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ORIGINAL ARTICLE

Early Outcomes After Extracardiac Conduit Fontan Operation Without Cardiopulmonary Bypass

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Abstract Cardiopulmonary bypass is associated with a systemic inflammatory response. The authors hypothesized that avoiding cardiopulmonary bypass would lead to improved postoperative outcomes for patients undergoing the extracardiac Fontan operation, the final stage in surgical palliation of univentricular congenital heart defects. A review of the Children's Heart Center Database showed a total of 73 patients who underwent an initial Fontan operation at Lucile Packard Children's Hospital at Stanford between 1 November 2001 and 1 November 2006. These patients were divided into two groups: those who underwent cardiopulmonary bypass ($n = 26$) and those who avoided cardiopulmonary bypass ($n = 47$). Preoperative demographics, hemodynamics, and early postoperative outcomes were analyzed. The two groups had comparable preoperative demographic characteristics and hemodynamics except that the average weight of the off-bypass group was greater (17.9 ± 9.1 vs 14.2 ± 2.7 kg; $P = 0.01$). Intraoperatively, the off-bypass group trended toward a lower rate of Fontan fenestration (4.3 vs 19.2%; $P = 0.09$), had lower common atrial pressures (4.6 ± 1.4 vs 5.5 ± 1.5 mmHg; $P = 0.05$), and Fontan pressures (11.9 ± 2.1 vs 14.2 ± 2.4 mmHg; $P \leq 0.01$), and required less blood product (59.1 ± 37.6 vs 91.9 ± 49.4 ml/kg; $P \leq 0.01$). Postoperatively, there were no significant differences in hemodynamic parameters, postoperative colloid requirements, duration of mechanical ventilation, volume or duration of pleural drainage, or duration of cardiovascular intensive care unit or hospital stay. Avoiding cardiopulmonary bypass influenced intraoperative hemodynamics and the incidence of fenestration but did not have a significant impact on the early postoperative outcomes of children undergoing the Fontan procedure.

Keywords Cardiopulmonary bypass · CHD–Fontan · Complications and management · CPB · Inflammatory response · Off-pump surgery · Outcomes

Abbreviations

AV	Atrioventricular
CAP	Common atrial pressure
CPB	Cardiopulmonary bypass
CVICU	Cardiovascular intensive care unit
DILV	Double inlet left ventricle
ECC	Extracardiac conduit
ECMO	Extracorporeal mechanical oxygenation
FFP	Fresh frozen plasma
HLHS	Hypoplastic left heart syndrome
PA/IVS	Pulmonary atresia with intact ventricular septum
PRBC	Packed red blood cells
PVR	Pulmonary vascular resistance
SVT	Supraventricular tachycardia
TPG	Transpulmonary gradient

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Introduction

Since its creation in 1971, the Fontan operation has evolved considerably as the final stage in surgical palliation of univentricular heart defects [1]. The extracardiac conduit (ECC) has emerged as an effective and, in many centers, the preferred strategy for completion of the cavopulmonary anastomosis [2]. Use of the ECC avoids extensive atrial surgery and protects the common atrium from elevated pressures in the Fontan pathway, both of which have been proposed as contributing to postoperative atrial arrhythmias [3]. As experience with the ECC has increased, operative techniques have been further refined to address important variables that lead to Fontan dysfunction such as myocardial depression, increased pulmonary vascular resistance, and inflammatory and ischemic stress associated with cardiopulmonary bypass (CPB) [3–5].

In the absence of concomitant intracardiac surgery, performance of the extracardiac Fontan using minimal or no extracorporeal circulatory support is gaining acceptance as a useful approach to optimize postoperative hemodynamics and prevent a significant systemic inflammatory response. Data on this evolving technique, however, are limited to a small number of series [4–9].

This report aims to describe the group of pediatric patients at a single institution who underwent the extracardiac Fontan operation without the use of CPB over a 5-year period, with a specific focus on the intraoperative course and early postoperative recovery. The results for this group are compared with those for a similar group of patients who had an extracardiac Fontan operation with CPB during the same period.

Patients and Methods

Institutional review board approval from Stanford University was obtained for this retrospective clinical study. A review of the Children's Heart Center Database identified a total of 75 patients who underwent a Fontan operation at Lucile Packard Children's Hospital between 1 November 2001 and 1 November 2006. All the patients received an ECC Fontan. Two patients during this period underwent a redo Fontan and were excluded from the analysis. The in- and outpatient medical records of the remaining 73 patients were reviewed for preoperative, operative, and postoperative data.

The preoperative demographics included age, weight, gender, cardiac diagnosis, dominant ventricle, and interval between bidirectional Glenn and Fontan procedures. The patients also were evaluated preoperatively with an echocardiogram and cardiac catheterization. These provided preoperative hemodynamics including ventricular function by echocardiogram, presence and degree of atrioventricular valve regurgitation, room air systemic arterial oxygen saturation, Glenn pressure, ventricular end-diastolic pressure, transpulmonary gradient (TPG), and pulmonary vascular resistance.

The intraoperative data included the presence of arrhythmias; the quantity of blood products administered intraoperatively, the average common atrial pressure (CAP), the average Fontan pressure, and the average TPG. Arrhythmias included documented deviations from normal sinus rhythm, including transient deviations.

The postoperative variables examined included CAP, Fontan pressure, and TPG for postoperative hours 0, 3, 6, and 24. We also examined duration of vasoactive medication infusions, peak lactate, quantity of blood products required on a per kilogram basis, and average duration of mechanical ventilation, defined as the time from the patient's arrival in the cardiovascular intensive care unit (CVICU) until tracheal extubation. Patients' extubated in the operating room were assigned a mechanical ventilation time of zero. Additional variables examined included total chest tube output on a per kilogram basis, duration of chest tube drainage in days, important clinical events such as infection and reoperation, and average CVICU stay and overall hospital stay in days.

Surgical Technique

All the patients in our analysis underwent extracardiac cavopulmonary connection performed by one of four faculty surgeons in the Division of Pediatric Cardiothoracic Surgery at our institution. For the majority of patients, the Fontan operation was optimally timed for the point at which they attained a weight of 15 kg. This allowed placement of an adult-sized conduit, ideally 20 mm or larger, thereby minimizing the potential for Fontan pathway obstruction. CPB was implemented for a variety of reasons including intracardiac repair, pulmonary artery plasty, aortic arch repair, and intraoperative arrhythmia.

The off-CPB Fontan involves standard reoperative techniques including median sternotomy, achievement of adequate exposure, placement of purse-string sutures in the right atrial appendage and inferior vena cava (IVC), isolation of the pulmonary artery anastomotic site, and subsequent anastomosis of a Gore-Tex extracardiac conduit tube graft (W.L. Gore and Associates, Inc., Flagstaff, AZ) between the central pulmonary artery system and the IVC. During the initial 4 years of our 5-year series, a centrifugal pump was used for active decompression of the IVC in 16 (34%) of the 47 off-CPB patients. This technique did not involve a full bypass circuit or any form of oxygenator. Except for the inclusion of a pump, this technique is similar to the passive IVC decompression technique used for the

remaining off-CPB patients. The IVC is cannulated directly to the right atrium and allowed to decompress passively while the inferior Fontan anastomosis is performed. As such, the patients in whom active IVC decompression was used are included in the off-CPB analysis.

As surgical experience with the off-CPB technique increased over the course of the series, active decompression was no longer used. Our surgical techniques, including the evolution of the off-CPB strategy, have been described previously in detail by Petrossian et al. [5]. Although it is possible that exposure to the pump used in the active decompression technique could have induced some inflammatory response, we chose to include these patients in the off-CPB group to be consistent with our earlier analysis [5].

Fontan Fenestration

Our preoperative process of patient selection includes hemodynamic criteria obtained at catheterization that predicts a successful Fontan without a permanent fenestration. The need for temporary perioperative fenestration, however, is determined based on intraoperative hemodynamics. After establishment of the Fontan circulation in the operating room, we measure Fontan pressure and CAP and calculate the TPG. Our criteria for placing a temporary fenestration are a TPG greater than 15 mmHg or a TPG of 10–15 mmHg with evidence of compromised systemic output manifested by hypotension, tachycardia, severe underfilling of the systemic ventricle by echocardiography, or acidemia.

Statistical Analysis

Data are described as frequencies and means with standard deviations. Medians also are reported for variables that had skewed distributions secondary to large outliers and in the case of conduit size. Associations between categorical predictors and CPB were compared using χ^2 tests, Fisher's exact test, or the Freeman–Halton exact test when the expected cell frequencies were low. Differences in the average scores on the continuous predictors for the CPB and off-CPB groups were compared with t tests (using the Satterthwaite adjusted degree of freedom in the case of unequal variance). For the cases in which the data were clearly skewed, Wilcoxon rank-sum tests were used to verify the inferences afforded by the adjusted t tests.

Results

Preoperative Characteristics

The preoperative characteristics of the two groups are listed in Table 1. As a group, the patients who received a Fontan off-CPB had a greater weight (17.9 ± 9 vs 14.2 ± 2.7 kg; $P = 0.01$) at the time of surgery. Although the off-CPB group had an outlier of 67 kg, with this outlier removed, a significant difference in weight still remained (16.9 ± 5.4 vs 14.2 ± 2.7 kg). The off-CPB patients also were older at the time of their initial Fontan (3.7 ± 1.3 vs 4.8 ± 2.9 years; $P = 0.03$). The groups did not differ significantly in terms of other preoperative characteristics including congenital cardiac diagnoses, dominant ventricle, gender, and interval from Glenn to Fontan.

The pre-Fontan hemodynamic data are summarized in Table 1. Catheterization data were available for 70 (95.8%) of the 73 patients. Oxygen saturation, Glenn pressure, ventricular end-diastolic pressure, TPG, and pulmonary vascular resistance did not differ significantly between the two groups. Based on preoperative echocardiography, a higher incidence of mildly decreased ventricular function was noted in the off-CBP group compared with the CPB group (17 vs 0%; $P = 0.04$).

Use of Cardiopulmonary Bypass

The CPB procedure was used for 26 (36%) of the 73 patients undergoing the Fontan operation. For 10 (38%) of 26 patients, a specific operative indication for the use of bypass was listed in the operative report including pulmonary artery plasty (4/26, 15%), intracardiac repair (2/26, 8%), aortic arch repair (1/26, 4%), and intraoperative supraventricular tachycardia (SVT) (1/26, 4%). A specific indication for the use of CPB was not listed for the remaining 62% of the patients, reflecting surgical preference.

Figure 1 demonstrates the temporal distribution of the Fontan operations by perfusion strategy. Reflecting the trend in surgical practice over time toward the off-CPB technique, 46% of the Fontan operations between 1 November 2001 and 31 December 2003 were performed as off-CPB procedures compared with 74% performed as off-CPB surgery from 1 January 2004 to 1 November 2006. One patient (1/26, 4%) in the CPB group had his Fontan initially planned as off-bypass surgery, but required conversion to bypass because of intraoperative SVT. The majority of patients in both groups (96% in the CPB group and 83% in the off-CPB group) had been exposed to CPB for previous palliative surgeries.

Intraoperative Course

The intraoperative characteristics of both groups are summarized in Table 2. Fenestrations were not routinely performed in either group, but there was a trend toward a higher incidence of fenestration creation in the CPB group (19.2 vs 4.3%; $P = 0.09$). The intraoperative hemodynamics differed significantly between the two groups in terms of CAP and Fontan

Table 1 Preoperative demographics and hemodynamics

	CPB ($n = 26$) n (%)	Off-CPB ($n = 47$) n (%)	P value
Demographics			
Age at time of Fontan (years)	3.7 ± 1.3	4.8 ± 2.9	0.03
Weight (kg)	14.2 ± 2.7	16.9 ± 5.4	0.01
Sex			0.32
Male	18 (69)	26 (55)	
Female	8 (31)	21 (45)	
Diagnosis			0.58
Tricuspid atresia	4 (15)	10 (21)	0.75
DILV	4 (15)	11 (23)	0.55
Heterotaxy	4 (15)	4 (9)	0.44
PA/IVS	1 (4)	5 (11)	0.41
HLHS	9 (35)	14 (30)	0.79
Other	4 (15)	3 (6)	0.24
Dominant ventricle			0.74
Left	11(42)	24 (51)	
Right	14 (54)	22 (47)	
Indeterminate	1 (4)	1 (2)	
Glenn to Fontan interval (years)	3.1 ± 1.3	3.6 ± 2.0	0.24
Preoperative hemodynamics			
Ventricular function by echo			0.04
Normal	26 (100%)	39 (83%)	
Mildly decreased	0 (0%)	8 (17%)	
AV valve regurgitation by echo			1.00
None–mild	23 (88%)	41 (87%)	
Moderate–severe	3 (12%)	6 (13%)	
Room air oxygen saturation	84 ± 7%	84 ± 5%	0.56
Glenn pressure (mmHg)	11.4 ± 3.3	10.3 ± 2.5	0.11
End-diastolic pressure (mmHg)	8.3 ± 2.3	8.2 ± 2.5	0.84
Transpulmonary gradient (mmHg)	5.0 ± 3.6	4.4 ± 2.2	0.44
PVR (Woods units)	1.9 ± 2.3	1.7 ± 0.6	0.64

CPB cardiopulmonary bypass, *DILV* double-inlet left ventricle, *PA/IVS* pulmonary atresia/intact ventricular septum, *HLHS* hypoplastic left heart syndrome, *echo* echocardiography, *AV* atrioventricular, *PVR* pulmonary vascular resistance

pressure, with the off-CPB group demonstrating lower intraoperative CAP (4.6 ± 1.4 vs 5.5 ± 1.5 mmHg; $P = 0.05$) as well as lower average Fontan pressure (11.9 ± 2.1 vs 14.2 ± 2.4 mmHg; $P \leq 0.01$). The TPG did not differ between the two groups. The off-CPB group required significantly less intraoperative blood product than the CPB group (59.1 ± 37.6 vs 91.9 ± 49.4 ml/kg; $P \leq 0.01$). The difference in blood product usage was not due to inclusion of bypass circuit priming volumes in the CPB group. We recorded only those blood products used by the cardiac anesthesia team after circuit priming. The two groups did not differ significantly in terms of total operative time, incidence of intraoperative arrhythmia, or percentage of patients' extubated in the operating room before transfer to the CVICU.

Postoperative Hemodynamics

Early postoperative data were available for 72 of the 73 patients. Significant components of the postoperative records for one patient early in the series were missing, and this patient was excluded from the analyses. A second patient had components of the CVICU nursing records missing and was excluded from only the hemodynamic analysis. For the remaining 71 patients, hemodynamic data including Fontan pressure, CAP, and TPG were collected for postoperative hours 0, 3, and 6 and for the morning of postoperative day 1 (Table 3). There was no significant difference in the postoperative hemodynamic profile between the two groups except for the Fontan pressure at postoperative hour 6, which was significantly lower in the CPB group (11.8 ± 3.2 vs 13.5 ± 2.9 mmHg; $P = 0.02$).

Pleural Fluid Drainage

Complete pleural drainage data were available for 72 of the 73 patients. In 13 patients, chylous pleural drainage was noted and confirmed by laboratory analysis demonstrating chylomicrons in the pleural fluid. The two groups

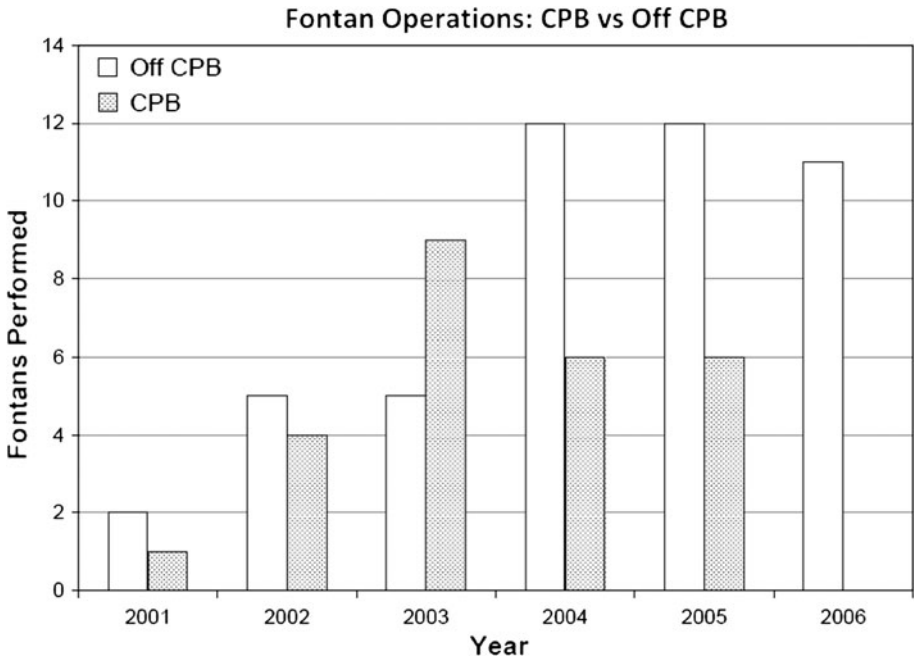

Fig. 1 Fontan operations using cardiopulmonary bypass (CPB) versus off-CPB over time

Table 2 Intraoperative course

	CPB	Off-CPB	*P* value
Fenestrated: *n* (%)	5/26 (19.2)	2/47 (4.3)	0.09
Median conduit size: mm (range)	18 (16–20)	20 (18–20)	
Blood products (ml/kg)	91.9 ± 49.4	59.1 ± 37.6	<0.01
Intraoperative arrhythmia: *n* (%)	9 (34.6)	12 (25.5)	0.42
Total operative time (min)	292 ± 105	262 ± 54	0.20
Average CAP (mmHg)	5.5 ± 1.5	4.6 ± 1.4	0.05
Average Fontan pressure (mmHg)	14.2 ± 2.4	11.9 ± 2.1	<0.01
Average TPG (mmHg)	8.2 ± 3.4	7.2 ± 2.2	0.30
Extubated in operating room: *n* (%)	11 (42.3)	16 (34.0)	0.61

CPB cardiopulmonary bypass, *CAP* common atrial pressure, *TPG* transpulmonary gradient

Table 3 Postoperative hemodynamics

	CPB	Off-CPB	*P* value
Postoperative hour 0			
Fontan pressure	14.1 ± 2.9	14.1 ± 3.1	0.98
Common atrial pressure	6.5 ± 3.1	6.6 ± 3.4	0.99
TPG	8.3 ± 3.5	7.7 ± 2.9	0.39
Postoperative hour 3			
Fontan pressure	13.7 ± 3.8	13.7 ± 2.9	0.98
Common atrial pressure	5.5 ± 3.2	6.5 ± 2.8	0.20
TPG	8.9 ± 4.8	7.3 ± 2.7	0.14
Postoperative hour 6			
Fontan pressure	11.8 ± 3.2	13.5 ± 2.9	0.02
Common atrial pressure	5.4 ± 3.0	6.5 ± 3.2	0.19
TPG	7.0 ± 3.9	7.2 ± 3.0	0.89
Postoperative day 1			
Fontan pressure	13.4 ± 4.1	13.3 ± 3.5	0.92
Common atrial pressure	7.2 ± 3.4	6.4 ± 3.5	0.34
TPG	7.3 ± 4.6	6.9 ± 3.1	0.67

CPB cardiopulmonary bypass, *TPG* transpulmonary gradient

All values are in units of mmHg

did not differ in quantity of pleural drainage nor in time from the operation through removal of the last chest tube (Table 4). We focused our attention on the postoperative fluid balance, specifically on pleural fluid drainage, and we did not collect data on the overall fluid balance after surgery.

Hospital Course

Neither group had any operative or hospital mortality. Two patients in the off-CPB group required extracorporeal membrane oxygenation (ECMO) for failure of the Fontan circulation. Both patients ultimately required reoperation and Fontan takedown. In addition to these two patients, the off-CPB group had five other reoperations including three reoperations for bleeding, one reoperation for sternal wound dehiscence, and one reoperation for notable omental herniation from a chest tube site. The one reoperation in the CPB group was a sternal reexploration for debridement secondary to mediastinitis.

No patients in either group underwent unplanned fenestration placement during the postoperative period. A comparison of clinically relevant hospital milestones between the two groups appears in Table 4. One outlier for the length and the complexity of the hospital course (i.e., 55 days of mechanical ventilation and a CVICU stay of 112 days) was noted in the off-CPB group. Both with and without this outlier included in the analyses, no significant differences were observed between the two groups in terms of requirement for intravenous colloid, crystalloid, or blood products through postoperative day 7; duration of mechanical ventilation; duration of vasoactive support; peak serum lactate; length of CVICU stay; or total hospital length of stay. Similarly, the two groups did not differ significantly in terms of important clinical events that altered the hospital course including infection, need for reoperation, need for ECMO, neurologic event such as a cerebral vascular accident, or new arrhythmia causing hemodynamic instability (Table 4).

Discussion

In our population of Fontan patients, avoidance of CPB improved intraoperative hemodynamics, as evidenced by lower common atrial and Fontan pressures. Our surgical philosophy has been that the preservation of cardiopulmonary function allowed by avoiding CPB should significantly decrease the need for routine Fontan fenestration. Indeed, there was a trend toward a lower rate of Fontan fenestration in the off-CPB group ($P = 0.09$). Similarly reflecting a more optimal operative course, the requirement for blood products in the operating room also was decreased for the off-CPB patients.

Table 4 Postoperative course

	CPB	Off-CPB	*P* value
Fluid requirements: postoperative day 0–7 (ml/kg) (mean/median)			
PRBCs	11.6 ± 17.6/7.2	12.5 ± 34.8/0	0.37
Platelets	1.1 ± 3.4/0	3.3 ± 11.1/0	0.60
FFP	5.4 ± 9.5/0	6.9 ± 15.6/0	0.61
Albumin 5%	34.8 ± 44.1/21.2	29.1 ± 36.6/22.4	0.51
Crystalloid	157.1 ± 105.5/145.0	168.0 ± 108.2/122.1	0.84
Hospital course (mean/median)			
Pleural drainage			
Volume per kg (ml)	193.1 ± 139.9/151.7	161.5 ± 193.5/116.0	0.47
Chest tube duration (days)	11.3 ± 7.7/9	10.2 ± 8.7/8	0.58
Time requiring vasoactives (h)	64.8 ± 44.7/68	111.4 ± 379.6/45	0.23
Time to extubation (h)	10.1 ± 32.3/3	42.8 ± 198.2/6	0.17
Peak lactate (mg/dl)	4.6 ± 2.4/4.4	3.9 ± 2.0/3.5	0.26
SI (μmol/l)	0.51 ± 0.27	0.43 ± 0.22	
CVICU stay (days)	6.3 ± 4.8/5	7.5 ± 16.1/5	0.39
Hospital stay (days)	16.0 ± 8.1/12.5	15.5 ± 16.9/11	0.87
Postoperative events: *n* (%)			
Infection	8/26 (30.8)	6/47 (12.8)	0.07
Reoperation	1/26 (3.8)	7/47 (14.9)	0.25
ECMO	0/26 (0)	2/47 (4.3)	0.54
Neurologic event	0/26 (0)	2/47 (4.3)	0.55
New arrhythmia	2/26 (7.7)	1/47 (2.2)	0.28

CPB cardiopulmonary bypass, *PRBC* packed red blood cells, *FFP* fresh frozen plasma, *SI* international system of units, *CVICU* cardiovascular intensive care unit, *ECMO* extracorporeal membrane oxygenation

Avoidance of CPB conferred important intraoperative benefits. However, the theorized hemodynamic and respiratory advantages of the off-CPB technique did not extend into the postoperative period. The two groups did not differ significantly in terms of postoperative CAP, TPG, or Fontan pressure except for Fontan pressure at postoperative hour 6, which was lower in the CPB group than in the off-CPB group (11.8 ± 3.2 vs 13.5 ± 2.9 mmHg; $P = 0.02$). Because TPG at postoperative hour 6 and postoperative Fontan pressures at hours 3 or 24 did not differ significantly, it is likely that this finding is clinically insignificant and occurred by chance. Furthermore, hospital milestones such as length of mechanical ventilator support, length of vasoactive infusions, duration and volume of pleural drainage, CVICU stay, and total hospital stay did not differ between the two groups.

Prior studies examining the perioperative course of off-CPB Fontan patients have been inconclusive in their results. Consistent with our hemodynamic findings, Tam et al. [10] reported no significant difference in Fontan pressures measured at 6, 12, and 24 h postoperatively. They did report significantly lower common atrial pressures in the off-CPB group at 6 and 12 h, with no significant difference measured at 24 h postoperatively.

Effects on pulmonary function also have varied considerably. Both Shikata et al. [7] and Xu et al. [8] reported shorter duration of mechanical ventilation, whereas neither Tam et al. [10] nor Navabi et al. [9] demonstrated a reduction in total mechanical ventilation by avoiding CPB. Shikata et al. [7] additionally described a reduction in pleural drainage volume at 12 and 48 h postoperatively, but they showed no difference in total pleural drainage or duration of chest tubes. Most recently, Navabi et al. [9] examined the effect on early outcomes for 102 patients who underwent fenestrated extracardiac Fontan procedures. In their cohort, avoiding CPB did not lead to any significant difference in early outcome variables. These published series vary considerably in size, preoperative characteristics, and use of Fontan fenestration. However, as a whole, a significant alteration in the post-Fontan course by avoiding CPB has not been clearly demonstrated.

Avoidance of CPB, with its associated inflammatory response and deleterious effects on cardiovascular and pulmonary function, remains an attractive alternative, particularly in the setting of the uniquely vulnerable Fontan circulation. In Fontan patients, prior studies have demonstrated a strong association between longer duration of CPB and prolonged inotropic and ventilatory support in the postoperative period [4]. Prolonged CPB and cardioplegia also have been implicated in increasing the risk for early postoperative failure or death [2, 11, 12].

In these studies, it was impossible to determine whether CPB was an independent risk factor for negative outcomes or acted as a surrogate for patients requiring longer, more complex operations involving repair of other anatomic lesions, such as AV valve repair and pulmonary arterioplasty. Despite this uncertainty, we speculate that CPB itself has a negative impact on postoperative physiology.

On a molecular level, CPB is hypothesized to contribute to a postoperative inflammatory response, leading to further organ system dysfunction. Bypass is thought to augment activation of the alternative complement pathway, leading subsequently to both a systemic inflammatory response and relative immunosuppression in some patients [13–16]. In addition, CPB has been linked with reperfusion injury of the lungs and capillary leak syndrome [17].

In the face of the available published evidence, the question is raised as to why Fontan patients would not benefit more dramatically in the postoperative period by avoiding CPB. As a result of careful Fontan candidate selection, our population represented a low-risk Fontan population. Both groups were well matched based on preoperative demographics, prior operations, hemodynamic measurements, and echocardiographic characteristics. We speculate that the benefits of avoiding bypass could manifest more significantly in patients who are marginal Fontan candidates due to either myocardial dysfunction or elevated pulmonary vascular resistance. However, these same marginal patients might benefit from the intraoperative hemodynamic protection afforded by the use of bypass during surgical dissection. Additionally, the refinement of perfusion techniques over time and improved myocardial protection during bypass may mitigate some of the frequently cited adverse effects of CPB and may offer an explanation for these results.

Our study had several limitations. It was retrospective in design and lacked randomization. As such, we cannot exclude the possibility of a selection bias between the two groups. Additionally, the cohort was too small to allow careful adjustment for treatment selection bias using a method such as statistical propensity scores. The small size of the cohort also limited the power of this study to detect smaller differences that a larger sample size might have shown. Hence, the trend toward lower rates of fenestration in the off-CPB group may have been statistically significant with a larger cohort. As noted in the Methods section, the decision to perform a Fontan fenestration was made intraoperatively based on hemodynamic measurements. Although the patients were well matched between the two groups for congenital cardiac diagnosis and pre-Fontan hemodynamics, there were some differences in preoperative variables including age, weight, and preoperative cardiac function by echocardiography.

Our surgical strategy for patients undergoing an ECC Fontan is to schedule surgery when the patient achieves a weight of approximately 15 kg, irrespective of the

intraoperative perfusion strategy, so that an adult-sized ($\geq$20 mm) ECC can be inserted. Therefore, we do not believe the differences in age and weight we observed between the groups reflect a difference in surgical strategy. Furthermore, although the study interval was limited to a 5-year period, there may have been other improvements in operative technique and postoperative critical care over time that could bias the results because more off-pump Fontans were performed in later years of the study period.

The extracardiac conduit Fontan operation can be safely and effectively performed without CPB and may confer benefits in terms of intraoperative hemodynamics, need for blood products, and reduced need for Fontan fenestration. We found no significant advantages with avoiding bypass in terms of postoperative recovery, length of CVICU stay, or total hospital stay. Future prospective, randomized studies with larger cohorts may help to elucidate whether the off-pump technique has potential benefits that may not have been elicited by our study. Furthermore, although there may not be notable differences in the early postoperative period, it is possible that avoidance of CPB and its associated proinflammatory state could be associated with improved long-term outcomes. It would be worthwhile to examine the long-term neurodevelopmental outcomes of off-bypass Fontan patients compared with patients exposed to bypass.

Conflict of interest The authors declare that they have no conflict of interest.

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