliation may be combined with reconstructive procedures that result in improvement in the pulmonary arterial architecture and prepare the patient for possible complete repair. In those patients who are clinically stable and enjoy acceptable levels of functional capacity, elective reconstructive surgical procedures would appear to

Figure 5. Freedom from reoperation for patients in group B after complete repair.

be a reasonable option when the pulmonary and collateral arterial circulation appears amenable to surgical improvement, when the risks of such surgical interventions appear to be low, and when the possibilities of success are high. Thus, careful assessment of individual patients is mandatory.

Our patient population is skewed toward the older age groups, reflecting the nature of our practice. Thus, our experience with neonates is limited. Repair of the simple forms of the anomaly in infants and small children has been reported by DiDonato and colleagues.¹⁸ Although our experience confirms the feasibility of surgical repair of this anomaly in small children and infants, our preference has been to indicate single-stage repair in selected patients. We have followed with interest the experience of Hanley and others who have proposed an aggressive, uniform surgical approach for the child born with this anomaly.¹⁹⁻²¹ The use of the midline approach for complex single-stage unifocalization procedures has allowed a concerted effort directed at the treatment of all neonates born with the anomaly rather than focusing only on the selected survivors of the first few years in life.

After complex unifocalization procedures in infants, methods have been proposed to determine intraoperatively which ventricular septal defects can be closed with resulting adequate right ventricular pressure. These methods rely on estimation of the total pulmonary resistance by means of continuous perfusion with a roller pump.¹⁹⁻²² Our preference has been to complete the repair and to measure right and left ventricular systolic pressures by means of direct needle puncture after discontinuation of cardiopulmonary bypass. Those patients in whom the PRV/LV systolic pressure ratio is greater than 0.85 have the ventricular septal defect reopened before completion of the surgical procedure.

Reactive airway disease has been an important cause of mortality and morbidity in patients undergoing surgical

TABLE 12. Group B: Number and types of interventions after complete repair

Intervention	Interval (y)*			
	No.	No. of patients	Mean	SD
RV-PA conduit revision	137	116†	9.8	5.9
Reclosure of VSD	29	29	6.1	6.2
Coil embolization	18	11	6.7	5.2
PA dilation (balloon-stent)	67	51	5.4	5.6
Aortic valve replacement	27	20	10.5	8.7
Tricuspid annuloplasty	10	10	14.8	9.8

RV-PA, Right ventricle–pulmonary artery; VSD, ventricular septal defect; PA, pulmonary artery.

*Interval is from complete repair to first reoperation.

†Twenty-one of 116 patients underwent more than one conduit reoperation.

procedures for this anomaly. In our series cardiorespiratory events were the most common cause of early and late death in both group A and B patients. Bronchospastic episodes appear to be particularly common in patients with associated velocardiofacial syndrome.²³

Patients who underwent staged reconstruction up to and including complete repair had the lowest perioperative mortality of all groups (3%). Single-stage repair in our series had a perioperative mortality of 7.8%. This fact supports our contention that the staged approach may be associated with less surgical risk, particularly in patients with complex pulmonary arterial circulation, absent central pulmonary arteries, and the presence of major aortopulmonary arterial collaterals. Our mortality for single-stage repair was similar to that reported in other series.^{24,25}

The need to reopen the ventricular septal defect at the time of attempted complete repair ($n = 22$, 6.5%) was a significant factor for early ($P = .001$) and late (univariate $P = .0007$ and multivariate $P = .00004$) mortality. This

TABLE 13. Group B: Late right ventricular pressure in patients undergoing conduit replacement as a predictor of death

	n	Mean (mm Hg)	Mean mm Hg	SD (mm Hg)	5-y survival (95% CI)	P value
After complete repair	313	58	59	16		
After FCX	85	50	54	17		
CR-FCX (change in RV pressure)	81	9	6.2	21		
CR-FCX <0	27				96.3 (87–100)	.726
CR-FCX <14	25				90.3 (78–100)	
CR-FCX >15	27				96.0 (87–100)	

FCX, First conduit exchange.

reflects the presence of intolerably high right ventricular pressures and unfavorable pulmonary arterial anatomy. The mean PRV/LV systolic pressure ratio for patients who underwent successful closure of the ventricular septal defect was 0.64. Although our policy has been to reopen the ventricular septal defect when the ratio is higher than 0.85, this study suggests that a ratio of greater than 0.7 is associated with higher early mortality ($P = .002$). Ten of 21 survivors of ventricular septal defect reopening underwent successful late closure of the defect, usually after pulmonary arterial runoff was improved by means of catheter interventions.

It is not yet clear whether a single-stage approach should be offered to all affected patients born with this anomaly. In our practice we have selected, for this approach, only those small children and infants with normal-sized or mild hypoplasia of the pulmonary arterial confluence and with accessible major aortopulmonary collateral arteries. All other patients continue to be treated with the staged approach.

Patients who have had successful repair are not free from the need for further surgical therapy. Revision of the right ventricular outflow tract has been the most common late intervention. One hundred sixteen patients underwent 137 conduit replacements. Given the results obtained with the available extracardiac conduits,²⁶ this is not likely to change significantly in the near future. Reclosure of residual or recurrent ventricular septal defects, which contribute to right ventricular hypertension, has been necessary and rewarding in some patients. Late development of aortic valve insufficiency has required aortic valve replacement or repair, a procedure often scheduled in conjunction with replacement of extracardiac conduits. Repeat cardiac catheterization with balloon dilatation, stenting of residual areas of stenosis, or both in the pulmonary arteries has been helpful in reducing pulmonary arterial resistance and in helping to optimize the distribution of pulmonary arterial blood flow.

Although the mere prosthetic replacement of missing or unusable segments of the pulmonary arterial tree has been shown to be possible with reported surgical techniques,^{27,28} such interventions do not obviate the problem of lack of

growth of the prosthesis and of scarring or stenosis of surgical anastomotic sites. The surgeon's inability to distribute the pulmonary blood flow equally to all available pulmonary arterial segments can have significant consequences for the repaired patient, particularly in terms of progression of pulmonary hypertension and ventilation-perfusion mismatch. These difficulties are proportional to the complexity of the pulmonary arterial malformation, and even with the help of catheter interventional techniques (balloon dilatation, stenting, or both), the results obtained with complex reconstructive techniques (unifocalization procedures) may not result in adequate decompression of the right ventricle. Careful follow-up of these patients is mandatory.

In conclusion, our series confirms that patients with tetralogy of Fallot and pulmonary atresia with complex malformations of the pulmonary arterial circulation can undergo complex reconstructive surgical procedures that prepare them for complete repair. The surgical risk of such interventions appears to be acceptable and can be minimized by prudent staging of the complex surgical interventions. Complete repair can be undertaken during a single surgical stage in selected patients in whom the malformation affecting the pulmonary arterial tree can be corrected during a midline sternotomy approach. Long-term survival is possible after corrective operations, although patients continue to require reinterventions, particularly for replacement of obstructed or incompetent valved extracardiac conduits. Balloon dilatation, stenting, or both of residual areas of obstruction in the reconstructed pulmonary arteries are important for improvement in the distribution of pulmonary arterial blood flow.^{29,30} Surgical reconstruction can be indicated in patients with a well-balanced physiology with few symptoms when their pulmonary arterial anatomy offers good opportunities for unifocalization and eventual complete repair.

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Discussion

Dr William G. Williams (Toronto, Ontario, Canada). Dr Cho and his colleagues are to be congratulated for presenting their very extensive experience with pulmonary atresia and ventricular septal defect and for illustrating the complete spectrum of pathology of this lesion.

The nomenclature *pulmonary atresia-ventricular septal defect* is somewhat unfortunate because it is a single name for an entity of many faces. It is appropriate for the Mayo Clinic group to present these data because the first extracardiac nonvalved conduit used for repair of this condition was inserted at the Mayo Clinic when Dr John Kirklin created a pericardial tube connecting the right ventricle to the pulmonary artery. His sentinel patient did well for more than 20 years after repair, and this gives rise to my first question. What is your current policy regarding the use of nonvalved conduits for palliation or repair of pulmonary atresia-ventricular septal defect? There are 137 conduit reoperations among the surviving patients: What do you recommend for those requiring conduit replacement, valve or no valve, and which type of connection?

Pulmonary atresia-ventricular septal defect, at the favorable end of the morphologic spectrum, is a close cousin of tetralogy; the management and outcomes are similar. In contrast, patients with nonconfluent and, indeed, absent pulmonary arteries are at the other end of the spectrum, and either palliation or repair is problematic.

As you have shown, these patients require unifocalization of their aortopulmonary collaterals to a single source of blood supply and then either connection to an arterial shunt, such as a Blalock-

Taussig shunt, or to the heart, with or without ventricular septal defect repair. The surgical alternatives may be a thoracotomy and unifocalization of one lung at a time or median sternotomy with reconstruction of both sides.

My second question is this: Given your extensive experience, what do you currently recommend as a protocol for managing those patients with nonconfluent, plus or minus absent, pulmonary arteries?

To be critical of your analysis, I think it was counterproductive to create 2 subgroups at the outset, in this case palliation only versus attempted repair. The power of the data would be greater if all 495 patients were included in the analysis to look for statistical correlations with, for example, successful repair as the outcome variable. One can then address the obvious question among others: Does the initial operation affect the probability of the patient having a successful repair?

Although the 2 groups you have created are clinically relevant, they are not entirely clean. The palliation group includes 45 patients who may undergo repair at some point when their assessment is completed, and conversely, the attempted repair group contains 22 patients in whom the ventricular septal defect had to be reopened, and they are therefore palliated.

The data set, of necessity, contains a plethora of numbers, and Dr Cho has done an excellent job in helping us understand the data. The bottom line, if my calculations are correct, is that successful repair was achieved in 60% of the 495 patients. That may reach as high as 70% if the current patients awaiting assessment undergo repair. Although 60% may seem disappointing, it is a considerable improvement over about 10 years ago, when only a third of these patients were undergoing repair. Have you analyzed the trend toward the increasing numbers of patients who are amenable to complete repair over time? What do you estimate as the probability of complete repair in the present era for a patient with pulmonary atresia–ventricular septal defect?

Finally, there are some older patients with ventricular septal defect who present as adults, usually with previous palliation. These patients tend to have a good long-term outlook in terms of survival. What is your current indication for intervention in the adult with pulmonary atresia–ventricular septal defect?

Dr Cho. Thank you, Dr Williams. I will answer these questions in order.

The first question concerned when to consider the use of a nonvalved conduit. In patients who have hypoplastic pulmonary arteries and pulmonary arteries that we would want to grow, we usually use a nonvalved conduit.

After repair, our preference has been the use of a valved conduit. We do not use nonvalved conduits on the basis of the criteria for complete repair. Patients had to have a pulmonary artery size greater than 50% of normal. We believe that is significant enough to allow for successful complete repair, although, as you saw, 6.5% of the patients did have to undergo reopening of the ventricular septal defect, probably as a result of the underlying morphology in the branch pulmonary arteries.

As to the third question, concerning management of nonconfluent pulmonary arteries, we use a pulmonary artery confluence graft. It is a T graft. Fifty-one patients had placement of a confluence graft, of whom 9 patients had placement before complete repair. The other 42 patients had placement of that T graft con-

nected to the right ventricular outflow tract reconstruction at the time of complete repair.

What is the probability of complete repair in this patient population? It is a diverse population, and perhaps at the end of this discussion, Dr Puga might comment on that. I always tell folks that if I could predict the future, I would bet on the ponies in Vegas. And I do not think anyone has that answer for this disease process.

Current indications for an adult patient, I think, depend on symptoms. If a patient has cyanosis or congestive heart failure, I think he or she should undergo some sort of palliation and a possible reconstructive procedure, right ventricular outflow tract reconstruction, or unifocalization leading to a potential complete repair at a later date.

Where the controversy lies is in those patients who are not symptomatic. If they have favorable morphology and if you can perform this operation with a low risk of mortality, as I believe that we have been able to demonstrate with the numbers, I believe that these patients should be offered an operation. The reason why they may be relatively asymptomatic is that they have a balanced physiology, but that can change.

Dr Christo I. Tchervenkov (*Montreal, Quebec, Canada*). I would like to acknowledge the significant contributions of the Mayo Clinic in the treatment of this difficult group of patients.

I would like to echo some of the comments that Dr Williams made and actually take the discussion a little bit further. Pulmonary atresia–ventricular septal defect is an extremely heterogeneous malformation with tremendous variation in the pulmonary circulation. On one end of the spectrum, patients with pulmonary atresia–ventricular septal defect have only native pulmonary arteries, and at the other end, they only have major aortopulmonary collateral arteries (MAPCAs) and no native pulmonary arteries. To clump all these morphologic characteristics together does cloud the picture in terms of statistical analysis and may prevent us from getting useful information that should be obtained from such a large series as to the optimal surgical approach for each subgroup.

In the Nomenclature Supplement of *The Annals of Thoracic Surgery* in April 2000, we suggested that these patients should be divided into 3 broad groups simply on the basis of the presence or absence of native pulmonary arteries (NPAs) and MAPCAs. In pulmonary atresia–ventricular septal defect type A there are only NPAs and no MAPCAs, in type B there are both NPAs and MAPCAs, and in type C there are only MAPCAs and no NPAs.

Because patients in these 3 groups may require different initial and subsequent treatment strategies and have different outcomes, have you tried to analyze your data with almost 500 patients in that fashion? If you have not done so, I would certainly hope that you would consider doing that.

Dr Cho. We have not analyzed it with respect to that classification. However, for patients who have a favorable anatomy, we have proceeded with a single-stage complete repair to include unifocalization in a number of patients. But they have to meet the criteria that I listed, and the major aortopulmonary collaterals have to be accessible through the midline. We performed unifocalization in 19 patients, of whom 10 underwent single-stage complete repair with unifocalization. Nine patients, as their last operation with complete repair, underwent some component of unifocalization and complete repair.

I thank you for your comments, but we have not specifically looked at that.

Dr Vadiyala M. Reddy (*San Francisco, Calif*). Dr Cho, I would like to echo the same concerns about clamping all these patients. At least the patients who have confluent central pulmonary arteries without a significant source of collaterals should probably be separated from this if the 2 pulmonary arteries are all supplying the entire lung. The prognosis and outcome in these patients would be completely different when compared with that in patients who have part of the lung at least supplied by the collaterals in association with the pulmonary arteries.

I have a few questions for you.

What pulmonary/systemic blood flow ratio would you recommend during a complete repair, because I know you have a substantial number of patients in whom you had to reopen the ventricular septal defect? One of the criteria you listed was predominant left-to-right shunt as an indication for a complete repair. Do you have an actual number for that? If you used an actual number, was it predictive of ventricular septal defect closure in all patients, or was it not?

The other question I have for you is this: From your data in the second group, about 70% or 72% of the patients had predominant supply from collaterals; however, you have unifocalized only 30% of the patients. Would unifocalizing more patients have increased the pulmonary bed to achieve a lower PRV/LV ratio or a lesser rate of reopening of the ventricular septal defect?

Dr Cho. Thank you, Dr Reddy. We do not have a specific pulmonary/systemic blood flow ratio before repair, but we do have

one after complete repair, as you saw. Those patients whom we checked with a 21-gauge spinal needle catheter, if they have a PRV/LV systolic ratio of greater than 0.85, we will automatically reopen that ventricular septal defect.

Dr Francisco J. Puga (*Rochester, Minn*). I just want to make a couple of brief comments.

One of the reasons we divided the patient population in this fashion is to compare the fate of patients with and without repair. Clearly, these 2 groups are exposed to different late events given their different hemodynamic conditions and, to some degree, the differences in pulmonary arterial morphologic features. The fact is that the survival curves are different for these 2 groups.

Management of patients with nonconfluent pulmonary arteries in our current experience is pretty much as stated in the presentation. In infants, though, we do not like to approach them with midline unifocalization if they are going to require a central prosthesis because this creates a tremendous future problem for the child. We believe that single-stage repair is indicated if the pulmonary arterial reconstruction can be achieved with their native tissue.

The question regarding pulmonary/systemic blood flow ratio does not really pertain to the selection of patients for complete repair because most of these patients have persistent stenotic areas in the pulmonary arterial tree, many of which can be resolved in the operating room by surgical means or with intraoperative stenting. It would only be significant in the patient who has a wide, open pulmonary artery circulation or the patient with unresolvable obstructive lesions, situations that happen only rarely.

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