Unifocalization and pulmonary artery reconstruction in patients with tetralogy of Fallot and major aortopulmonary collateral arteries who underwent surgery before referral

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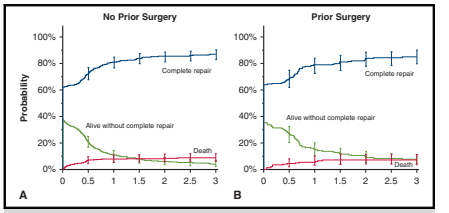
ABSTRACT

Objective: The study objective was to characterize and analyze outcomes in patients with tetralogy of Fallot and major aortopulmonary collateral arteries who had undergone surgery elsewhere before referral (prereferral surgery).

Methods: Patients with tetralogy of Fallot and major aortopulmonary collateral arteries who underwent surgery between 2001 and 2019 at our center were reviewed. Prereferral surgery and unoperated patients were compared, as were subsets of prereferral surgery patients who had undergone different types of prior procedures. Primary outcomes included complete repair with survival to 6 months, death, and perioperative metrics.

Results: Of 576 patients studied, 200 (35%) had undergone a wide range and number of prior operations elsewhere, including 92 who had pulmonary blood supply through a shunt and 108 who had a right ventricle pulmonary artery connection. Patients who underwent prereferral surgery with an existing right ventricle pulmonary artery connection had undergone more prereferral surgery procedures than those with a shunt and were more likely to have a right ventricle outflow tract pseudoaneurysm or pulmonary artery stent (all $P < .001$) at the time of referral. The cumulative incidences of complete repair and death were similar regardless of prereferral surgery status, but the cumulative incidence of complete repair with 6-month survival was higher ($P = .002$) and of death lower ($P = .18$) in patients who had prior right ventricle pulmonary artery connection compared with those who had received a prior shunt only.

Conclusions: Our comprehensive management strategy for tetralogy of Fallot and major aortopulmonary collateral arteries can be applied with excellent procedural results in both unoperated patients and those who have undergone multiple and varied procedures elsewhere. (J Thorac Cardiovasc Surg 2020;160:1268-80)



Cumulative incidence of complete repair, death, and alive by PRS status.

CENTRAL MESSAGE

Despite diverse prereferral management strategies, patients with TOF/MAPCAs achieved comparable rates of complete repair with low mortality whether treated primarily or secondarily at our center.

PERSPECTIVE

TOF/MAPCAs remain a challenging congenital heart defect to manage, resulting in a diverse array of palliative surgical strategies that can temporize a child who may eventually present for complete repair by unifocalization and intracardiac septation. This study aims to understand the outcomes for this cohort and to demonstrate that favorable results usually can be achieved.

See Commentaries on pages 1281 and 1282.

Our institutional approach to the management of tetralogy of Fallot with major aortopulmonary collateral arteries (TOF/MAPCAs) emphasizes early complete unifocalization and repair, typically in a single stage.[1-3] This condition may be managed differently at other centers,[4-18] and a

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Abbreviations and Acronyms

LPCHS = Lucile Packard Children's Hospital at Stanford
MAPCA = major aortopulmonary collateral artery
PA = pulmonary artery
PRS = prereferral surgery
RV = right ventricle
RVOT = right ventricular outflow tract
TOF = tetralogy of Fallot
VSD = ventricular septal defect

substantial subset of the patients we treat have undergone prereferral surgery (PRS) externally. In previous studies, PRS was not associated with important differences in outcome,[3] but we have not evaluated this issue in depth. Patients who have undergone PRS are typically older than unoperated patients and may have been left with heterogeneous lung perfusion and pressure, sometimes with consequent pulmonary vascular disease or parenchymal hypoplasia, in the setting of residual reconstructed pulmonary artery (PA) bed stenosis, vessel loss or occlusion, persistent MAPCAs, or unrestricted flow through an open ventricular septal defect (VSD) with a right ventricle (RV) to PA connection. Moreover, patients who have undergone PRS pose unique reoperative challenges: multiple prior sternotomies, RV outflow tract (RVOT) pseudoaneurysms, catheter-based PA stents, and occluded vessels in these patients increase reoperative surgical complexity. Given a desire to provide specific outcome data to this population, and the substantial proportion of our patients who have undergone PRS, we undertook a focused evaluation of preoperative characteristics, intraoperative factors, and outcomes.

MATERIALS AND METHODS

Patients

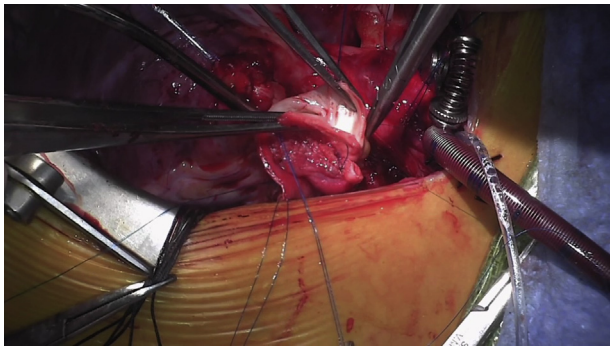
A retrospective review was performed to collect data on all patients with TOF/MAPCAs who underwent surgery at Lucile Packard Children's Hospital at Stanford (LPCHS) from November 2001 to May 2019. In general, regardless of prior operative status, all patients with anatomy and physiology conducive to achieving intracardiac repair with a low RV systolic pressure (<50% of systemic systolic pressure or mean central PA pressure ≤25 mm Hg), based on detailed cardiac catheterization and angiography data, along with computed tomographic imaging in some cases, were considered. A small percentage of patients were deemed inoperable because of irreversible pulmonary vascular disease, substantial and long-standing vessel loss (where the number of unsalvageable segmental arteries supplied more than 40%-50% of the total lung parenchyma), or refractory noncardiovascular comorbidity, but data were not available for this cohort. Patients who underwent complete repair by one of the authors (F.L.H.) at a prior institution[1] and had undergone additional surgery at LPCHS were captured in the database but were excluded from this study.

Patients were grouped according to specific procedural factors and the status of the circulation at the time of referral: no PRS (including patients who had undergone transcatheter interventions only), systemic-to-PA shunt/connection, RV-PA connection with fenestrated or open VSD, or RV-PA connection with closed VSD (including patients with an unintentional residual VSD). Patients who underwent sternotomy and an aborted procedure were grouped with patients who had a prior systemic-to-PA shunt/connection to account for reoperative status and physiology. Preintervention anatomic data were recorded, but the native anatomy of the pulmonary circulation was not always known in detail to the investigators. Regular follow-up was performed at our center or as ongoing clinical consultation with patients who were referred from elsewhere. Patients were followed until the most recent evaluation at our center or elsewhere, death, or loss to follow-up.

Surgery

Our approach to surgery in patients with TOF/MAPCAs has been detailed.[1-3] In brief, our programmatic management algorithm aims for early complete unifocalization and intracardiac repair incorporating all lung segments, with augmentation of PA branches (whether native PAs or MAPCAs) down to the segmental level as needed. Complete repair refers to full unifocalization or PA augmentation, VSD closure, and placement of a conduit from the RV to the unifocalized PAs. In general, the goal is to complete the repair in one operation if low RV systolic pressure (<50% of systolic systemic pressure) can be achieved; otherwise, the reconstructed PA circulation is supplied by a central systemic-to-PA shunt.[19] In patients with borderline anatomy or physiology for repair, as estimated by the surgeon's assessment of the preoperative imaging, hemodynamics, and intraoperative reconstruction, an intraoperative flow study is used selectively to estimate postreconstruction PA resistance.[20]

In PRS patients, the same philosophy applies, with reconstruction of the PA circulation (unifocalization of MAPCAs, revision of prior unifocalization, PA augmentation, branch ostioplasty, and recruitment of occluded PA branches or MAPCAs as indicated), full VSD closure, and RV-PA conduit placement, using techniques described in detail previously (Video 1).[1,2,19,21-23] In patients with a previously placed PA stent, the stent is removed (or transected if removal is not feasible) and the vessel augmented with a patch (typically pulmonary homograft tissue). Atretic proximal and intraparenchymal PA or MAPCA branches are identified on preoperative imaging and incorporated into the reconstruction if feasible, generally based on size and accessibility.[24]



VIDEO 1. The fundamental techniques used in revision surgery for TOF/MAPCAs are demonstrated, emphasizing extensive distal dissection into lung parenchyma after branch PA or MAPCA mobilization, management of existing catheter-based stent therapy, segmental and subsegmental vessel interrogation, and multilevel homograft patch augmentation. Video available at: https://www.jtcvs.org/article/S0022-5223(20)30746-7/fulltext.

Outcomes

The primary outcomes for this study were cumulative incidences of mortality and complete repair over time from the initial surgery at our center; this interval was chosen given the variability in timing of referral and our desire to provide patient-centric outcome data based on treatment at our center. Additional outcomes included hospital mortality, length of hospital stay, and for patients undergoing complete repair, early postrepair RV systolic pressure, RV:aortic systolic pressure ratio, and results of predischarge lung perfusion scintigraphy.[25] RV systolic and aortic pressures were measured by direct pressure manometry in the operating room after separation from bypass. Lung perfusion measurements were described previously, with left-right imbalance (maldistribution) defined as less than 30% or greater than 60% of total pulmonary blood flow to the left lung, and extreme imbalance defined as less than 20% or greater than 70% to the left lung.[25] For patients with regional perfusion data (ie, upper, middle, lower zones), the percentages of total left or right lung flow to each region were calculated. Regional perfusion imbalance was defined for upper and lower lung fields within each lung as percentage of flow greater than 1 standard deviation above or below the population mean for that region.

Data Analysis

Data were presented as number (%) or median (25th-75th percentiles). Comparison of categorical variables between groups was performed using the Fisher exact test. Nonparametric comparison of continuous variables was performed using the Wilcoxon rank-sum test or the Kruskal–Wallis test. Cumulative incidence functions were estimated for the 3 competing outcomes (complete repair with survival for at least 6 months, death, and alive without complete repair) using Gray's method,[26] and time-related competing outcomes were depicted with cumulative incidence curves. Comparison of cumulative incidence functions between groups was performed using Gray's test. Limited multivariable analysis was conducted for competing outcomes to account for age at the first LPCHS surgery, number of prereferral surgeries, and type of PRS by fitting proportional subdistribution hazards regression model using the Fine and Gray method.[27] Cumulative incidence estimates were presented as proportion with 95% confidence interval. For the purposes of outcome categorization, patients who died within 6 months of complete repair were grouped as "death" and patients who died more than 6 months after complete repair were grouped as "complete repair with survival for 6 months or more." A 6-month (as opposed to 30-day) interval was chosen in a effort to provide conservative estimates of positive outcomes. Cases with missing data were excluded from analysis on a case-wise basis. R version 3.3.1 was used for statistical analysis.

RESULTS

Patients

From November 1 to May 2019, 601 patients with TOF/MAPCAs underwent surgery at our center; 25 of these patients underwent surgery after complete repair at the prior institution of the primary surgeon (F.L.H.) and were excluded from this study. The study cohort included the remaining 576 patients, 200 (35%) of whom had undergone PRS. Eight patients who had undergone catheter interventions only (ductal stent in 3, RVOT stent in 2, balloon pulmonary valvuloplasty in 2, MAPCA stent in 1) were included in the "no prior surgery" group. Baseline characteristics are summarized in Table 1. PRS patients were significantly older, were more likely to have native confluent central PAs, and had fewer MAPCAs than those without PRS, but were demographically and diagnostically similar in other respects.

Prereferral Surgery Cohort

The annual number of TOF/MAPCAs cases during the study period ranged from 20 to 54, with 14% to 47% having undergone PRS. Although the balance of cases varied from year to year, there was a trend toward more PRS cases over time; 26% of the overall TOF/MAPCAs cohort, 33% of PRS patients, and 44% of patients with a prior RV-PA connection were referred after 2015. Likewise, in the last quartile of the study period, PRS patients commonly had RVOT pseudoaneurysm (54%), existing PA stent (46%), occluded proximal PA branch (38%), or an occluded PA branch at any level incorporated into the reconstruction (43%).

TABLE 1. Demographic and diagnostic features and early outcomes after the first surgery at Lucile Packard Children's Hospital at Stanford according to prereferral surgery status

		Cardiac surgery before referral		
	Total (n = 576)	No (n = 376)	Yes (n = 200)	*P* value
Age at first LPCHS surgery (y)	0.6 (0.3, 2.2)	0.4 (0.2, 0.6)	3.0 (1.1, 6.1)	<.001
Chromosome 22q11 deletion	205 (38%)	135 (38%)	70 (39%)	.78
Alagille syndrome	16 (3%)	11 (3%)	5 (2%)	>.99
Native anatomy				
Ductus to 1 lung	46 (8%)	35 (9%)	11 (7%)	.32
Confluent central PAs	409 (76%)	278 (74%)	131 (82%)	.044
No. of MAPCAs	4 (3, 5)	4 (3, 5)	3 (2, 4)	<.001
Complete repair at first LPCHS surgery	378 (66%)	245 (65%)	133 (66%)	.78
Flow study performed first LPCHS surgery	88 (15%)	54 (14%)	34 (17%)	.40
Postoperative hospital stay (d)	15 (10, 27)	17 (11, 31)	14 (9, 22)	<.001
ICU stay (d)	9 (6, 18)	9 (7, 20)	8 (6, 14)	.033
Early death after first LPCHS surgery	22 (4%)	16 (4%)	6 (3%)	.50

LPCHS, Lucile Packard Children's Hospital at Stanford; *PA*, pulmonary artery; *MAPCA*, major aortopulmonary collateral artery; *ICU*, intensive care unit.

Prereferral Surgery Patients With a Prior Systemic-to-Pulmonary Artery Connection

At referral, 92 PRS patients (46%) had a systemic-to-PA connection; 18 (9%) had an aortopulmonary window alone, 32 (16%) had a shunt without unifocalization, 39 (19.5%) had a shunt or aortopulmonary window with complete (n = 12) or partial (n = 27) unifocalization, and 3 (2%) had undergone sternotomy without intervention (Figures 1-4). The majority of these patients had no prior surgery on MAPCAs. Existing PA stents were uncommon in shunted patients, and acquired atresia of a proximal PA branch was documented in 10%. This cohort was older than unoperated patients, but younger than those with an RV-PA connection (Tables 1 and 2).

Prereferral Surgery Patients With a Prior Right Ventricle-Pulmonary Artery Connection

PRS patients with a prior RV-PA connection (108; 54%) were significantly older than unoperated patients or those with a prior systemic-to-PA shunt, and more likely to undergo complete repair during the initial LPCHS surgery (Table 2). Compared with PRS patients with a systemic-to-PA shunt, this subset had undergone more prior surgeries, more often had undergone prior unifocalization, were more likely to have branch PA stents, and had higher preoperative oxygen saturation (all $P < .001$). An RVOT pseudoaneurysm was present in 5 of 13 patients (38%) with a patch and 7 of 85 patients (8%) with a conduit ($P = .009$).

Among patients with a prior RV-PA connection, 74 had an open VSD (no patch in 54, fenestrated patch in 20) and 34 had a closed VSD (6 with an unintended residual defect). RV systolic pressure was supra-systemic in approximately 10% of patients with an RV-PA connection and systemic in 61%, more often in those with an open than a closed VSD (Table 2). Patients with an open VSD had undergone more prior surgeries than those with a previously closed VSD, but prior unifocalization was similarly common.

Procedural Outcomes: Initial Surgery at Lucile Packard Children's Hospital at Stanford

Complete repair was performed during the first LPCHS surgery in approximately two-thirds of patients, regardless of PRS status (Table 1). There was no

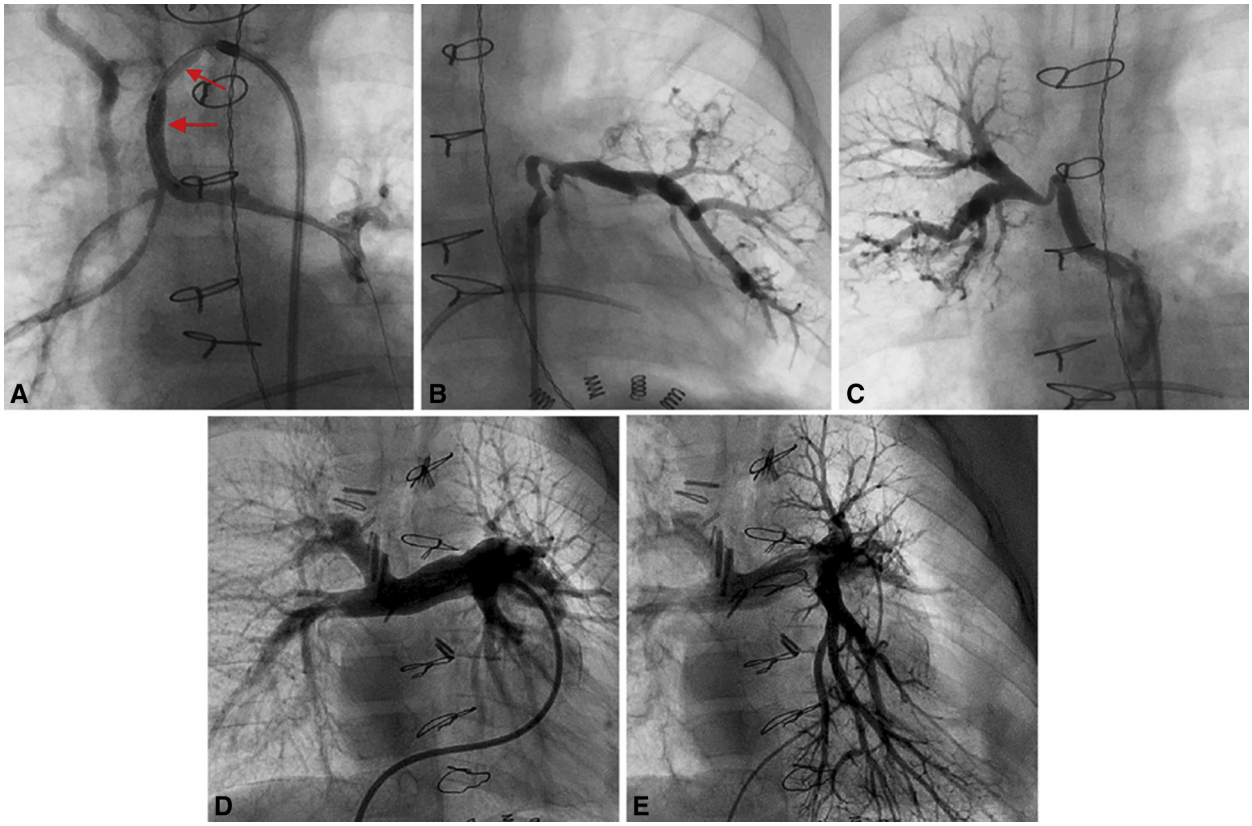


FIGURE 1. This series of angiograms depict the anatomy of a patient who was referred at 1.1 years of age after a systemic-to-PA shunt (partially stented in this image) to the central PAs with partial unifocalization. A, Angiogram through the partially stented shunt (*red arrows*) depicting the central PAs and right-sided partial unifocalization. B and C, Selective angiography of 2 single supply MAPCAs arising from the descending aorta. This patient underwent complete repair in a single operation at our center, with a postoperative systolic RV pressure of 27 mm Hg. D and E, These postoperative angiograms, 1 year after repair, show the reconstructed (D) right and (E) left PAs. The systolic central PA pressure was 26 mm Hg, and no interventions were performed.

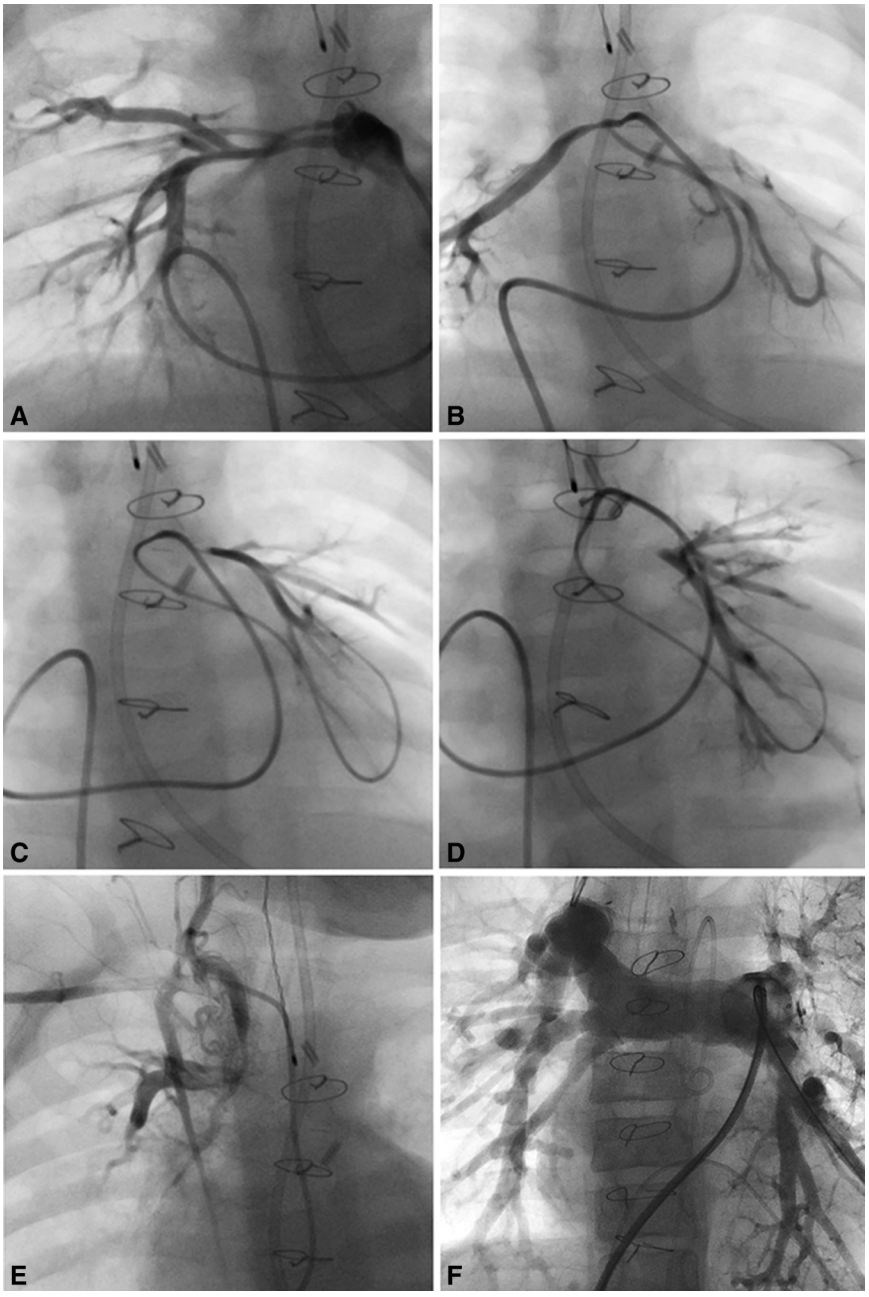


FIGURE 2. This series of angiograms depict the anatomy of a patient who underwent partial unifocalization, fenestrated VSD closure, and placement of an RV-PA conduit before referral. At the time of referral, the partially unifocalized MAPCAs are stenotic and hypoplastic (A and B), with 2 atretic branches to the left lung (C and D) that were imaged through a small peripheral connection to one of the MAPCAs but did not fill by central angiography, and (E) there is a residual MAPCA to the right upper lobe. The initial procedure at our center consisted of complete PA reconstruction supplied by a central shunt at 9 months of age. After complete repair during a subsequent LPCHS operation, at 1.5 years of age, the RV systolic pressure was 38 mm Hg. F, This central PA angiogram performed at 9 years of age shows the reconstructed PA system; the systolic main PA pressure was 26 mm Hg.

difference in early mortality according to PRS status, and the durations of postoperative intensive care unit and hospital stays were slightly but significantly shorter in PRS patients.

Patients with systemic-to-PA shunt PRS were less likely than those with RV-PA connection or non-PRS to have complete repair at the first LPCHS surgery (Table 2). Within this subset, no demographic or historical features, including prior partial or complete unifocalization, were associated with the likelihood of complete repair during the first LPCHS surgery. All 20 shunted patients who had a flow study to determine whether complete repair would be

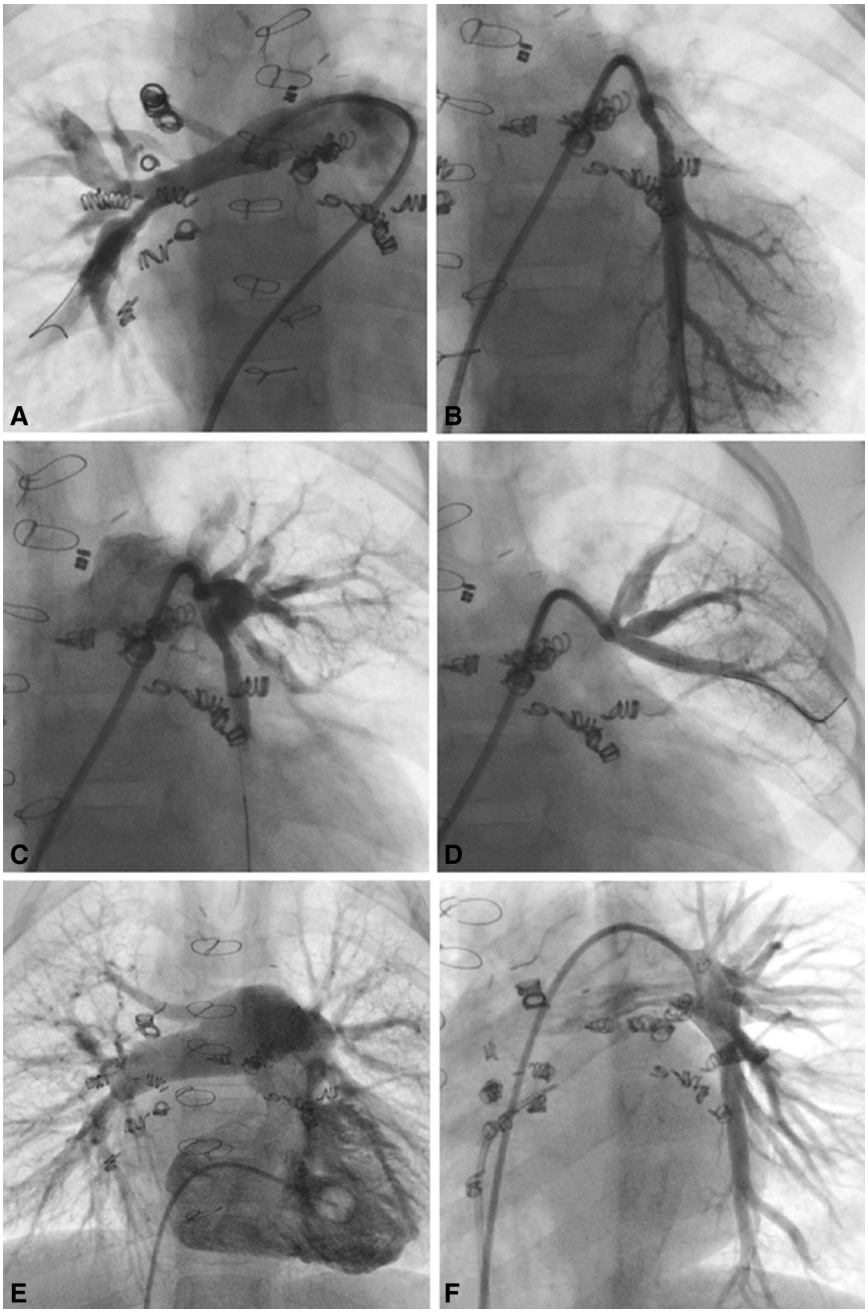


FIGURE 3. This series of angiograms is from a patient who was referred at 4.6 years of age after placement of an RV-PA conduit and VSD closure without unifocalization (MAPCAs embolized). A-D, Preoperative angiograms demonstrate the residual lobar and segmental stenoses in the (A) right and (B-D) left PA systems. PA reconstruction and complete repair were performed during the first surgery at our center, with an postoperative RV systemic pressure of 24 mm Hg. E and F, Angiograms from the 1-year postrepair catheterization show the reconstructed branch PA anatomy. The systolic main PA pressure during catheterization was 33 mm Hg.

feasible at the first operation passed the study and were repaired.

Patients with RV-PA connection PRS were more likely to undergo recruitment of occluded PA/MAPCA branches and to have a complete repair at the first LPCHS surgery than those with a prior shunt (Table 2). Among patients with a previously closed VSD, 91% had complete repair during the first LPCHS surgery. However, among patients with a prior RV-PA connection and an open VSD, 69% underwent complete repair during the first surgery, whereas 31% had revision unifocalization and PA reconstruction without VSD closure (either to a shunt or leaving the RV-PA

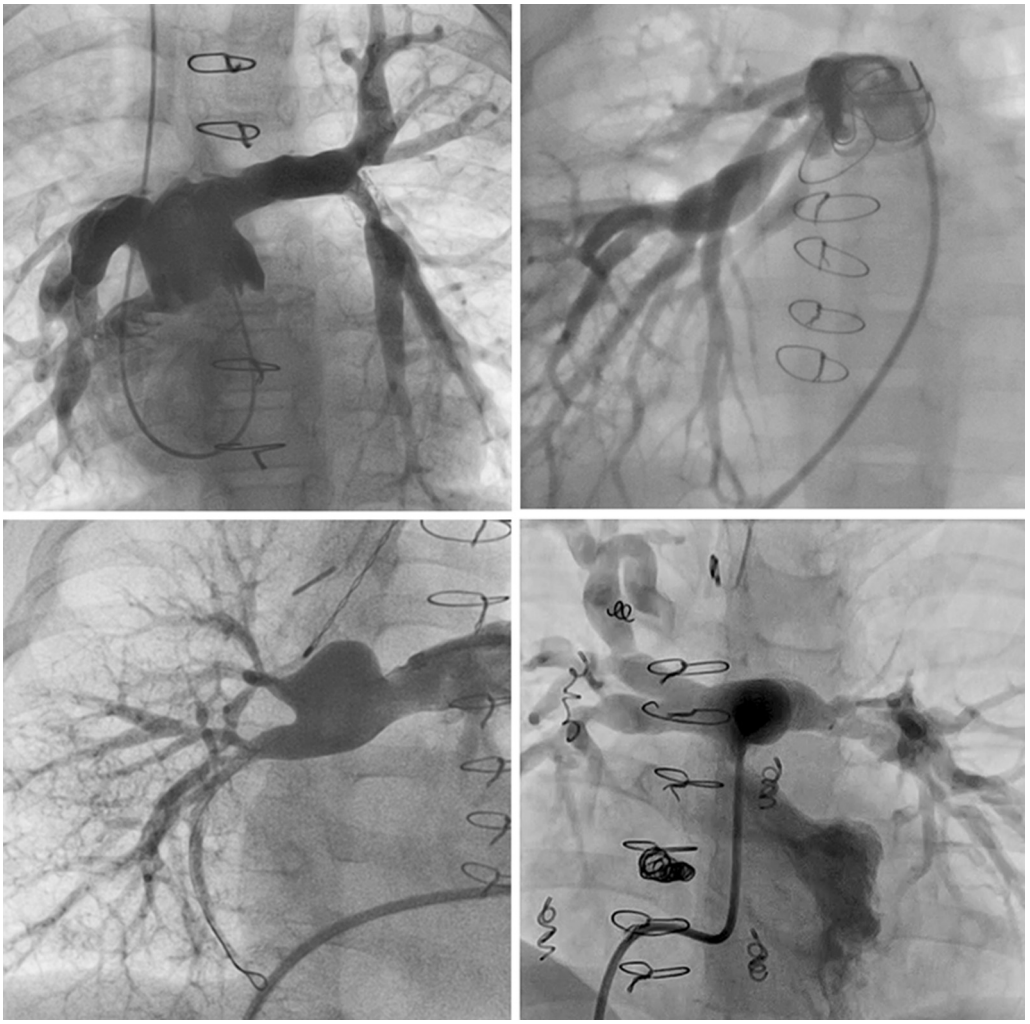


FIGURE 4. This series of main PA angiograms in 4 different patients with TOF/MAPCAs demonstrates some of the various postoperative anatomies encountered in patients referred after surgery that included RV-PA connection. The images show irregular distribution of branches, residual stenosis of unifocalized MAPCAs and native PAs, occlusion/absence of proximal, lobar, or segmental branches, and stents with neo-intimal obstruction.

connection in place). In most of these patients who did not undergo complete repair at the first LPCHS procedure, 1 branch PA system was more severely affected than the other, and the a priori aim was to reconstruct the more severely affected system and complete the repair at a second operation. Approximately one-fifth of patients with an open VSD (n = 14) had a flow study performed before deciding whether to complete the repair, similar to the percentage of patients with a prior shunt, and 9 patients (64%) underwent complete repair. Postoperatively, patients with a prior RV-PA connection and an open VSD had significantly longer stay in the intensive care unit than those with a previously closed VSD.

Procedural Outcomes: Complete Repair

In the entire cohort, a total of 517 patients underwent complete repair at the initial LPCHS surgery (n = 378) or a subsequent operation (n = 139). Although only 51 of 74 patients with RV-PA connection PRS with an open VSD underwent complete repair during the first LPCHS surgery, all but 6 were later completely repaired. PRS patients had higher early postrepair RV systolic pressure and RV:aortic systolic pressure ratio than unoperated patients, and there were several differences in lateral and regional lung perfusion distribution (Table 3). PRS patients with 1 or more atretic branches unifocalized at the time of repair were more likely to have unbalanced left-right pulmonary blood flow distribution (52% vs 21%; $P = .002$), although there was no difference in the postrepair PA:aortic pressure ratio.

There was no difference in RV pressure or lung perfusion metrics between PRS patients who had a prior shunt and patients with a prior RV-PA connection (Table 3). Patients presenting to LPCHS with an atretic branch and who had this branch incorporated into the PA reconstruction at

TABLE 2. Characteristics at the time of first surgery at Lucile Packard Children's Hospital at Stanford of patients who had prereferral surgery according to prior surgery type and ventricular septal defect status

	Total (n = 200)	Systemic-to-PA shunt (n = 92)	RV-PA connection (n = 108)	*P* value	RV-PA connection VSD closed (n = 34)	RV-PA connection VSD open (n = 74)	*P* value
Age at first LPCHS surgery (y)	3.0 (1.1, 6.1)	1.2 (0.7, 5.4)	4.0 (2.0, 7.4)	<.001	4.7 (2.4, 11.6)	4.0 (1.8, 6.2)	.14
Chromosome 22q11 deletion	70 (39%)	34 (43%)	36 (36%)	.44	11 (37%)	25 (36%)	>.99
Alagille syndrome	5 (2%)	3 (3%)	2 (2%)	.66	1 (3%)	1 (1%)	.53
Native anatomy							
Ductus to 1 lung	11 (7%)	4 (5%)	7 (8%)	.55	1 (4%)	6 (9%)	.67
Confluent central PAs	131 (82%)	57 (77%)	74 (87%)	.14	22 (96%)	52 (84%)	.27
No. of MAPCAs	3 (2, 4)	3 (2, 4)	2 (1, 4)	.044	1 (1, 3)	3 (1, 4)	.11
No. of surgeries before LPCHS	2 (1, 2)	1 (1, 2)	2 (1, 3)	<.001	2 (1, 3)	2 (1, 3)	.76
Existing RVOT connection type							
Conduit	85 (87%)	-	85 (87%)	-	23 (96%)	62 (84%)	.18
Patch	13 (13%)	-	13 (13%)		1 (4%)	12 (16%)	
RVOT pseudoaneurysm	13 (6%)	0 (0%)	13 (12%)	<.001	2 (6%)	11 (15%)	.22
Proximal branch PA occlusion	29 (14%)	9 (10%)	20 (19%)	.11	3 (9%)	17 (23%)	.11
Prior PA/MAPCA stents	49 (24%)	7 (8%)	42 (39%)	<.001	10 (29%)	32 (43%)	.21
Unifocalization ± PA augmentation							
No	75 (38%)	53 (58%)	22 (20%)	<.001	5 (15%)	17 (23%)	.45
Partial	85 (42%)	27 (29%)	58 (54%)		18 (53%)	40 (54%)	
Yes	40 (20%)	12 (13%)	28 (26%)		11 (32%)	17 (23%)	
Prior VSD closure							
Fenestrated/residual	26 (13%)	0 (0%)	26 (24%)	<.001	6 (18%)	20 (27%)	<.001
No	146 (73%)	92 (100%)	54 (50%)		0 (0%)	54 (73%)	
Yes	28 (14%)	0 (0%)	28 (26%)		28 (82%)	0 (0%)	
Preoperative systemic arterial oxygen saturation (%)	83 (78, 91)	80 (75, 83)	90 (83, 96)	<.001	97 (94, 98)	85 (81, 91)	<.001
RV systolic pressure							
Sub-systemic (<75%)			8 (8%)		6 (21%)	2 (3%)	<.001
Sub-systemic (75%-99%)			23 (23%)		12 (41%)	11 (15%)	
Systemic			62 (61%)		8 (28%)	54 (74%)	
Supra-systemic			9 (9%)		3 (10%)	6 (8%)	
Atretic PA/MAPCA branch unifocalized	35 (18%)	5 (5%)	30 (28%)	<.001	8 (24%)	22 (30%)	.64
Bilateral (vs unilateral) PA reconstruction	137 (70%)	62 (70%)	75 (70%)	.96	25 (76%)	50 (68%)	.39
Complete repair at first LPCHS surgery	133 (66%)	51 (55)%	82 (76%)	.003	31 (91%)	51 (69%)	.015
Flow study performed first LPCHS surgery	34 (17%)	20 (22%)	14 (13%)	.13	0 (0%)	14 (19%)	.004
ICU stay (d)	8 (6, 14)	9 (6, 14)	8 (5, 15)	.35	6 (3, 8)	9 (6, 15)	.045
Postoperative hospital stay (d)	14 (9, 22)	14 (9, 23)	13 (8, 22)	.30	13 (9, 21)	14 (8, 22)	.53
Early death after first LPCHS surgery	6 (3%)	3 (3%)	3 (3%)	>.99	2 (6%)	1 (1%)	.23

PA, Pulmonary artery; *RV*, right ventricle; *VSD*, ventricular septal defect; *LPCHS*, Lucile Packard Children's Hospital at Stanford; *MAPCA*, major aortopulmonary collateral artery; *RVOT*, right ventricular outflow tract; *ICU*, intensive care unit.

LPCHS were more likely to have postrepair left-right flow imbalance than those who did not (52% vs 24%; $P = .017$), although the RV pressure (28 [25-34] vs 35 [28-40], $P = .003$) and PA:aortic pressure ratio (0.33 [0.28-0.38] vs 0.37 [0.31-0.43], $P = .031$) were lower in the former cohort. Likewise, patients presenting to LPCHS with a proximal left or right PA occlusion (different from atretic branch recruitment) and who underwent reconstruction of the occluded PA at LPCHS were more likely to have left-right perfusion imbalance (56% vs 25%, $P = .018$) or extreme imbalance (31% vs 6%, $P = .007$). There were no significant differences in RV pressure,

TABLE 3. Early outcomes after complete repair according to prior surgical status

		Cardiac surgery before LPCH			Prior surgery type		
	Total (n = 517)	No (n = 338)	Yes (n = 179)	*P* value	Shunt (n = 77)	RV-PA connection (n = 102)	*P* value
Age at repair (y)	0.8 (0.4, 2.8)	0.5 (0.3, 1.0)	3.1 (1.3, 7.2)	<.001	1.6 (0.9, 6.2)	4.2 (2.0, 7.8)	<.001
Postrepair RV systolic pressure (mm Hg)	32 (27, 38)	30 (27, 35)	34 (28, 40)	.004	35 (28, 40)	32 (28, 38)	.074
Postrepair RV:aortic pressure ratio	0.35 (0.29, 0.40)	0.34 (0.28, 0.40)	0.36 (0.30, 0.42)	.017	0.38 (0.30, 0.43)	0.35 (0.29, 0.40)	.18
ICU stay (d)	8 (6,14)	9 (6, 15)	8 (5, 13)	.065	8 (6, 12)	8 (5, 14)	.65
Postoperative hospital stay (d)	14 (9,23)	16 (11, 25)	13 (8, 22)	<.001	12 (8, 20)	13 (8, 21)	.61
Early death after complete repair surgery	11 (2%)	6 (2%)	5 (3%)	.53	1 (1%)	4 (4%)	.39
Discharge lung perfusion scan findings							
Right lung total perfusion (%)	57 (51, 64)	56 (50, 61)	61 (54, 69)	<.001	61 (54,69)	61 (54,70)	>.99
Right upper zone perfusion (%)	10 (7, 12)	9 (7, 12)	10 (7, 13)	.35	10 (7, 12)	11 (8, 13)	.20
Right middle zone perfusion (%)	28 (24, 33)	28 (23, 32)	30 (26, 34)	.011	30 (25, 33)	30 (26, 34)	.95
Right lower zone perfusion (%)	19 (15, 23)	18 (14, 22)	20 (17, 25)	<.001	20 (17, 25)	21 (17, 25)	.75
Left lung total perfusion (%)	43 (36, 49)	44 (39, 50)	39 (31, 46)	<.001	39 (31, 46)	39 (30, 46)	.98
Left upper zone perfusion (%)	10 (8, 13)	11 (8, 14)	9 (6, 11)	<.001	10 (7, 12)	8 (6, 11)	.20
Left middle zone perfusion (%)	20 (16, 24)	20 (17, 24)	19 (14, 23)	.046	18 (14, 23)	19 (14, 24)	.97
Left lower zone perfusion (%)	12 (9, 16)	13 (10, 16)	11 (7, 15)	.004	11 (7, 15)	11 (7, 15)	>.99
Left:right flow imbalance	90 (23%)	55 (20%)	35 (29%)	.067	13 (23%)	22 (35%)	.16
Extreme left:right flow imbalance	30 (8%)	19 (7%)	11 (9%)	.54	4 (7%)	7 (11%)	.53
Regional flow imbalance							
Regional imbalance within right lung	123 (37%)	85 (37%)	38 (36%)	>.99	19 (40%)	19 (33%)	.42
Regional imbalance within left lung	122 (36%)	76 (33%)	46 (44%)	.066	18 (38%)	28 (48%)	.33
Regional imbalance within either lung	192 (57%)	129 (56%)	63 (60%)	.48	27 (57%)	36 (62%)	.69

Lung perfusion data available after complete repair in 389 patients, with regional right lung data available in 337 and regional left lung data in 336. Definitions of imbalance and extreme imbalance as described in the "Materials and Methods" section. *LPCH*, Lucile Packard Children's Hospital; *RV-PA*, right ventricle to pulmonary artery; *ICU*, intensive care unit.

PA:aortic pressure ratio, or lung perfusion metrics according to whether prior unifocalization had been performed or there were PA stents.

Time-Related Outcomes

Follow-up was available for a median of 2.6 years (0.4-7.5) after initial surgery at our center and for a median of 2.8 years (0.3-7.5) after complete repair, with no difference between patients who had and had not undergone PRS (2.0 [0.4-7.1] vs 3.1 years [0.2-7.7]; $P = .39$). PRS patients with a prior systemic-to-PA shunt had longer follow-up than those with a prior RV-PA connection (5.0 [1.0-9.3] vs 1.2 years [0.1-4.7]; $P < .001$), reflecting the increasing number of patients referred after an RV-PA connection later in our experience.

Among the 67 PRS patients whose first LPCHS surgery did not result in complete repair, 46 were repaired at a median of 0.7 years (0.6-1.6 years) after the first surgery. Of the 21 patients who had not undergone complete repair, 10 died (median 0.7 years after the first LPCHS surgery [0.2-1.0 years]), 6 had PA hypertension or were otherwise unsuitable for repair at the time of most recent evaluation (6.7 years [2.9-10.7 years] after the first LPCHS surgery), 3 were expected to undergo complete repair, 1 was recommended to have repair but did not return, and 1 was lost to follow-up. PRS patients did not differ from unoperated patients in the cumulative incidence of repair or mortality over time (Figure 5).

Compared with previously shunted patients, the cumulative incidence of complete repair with 6-month survival was higher ($P = .002$) and of death lower ($P = .18$) in patients who had prior RV-PA connection (Figure 5). Details of competing outcomes are presented in Table E1. On limited multivariable analysis, age at first LPCHS surgery did not substantially alter these relationships.

DISCUSSION

The heterogeneity of native pulmonary blood supply in patients with TOF/MAPCAs makes this one of the most challenging congenital cardiovascular anomalies to treat consistently and well. Likewise, assessment of risk factors for better or worse outcome is confounded by this anatomic heterogeneity and by the variable management across institutions. The Pulmonary Artery Reconstruction program at

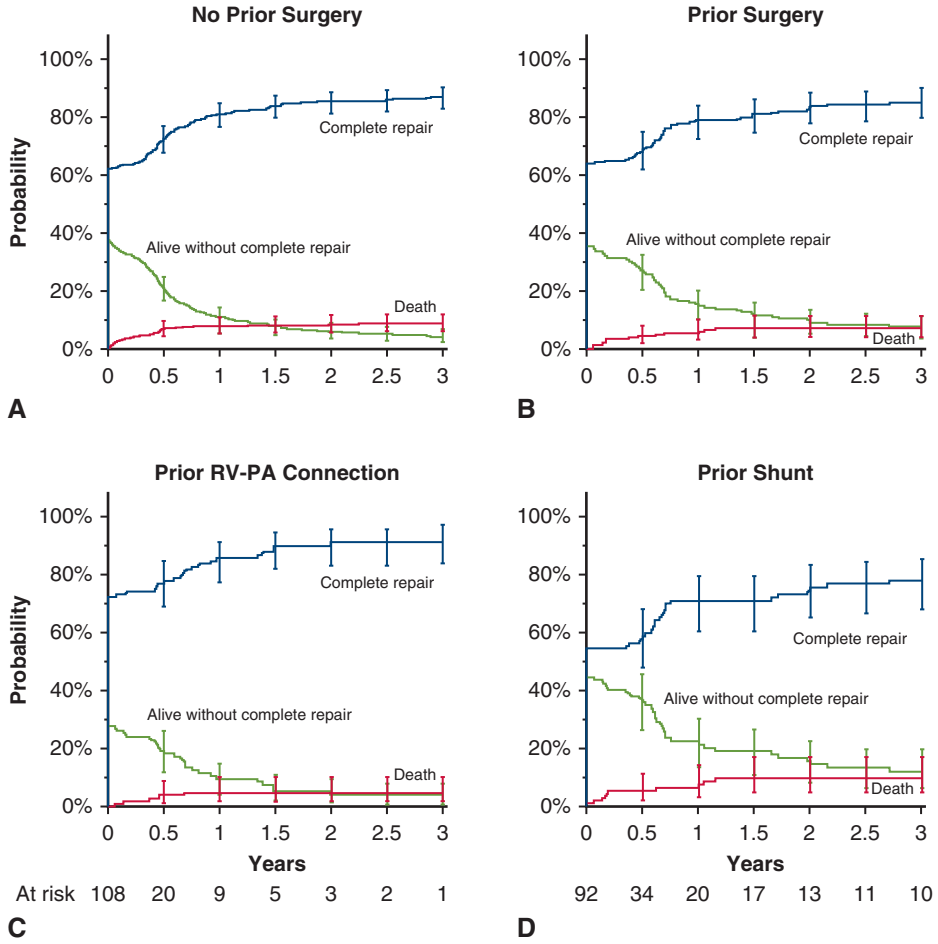


FIGURE 5. These competing outcome curves depict cumulative incidences of death (*red*), complete repair (with survival for at least 6 months) (*blue*), and alive without complete repair (*black*) from the time of first surgery at our center. A, For patients who had no prior surgery, the cumulative incidence of death was 8% (5%-11%) at 1 year, 8% (6%-12%) at 2 years, and 9% (6%-12%) at 3 years after the first LPCHS surgery. B, In the prior surgery group, the cumulative incidence of death was 6% (3%-10%) at 1 year and 7% (4%-11%) at 2 and 3 years, with no significant difference between groups ($P = .49$). The cumulative incidence of complete repair was (A) 81% (77%-85%) at 1 year, 85% (81%-89%) at 2 years, and 87% (83%-90%) at 3 years in the no prior surgery cohort and (B) 79% (73%-84%), 84% (78%-88%), and 86% (80%-90%) at 1, 2, and 3 years, respectively, in the prior surgery group ($P = .54$). C and D, Among patients who had prior surgery, the cumulative incidence of death was (C) 5% (2%-10%) at 1, 2, and 3 years after the first LPCHS surgery in the RV-PA connection group and (D) 8% (3%-14%) at 1 year and 10% (5%-17%) at 2 and 3 years in the shunt group, which was not significantly higher over time than in the RV-PA connection group ($P = .18$). The cumulative incidence of complete repair was (C) 86% (77%-91%) at 1 year, 91% (83%-96%) at 2 years, and 93% (84%-97%) at 3 years in the RV-PA connection cohort, and (D) 71% (60%-79%), 76% (65%-83%), and 78% (68%-85%) at 1, 2, and 3 years, respectively, in the shunt group ($P = .002$).

Stanford is focused on the comprehensive management of TOF/MAPCAs and other complex anomalies of the PA system, including Williams and Alagille syndromes, isolated ductal origin of a branch PA, and peripheral PA stenosis or MAPCAs associated with other intracardiac anomalies. We have also devoted considerable effort to investigating outcomes in these populations.[1-3,19-25,28] In general, procedural and midterm survival with low RV and PA pressures are excellent in our large cohort of patients with TOF/MAPCAs. However, there are subsets of complicated patients in whom outcomes are not as favorable or for whom detailed results have not been evaluated. More than one-third of patients treated in our program are referred after prior surgical procedures elsewhere, with previous interventions ranging from simply a single systemic-to-PA shunt placement to 5 or more operations consisting of multiple unifocalization procedures and RV-PA connection through both thoracotomy and sternotomy approaches. In these patients, residual central and peripheral PA stenoses are almost universal, PA or MAPCA branches have sometimes become occluded, and other complicating factors such as PA stents and RVOT pseudoaneurysms are not uncommon. The variability of anatomic and postprocedural findings not only makes it difficult to analyze these patients but also presents

a challenge for informing families of expected outcomes, which is critical when making decisions about major surgery that requires travel and significant disruption to work and life. The need to provide more patient-specific outcome data to families considering surgery at our center was one of the primary motivations for this study. Secondarily, this study demonstrates that patients with complex MAPCA who have undergone, at times multiple, palliative operations, can and should be considered for reoperative surgery leading to intracardiac septation and complete repair (Figure 6).

An increasing proportion of patients with TOF/MAPCAs who are referred to our center have undergone PRS, and most have undergone 2 or more operations. Despite the added complexity and adverse circulatory circumstances in many of these patients, complete repair with excellent survival and low postoperative RV pressure was achieved in the majority, comparable to unoperated patients. Appropriate patient selection was paramount to these results and driven by a thorough evaluation of the salvageable lung perfusion (ie, at least ~50% of healthy, low-resistance, segmental vessels must be deemed recruitable by Pulmonary Artery Reconstruction program consensus), regardless of the initial PRS management.

Accounting for this intrinsic selection bias, several notable findings regarding PRS characteristics are useful in informing patients considering reoperative surgery. Although patients with a prior RV-PA connection seemed more complex than previously shunted patients by some metrics, such as the number of prior operations, frequency of PA stents, proximal PA branch occlusions, and recruitment of occluded branches into the reconstruction, time-related outcomes were better. There was a clear difference in the cumulative incidences of complete repair and survival between patients with a prior RV-PA connection and patients with a prior shunt. The survival difference between these groups was largely evident by 1 year after the initial operation at LPCHS. These differences could be related to a number of factors, including patient selection bias (patients with more favorable anatomy originally were more likely to have surgery in general, or an RV-PA connection in particular, with the most favorable cohort having undergone VSD closure), differential benefit provided by an RV-PA connection versus a shunt, survival or other patient-related bias (RV-PA connection patients were older), or simply chance. Concluding that an RV-PA connection is a better initial palliative operation than a systemic-to-PA shunt would be faulty, given the tremendous uncaptured variability inherent in this retrospective data set.

The fact that major outcomes did not differ significantly between unoperated patients and patients who had undergone various surgical and often interventional procedures does not imply that PRS status is unimportant. These were both selected populations, and patients treated externally who did not survive or were not accepted for surgery were obviously not accounted for in this analysis. What these findings do tell us, however, is that patients determined to be suitable candidates for surgery after PRS, given

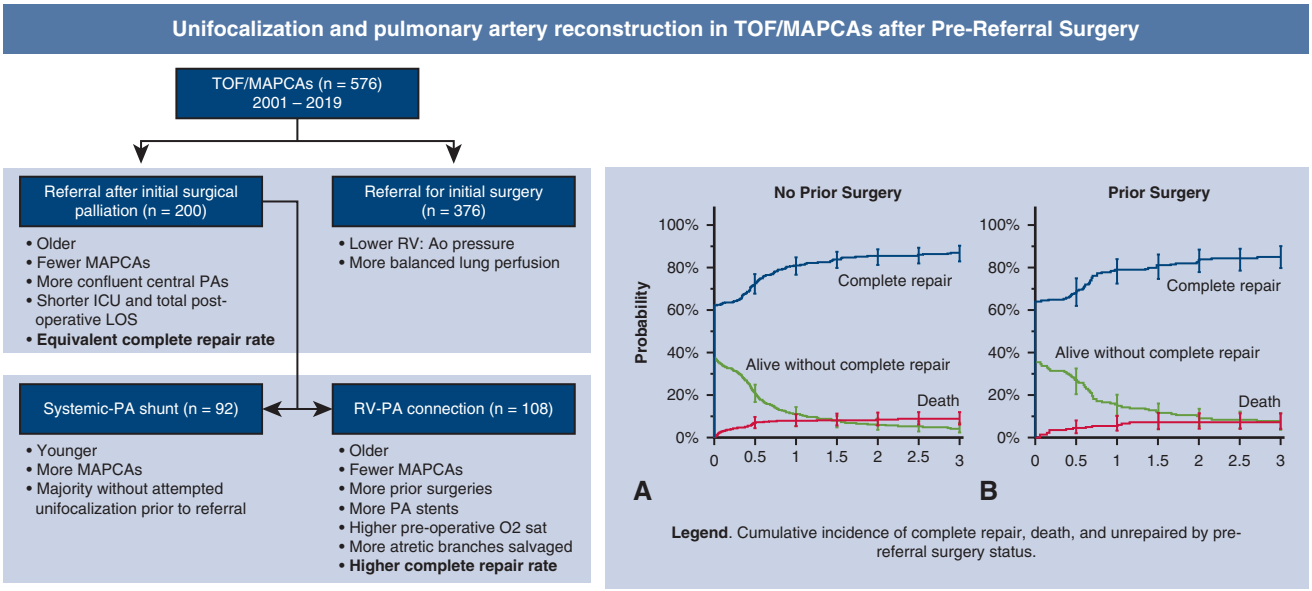


FIGURE 6. Characteristics and outcomes in patients who were referred with prior versus no prior surgical intervention. *TOF*, Tetralogy of Fallot; *MAPCA*, major aortopulmonary collateral artery; *PA*, pulmonary artery; *ICU*, intensive care unit; *LOS*, length of stay; *RV*, right ventricle; *AO*, aorta.

our general guidelines, can have excellent outcomes, similar to those in previously unoperated patients. We have also found this to be true in unoperated patients referred at an older age,[29] but the inference from such findings should not be that the strategy, sequence of, or age at treatment do not matter.

Accounting for the added complexity of reoperative MAPCA surgery is difficult, but it clearly increases morbidity risk. Removal of PA stents and recruitment of occluded vessels are technically demanding, but their contribution to outcome is not easy to ascertain. Nevertheless, in this selected population, the number of prior operations, presence of PA stents, and extent of prior unifocalization were not associated with differences in survival or RV pressure, although there were differences in pulmonary blood flow distribution associated with identified proximal PA branch occlusion or incorporation of atretic branches, as also observed in a prior study.[24] Left-right pulmonary flow imbalance after repair in PRS patients was likely reflective of pre-existing heterogeneity of salvageable low-resistance vessels, which may not be entirely correctable at the time of revision.

Although we analyzed differences in outcomes according to the number, types, and details of previous surgeries, the point of this study was not to draw conclusions about the relative benefits or drawbacks of prior surgical approaches. The study cohort comprised a heterogeneous but selected patient population of patients who (1) had undergone and survived prior surgeries elsewhere, (2) were referred for and chose to undergo reoperation at our center, and (3) were determined to be suitable candidates for repair with a good result. Thus, this study cannot be generalized and should not be interpreted to provide insight into different management strategies (eg, RV-PA connection vs shunting).

Study Limitations

There are a number of important limitations to this study in addition to those noted. Immediate postoperative RV:aortic systolic pressure ratios are a consistent metric by which to measure immediate outcomes, but may not reflect the true long-term physiology of these patients. Every attempt is made to surveil these patients during follow-up with clinical, catheterization, lung perfusion, and echocardiographic data, as has been detailed in prior reports.[3,30] Regardless of PRS status, greater than 90% of our patients are referred from other institutions, and the availability of long-term follow-up data is variable.

We recorded a number of reliably ascertained features and grouped patients into discrete (but still internally heterogeneous) categories in an effort to understand whether such variables were associated with important differences in outcomes. However, we did not evaluate numerous other potentially relevant anatomic and physiologic factors, such as individual vessel morphology or size, occlusion of segmental or subsegmental branches that were not recruited into the reconstruction, and segmental pulmonary vascular resistance.

This study does not include patients who were referred but did not undergo surgery at our center. A small percentage of patients, who have usually undergone prior interventions, are determined not to be candidates for repair with a good outcome (ie, RV pressure <50% systemic) due to pulmonary vascular disease, loss of vessels, lack or surgical targets, and other anatomic/physiologic features. We do not track such patients, but they are a small minority (<5%) of the referrals we consider. Also, we did not evaluate prior transcatheter interventions, other than presence of PA stents, although such interventions were common in the PRS cohort. For the competing outcomes analysis, we defined complete repair as survival 6 months or more post-repair. That time frame was deliberately liberal and underestimates that cumulative incidence of complete repair. However, we believe that the relevant metric in this case is not simply performance of the repair but survival through the perioperative and early period.

CONCLUSIONS

Prior surgical procedures, ranging from isolated shunts to multistage unifocalization and repair with extensive residual PA disease, even in patients with occluded central or peripheral branches, PA stents, or supra-systemic RV pressure, does not preclude PA reconstruction and complete repair with low postoperative RV pressure. From our perspective, the goal of managing patients with this complex condition is survival with right heart physiology as close as possible to normal, with the aim of preserving the long-term health of the RV and appropriate distribution of pulmonary blood flow to lung parenchyma. In prior studies, we demonstrated that complete unifocalization and repair early in life results in excellent survival with RV pressures well below half-systemic in a large majority of patients.[3] In this focused evaluation of patients who underwent surgical intervention on the pulmonary circulation before referral to our center, we found that similarly excellent outcomes can be achieved in properly selected patients. Preoperative evaluation aimed at estimating potential achievable PA pressure allows identification of patients with an acceptable likelihood of repair with a good result. Further studies will be needed to document longer term outcomes in this complex patient population.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

References

1. Reddy VM, Liddicoat JR, Hanley FL. Midline one-stage complete unifocalization and repair of pulmonary atresia with ventricular septal defect and major aortopulmonary collaterals. *J Thorac Cardiovasc Surg*. 1995;109:832-45.
2. Ma M, Hanley FL. Comprehensive management of major aortopulmonary collaterals in the repair of tetralogy of Fallot. *Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu*. 2017;21:75-82.
3. Bauser-Heaton H, Borquez A, Han B, Ladd M, Asija R, Downey L, et al. Programmatic approach to management of tetralogy of Fallot with major aortopulmonary collateral arteries: a 15-year experience with 458 patients. *Circ Cardiovasc Interv*. 2017;10:e004952.
4. Liao PK, Edwards WD, Julsrud PR, Puga FJ, Danielson GK, Feldt RH. Pulmonary blood supply in patients with pulmonary atresia and ventricular septal defect. *J Am Coll Cardiol*. 1985;6:1343-50.
5. Iyer KS, Mee RBB. Staged repair of pulmonary atresia with ventricular septal defect and major systemic to pulmonary artery collaterals. *Ann Thorac Surg*. 1991;51:65-72.
6. Rome JJ, Mayer JE, Castaneda AR, Lock JE. Tetralogy of Fallot with pulmonary atresia. Rehabilitation of diminutive pulmonary arteries. *Circulation*. 1993;88(4 Pt 1):1691-8.
7. Tchervenkov CI, Salasidis G, Cecere R, Béland MJ, Jutras L, Paquet M, et al. One-stage midline unifocalization and complete repair in infancy versus multiple-stage unifocalization followed by repair for complex heart disease with major aortopulmonary collaterals. *J Thorac Cardiovasc Surg*. 1997;114:727-37.
8. Cho JM, Puga FJ, Danielson GK, Dearani JA, Mair DD, Hagler DJ, et al. Early and long-term results of the surgical treatment of tetralogy of Fallot with pulmonary atresia, with or without major aortopulmonary collateral arteries. *J Thorac Cardiovasc Surg*. 2002;124:70-81.
9. Duncan BW, Mee RB, Prieto LR, Rosenthal GL, Mesia CI, Qureshi A, et al. Staged repair of tetralogy of Fallot with pulmonary atresia and major aortopulmonary collateral arteries. *J Thorac Cardiovasc Surg*. 2003;126:694-702.
10. Gupta A, Odim J, Levi D, Chang RK, Laks H. Staged repair of pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries: experience with 104 patients. *J Thorac Cardiovasc Surg*. 2003;126:1746-52.
11. Boshoff D, Gewillig M. A review of the options for treatment of major aortopulmonary collateral arteries in the setting of tetralogy of Fallot with pulmonary atresia. *Cardiol Young*. 2006;16:212-20.
12. Farouk A, Zahka K, Siwik E, Erenberg F, Al-Khatib Y, Golden A, et al. Individualized approach to the surgical treatment of tetralogy of Fallot with pulmonary atresia. *Cardiol Young*. 2009;19:76-85.
13. Davies B, Mussa S, Davies P, Stickley J, Jones TJ, Barron DJ, et al. Unifocalization of major aortopulmonary collateral arteries in pulmonary atresia with ventricular septal defect is essential to achieve excellent outcomes irrespective of native pulmonary artery morphology. *J Thorac Cardiovasc Surg*. 2009;138:1269-75.
14. Carotti A, Albanese SB, Filippelli S, Ravà L, Guccione P, Pongiglione G, et al. Determinants of outcome after surgical treatment of pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries. *J Thorac Cardiovasc Surg*. 2010;140:1092-103.
15. Liava'a M, Brizard CP, Konstantinov IE, Robertson T, Cheung MM, Weintraub R, et al. Pulmonary atresia, ventricular septal defect, and major aortopulmonary collaterals: neonatal pulmonary artery rehabilitation without unifocalization. *Ann Thorac Surg*. 2012;93:185-91.
16. Zhu J, Meza J, Kato A, Saedi A, Chetan D, Parker R, et al. Pulmonary flow study predicts survival in pulmonary atresia with ventricular septal defect and major aortopulmonary collateral arteries. *J Thorac Cardiovasc Surg*. 2016;152:1494-503.
17. Soquet J, Liava'a M, Eastaugh L, Konstantinov IE, Brink J, Brizard CP, et al. Achievements and limitations of a strategy of rehabilitation of native pulmonary vessels in pulmonary atresia, ventricular septal defect, and major aortopulmonary collateral arteries. *Ann Thorac Surg*. 2017;103:1519-26.
18. Barron DJ, Kutty RS, Stickley J, Stümper O, Botha P, Khan NE, et al. Unifocalization cannot rely exclusively on native pulmonary arteries: the importance of recruitment of major aortopulmonary collaterals in 249 cases. *Eur J Cardiothorac Surg*. 2019;56:679-87.
19. Bauser-Heaton H, Ma M, Wise-Faberowski L, Asija R, Shek J, Zhang Y, et al. Outcomes after initial unifocalization to a shunt in complex tetralogy of Fallot with MAPCAs. *Ann Thorac Surg*. 2019;107:1807-15.
20. Reddy VM, Petrossian E, McElhinney DB, Moore P, Teitel DF, Hanley FL. One-stage complete unifocalization in infants: when should the ventricular septal defect be closed? *J Thorac Cardiovasc Surg*. 1997;113:858-68.
21. Carrillo SA, Mainwaring RD, Patrick WL, Bauser-Heaton HD, Peng L, Reddy VM, et al. Surgical repair of pulmonary atresia with ventricular septal defect and major aortopulmonary collaterals with absent intrapericardial pulmonary arteries. *Ann Thorac Surg*. 2015;100:606-13.
22. Mainwaring RD, Ibrahimiye AN, Hanley FL. Surgical technique for reconstruction of peripheral pulmonary artery stenosis and other complex peripheral reconstructions. *Ann Thorac Surg*. 2016;102:e181-3.
23. Bauser-Heaton H, Ma M, McElhinney DB, Goodyer WR, Zhang Y, Chan FP, et al. Outcomes after aortopulmonary window for hypoplastic pulmonary arteries and dual-supply collaterals. *Ann Thorac Surg*. 2019;108:820-7.
24. Asija R, Koth AM, Velasquez N, Chan FP, Perry SB, Hanley FL, et al. Postoperative outcomes of children with tetralogy of Fallot, pulmonary atresia, and major aortopulmonary collaterals undergoing reconstruction of occluded pulmonary artery branches. *Ann Thorac Surg*. 2016;101:2329-34.
25. Wise-Faberowski L, Irvin M, Lennig M, Long J, Nadel HR, Bauser-Heaton H, et al. Assessment of the reconstructed pulmonary circulation with lung perfusion scintigraphy after unifocalization and repair of tetralogy of Fallot with major aortopulmonary collaterals. *World J Pediatr Congenit Heart Surg*. 2019;10:313-20.
26. Gray RJ. A class of K-sample tests for comparing the cumulative incidence of a competing risk. *Ann Stat*. 1988;16:1141-54.
27. Fine JP, Gray RJ. A proportional hazards model for the subdistribution of a competing risk. *JASA*. 1999;94:496-509.
28. Bauser-Heaton H, Borquez A, Asija R, Wise-Faberowski L, Zhang Y, Downey L, et al. Pulmonary reinterventions after complete unifocalization and repair in infants and young children with tetralogy of Fallot with major aortopulmonary collaterals. *J Thorac Cardiovasc Surg*. 2018;155:1696-707.
29. Vaikunth S, Bauser-Heaton H, Lui GK, Wise-Faberowski L, Chan FP, Asija R, et al. Repair of untreated older patients with tetralogy of Fallot with major aortopulmonary collaterals. *Ann Thorac Surg*. 2019;107:1218-22.
30. Mainwaring RD, Reddy VM, Peng L, Kuan C, Palmon M, Hanley FL. Hemodynamic assessment after complete repair of pulmonary atresia with major aortopulmonary collaterals. *Ann Thorac Surg*. 2013;95:1397-402.

Key Words: unifocalization, MAPCAs, pulmonary atresia, tetralogy of Fallot, reoperation

TABLE E1. Details of competing outcomes

Cohort	Size	Complete repair	Death	Alive without repair	Alive without repair (<3 y)
No prior surgery	376	322 (86%)	32 (9%)	14 (4%)	8 (2%)
Prior surgery	200	169 (85%)	14 (7%)	11 (6%)	6 (3%)
Prior RV-PA Connection	108	98 (91%)	5 (5%)	1 (1%)	4 (4%)
Prior shunt	92	71 (77%)	9 (10%)	10 (11%)	2 (2%)

RV-PA, Right ventricle to pulmonary artery.