Intermediate results after complete repair of tetralogy of Fallot in neonates

From July 1988 through September 1993, 30 neonates with symptomatic tetralogy of Fallot underwent complete repair. Sixteen patients had tetralogy and pulmonary stenosis, 9 had pulmonary atresia, 3 had nonconfluent pulmonary arteries, and 2 had both pulmonary atresia and nonconfluent pulmonary arteries. The median age at operation was 11 days (mean $\pm$ standard error of the mean, 12.6 ± 2.9 days), with a mean weight of 3.1 ± 0.1 kg (range 1.5 to 4.4 kg). Preoperatively, 14 patients were receiving an infusion of prostaglandin, 13 were mechanically ventilated, and 6 required inotropic support. Right ventricular outflow tract obstruction was managed by a limited transannular patch in 25 patients, infundibular muscle division with limited resection in 15, and insertion of a right ventricle-pulmonary artery valved aortic homograft conduit in 5 patients. Follow-up was complete at a median interval of 24 months (range 1 to 62 months). There were no hospital deaths and two late deaths, for 1-month, 1-year, and 5-year actuarial survivals of 100%, 93%, and 93%, respectively. The hazard function for death had a rapidly declining single phase that approached zero by 6 months after the operation. Both late deaths occurred in patients with tetralogy of Fallot and pulmonary atresia who had undergone aortic homograft conduit reconstruction, so that the only independent risk factor for death was the use of a valved homograft conduit ($p \leq 0.005$). Eight patients required reoperation, resulting in 1-month, 1-year, and 5-year freedom from reoperation rates of 100%, 93%, and 66%, respectively. Indications for reoperation were branch left pulmonary artery stenosis in 5 patients, residual right ventricular outflow tract obstruction in 2 patients, and severe pulmonary insufficiency in 1 patient. Independent risk factors for reoperation included an intraoperative pressure ratio between the right and left ventricles of 0.75 or greater ($p = 0.01$), Doppler residual left pulmonary artery stenosis of 15 mm Hg or more, or Doppler right ventricular outflow tract obstruction gradient of 40 mm Hg or more at hospital discharge ($p = 0.002$ and 0.02 , respectively). This series demonstrates the safety of early hemodynamic repair of symptomatic tetralogy of Fallot in neonates. It also emphasizes the importance of relieving all sources of right ventricular outflow tract obstruction at the initial operation, particularly that located at the site of insertion of the ductus arteriosus, which may be difficult to diagnose in the neonate before ductal closure occurs. The safety and efficacy of valved aortic homograft conduits in neonates requires further investigation. (J THORAC CARDIOVASC SURG 1995;109:332-44)

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The optimal surgical management of neonates with symptomatic tetralogy of Fallot remains controversial. Some authors advocate the use of an initial palliative shunt followed by complete repair at a later date, whereas others advocate complete repair in the neonatal period.¹⁻⁴ Primarily as a result of the development of hypothermic circulatory arrest and low-flow hypothermic cardiopulmonary bypass, improved anesthetic management of neonates and infants, and advances in postoperative care, we have developed a policy of early hemodynamic

repair of symptomatic tetralogy of Fallot in the neonate whenever technically feasible. This approach avoids the risk of two cardiac operations and eliminates the complications of pulmonary artery shunting, including a nonfunctioning shunt, pulmonary artery distortion, or development of pulmonary vascular occlusive disease. There is also the theoretical advantage that this approach may minimize secondary damage to vital organs, particularly the heart, lungs, and brain. We do continue to use a palliative shunt in patients with severely diminutive pulmonary arteries and extensive aortopulmonary collaterals and in selected patients with aberrant coronary arteries. The results of early complete repair in the symptomatic neonate, including the risk for early and late death, adequacy of repair, and reoperation rate, constitute the basis of the present report.

Methods

Patient population. The medical records of 37 patients who underwent either a palliative procedure or operative repair of tetralogy of Fallot in the neonatal period from July 1988 through September 1993 were reviewed. Among the 30 patients undergoing complete repair, there were 21 boys and 9 girls, with an age range from 2 days to 28 days (median 11 days).

Surgical techniques. Patients were intubated and monitored in standard fashion. Prostaglandins were discontinued in patients receiving a preoperative infusion. The intracardiac portion of the repair was performed with the aid of low-flow hypothermic cardiopulmonary bypass with or without intermittent periods of hypothermic circulatory arrest. A single dose of cold blood-potassium cardioplegic solution (20 ml/kg) was used in all patients and was repeated if the aortic crossclamp time exceeded approximately 40 minutes. Aortic crossclamp times ranged from 22 to 57 minutes (mean $\pm$ standard error of the mean, 39 ± 2 minutes), and bypass times from 45 to 121 minutes (mean $\pm$ standard error of the mean, 71 ± 7 minutes). Right and left ventricular pressures were measured before chest closure by direct needle puncture.

Tetralogy of Fallot and pulmonary stenosis ($n = 16$). Patients with tetralogy of Fallot and pulmonary stenosis underwent transatrial repair. Through a right atriotomy, the parietal and septal extensions of the infundibular septum were incised, and obstructing muscle bundles were divided and resected as necessary. The ventricular septal defect was closed, a period of circulatory arrest being used in 10 patients. The pulmonary valve anulus was measured during the operation, and the Z-value was derived from standardized nomograms.⁵ Thirteen patients with Z-values less than approximately -2 underwent transannular patching, and three patients with a Z-value greater than -2 underwent subannular patching.

Tetralogy of Fallot and pulmonary atresia ($n = 9$). Seven patients with tetralogy of Fallot and pulmonary atresia underwent transventricular ventricular septal defect clo-

sure, and two underwent transatrial closure. In all patients a period of circulatory arrest was used, and all underwent infundibular muscle division with limited resection. The right ventricular outflow tract was managed by a transannular patch in six patients with valvular atresia and by insertion of an aortic homograft from the right ventricle to the pulmonary artery in three patients with atresia of the main pulmonary trunk.

Tetralogy of Fallot and nonconfluent pulmonary arteries ($n = 3$). All patients with tetralogy of Fallot and nonconfluent pulmonary arteries underwent transatrial closure of the ventricular septal defect, primary anastomosis of the central pulmonary arteries, placement of a transannular patch, and division of infundibular muscle bundles with limited resection. A period of circulatory arrest was used in all patients.

Tetralogy of Fallot, nonconfluent pulmonary arteries, and pulmonary atresia ($n = 2$). Both patients underwent ventricular ventricular septal defect closure and pulmonary artery reconstruction during a period of circulatory arrest. In both cases, the right ventricular outflow tract was managed by insertion of an aortic homograft from the right ventricle to the reconstructed main pulmonary artery.

Follow-up. Before hospital discharge, all patients underwent a chest roentgenogram, standard 12-lead electrocardiogram, transthoracic echocardiogram with Doppler examination of the heart and great vessels, and 24-hour Holter monitor study. Follow-up data were complete and were obtained by direct family contact from the hospital record and through correspondence with the referring cardiologist.

Statistical analysis. The medical record of each patient was reviewed to determine the morphologic, clinical, surgical, and follow-up data (Appendix 1). Preoperative and postoperative echocardiograms, cineangiograms, and hemodynamic data were reviewed with particular attention paid to the morphologic features of the initial lesion and the presence of postoperative residual lesions. All derived data were recalculated. Nakata indices and McGoon ratios were measured from preoperative cineangiograms according to standard criteria. Standard methods were used to obtain means, medians, and standard errors. t Tests were calculated under both equal and unequal variance, the unequal variance being selected if the F statistic for the equality of variances was associated with a p value of 0.05 or less. Group data are presented as the mean plus or minus standard error of the mean, and proportional data are presented with their 70% confidence limits. Two-tailed p values are used throughout. The significance of categorical variables was analyzed by χ^2 analysis, unless the numerator of any proportion had fewer than five events, in which case Fisher's exact two-tailed t test was used. The significance of continuous variables was analyzed by a generalized linear (simple) regression model. To test for statistical independence, variables significant by simple regression analysis were entered into a stepwise multiple regression analysis and retained if the corresponding p value was 0.15 or less. Actuarial survival data, rates of freedom from reoperation, and hazard functions were derived by the methods of Kaplan and Meier.

Fig. 1. Actuarial survival after complete repair of tetralogy of Fallot.

Table I. Results of simple and stepwise multiple regression analysis to test for relationship of morphology and perioperative variables to death

	Simple regression		Stepwise regression	
	F statistic	p Value	F statistic	p Value
Use of a homograft	15.56	0.0005	15.55	0.0005
Preoperative use of inotropic drugs	11.20	0.002	4.35	0.04
Transventricular VSD approach	5.60	0.025	2.614	0.11
Pulmonary atresia	3.94	0.05	1.90	0.18
Cardiopulmonary bypass time	5.35	0.03	1.44	0.242
No transannular patch	6.84	0.01	0.145	NS

Variables significant at the $p \leq 0.30$ level were entered into the multiple regression analysis and retained if the corresponding p value was ≤ 0.15 . See Appendix 1 for definitions and complete listing of variables tested. VSD, Ventricular septal defect; NS, not significant.

Results

Survival. Twenty-eight (93%) of the 30 patients undergoing complete repair of tetralogy of Fallot in the neonatal period were alive at the end of the follow-up period. There were no hospital deaths and two late deaths. Both deaths occurred at home and were sudden, occurring at 7 and 8 weeks after the operation. Both patients had tetralogy of Fallot and pulmonary atresia with confluent pulmonary arteries. The calculated Nakata indices were 99 and 123 cm^2/m^2 and the McGoon ratios were 1.08 and 1.12.

Operation in both patients consisted of transventricular ventricular septal defect closure, infundibular muscle division with limited resection, and insertion of an aortic homograft (8 mm and 12 mm) from the right ventricle to the pulmonary artery. Both patients had uncomplicated postoperative recoveries, along with normal discharge Holter monitor studies and Doppler echocardiograms. An autopsy obtained in one patient was unrevealing, leaving the reason for death obscure in both patients.

At a median follow-up of 24 months (range 1 to 62 months), the 1-month, 1-year, and 5-year actuarial survivals were 100%, 93%, and 93%, respectively (Fig. 1). Perioperative variables analyzed for their relationship to death, along with their associated F statistic and p value, are shown in Appendix 1. Several perioperative variables were significantly related to death by simple regression analysis (Table I). These included the use of preoperative inotropic agents, presence of pulmonary atresia, use of an aortic homograft, use of the transventricular approach to repair the ventricular septal defect, and the length of the cardiopulmonary bypass period. By multiple regression analysis, however, only the use of an aortic homograft and the use of preoperative inotropic agents were independently significant, the former remaining highly so (Table I).

There were no deaths associated with any reoperation, eliminating reoperation as a significant risk factor for death. The hazard function for death, which included both the initial operation and any

Fig. 2. Hazard function for death after complete repair of tetralogy of Fallot in neonates.

subsequent reoperation, had a rapidly declining single phase that approached zero by 6 months after the operation (Fig. 2).

Reoperation. Eight patients (27%) required reoperation at a median interval of 15 months (range 4 to 23 months) after the initial operation. Four of 16 patients with tetralogy of Fallot and pulmonary stenosis, and 4 of 14 patients with either pulmonary atresia or nonconfluent pulmonary arteries required reoperation. Indications for reoperation in patients with tetralogy of Fallot and pulmonary stenosis included isolated left pulmonary artery stenosis ($n = 1$), left pulmonary artery stenosis with annular hypoplasia ($n = 1$), residual right ventricular outflow tract obstruction ($n = 1$), and severe pulmonary insufficiency with tricuspid valve regurgitation ($n = 1$). Corrective procedures included left pulmonary artery angioplasty in the first two patients, with extension across the anulus in the second patient, and insertion of a valved homograft conduit from the right ventricle to the pulmonary artery in the latter two patients, in addition to tricuspid annuloplasty in the last patient.

Two patients with tetralogy of Fallot and *pulmonary atresia* required reoperation for left pulmonary artery stenosis. Both underwent insertion of a valved homograft conduit from the right ventricle to the pulmonary artery with extension past the site of left pulmonary artery stenosis. Two patients with tetralogy of Fallot and *nonconfluent pulmonary arteries* required reoperation, one for residual right ventric-

ular outflow tract obstruction and tricuspid regurgitation and the second for left pulmonary artery stenosis and a small residual ventricular septal defect. The first patient underwent resection of infundibular muscle bundles and patch widening of the right ventricular outflow tract, along with tricuspid annuloplasty. The second patient underwent insertion of a 16 mm aortic homograft from the right ventricle to the pulmonary artery with extension past the left pulmonary artery stenosis, along with transventricular closure of the residual ventricular septal defect.

Cumulatively, there were eight reoperations in eight patients, five for branch left pulmonary artery stenosis, two for right ventricular outflow tract obstruction, and one for severe pulmonary valve insufficiency with tricuspid regurgitation. The resultant 1-month, 1-year, and 5-year freedom from reoperation rates were 100%, 93%, and 66%, respectively (Fig. 3). Variables analyzed for their relationship to reoperation, along with their associated F statistic and p value, are given in Appendix 1. By both simple and multiple regression analysis, several perioperative and morphologic variables were significantly related to the risk of reoperation (Table II). The most significant factors were the presence of post-operative residual lesions detected on the discharge echocardiogram, and include the presence of residual left pulmonary artery stenosis of greater than 15 mm Hg, the presence of a residual ventricular septal defect, and the presence of residual right ventricular

Fig. 3. Freedom from reoperation (FFR) after complete repair of tetralogy of Fallot in neonates.

Table II. Results of simple and stepwise multiple regression analysis to test for relationship of morphology and perioperative variables to freedom from reoperation

	Simple regression		Stepwise regression	
	F statistic	p Value	F statistic	p Value
Residual LPA stenosis	9.98	0.002	15.12	0.0006
PRV/LV ≥ 0.75	5.51	0.01	5.53	0.03
Residual VSD	5.64	0.02	4.13	0.05
Presence of PDA	3.04	0.08	2.60	0.11

Variables significant at the $p \leq 0.30$ level were entered into the multiple regression analysis, and retained if the corresponding p value was ≤ 0.15 . See Appendix 1 for definitions and complete listing of variables tested. LPA, Left pulmonary artery; $P_{RV/LV}$, intraoperative ratio of right ventricular to left ventricular pressure; VSD, ventricular septal defect; PDA, patent ductus arteriosus.

outflow tract obstruction (≥ 40 mm Hg). The sole intraoperative variable predictive of reoperation was the right ventricular/left ventricular pressure ratio, a ratio of 0.75 or more associated with a p value of 0.01, and a ratio of 0.60 or more with a p value of 0.05. The only morphologic feature suggestive of an increased risk was the presence of a patent ductus arteriosus before the initial operation, although this factor was eliminated by stepwise regression analysis (Table II). The presence of significant associated morphologic abnormalities, such as pulmonary atresia and nonconfluent pulmonary arter-

Table III. Frequency of major associated morphologic abnormalities in patients undergoing repair or palliation

	TOF		TOF/PA		TOF/NCPA		TOF/PA/NCPA	
	No.	%	No.	%	No.	%	No.	%
Repair	16	53	9	30	3	10	2	7
Palliation	2	29	4	57	0	0	1	14
Totals	18	49	13	35	3	8	3	8

TOF, Tetralogy of Fallot; PA, pulmonary atresia; NCPA, nonconfluent pulmonary arteries.

ies at the initial operation, did not increase the risk for reoperation.

Palliative procedures. Seven neonates underwent a palliative procedure as the initial operation during the same study period. A palliative procedure was selected because of severely diminutive pulmonary arteries in five patients, presence of an aberrant left coronary artery arising from the right coronary artery and crossing the infundibulum in one patient who would have required a long transannular patch, and critically ill condition of one patient who had concomitant echocardiographic evidence of severe right ventricular dysfunction. The frequency of major associated morphologic abnormalities was not different from that of patients undergoing complete repair (Table III). As compared with patients undergoing repair, patients undergoing palliation had significantly smaller pulmonary arteries as assessed

Table IV. Comparison of perioperative variables among patients undergoing palliation or repair

	Palliative procedures (n = 7)	Complete repair (n = 30)	p Value
Age at operation (mean $\pm$ SEM)	11.4 $\pm$ 3.1 days	12.6 $\pm$ 2.9 days	NS
Male:female distribution	6:1 (86%)	7:3 (70%)	NS
Operative weight (mean $\pm$ SEM)	3.00 $\pm$ 0.43 kg	3.21 $\pm$ 0.13 kg	NS
Body surface area (mean $\pm$ SEM)	0.19 $\pm$ 0.02 m ²	0.21 $\pm$ 0.01 m ²	NS
Preoperative stay* (mean $\pm$ SEM, range)	5 $\pm$ 3 days, 1-21 days	5 $\pm$ 1 days, 1-17 days	NS
Postoperative stay* (mean $\pm$ SEM, range)	16 $\pm$ 4 days, 5-31 days	23 $\pm$ 7 days, 7-201 days	NS
Preoperative prostaglandin use (n, %)	4 (57%)	14 (47%)	NS
Preoperative mechanical ventilation (n, %)	5 (71%)	13 (43%)	NS
Preoperative use of inotropic drugs (n, %)	1 (14%)	6 (21%)	NS
Preoperative saturation	79% $\pm$ 3%	80% $\pm$ 2%	NS
Preoperative hematocrit value	48.4% $\pm$ 2%	45.5% $\pm$ 1%	NS
Right pulmonary artery (mean $\pm$ SEM)	3.11 $\pm$ 0.40 mm	4.01 $\pm$ 0.13 mm	0.01
Left pulmonary artery (mean $\pm$ SEM)	3.07 $\pm$ 0.46 mm	3.92 $\pm$ 0.15 mm	0.03
Nakata index (mean $\pm$ SEM)	81 $\pm$ 17 mm/m ²	126 $\pm$ 9 mm/m ²	0.03
McGoon ratio (mean $\pm$ SEM)	0.84 $\pm$ 0.12	1.13 $\pm$ 0.04	0.007
Reoperations (total, %)	6 (86%)	8 (27%)	0.0001
Deaths	1 (14%)	2 (7%)	NS

SEM, Standard error of the mean; NS, not significant.

*Refers to the initial hospitalization only.

by both direct measurement and standard indices (Table IV), which likely reflects a selection bias of entering patients into a palliative procedure because of the diminutive pulmonary arteries. Conversely, there were no differences in age, weight, body surface area, use of preoperative mechanical ventilation, prostaglandins, or inotropic agents between the two groups of patients (Table IV).

Initial palliative procedures included insertion of a systemic-pulmonary shunt in six patients and transannular patching without ventricular septal defect closure in one patient. No operative or late deaths were associated with the initial operative procedures. Three hemodynamic repairs and three further palliative procedures were performed on six patients, and the seventh patient awaits further assessment and possible hemodynamic repair. Reoperative procedures included transatrial, transpulmonary repair in one patient, insertion of a right ventricle-pulmonary artery homograft conduit with ventricular septal defect closure in two patients, and insertion of a right ventricle-pulmonary artery conduit without ventricular septal defect closure in three patients because of continued severe pulmonary artery hypoplasia. There was one death, occurring in a patient with Alagille syndrome and severely diminutive pulmonary arteries (Nakata index of 48 cm²/m², McGoon ratio of 0.58) that did not grow despite a patent 4 mm systemic-pulmonary shunt. Reoperation consisted of insertion of a 13 mm homograft conduit from the right ventricle to the

central pulmonary artery without ventricular septal defect closure; however, the patient died of progressive severe hypoxemia in the perioperative period.

Follow-up was complete at a median interval of 19 months (range 1 to 40 months). The 1-month, 1-year, and 3-year actuarial survival of 100%, 100%, and 80% were not different from those of patients undergoing complete repair. The 1-month, 1-year, and 3-year freedom from reoperation rates of 100%, 50%, and 0%, however, were significantly lower than those in patients undergoing early hemodynamic repair ($p < 0.0001$). In summary, 13 procedures were performed on seven patients who underwent an initial palliative procedure, done principally because of severely diminutive pulmonary arteries. These operations resulted in a successful hemodynamic repair in three patients, palliation in three patients (all of whom await further consideration for hemodynamic repair), and death in one patient.

Discussion

The surgical management of tetralogy of Fallot has undergone considerable change since the lesion was first palliated by a subclavian-pulmonary artery shunt by Blalock and Taussig⁶ in 1945. Hemodynamic repair was first achieved by Lillehei and associates⁷ in 1954 using cross-circulation and was advanced by Kirklin and associates⁸ in 1955 through the use of a mechanical pump-oxygenator. Kirklin and his associates formulated a staged approach to repair that continues to be used with excellent

results at many centers. It consists of initial systemic-pulmonary shunting followed by complete repair at an older age.⁴ Ebert and Turley⁹ reported on the successful repair of cyanotic lesions in infants, and Castaneda and colleagues¹⁰ advanced this idea further by advocating repair of many congenital lesions in neonates.

The unifying morphologic feature in the tetralogy of Fallot is the anterior displacement of the infundibular septum, resulting in a malalignment ventricular septal defect and right ventricular outflow tract obstruction. The severity of the right ventricular outflow tract obstruction may be related to the degree of infundibular septal displacement, with severe displacement resulting in pulmonary atresia.¹¹ Anderson, Devine, and del Nido¹² emphasized that ventricular septal defect and pulmonary atresia is more accurately referred to as tetralogy of Fallot with pulmonary atresia, in that the anteriorly displaced infundibular septum is reminiscent of the principal morphologic feature in tetralogy of Fallot.

In the fetus with tetralogy of Fallot, blood flow across the foramen ovale to the left ventricle and across the tricuspid valve to the right ventricle is probably not altered.¹³ Because of right ventricular outflow tract obstruction, a portion of the blood returning to the right ventricle is diverted away from the main pulmonary artery into the ascending aorta through the ventricular septal defect. Because of the nonrestrictive nature of the ventricular septal defect in tetralogy, the right ventricle functions against systemic (placental) vascular resistance. Therefore, even in the presence of pulmonary atresia, the right ventricle in the fetus with tetralogy of Fallot has normal right ventricular pressure and compliance. Successful hemodynamic repair in the neonate therefore has the real potential of avoiding the development of the right ventricular hypertrophy and dysfunction that is part of the tetrad in the tetralogy of Fallot.

In cases of severe pulmonary stenosis, blood flow to the lungs is supplied by the descending aorta through reverse flow in the ductus arteriosus, and in the case of complete atresia, the ductus conducts a greatly reduced quantity of blood flow to the highly resistant pulmonary vascular circulation.^{11, 13} Elzenga and Gittenberger-de Groot¹⁴ studied the relationship of the ductus arteriosus to branch pulmonary artery stenoses in lesions with right ventricular outflow tract obstructions. They found that pulmonary artery stenoses were common in tetralogy of Fallot with pulmonary atresia and that the stenoses

were located at the ductus insertion site. In fact, pulmonary artery stenoses did not occur either on the pulmonary artery contralateral to the ductus insertion site or when the ductus was absent. Histologically, the stenoses are composed of ductal tissue, which, in the severest cases, results in nonconfluent pulmonary arteries.

It is therefore likely that branch pulmonary artery stenoses are related to the ductus arteriosus insertion site. The hemodynamic significance of this potential area of stenosis can probably not be adequately evaluated in the neonate before the ductus has closed completely, especially if the patient is receiving prostaglandins. However, even in patients not receiving prostaglandins, the reduced pulmonary blood flow associated with tetralogy of Fallot may underestimate the hemodynamic significance of the underlying lesion, only to become apparent once adequate pulmonary blood flow is established. Consideration must therefore be given to including the ductus insertion site in the operative repair at the time of the initial procedure.

The severity of the morphologic features in neonates with tetralogy of Fallot, in addition to the prevalence of additional major cardiac anomalies, accounts for the early presentation and need for early intervention. As compared with infants, for example, neonates are more likely to have annular hypoplasia, and transannular patching is more often required in neonates than in older patients. Eighty-one percent (13/16) of neonates with tetralogy of Fallot and pulmonary stenosis in the present series required transannular patching, as compared with 36% (19/58) in infants undergoing repair under similar practice guidelines.¹⁵ Similarly, 100% (14/14) of the neonates with tetralogy of Fallot and pulmonary stenosis in the Boston Children's Hospital series required transannular patching,¹⁶ as compared with 71% (29/41) of their infant population.¹⁷ Major associated cardiac anomalies, including pulmonary atresia and nonconfluent pulmonary arteries are also more prevalent in neonates. Forty-seven percent of the neonates in the present series and 48% in the Boston series (13/27) had significant additional anomalies, significantly higher than rates reported in infants undergoing complete repair.¹ Both the severity of the morphologic features and the prevalence of major cardiac anomalies argue against treating this group of patients in a manner analogous to their older counterparts.

Operative considerations. A possibly important contribution in decreasing the mortality and improv-

Fig. 4. Operative technique used to manage the ductus insertion site during complete repair of tetralogy of Fallot and pulmonary stenosis. The ductus insertion site is augmented by either a single (A) or double (B) patch of autologous pericardium or synthetic material.

ing ventricular function after repair of tetralogy of Fallot in infants has been limiting or avoiding the use of a ventriculotomy during the repair.¹⁸ This approach should have similar advantages in the treatment of neonates, but with some additional important considerations. As suggested earlier, annular hypoplasia is generally more severe in the neonate, so that the requirement for transannular patching is increased. When the need for transannular patching is being considered, it should be borne in mind that standard nomograms were derived from an older patient population and may not accurately reflect the unique morphologic features of neonatal tetralogy.¹ Conversely, the need for extensive infundibular muscle division and resection is reduced in the neonate, because the right ventricle is more compliant and not likely to have important hypertrophy.

An important technical consideration lies in the management of the ductus insertion site. As indicated earlier, the reverse flow in the ductus may account for the high incidence of branch pulmonary artery stenosis, the hemodynamic significance of which may be difficult to determine before the operation. The operative technique should therefore include angioplasty of the ductus insertion site at the time of complete repair. For patients with *tetralogy of Fallot and pulmonary stenosis*, the transan-

nular patch is extended distally past the ductus insertion site (Fig. 4, A). Often, we have found that because of the posterior deviation of the left pulmonary artery, a double patch technique is easier to tailor to the angulation of the left pulmonary artery, with a pericardial patch used for angioplasty of the ductus insertion site and a synthetic patch for the proximal transannular patch (Fig. 4, B). The ductus is doubly ligated and divided to optimize mobilization of the branch pulmonary arteries. For patients with *muscular pulmonary atresia*, for whom the use of a conduit is necessary, a cryopreserved pulmonary homograft is divided through one of the branches (Fig 5, A). The branch of the homograft is then used as an extension to enlarge the ductus insertion site (Fig 5, B). Finally, for *pulmonary atresia and non-confluent pulmonary arteries*, the branch pulmonary arteries are completely divided and separated, and the back wall is anastomosed in end-to-end fashion. The anterior wall is then grafted with the pulmonary homograft (Fig. 6, A to C). Alternatively, the central pulmonary artery confluence is opened into both branches and the spatulated distal end of a pulmonary homograft is used to augment the hypoplastic segment. These relatively small modifications in the operative technique can generally be performed at low risk and ideally will reduce the prevalence of residual pulmonary artery stenosis at the ductus insertion site.

Fig. 5. Operative technique used to manage the ductus insertion site during complete repair of tetralogy of Fallot and muscular pulmonary atresia. The pulmonary homograft used for right ventricular outflow tract reconstruction is divided through one of the branch pulmonary arteries (A). This extension is used to augment the ductus insertion site (B).

Fig. 6. Operative technique used to manage the ductus insertion site during complete repair of tetralogy of Fallot, muscular pulmonary atresia, and nonconfluent pulmonary arteries. The branch pulmonary arteries are completely mobilized and divided. As illustrated here, both branch pulmonary arteries originate from the ductus arteriosus (A). The posterior walls of the divided branch pulmonary arteries are anastomosed in end-to-end fashion (B), and the homograft is grafted onto their anterior surface (C).

Survival. The reported early hospital mortality for the repair of tetralogy of Fallot in several heterogeneous groups of patients varies between 2% and 5%.¹ Traditional incremental risk factors for early death, such as small size, young age, and the presence of pulmonary atresia or nonconfluent pulmonary arteries, were neutralized in this series of neonates. Other variables, such as a previous Potts anastomosis or multiple previous palliative procedures, are avoided completely by a protocol of early complete repair, whereas new variables, such as use of an aortic homograft to reconstruct the right ventricular outflow tract, are introduced. The size of the pulmonary arteries remains a difficult issue to resolve, because patients with extremely small pulmonary arteries did not primarily undergo repair. However, the size of the pulmonary arteries in this selected group of patients undergoing complete repair was not a risk factor, implying that pulmonary arteries with a preoperative Nakata index of $126 \pm 9 \text{ cm}^2/\text{m}^2$ (range 60 to $160 \text{ cm}^2/\text{m}^2$) or a McGoon ratio of 1.13 ± 0.05 (range 0.73 to 1.58) are of adequate size to achieve successful complete repair in neonates. When patients with severe hypoplasia of the pulmonary arteries do undergo complete repair and the postrepair right ventricular/left ventricular pressure ratio is 1.0 or more, perforation of the patch used to close the ventricular septal defect is indicated. Intermediate-term survival was excellent in this series of patients, and careful follow-up will be important to determine long-term survival.

The only deaths in this series occurred in two patients with small-sized cryopreserved homografts. Both patients had uneventful early recoveries and no evidence of residual hemodynamic lesions or arrhythmias at hospital discharge. Death was sudden and unexplained in each patient. Although use of an aortic homograft was an incremental risk factor, it is hazardous to draw firm conclusions with only two occurrences. However, our experience with aortic homografts in neonates undergoing repair for other anomalies has suggested that rapid, early obstruction from homograft calcification and shrinkage is relatively common. This appears to be particularly true for small-sized grafts, in which even minor decreases in diameter may result in important obstruction. We now avoid aortic homografts for right ventricular outflow tract reconstruction whenever possible and prefer the use of pulmonary homografts in this situation.

Reoperation. The prevalence, indications, and outcomes for reoperation in neonates undergoing

complete repair appear to be different from those of their older counterparts. In a collective review of several published series, including data from their own unit, Backer and Idriss¹⁹ noted that the prevalence of reoperation in older patients had declined steadily over time, averaging 5.2% in 1838 patients. This compares to a reoperative rate of 25% in the present series and that reported from the Boston Children's Hospital (14 reoperations in 57 patients, combined series).¹⁶ Whereas such comparisons must be interpreted with great caution in that they represent very different time periods, patient populations, and operative strategies, they do attest to the high reoperative rate in neonates undergoing complete repair.

The principal indications for reoperation are different between neonates and older patients undergoing complete repair. In the older group, the most common procedures performed at the time of reoperation are closure of a residual ventricular septal defect (95%), repair of residual right ventricular outflow tract obstruction (70%), pulmonary valve replacement (55%), and repair of right ventricular aneurysm (22%).^{19, 20} By comparison, the most commonly performed procedures during reoperation in neonates are correction of left pulmonary artery stenosis (86%), repair of residual right ventricular outflow tract obstruction (28%), and repair of residual ventricular septal defect (14%). Finally, the mortality for reoperations in neonates versus older patients may be different, averaging 17% in the older age group, as compared with no reported mortality in the 14 patients who underwent reoperation after initial neonatal repair. It therefore appears likely that the prevalence, indications, and outcome of patients undergoing complete repair in the neonatal period are different from those reported on from an older population.

The clearest strategy for reducing the high reoperative rate is to recognize that in utero reversal of ductal blood flow may cause severe postnatal stenosis at the insertion site on the pulmonary artery. This area of potential stenosis may be very difficult, if not impossible, to recognize in the neonate before ductal closure. Patients requiring preoperative prostaglandins or those with pulmonary atresia and/or nonconfluent pulmonary arteries are considered to be at highest risk; however, all neonates with symptomatic tetralogy of Fallot are also at risk, in that the reduced pulmonary blood flow before correction may underestimate the severity of the underlying branch pulmonary artery stenosis. Including the

ductus insertion site into the initial operative repair may substantially reduce the rate of reoperation after the repair of tetralogy of Fallot in neonates.

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Discussion

Dr. Frank L. Hanley (*San Francisco, Calif.*). Dr. Hennein has described an excellent series of neonatal repair of tetralogy of Fallot. We have taken a similar approach to these patients. As a number of centers demonstrate similar outstanding results of repair in the neonatal or early infancy period, this undoubtedly will become the approach of choice.

Our series consists of 16 patients treated over the past 18 months. We believe the size of the branch pulmonary arteries has no effect on whether to proceed with a repair, so long as there are no large aortopulmonary collaterals and the true pulmonary arteries provide essentially all of the pulmonary blood flow. Central confluence and the presence of pulmonary atresia rather than pulmonary stenosis are also not important considerations. We agree that the size of the branch pulmonary arteries does not seem to affect the medium-term outcome.

In general, we believe that if a transannular patch is necessary in the neonate, the patch should extend onto both branch pulmonary arteries. The hemodynamics that are set up (even if the branch pulmonary artery orifices do not appear stenotic) when the transannular patch is limited to the main pulmonary artery are likely to lead to gradients of the branch pulmonary artery orifices. It seems that you have observed this in your series and corrected it.

Do you have a series of patients in whom you have routinely patched onto the left pulmonary artery, and do you now patch onto the right pulmonary artery as well?

Dr. Hennein. We do agree that complete repair, as you also advocate, is the proper approach to neonatal tetralogy repair for some of the reasons that we mentioned before.

With regard to patching onto both branch pulmonary arteries, we are most concerned with the area of stenosis where the ductus inserts. In these patients with severe right ventricular outflow tract obstruction, flow in the ductus is reversed and there is often a stenosis at the ductal insertion point on the pulmonary artery. That is probably the main point to address at the time of operation—not just to patch both pulmonary arteries, but to patch the area where the ductus inserts. For the most part, this is on the left pulmonary artery, and so it would be the one most at risk for the development of branch pulmonary artery stenosis.

We have used the double-patch technique in a series of four to six patients. The early follow-up has shown very good results, with the discharge echocardiograms demonstrating a very low gradient. We are happy with that technique.

Dr. Gerhard Ziemer (*Hannover, Germany*). I have a question regarding your use of homografts. You found homograft conduits to be a risk factor for late outcome. Is this specifically true for homografts only or is it rather a

feature of conduit use in general? If it is a specific homograft problem only, one could just use valveless polytetrafluoroethylene tubes, buying some regurgitation, which in the vast majority of patients with tetralogy is well tolerated as we know from transannular patching.

Dr. Hennein. We are concerned about the use of aortic homografts, especially the small aortic homografts required in neonates. Aortic homografts might contract and may calcify more quickly, resulting in a higher likelihood of early dysfunction. We do not have the same concern about pulmonary homografts used in neonates. This concern is specifically over small aortic homografts, although we do not know whether aortic homografts constitute a risk factor over a large number of patients.

Mr. Magdi Yacoub (*London, England*). You used complete small conduits in these patients. What do you think about using a monocusp and retaining the patient's own tissue, at least in part, and also having the additional advantage of a valve mechanism rather than just a patch?

Dr. Hennein. That is an excellent idea. We have not used that approach, though, and we would be interested in finding out other people's experience with that approach. The use of the small aortic homograft really does pose a unique set of problems both in the early period and in the need for subsequent reoperation.

Appendix 1 is on page 344.

Appendix 1. Variables analyzed for relationship to death and freedom from reoperation in patients undergoing complete repair of tetralogy of Fallot in the neonatal period

	Death		Freedom from reoperation	
	<i>F statistic*</i>	<i>p Value†</i>	<i>F statistic*</i>	<i>p Value†</i>
Preoperative variables				
Sex	0.408	NS	0.292	NS
Age	0.461	NS	0.036	NS
Body surface area	0.330	NS	0.821	NS
Operative weight‡	0.395	NS	0.972	NS
ASA risk class	2.006	0.157	1.451	0.22
Inotropic support	7.897	0.005	0.53	NS
Prostaglandins	2.154	0.142	0.00	NS
Mechanical ventilation	2.485	0.115	.359	NS
Preoperative saturation	0.350	NS	0.041	NS
Preoperative hematocrit value	0.012	NS	0.163	NS
Preoperative stay	0.035	NS	0.18	NS
Postoperative stay	0.184	NS	0.409	NS
Total hospital stay	0.188	NS	0.439	NS
Morphologic variables				
Pulmonary atresia	3.701	0.054	0.639	NS
Nonconfluent pulmonary arteries	0.429	NS	0.545	NS
Pulmonary anulus size	0.562	NS	0.120	NS
LPA size	0.050	NS	0.045	NS
RPA size	2.195	0.15	0.695	NS
Nakata index	0.168	NS	0.049	NS
McGoon ratio	0.041	NS	0.186	NS
Presence of PDA‡	1.071	NS	3.04	0.08
Atrial septal defect	0.077	NS	.395	NS
VSD morphology	0.248	NS	0.451	NS
Abnormal coronary anatomy	0.221	NS	2.550	0.11
Operative variables				
Staff surgeon	0.626	NS	1.212	NS
Transventricular VSD approach	5.00	0.025	1.59	0.207
No IMD	2.802	0.09	0.151	NS
No transannular patch	5.893	0.01	1.12	NS
Homograft reconstruction	10.714	0.001	2.182	0.14
CPB	5.358	0.03	0.449	NS
XCT	0.623	NS	0.047	NS
Circulatory arrest time	0.097	NS	0.513	NS
PFO closed	2.644	0.104	1.756	0.185
$P_{RV/LV} \geq 0.75$	0.330	NS	5.51	0.01
Postoperative variables				
Residual VSD	0.690	NS	5.639	0.018
Residual LPA stenosis	0.361	NS	9.977	0.002
Residual RVOTO	2.302	NS	1.20	NS

ASA, American Society of Anesthesiology risk stratification; CPB, cardiopulmonary bypass time; IMD, infundibular muscle division and limited resection; LPA, left pulmonary artery; NS, not significant; PDA, patent ductus arteriosus; PFO, patent foramen ovale; $P_{RV/LV}$, ratio of systolic right ventricular pressure to left ventricular pressure; RPA, right pulmonary artery; RVOTO, right ventricular outflow tract obstruction; VSD, ventricular septal defect; XCT, aortic crossclamp time.

* χ^2 statistic used for analysis of categoric data.

†p value given if ≤ 0.25 .

‡Testing for the presence of either a reverse or normal duct.