Severe aortopulmonary collaterals are associated with lower transplant-free survival in patients undergoing staged single ventricle palliation

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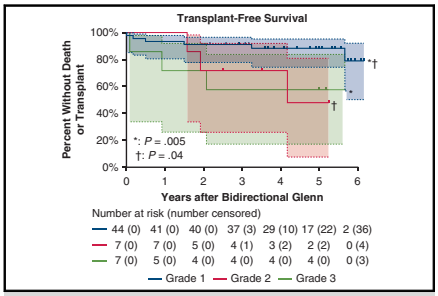
ABSTRACT

Objective: To identify risk factors for aortopulmonary collateral (APC) development and assess the impact of severe APCs in children undergoing staged single ventricle palliation.

Methods: Children undergoing a bidirectional Glenn operation between January 1, 2016, and March 31, 2021, at our center were included. All underwent angiography prior to Glenn and Fontan; APC flow was graded on a scale of 0 (no appreciable collateral flow) to 4 (severe burden). Demographic data, congenital diagnosis, clinical history, and outcomes were stratified by Glenn assessment; Fontan outcomes were stratified by pre-Fontan grade.

Results: Sixty patients met the inclusion criteria, all of whom had angiographic evidence of APCs. There were 7 transplants and 9 deaths in the cohort. There were no significant differences in demographics among the patients. Right ventricular morphology was more common in patients with severe pre-Glenn collaterals (24 of 44 vs 2 of 6 vs 7 of 8; $P = .014$). Longer stage 1 aortic cross-clamp duration was associated with greater severity pre-Glenn (44 minutes vs 34 minutes vs 66 minutes; $P = .023$). Patients with grade 3 pre-Glenn collaterals more commonly required transplantation than those with grade 1 collaterals ($P < .001$) and had lower overall transplant-free survival than those with grade 1 ($P = .005$) or grade 2 ($P = .04$) collaterals.

Conclusions: The ubiquity of APCs in this study demonstrates their prevalence in single ventricle disease. Right ventricular morphology and prolonged aortic cross-clamp duration are associated with higher burden. Greater severity was associated with decreased transplant-free survival. These data emphasize the negative long-term impact of these collaterals. (JTCVS Open 2023;16:844-54)



Transplant-free survival is lower in patients with severe aortopulmonary collaterals (*shaded area*, 95% CI).

CENTRAL MESSAGE

Greater severity of aortopulmonary collaterals was associated with decreased transplant-free survival. These data emphasize the negative long-term impact on clinical outcomes and resource utilization.

PERSPECTIVE

Aortopulmonary collaterals are well-described yet controversial sequelae of single ventricle palliation. Some advocate for aggressive management, while others argue that their impact is minimal. In this cohort, increasing severity of collateral burden is associated with poorer long-term transplant-free survival. Identification of high-risk patients may improve outcomes through targeted management.

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Abbreviations and Acronyms
APC = aortopulmonary collateral
BDG = bidirectional Glenn

▶ Video clip is available online.

Single ventricle congenital heart disease is a spectrum of structural cardiac defects that result in one functional ventricle. These defects often are not amenable to primary repair and require a 3-stage reconstructive procedure to optimize cardiac physiology. The formation of aortopulmonary collateral (APC) arteries is a well-described sequela after staged single ventricle palliation. The development of APCs has previously been associated with longer duration of ventilation, greater chest tube drainage volume and duration of use, and longer intensive care stay and overall hospital stay.[1-3] The true clinical significance of APC flow remains controversial, however.

It is possible that a heterogeneous patient population may explain these differences. Some patients appear to tolerate a large collateral burden, while others are significantly affected by this additional pulmonary shunt. Additionally, some may benefit from embolization, while others may depend on the supplemental pulmonary flow.

Inflammatory states have been previously suggested as angiogenic stimuli, particularly through macrophage translocation and secretion of both angiogenic and inflammatory markers.[4,5] In the setting of capillary leak and low extracellular matrix proteins, macrophages translocate and secrete proteins that modify the extracellular matrix and encourage angiogenesis.[4-6] Inflammatory stimuli, such as chest tube placement at pleural apices, may predispose patients to APC development.

Although some data support aggressive search and control,[2] other studies have demonstrated a limited effect of embolization and favor conservative management.[3,7] In this study, our primary aim was to characterize the clinical impact of APCs in patients with single ventricle physiology. Given the associations with poorer short-term outcomes,[1,3,8] we hypothesized that greater APC severity in our cohort is directly associated with poorer in-hospital and long-term outcomes, particularly transplant-free survival.

PATIENTS AND METHODS

Inclusion Criteria

All children undergoing bidirectional Glenn palliation (BDG) between January 1, 2016, and March 31, 2021, at our center were included. This selection was due to the heterogeneity of stage 1 procedures, as well as to capture those who progressed directly to transplantation, were not candidates for stage 3 palliation (Fontan) or died prior to Fontan. Patients who underwent preoperative cardiac catheterization prior to BDG were included. If catheterization data were present prior to Fontan or transplant, these data were assessed separately for longitudinal follow-up.

Study Design and Variables

The severity of APC flow by angiography was retrospectively graded on a qualitative scale of 0 to 4 points according to previously published guidelines by an interventional congenital cardiologist blinded to patient outcomes (Video 1, Figure 1).[8] Determination was made with a standard approach via an ascending aortogram in all patients. Preoperative and postoperative clinical outcomes along with transplant-free survival were assessed. Transplant-free survival was defined as the earliest time to transplant or death. Demographics and procedural history were grouped by pre-BDG severity prior to embolization. In-hospital outcomes and transplant-free survival were grouped by severity grade following embolization attempts.

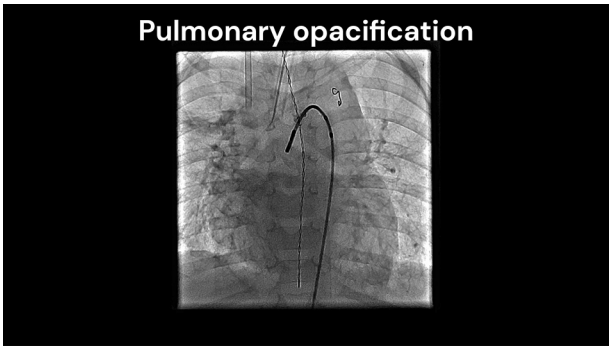
The study protocol and publication of data was approved by the Vanderbilt University Institutional Review Board (211077; October 13, 2021), which waived the requirement for patient written consent for the publication of study data. The waiver was granted based on our sole use of data regularly collected as standard of care and that this study could not be practicably carried out with the small population that would be disproportionately affected by losses.

The following demographic data were collected: age at procedure, gestational age at birth, sex, race, height and weight at procedure, primary and secondary congenital heart disease, syndrome or chromosomal abnormality, ductal dependency, and ventricular morphology. Procedural history included pre-BDG intervention type, stage 1 shunt type, interstage interventions, post-BDG interventions, date of transplant, and date of death. Catheterization data included arterial and venous saturation, end-diastolic pressure, APC grade, dominant collateral laterality, embolization, pulmonary arterial angioplasty or stenting, and placement of a shunt or a ventricle to pulmonary artery conduit. Branch pulmonary artery oxygen step-ups were not used to quantify APC flow.

Procedural data included oxygen saturation at admission, preoperative nitric oxide use, preoperative hemoglobin, presence or absence of preoperative supplemental oxygen, preoperative cardiac arrest or extracorporeal life support, primary and secondary procedure, cardiopulmonary bypass and aortic cross-clamp times, intraoperative and 24-hour blood product utilization, mechanical ventilation duration, open sternum duration, and chest tube side, duration, and output. As standard practice, chest tubes were removed after drainage was <5 mL/kg/day for 2 consecutive days. Complications included reoperation for bleeding, unplanned interventional catheterization, cardiac arrest, extracorporeal life support, chylothorax, phrenic nerve palsy, vocal cord paralysis, pneumonia, deep or superficial wound infections, urinary tract infection, necrotizing enterocolitis, bacteremia or sepsis, cardiac reoperation, and noncardiac reoperation. Other data included oxygen saturation at discharge, presence or absence of supplemental oxygen at discharge, overall hospital length of stay, and length of stay in the intensive care unit.

Statistical Analysis

Demographic and clinical details were summarized with descriptive statistics. Patient data were assessed between groups using the χ^2 or Kruskal-Wallis test as appropriate. Continuous variables were represented as median and interquartile range. The Kaplan-Meier method with a pairwise log-rank test was used for survival comparisons. Survival charts were truncated once the number of patients at risk fell below 10% of the initial cohort at risk. Post hoc testing was performed with the 2-tailed Z test for categorical variables and the Mann-Whitney U test for continuous variables. All statistical analyses were performed with SPSS (IBM), and $P < .05$ was considered to indicate statistical significance.



VIDEO 1. Representative cardiac catheterization films with defining features of each severity grade 1 to 4. Video available at: https://www.jtcvs.org/article/S2666-2736(23)00280-2/fulltext.

RESULTS

Patient Characteristics

Sixty patients met the inclusion criteria during the study period (Figure 2). Of these 60, 2 patients could not be assessed pre-BDG and were excluded from our analysis. There were 7 transplants and 9 deaths. Demographic characteristics of the study cohort are summarized in Table 1. All patients had angiographic evidence of APCs of varying degrees of severity; pre-BDG catheter assessment revealed 44 grade 1 APCs, 6 grade 2 APCs, and 8 grade 3 APCs. In contrast, longitudinal follow-up assessment identified 15 grade 1 APCs, 26 grade 2 APCs, 16 grade 3 APCs, and 1 grade 4 APCs. The patient with grade 4 APCs was considered grade 3+ for comparisons between groups at Fontan. Of these 58 longitudinal follow-up catheterizations, 51 progressed to Fontan or transplant; there were 15 grade 1 APCs, 25 grade 2 APCs, and 11 grade 3+ APCs at the time of surgery. Right ventricular morphology was more common in groups with more severe pre-BDG APCs: 54.5% (24 of 44) of patients with grade 1, 33.3% (2 of 6) with grade 2, and 87.5% (7 of 8) with grade 3 ($P = .014$), with post hoc analysis revealing a difference in proportions between the grade 2 and grade 3 groups ($P = .036$). There were no other significant demographic differences among the groups.

Cardiac Catheterization Assessment

Tables E1 and E2 summarize data from catheterization assessment prior to BDG and Fontan, respectively. There were no significant differences at the pre-BDG assessment. Of the 2 patients that underwent embolization, only 1 resulted in a radiographically significant decrease in collateral burden from grade 3 to grade 2. Among patients undergoing pre-Fontan catheterization, 41.2% (7 of 17) in the grade 3+ severity group required APC embolization, compared to 0% (0 of 15) for grade 1 and 3.8% (1 of 26) for grade 2 ($P < .001$). Post hoc analyses revealed a greater proportion

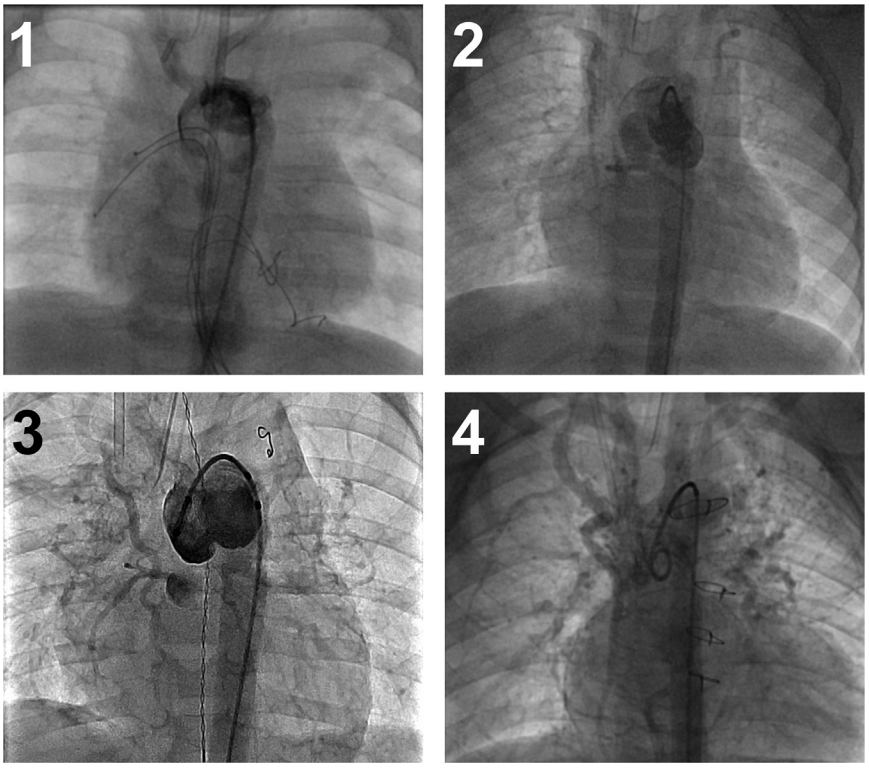


FIGURE 1. Aortopulmonary collaterals identified in cardiac catheterization ordered by increasing severity from 1 (no appreciable collateral flow) to 4 (severe collateral burden).

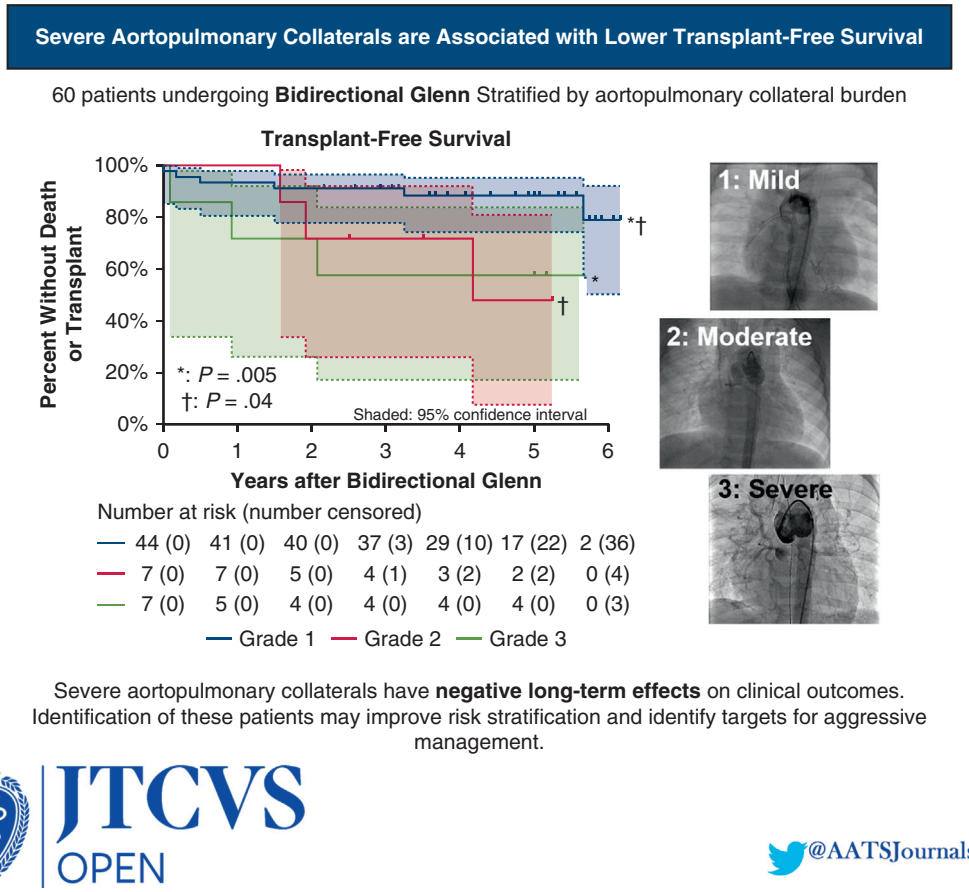


FIGURE 2. Graphical abstract illustrating study design and outcomes. Patients were stratified according to qualitative pre-Glenn severity grading based on catheter assessment. There were no grade 4 patients at Glenn.

of grade 3+ embolizations compared to either grade 1 or grade 2 ($P = .005$ and .002, respectively). As shown in Tables 2 and 3, there was no significant association between the laterality of identified APCs and site of chest tubes at the prior stage for either pre-BDG or pre-Fontan assessment. Concordance was determined by dominant APC location and the presence of apical chest tubes at the previous stage.

Hospital Course and Procedural History

Table 4 summarizes the patients' procedural history stratified by pre-BDG assessment. There was a significant difference in post-BDG procedures ($P = .003$), with subanalysis revealing a greater proportion of transplants in patients with grade 3 pre-BDG APCs ($P = .002$). Post hoc analysis revealed that patients with grade 3 APCs were more likely undergo transplant compared to those with grade 1 or 2 APCs ($P = .001$ and .040, respectively). None of the 7 transplant recipients in the cohort progressed to Fontan prior to transplantation. The hospital courses of patients undergoing stage 1, BDG, and Fontan, including preoperative and postoperative data, are described in Tables E3, E4, and E5, respectively. Superficial sternal infection was more common after stage 1 in patients with grade 2 pre-BDG APCs (0 of 44 vs 2 of 6 vs 0 of 8; $P = .001$). Longer aortic cross-clamp duration in stage 1 was associated with higher grade of APCs at BDG (44 minutes vs 34 minutes vs 66 minutes; $P = .023$), with post hoc analysis demonstrating a higher median cross-clamp duration in patients with grade 3 APCs compared to those with grade 1 APCs ($P = .007$). However, this association was lost when excluding procedures without aortic cross-clamping, such as pulmonary arterial banding or Blalock-Taussig-Thomas shunt placement (60 minutes vs 62 minutes vs 66 minutes; $P = .24$). Patients with grade 2 APCs at BDG required fewer days in intensive care (4.5 days vs 2 days vs 3 days; $P = .019$), with post hoc analysis revealing shorter intensive care stays in grade 2 APCs compared to grade 1 APCs ($P = .005$). Patients with grade 2 pre-Fontan APCs had a greater median preoperative hemoglobin concentration (14.2 vs 15.1 vs 14.1 mg/dL; $P = .039$), with post hoc analysis revealing greater concentration in grade 2 APCs compared to grade 1 APCs ($P = .021$).

Notable nonsignificant outcomes at Glenn included 24-hour postoperative chest tube output ($P = .65$), duration

TABLE 1. Patient demographic characteristics stratified by pre-Glenn aortopulmonary collateral severity

Characteristic	Pre-Glenn grade			*P* value
	1 (N = 44)	2 (N = 6)	3 (N = 8)	
Gestational age, wk, median (IQR)	39 (38-39)	39 (37-39)	39 (39-39)	.63
Sex, n (%)				.55
Male	25 (56.8)	2 (33.3)	4 (50)	
Female	19 (43.2)	4 (66.7)	4 (50)	
Race, n (%)				.81
Caucasian	33 (75)	6 (100)	6 (75)	
African American	8 (18.2)	0	1 (12.5)	
Hispanic	1 (2.3)	0	1 (12.5)	
Asian	1 (2.3)	0	0	
Native American	1 (2.3)	0	0	
Chromosomal abnormality or syndrome, n (%)				.26
15q11.2 deletion	0	1 (16.7)	0	
Fetal drug exposure	4 (9.1)	0	1 (12.5)	
Heterotaxy; asplenia	1 (2.3)	0	0	
Heterotaxy; polysplenia	1 (2.3)	0	0	
Other	1 (2.3)	1 (16.7)	1 (12.5)	
Primary congenital diagnosis, n (%)				.93
Congenitally corrected transposition of the great arteries	1 (2.3)	0	0	
Complete atrioventricular septal defect	2 (4.5)	0	0	
Double-inlet left ventricle	4 (9.1)	0	1 (12.5)	
Double-outlet right ventricle	4 (9.1)	1 (16.7)	0	
Ebstein anomaly	1 (2.3)	0	0	
Hypoplastic left heart syndrome	18 (40.9)	2 (33.3)	7 (87.5)	
Pulmonary atresia	4 (9.1)	1 (16.7)	0	
Tricuspid atresia	10 (22.7)	2 (33.3)	0	
Ventricular morphology, n				.014
Left	20 (45.5)	3 (50)	1 (12.5)	
Right	24 (54.5)	2 (33.3)	7 (87.5)	
Intermediate	0	1 (16.7)	0	
Ductal-dependent systemic flow, n (%)	36 (81.8)	5 (83.3)	8 (100)	.42

IQR, Interquartile range.

of mechanical ventilation ($P = .55$), and overall length of stay ($P = .34$).

Patient Outcomes

There was no significant difference in overall or 1-year survival ($P = .25$ and .56, respectively). By pairwise comparison, patients with grade 3 pre-BDG APCs were more likely to progress to transplantation compared to those with grade 1 APCs ($P = .004$), but not compared to those with grade 2 APCs ($P = .59$). Transplant-free survival differed significantly across the study period ($P = .009$; Figure 3). Pairwise comparison revealed that both grade 2 and grade 3 pre-BDG APCs were associated with poorer transplant-free survival compared to grade 1 APCs ($P = .040$ and .005, respectively); however, 1-year transplant-free survival did not differ significantly ($P = .11$). 1-year transplant-free survival was 93.2%

TABLE 2. Dominant collateral laterality at Glenn and concordance with chest tube location at stage 1

Parameter	Pre-Glenn grade			*P* value
	1 (N = 44)	2 (N = 6)	3 (N = 8)	
Predominant collateral laterality, n (%)				.14
Left	0	0	0	
Right	13 (29.5)	4 (66.7)	4 (50)	
Bilateral	31 (70.5)	2 (33.3)	4 (50)	
Concordant collateral laterality with previous chest tube placement (n)	16 (36.4)	2 (33.3)	4 (50)	.67

TABLE 3. Dominant collateral laterality at Fontan and concordance with chest tube location at Glenn

Parameter	Pre-Fontan grade (n)			*P* value
	1 (N = 15)	2 (N = 26)	3+ (N = 17)	
Predominant collateral laterality, n (%)				.46
Left	1 (6.7)	0	0	
Right	4 (26.7)	8 (30.8)	7 (41.2)	
Bilateral	10 (66.7)	18 (69.2)	10 (58.8)	
Concordant collateral laterality with previous chest tube placement, n (%)	9 (60)	16 (61.5)	8 (47.1)	.75

for grade 1, 100% for grade 2, and 71.4% for grade 3 pre-BDG APCs. Transplant-free survival at maximal follow-up was 78.4% in grade 1, 47.6% in grade 2, and 0% in grade 3 APCs.

DISCUSSION

The high proportion of patients in this study with angiographic evidence of APCs emphasizes their prevalence within the single ventricle population. We identified that increasing APC severity at BDG is associated with decreased transplant-free survival. Our data underscore the negative long-term impact of severe APCs at BDG. This effect includes attempts to control collateral flow prior to BDG. However, we did not identify differences in mortality or clinically relevant short-term outcomes among the severity groups. As such, the differences between severity groups likely are driven primarily by greater progression to transplantation and may be a gradual effect over time. This time dependence may reflect the controversies surrounding previous studies, many of which assessed the effects of APCs on short-term outcomes.[1,3,7,8]

In their study of 137 children after Fontan, Kanter and Vincent demonstrated that a significant APC burden may be associated with progression to cardiac failure.[2] Although these patients were assessed at Fontan, the authors' results endorse our finding of decreased transplant-free survival associated with APC flow. Our cohort study demonstrates that for single ventricle patients, severe APCs at pre-Glenn angiographic assessment is associated with poorer transplant-free survival.

In our cohort, right ventricular morphology was the sole anatomic factor associated with increased APC severity, which previously has been associated with worse transplant-free survival.[9] We identified that longer aortic

TABLE 4. Procedural history stratified by pre-Glenn aortopulmonary collateral severity

Procedure	Pre-Glenn grade			*P* value
	1 (N = 44)	2 (N = 6)	3 (N = 8)	
Pre-Glenn intervention type, n (%)				.17
None	4 (9.1)	0	0	
Transcatheter ductal stenting	10 (22.7)	0	0	
Norwood	18 (40.9)	3 (50)	8 (100)	
Blalock-Taussig-Thomas shunt	8 (18.2)	2 (33.3)	0	
Pulmonary arterial banding	2 (4.5)	0	0	
Other	2 (4.5)	1 (16.7)	0	
Norwood shunt type, n (%)				.17
Blalock-Taussig-Thomas	8 (44.4)	2 (66.7)	1 (12.5)	
Sano	10 (55.6)	1 (33.3)	7 (87.5)	
Interstage intervention, n (%)				.61
None	27 (61.4)	3 (50)	4 (50)	
Interventional catheterization	7 (15.9)	2 (33.3)	3 (37.5)	
Surgical revision	10 (22.7)	1 (16.7)	1 (12.5)	
Post-Glenn intervention, n (%)				.003
None	2 (4.5)	1 (16.7)	0	
Fontan	30 (68.2)	3 (50)	3 (37.5)	
Glenn takedown	4 (9.1)	0	1	
Interventional catheterization	5 (11.4)	1 (16.7)	0	
Shunt revision	0	0	1 (12.5)	
Transplant	3 (6.8)	0	4 (50)	.002
Other	0	1 (16.7)	0	

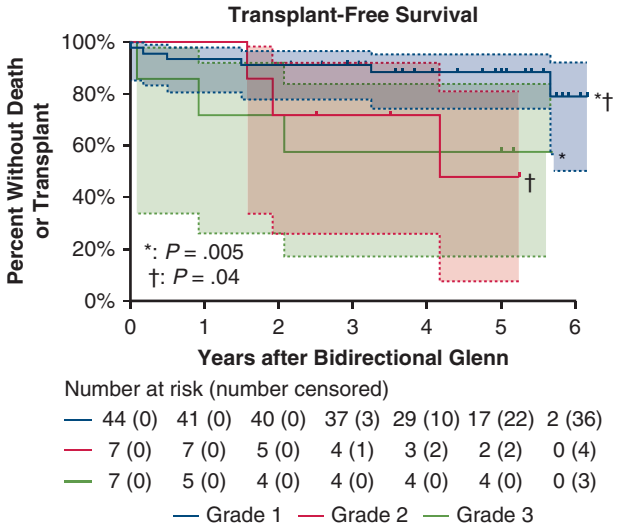


FIGURE 3. Kaplan-Meier curve with log-rank testing showing significantly lower transplant-free survival over the duration of the study in grade 2 (*red*) and grade 3 (*green*) pre-Glenn aortopulmonary collaterals compared to grade 1 (*blue*). *Shading* indicates 95% confidence intervals.

cross-clamp duration at stage 1 was associated with increasingly severe APCs at BDG; however, whether this association is a proxy for more complicated anatomy, longer overall procedure time, or consequences of myocardial preservation injury is unclear.

Our findings fail to support a hypothesis that chest tube position is relevant to APC side or severity, contrasting with the findings of Glatz and colleagues[1] suggesting that pleural inflammation due to prior chest tube placement is associated with APC formation. Although we found that superficial infection after stage 1 procedures was associated with grade 2 APCs at BDG, this conclusion is limited by the small number of patients in this severity group.

Previous studies have shown that patients with significant APCs at Fontan have a higher incidence of prolonged pleural effusions, and that chest tube duration is significantly shorter in those with preoperative APC occlusion.[1,3,8] We found no significant differences in chest tube duration or hospital length of stay. Prior studies on the benefits of APC embolization prior to Fontan is controversial; some have suggested a benefit,[1,3,8] whereas others have suggested no effect.[2,7] Although it is our institutional practice to reduce the APC flow burden if necessary to prepare for BDG, we did not analyze the efficacy of embolization, as we do not currently have systematic practices to quantify APC burden.

Limitations to the interpretation of our results include the small and heterogenous study population, especially when subdivided into severity groups. Our findings are also limited by the study's retrospective nature and qualitative grading of collateral burden by angiography alone, rather than by the current gold standard, quantitative magnetic resonance imaging. The targets for embolization are at the discretion of the proceduralist based on perceived clinical severity and current clinical status, and our study was not capable of analyzing the effects of APC embolization on outcomes or progression to transplant. Our center's approach is for patients to undergo catheterization prior to each stage, but some centers are favoring chest computed tomography to evaluate the branch pulmonary arteries. We do not have experience in relying solely on this method for preoperative assessment. Future directions may include further investigation into the natural history of these collateral arteries after transplantation to assess for APC regression.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: congenital cardiac, single ventricle, heart transplantation

TABLE E1. Pre-Glenn catheter assessment data with hemodynamics and additional procedures

Parameter	Pre-Glenn grade			*P* value
	1 (N = 44)	2 (N = 6)	3 (N = 8)	
Mixed venous saturation, %, median (IQR)	54 (49-58)	51 (47-54)	52 (48-57)	.53
Pulmonary venous saturation, %, median (IQR)	96 (95-98)	95 (95-96)	97 (96-98)	.36
Aortic saturation, %, median (IQR)	77 (74-80)	74 (72-79)	76 (72-79)	.68
Ventricular end-diastolic pressure, mm Hg, median (IQR)	7 (5-8)	6 (5-7)	8 (7-8)	.38
Collateral embolization, n (%)	1 (2.3)	0	1 (12.5)	.31
Balloon angioplasty, n (%)	6 (13.6)	1 (16.7)	0	.52
Conduit or shunt placement, n (%)	7 (15.9)	1 (16.7)	2 (25)	.82

IQR, Interquartile range.

TABLE E2. Pre-Fontan catheter assessment with hemodynamics and additional procedure variables

Parameter	Pre-Fontan grade			*P* value
	1 (N = 15)	2 (N = 26)	3+ (N = 17)	
Mixed venous saturation, %, median (IQR)	65 (59-70)	65 (62-67)	61 (51-65)	.08
Pulmonary venous saturation, %, median (IQR)	95 (94-96)	96 (94-96)	96 (95-96)	.95
Aortic saturation, %, median (IQR)	83 (80-85)	83 (78-85)	83 (76-84)	.73
Ventricular end-diastolic pressure, mm Hg, median (IQR)	8 (5-10)	7 (5-8)	9 (7-10)	.07
Collateral embolization, n (%)	0	1 (3.8)	7 (41.2)	<.001
Balloon angioplasty, n (%)	0	2 (7.7)	1 (5.9)	.56
Conduit or shunt placement, n (%)	0	1 (3.8)	0	.54

IQR, Interquartile range.

TABLE E3. Stage 1 hospital course and complications stratified by pre-Glenn collateral severity prior to embolization

Parameter	Pre-Glenn grade			*P* value
	1 (N = 44)	2 (N = 6)	3 (N = 8)	
Age at procedure, mo, median (IQR)	0.20 (0.16-0.39)	0.16 (0.13-0.89)	0.13 (0.08-0.38)	.41
Preoperative height, cm, median (IQR)	51.0 (49.5-53.0)	49.0 (45.5-50.0)	50.5 (49.3-53.0)	.23
Preoperative weight, kg, median (IQR)	3.60 (3.20-4.00)	3.23 (2.90-3.50)	3.55 (3.21-4.15)	.32
Preoperative saturation, %, median (IQR)	89 (83-91)	88 (81-89)	85 (82-92)	.56
Preoperative nitric oxide use, n (%)	1 (2.3)	1 (16.7)	0	.27
Preoperative hemoglobin, mg/dL, median (IQR)	14.6 (13.0-16.0)	13.9 (13.0-15.0)	14.0 (11.5-15.5)	.58
Preoperative supplemental oxygen, n (%)				.95
Nasal cannula	5 (11.4)	1 (16.7)	1 (12.5)	
CPAP	2 (4.5)	0	0	
Mechanical ventilation	5 (11.4)	1 (16.7)	2 (25)	
Preoperative cardiac arrest, n (%)	1 (2.3)	0	0	.79
Preoperative ECMO, n (%)	2 (4.5)	0	0	.62
CPB time, min, median (IQR)	162 (61-212)	126 (70-188)	208 (200-273)	.053
Aortic cross-clamp time, min, median (IQR)	44 (0-61)	34 (0-62)	66 (63-77)	.023
Intraoperative RBC administration, mL/kg, median (IQR)	127.1 (19.7-172.2)	77.0 (35.4-128.6)	131.1 (89.0-167.0)	.49
24-hr postoperative RBC administration, mL/kg, median (IQR)	0 (0-5.17)	0	0	.79
Duration of ventilation, h, median (IQR)	115.4 (77.5-210.8)	209.0 (52.9-286.5)	180.9 (122.0-262.3)	.53
Open sternum, n (%)	15 (34.1)	5 (83.3)	6 (75)	.19
Duration of open sternum, d, median (IQR)	4 (2-6)	4 (2-4)	5 (1-9)	.63
Duration of chest tube, d, median (IQR)	8 (7-10)	18 (5-25)	14 (10-23)	.054
24-h chest tube output, mL/kg, median (IQR)	50.8 (27.2-68.0)	54.3 (46.3-60.6)	48.0 (30.4-75.2)	.89
Bleeding requiring reoperation, n (%)	3 (6.8)	2 (33.3)	2 (25)	.25
Unplanned interventional catheterization, n (%)	9 (20.5)	0	2 (25)	.32
Cardiac arrest, n (%)	5 (11.3)	0	1 (12.5)	.57
Extracorporeal life support, n (%)	6 (13.6)	1 (16.7)	1 (12.5)	.90
Chylothorax, n (%)	2 (4.5)	2 (33.3)	1 (12.5)	.17
Phrenic nerve palsy, n (%)				.65
Left	2 (4.5)	0	0	
Right	2 (4.5)	1 (16.7)	0	
Vocal cord paralysis, n (%)	8 (18.2)	1 (16.7)	4 (50)	.39
Pneumonia, n (%)	1 (2.3)	1 (16.7)	0	.27
Deep wound infection, n (%)	4 (9.1)	0	1 (12.5)	.65
Superficial wound infection, n (%)	0	2 (33.3)	0	.001
Urinary tract infection, n (%)	1 (2.3)	0	0	.79
Necrotizing enterocolitis, n (%)	1 (2.3)	0	2 (25)	.07
Sepsis, n (%)	7 (15.9)	0	4 (50)	.09
Cardiac reoperation, n (%)	8 (18.2)	0	0	.10
Noncardiac reoperation, n (%)	7 (15.9)	1 (16.7)	3 (37.5)	.61
Discharge oxygen saturation, %, median (IQR)	84 (82-87)	83 (79-86)	82 (80-87)	.49
Hospital length of stay, d, median (IQR)	39 (25-76)	52 (40-60)	70 (47-81)	.23
ICU length of stay, d, median (IQR)	16 (10-27)	25 (8-43)	19 (15-33)	.59

IQR, Interquartile range; *CPAP*, continuous positive airway pressure; *ECMO*, extracorporeal life support; *CPB*, cardiopulmonary bypass.

TABLE E4. Glenn hospital course and complications stratified by pre-Glenn collateral severity following embolization

Parameter	Pre-Glenn grade			*P* value
	1 (N = 44)	2 (N = 7)	3 (N = 7)	
Age at procedure, mo, median (IQR)	4.94 (4.16-5.91)	5.35 (5.09-6.44)	4.66 (5.43-5.58)	.45
Preoperative height, cm, median (IQR)	62 (59-65)	62 (60.6-64)	60.5 (59.3-62)	.66
Preoperative weight, kg, median (IQR)	6.35 (5.78-7.01)	6.64 (6.33-7.50)	6.50 (5.65-7.05)	.50
Preoperative saturation, %, median (IQR)	81.5 (78-85)	77 (75-86)	80 (79-81)	.64
Preoperative nitric oxide use, n (%)	16 (36.4)	2 (28.6)	2 (28.6)	.87
Preoperative hemoglobin, mg/dL, median (IQR)	12.8 (12.0-14.0)	14.0 (14.0-14.7)	13.1 (12.0-14.0)	.29
Preoperative supplemental oxygen, n (%)				.40
Nasal cannula	9 (20.5)	1 (14.3)	0	
CPB time, min, median (IQR)	77.0 (56.0-131.0)	81.0 (72.0-111.0)	77.0 (67.0-93.0)	.89
Aortic cross-clamp time, min, median (IQR)	0 (0-6.0)	0 (0-5.0)	0 (0-0)	.32
Intraoperative RBC administration, mL/kg, median (IQR)	42.81 (15.69-70.11)	37.24 (16.89-56.81)	43.08 (19.55-48.22)	.75
24-h postoperative RBC administration, mL/kg, median (IQR)	0 (0)	0 (0-10.25)	0 (0)	.10
Duration of ventilation, h, median (IQR)	15.69 (10.17-42.31)	15.58 (11.86-22.24)	12.00 (6.50-35.49)	.55
Open sternum, n (%)	3 (6.8)	0	0	.61
Duration of chest tube, d, median (IQR)	4.0 (3.0-5.0)	3.0 (3.0-4.0)	4.0 (3.0-5.0)	.40
24-h chest tube output, mL/kg, median (IQR)	28.64 (18.94-47.73)	34.05 (28.17-35.83)	31.79 (29.34-42.53)	.65
Bleeding requiring reoperation, n (%)	3 (6.8)	0	0	.61
Unplanned interventional catheterization, n (%)	6 (13.6)	0	3 (42.9)	.07
Cardiac arrest, n (%)	1 (2.3)	0	0	.85
Extracorporeal life support, n (%)	3 (6.8)	0	0	.61
Chylothorax, n (%)	2 (4.5)	1 (14.3)	1 (14.3)	.46
Deep wound infection, n (%)	2 (4.5)	1 (14.3)	0	.45
Necrotizing enterocolitis, n (%)	2 (4.5)	1 (14.3)	0	.45
Sepsis, n (%)	2 (4.5)	1 (14.3)	0	.45
Cardiac reoperation, n (%)	6 (13.6)	1 (16.7)	1 (14.3)	.98
Supplemental oxygen at discharge, n (%)	1 (2.4)	0	0	.85
Discharge oxygen saturation, %, median (IQR)	81.0 (78.0-83.0)	84.0 (82.0-85.0)	78.0 (76.0-82.0)	.09
Hospital length of stay, d, median (IQR)	12.5 (9.0-20.0)	10.0 (7.0-16.0)	19.0 (13.0-29.0)	.34
Intensive care length of stay, d, median (IQR)	4.5 (3.0-7.0)	2.0 (1.0-3.0)	3.0 (2.0-6.0)	.019

There were no instances of preoperative arrest or extracorporeal life support. There was no postoperative phrenic nerve palsy, vocal cord paralysis, pneumonia, superficial wound infections, urinary tract infections, or noncardiac reoperations. Only 3 grade 1 aortopulmonary collaterals had open sternums postoperatively, thus duration was not compared.
IQR, Interquartile range; *CPB*, cardiopulmonary bypass.

TABLE E5. Fontan hospital course and complications stratified by pre-Fontan collateral severity following embolization

Parameter	Pre-Fontan grade			*P* value
	1 (N = 15)	2 (N = 25)	3+ (N = 11)	
Age at procedure, mo, median (IQR)	45.53 (36.70-48.34)	46.29 (38.60-54.93)	36.10 (26.92-45.24)	.31
Preoperative height, cm, median (IQR)	99 (94.3-104.9)	97.1 (95.5-103)	89 (84.8-96.3)	.10
Preoperative weight, kg, median (IQR)	14.50 (12.80-16.50)	15.20 (13.60-16.20)	14.10 (12.00-16.10)	.86
Preoperative saturation, %, median (IQR)	82 (81-85)	83 (80-86)	83 (82-85)	.78
Preoperative nitric oxide use, n (%)	5 (33.3)	7 (28.0)	3 (27.3)	.92
Preoperative hemoglobin, mg/dL, median (IQR)	14.2 (12.8-14.9)	15.1 (14.5-16.4)	14.1 (13.4-14.9)	.039
Preoperative supplemental oxygen, n (%)				.71
Nasal cannula	0	1 (4.0)	0	
Mechanical ventilation	2 (13.3)	1 (4.0)	1 (9.1)	
CPB time, min, median (IQR)	136.0 (94.0-159.0)	118.0 (105.0-177.0)	148.0 (128.0-168.0)	.53
Aortic cross-clamp time, min, median (IQR)	0 (0-5.0)	0 (0-49.0)	70.0 (7.0-81.0)	.06
Intraoperative RBC administration, mL/kg, median (IQR)	32.22 (23.03-37.77)	24.94 (16.88-39.64)	42.50 (30.44-48.67)	.14
24-h postoperative RBC administration, mL/kg, median (IQR)	0 (0-0)	0 (0-10.36)	0 (0-16.21)	.13
Duration of ventilation, h, median (IQR)	11.56 (7.14-13.98)	11.79 (6.95-32.67)	15.30 (11.95-47.53)	.23
Open sternum, n (%)	1 (6.7)	1 (4.0)	1 (9.1)	.83
Duration of open sternum, d, median (IQR)	14	2	7	.37
Chest tube duration, d, median (IQR)	5.0 (4.0-9.0)	6.0 (4.0-7.0)	6.0 (4.0-8.0)	.84
24-h chest tube output, mL/kg, median (IQR)	53.13 (30.14-59.50)	39.51 (34.57-62.64)	42.44 (32.77-72.01)	.99
Bleeding requiring reoperation, n (%)	2 (13.3)	0	2 (18.2)	.11
Unplanned interventional catheterization, n (%)	2 (13.3)	0	2 (18.2)	.11
Cardiac arrest, n (%)	1 (6.7)	0	0	.29
Extracorporeal life support, n (%)	2 (13.3)	1 (4.0)	1 (9.1)	.56
Chylothorax, n (%)	2 (13.3)	1 (4.0)	0	.31
Phrenic nerve palsy, n (%)				.16
Left	0	0	0	
Right	0	0	1 (9.1)	
Vocal cord paralysis, n (%)	1 (6.7)	0	0	.30
Pneumonia, n (%)	0	4 (16.0)	1 (9.1)	.26
Deep wound infection, n (%)	1 (6.7)	0	2 (18.2)	.10
Sepsis, n (%)	2 (13.3)	0	2 (18.2)	.11
Cardiac reoperation, n (%)	1 (6.7)	1 (4.2)	1 (9.1)	.84
Noncardiac reoperation, n (%)	0	1 (4.0)	0	.59
Supplemental oxygen at discharge, n (%)	0	2 (8.3)	0	.40
Discharge oxygen saturation, %, median (IQR)	89.0 (83.0-92.0)	90.5 (88.0-93.0)	93.0 (90.0-97.0)	.29
Hospital length of stay, d, median (IQR)	8.5 (7.0-15.0)	11.0 (9.0-17.0)	15.0 (8.0-175.0)	.32
Intensive care length of stay, d, median (IQR)	3.0 (2.0-5.0)	3.0 (1.0-7.0)	3.0 (2.0-10.0)	.77

There were no instances of urinary tract infection, necrotizing enterocolitis, or postoperative superficial infections. *IQR*, Interquartile range; *CPB*, cardiopulmonary bypass.