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Extracorporeal membrane oxygenation for intraoperative cardiac support in children with congenital heart disease☆,☆☆

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Abstract

Objective: Extracorporeal membrane oxygenation (ECMO) is commonly used in children to allow recovery from ischemic injury or cardiac surgery, to support the circulation in case of end-stage cardiomyopathy, as bridge-to-bridge therapy and as bridge to transplantation as well. It has achieved success in providing cardiac support for these kind of patients with expected mortality due to severe myocardial dysfunction. In this modern era, ECMO support should be considered an important option for children with cardiopulmonary failure refractory to medical therapy or resuscitation. We report our experience in pediatric patients supported by ECMO for intraoperative cardiac failure between November 1991 and December 2006. **Methods and results:** Sixty-six patients with a mean age of 5.2±4 years (range: 1 day–17 years) and mean weight of 14.3±11 kg (range: 2.8–69 kg) had intraoperative ECMO support for failure to wean off cardiopulmonary bypass (n=46, 69.7%), low cardiac output syndrome (n=8, 12.1%), isolated right ventricular failure (n=6, 9.1%), isolated left ventricular failure (n=3, 4.5%), malignant arrhythmia (n=1, 1.5%) and pulmonary hypertension (n=2, 3.1%). Mean duration of ECMO support was 5.1±3 days. Overall 30 (45.4%) patients were successfully weaned off ECMO and survived to decannulation. Overall 6 (9.1%) patients were successfully bridged to heart transplantation while on ECMO support. Thirty patients died (54.4%) (16 while on ECMO and 14 after decannulation) because of multi-factorial complications, i.e. cerebral hemorrhage, pulmonary failure, consumption coagulopathy and therapy-resistant myocardial insufficiency, leding to an overall hospital mortality rate of 45.4%. Mean survival time after decannulation was 28±16 h. Overall survival rate on ECMO as bridge to recovery and transplantation has been 54.5% with successful hospital discharge of patients. **Conclusions:** Our experience shows that ECMO support can be offered intraoperatively to any children after palliative or corrective surgery for congenital heart disease with potentially reversible pulmonary, cardiac or cardiopulmonary failure. In the majority of patients who did not survive late after weaning from ECMO support, significant myocardial dysfunction persisted or pulmonary hypertensive events. Nevertheless, an acceptable proportion of patients who were successfully weaned from ECMO ultimately survived to leave the hospital.

Keywords: Extracorporeal membrane oxygenation; Congenital; Recovery; Transplantation

1. Introduction

Increasing complex repairs in neonates and infants with complicated congenital heart diseases have led to increased use of extracorporeal membrane oxygenation (ECMO) support [1–10]. It has become an integral part of the decision-making of pediatric cardiac surgeons, when patients demonstrate cardiopulmonary failure, particularly during weaning from cardiopulmonary bypass (CPB). Use of ECMO in such a high-risk population is associated with significant morbidity and mortality, with an overall survival rate remaining at approximately 40% [11].

We have previously reviewed and published our entire experience with ECMO from 1987 to 2005 [12–14]. This present report describes the demographic profile, clinical variables, technical considerations and clinical outcome of children in whom ECMO was used for intraoperative circulatory failure after repair of their congenital heart anomalies and to identify the relationship of these with survival outcomes.

2. Patients and methods

Institutional Review Board approval was waived for this restrospective review.

We retrospectively reviewed the medical records (hospital admission records, operative reports, perfusion data, and pediatric intensive care unit) to collect demographic information and survival outcome of 66 children (<18 years old) who underwent either corrective or palliative congen-

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Table 1
Demographic profile of patients requiring ECMO for intraoperative circulatory failure

Demography	
Number of patients (*n*)	66
Male (*n*, %)	38 (57.5)
Female (*n*, %)	28 (42.4)
Age range	1 day–17 years
Mean age ± S.D. (years)	5.2 ± 4
Weight range (kg)	2.3–69
Mean weight ± S.D. (kg)	14.3 ± 11

ECMO, extracorporeal membrane oxygenation; S.D., standard deviation.

ital heart surgery that were then supported with ECMO intraoperatively in our institution between November 1991 and December 2006 (Table 1). These patients represented 55% of the total pediatric patients placed on ECMO support during this period.

ECMO was applied with the same cannulae used for CPB and connected with oxygenator. The goal was to provide a systemic oxygenated blood flow of average 2.4 l/min/m^2 as full circulatory support.

In infants with a body weight of <5 kg, a 1/4-inch tubing circuit (Jostra, Hirlingen, Germany or Medtronic, Anaheim, CA) with a 50-ml centrifugal pump (Medtronic, Eden Prairie, MN) was used. In children weighing >5–15 kg, a 3/8-inch venous line with a Bio-Medicus centrifugal pump (Bio-Medicus Co, Eden Prairie, MN) using a pediatric pump head was used. This latter circuit permits a wider range of pump flows, which is required to accommodate the varied weight range in children. In children weighing >15 kg, we used a centrifugal pump head of 80 ml and a 3/8-inch flow probe, and a 3/8 tubing flow circuit with a pediatric arterial filter (Dideco D 734). A membrane oxygenator (Jostra M 16, SciMed 1500, 2500, Ultox I or III) was used in nearly all cases except when a heparin-bonded circuit (Minimax, Maxima, Jostra AG, Hirrlingen, Germany) including a hollow-fiber oxygenator was used during the initial few hours of cardiac support. Minimal systemic heparinization was used until mediastinal bleeding was well controlled; subsequently, anticoagulation to activated clotting times (ACTs) of 180–200 s was instituted. At this point, the oxygenator was changed to a membrane type used for routine ECMO support.

ECMO circuit was established via the original bypass cannulae. The patient was then converted to a closed ECMO system with brief clamping of the cannulae and connection of new sterile lines on the operative field. The arterial cannulae were inserted directly into the aorta and a metal-angled venous cannula into the right atrium and exteriorized at the bottom of the sternal skin incision. To improve venous return, bicaval cannulation has been converted to a two-stage, single venous cannula. The advantage of the thin-walled armored or metal cannulae is that the effective internal diameter is larger for the same outside diameter, and, therefore, flow is greatly improved.

The ECMO machine was filled with human albumin 20%, fresh frozen plasma, and sodium bicarbonate before its connection to the cannulae. The absolute ECMO flow was between 0.2 and 3.5 l/min, of which a flow between 60 and 250 ml/kg/min depending on the present cardiac function, physiology, serum lactate levels, and mixed venous oxygen saturation.

The patients were not cooled during ECMO mechanical circulatory support. Inotropic drugs were continued on in most patients to have some cardiac ejection, particularly in patients where the left ventricle was not vented. If no ejection was seen on the arterial pressure tracing, echocardiography was done to determine whether the left ventricle was distended and whether decompression was necessary. Regardless, echocardiography was performed in all patients within 1 or 2 days of starting ECMO support, specifically to determine if any potentially correctable cardiac defects were present.

Ventilator settings are generally set to 'ECMO resting settings', which are usually a rate of 10, positive end-expiratory pressure of 10, and 40% FiO_2. All patients on mechanical support were given neuromuscular blocking agents and heavily sedated with benzodiazepine and narcotic analgesia.

Weaning from ECMO was accomplished by maximizing inotropic and ventilator support and gradually decreasing ECMO flow rates in a fashion similar to weaning from CPB. When flow rates were decreased to approximately 25% of maximal support, the bridge between the arterial and venous systems was opened by turning the stopcocks allowing blood flow through the bridge from arterial to venous side. The arterial and venous limb above the bridge was clamped to isolate the patient from ECMO flow and the circuit was allowed to recirculate. Once the patient was off complete support, hemodynamic stability was monitored, and tissue perfusion was assessed by serial arterial blood gases with serum lactate and base deficit values. Transesophageal echocardiography was frequently used to assess myocardial function during the weaning process. Cannulae were then removed after approximately 1 h of hemodynamic stability. All purse-string sutures were left in place and resnared. The chest was stented open after cannula removal [12].

2.1. Statistical analysis

All data were analyzed with the SPSS 12.0 for Windows software program (SPSS, Chicago, IL, USA). Demographic variables are expressed as absolute and percentage frequency values and continuous data as mean ± standard deviation (S.D.), as appropriate. Variables examined included age, weight, sex, duration of CPB, duration of ECMO support, and presence of acidosis, lactate and creatinine levels on initiation of ECMO. χ^2-test or Fisher exact test was used to assess categorical comparisons between survivors and non-survivors. Differences between these groups were tested by the Student's *t*-test and checked by the Mann–Whitney *U*-test. Values of $P<0.05$ were considered statistically significant. End points included death on ECMO support, survival to decannulation, death after decannulation, and survival until heart transplantation (Htx).

Survival to decannulation was defined as survival during stop of ECMO support in hemodynamic stability thus allowing decannulation. Death after decannulation was defined as mortality occurring after total removal of ECMO support.

Survival to Htx was defined as survival during ECMO support until Htx was performed.

3. Results

3.1. Demographic profile

Between November 1991 and December 2006, a total of 66 children with congenital heart diseases required ECMO after correction of their congenital anomalies. Mean age was 5.2±4 years (range 1 day to 17 years) and mean weight of 14.3±11 kg (range 2.8–69 kg) (Table 1).

3.2. Indications for ECMO support

The diagnosis and surgical procedures for which 66 children received ECMO support intraoperatively are summarized in Table 2. Among these children, failure to wean from CPB was the main indication in 46 (69.7%) and low cardiac output syndrome (LCOS) in 8 (12.1%) patients, isolated RVF in 6 (9.1%) patients, isolated LVF in 3 (4.5%) patients, pulmonary hypertension in 2 (3.1%), and malignant arrhythmia in 1 (1.5%) (Tables 2 and 3). Eight (12.1%)

Table 3
Summary of indications for intraoperative ECMO support

Indications for support	*n* (%)
Failure to wean from CPB	46 (69.7)
Low output syndrome	8 (12.1)
Right ventricular failure	6 (9.1)
Left ventricular failure	3 (4.5)
Pulmonary hypertension	2 (3.1)
Malignant arrhythmia	1 (1.5)
Total	66

CPB, cardiopulmonary bypass; ECMO, extracorporeal membrane oxygenation.

Table 2
Diagnosis, surgical procedures and outcome of children undergone intraoperative ECMO support

Diagnosis	*n*	Operation	Indication for ECMO	Outcome (*n*)
TGA	14	Arterial switch operation	Failure to wean from CPB	*n*=4 HD, *n*=1 Htx, *n*=9 WSD
AV stenosis (post-AV balloon dilatation)	6	AV replacement (homograft)	Failure to wean from CPB	*n*=4 HD, *n*=2 WSD
DORV	6	Total correction	Failure to wean from CPB	*n*=3 HD, *n*=1 Htx, *n*=2 WSD
CAVSD (in pulmonary hypertension)	4	Total correction	LCOS	*n*=2 HD, *n*=2 WSD
ALCAPA (in Bland–White–Garland syndrome)	3	Direct LCA implantation	Failure to wean from CPB	*n*=1 HD, *n*=2 WSD
TOF (post-correction, PV insufficiency, TV insufficiency, VSD and ASD)	3	PV replacement (heterograft), ASD and VSD closure, TV repair	Failure to wean from CPB	*n*=1 HD, *n*=1 Htx, *n*=1 WSD
PA hypoplasia (post-DORV correction)	3	PV replacement (homograft)	Failure to wean from CPB	*n*=1 HD, *n*=2 WSD
HLHS	2	Norwood operation	Failure to wean from CPB	*n*=1 HD, *n*=1 WSD
PV atresia (with MAPCAS and VSD) in Erb-Duchenne	2	Central AP shunt, closure of MAPCAS	Failure to wean from CPB	*n*=1 HD, *n*=1 WSD
TGA (with restrictive VSD)	2	Fontan operation	LCOS	*n*=1 HD, *n*=1 WSD
DORV (with MV atresia, malposition of great arteries and aortic arch hypoplasia)	2	Damus–Kaye–Stansel operation, aortic arch reconstruction (prosthesis interposition)	Malignant arrhythmia	*n*=1 HD, *n*=1 WSD
Truncus arteriosus communis	2	Total correction	Pulmonary hypertension	*n*=1 HD, *n*=1 WSD
Pulmonary atresia, VSD (post-unifocalization and bilateral PA enlargement, post-central shunt)	2	Total correction with xenograft RPA enlargement and shunt closure	Failure to wean from CPB	*n*=1 HD, *n*=1 WSD
Total anomalous pulmonary venous return	2	Total correction	RVF	*n*=1 HD, *n*=1 WSD
MV steno-insufficiency (post-CAVSD correction)	2	MV replacement	LVF	*n*=1 HD, *n*=1 WSD
MV, TV and PV insufficiency (post-CAVSD correction)	2	MV, TV and PV repair	RVF	*n*=1 HD, *n*=1 WSD
Single ventricle (with TV atresia, VSD, post-Waterston shunt)	1	Modified Fontan, RA-RV homograft, VSD closure, MV repair	RVF	Htx
Truncus arteriosus (with hypoplastic AV and ascending aorta, ASD, VSD, PDA)	1	Damus–Kaye–Stansel operation, enlargement of aortic arch, central AP shunt	Failure to wean from CPB	HD
LVOT obstruction, TV and MV insufficiency in TGA (post-Senning)	1	LVOT myectomy, TV and MV repair	LVF	Htx
TV insufficiency, AV stenosis and LVOT obstruction (in Ebstein anomaly)	1	TV replacement, LVOT myectomy	RVF	Htx
PA stenosis in TGA (post-Rastelli operation)	1	PV replacement (homograft)	Failure to wean from CPB	HD
AV, TV and MV insufficiency (post-TGA correction in pulmonary hypertension)	1	AV, TV and MV repair	Failure to wean from CPB	HD
MV insufficiency in dextrocardia (with ASD, VSD)	1	MV replacement, ASD and VSD closure	LCOS	HD
MV and TV insufficiency (in pulmonary hypertension)	1	MV and TV repair, atrial wall reduction	Failure to wean from CPB	WSD
AV stenosis	1	AV repair	LVF	HD

TGA, transposition of great arteries; CPB, cardiopulmonary bypass; HD, hospital death; Htx, heart transplantation; WSD, weaned and survived to discharge; AV, aortic valve; DORV, double outlet right ventricle; CAVSD, complete atrioventricular septal defect; LCOS, low cardiac output syndrome; ALCAPA, anomalous left coronary artery origin from pulmonary artery; LCA, left coronary artery; TOF, tetralogy of Fallot; PV, pulmonary valve; TV, tricuspid valve; VSD, ventricular septal defect; ASD, atrial septal defect; PA, pulmonary artery; HLHS, hypoplastic left heart syndrome; MAPCAS, major aortopulmonary collateral arteries; MV, mitral valve; RPA, right pulmonary artery; RVF, right ventricular failure; LVF, left ventricular failure; RA-RV, right atrium-right ventricle; LVOT, left ventricular outflow tract; PDA, patent ductus arteriosus; ECMO, extracorporeal membrane oxygenation.

Table 4
Regimen at admission of patients undergone intraoperative ECMO support

Regimen	*n* (%)
Emergency	47 (71.2)
Urgent	11 (16.7)
Elective	8 (12.1)
Total (*n*)	66

ECMO, extracorporeal membrane oxygenation.

children were operated on electively, while 11 (16.7%) had urgent operation and 47 (71.2%) had emergency surgery due to late referral from other hospitals (Table 4).

3.3. Outcome

Mean duration of ECMO support was 5.1±3 days. Overall 30 (45.4%) patients were successfully weaned off ECMO and survived to decannulation. A total of 6 (9.1%) patients were successfully bridged to Htx while on ECMO support. Thirty patients died (54.4%) (16 while on ECMO and 14 after decannulation) because of multi-factorial complications, i.e. cerebral hemorrhage, pulmonary failure, consumption coagulopathy and therapy-resistant myocardial insufficiency, leading to an overall hospital mortality rate of 45.4%. Mean survival time after decannulation was 28±16 h. Overall survival rate on ECMO as bridge to recovery and transplantation was 54.5% with successful hospital discharge of patients (Tables 2 and 5).

Table 5
Outcome of intraoperative ECMO support in overall population

	Outcome (*n*=66)
Duration (days) (Mean±S.D.)	5.1±3
Weaned off ECMO (survival to decannulation) *n* (%)	30 (45.4)
Bridge to Htx *n* (%)	6 (9.1)
Complications *n* (%)	
Cerebral hemorrhage	25 (37.8)
Reexploration for bleeding	25 (37.8)
Circuit thrombus formation	13 (19.6)
Persistent myocardial failure	13 (19.6)
Cannulation site bleeding	8 (12.1)
Consumption coagulopathy	6 (9.1)
Mortality on ECMO support *n* (%)	16 (24.2)
Mortality after decannulation *n* (%)	14 (21.2)
Overall hospital mortality *n* (%)	30 (45.4)
Overall survival on ECMO (as bridge to recovery and Htx) *n* (%)	36 (54.5)

S.D., standard deviation; Htx, heart transplantation; ECMO, extracorporeal membrane oxygenation.

Hence, according to statistical analysis, mortality was not correlated to age, weight, or sex (Table 6). Interestingly, longer duration of CPB did not result in statistically poorer outcome. However, longer duration of ECMO support was strongly associated with mortality ($P<0.05$). Likewise, high arterial serum lactate levels at the start of ECMO initiation was significantly associated with mortality ($P<0.05$). Acidosis and the presence of renal insufficiency on ECMO, as manifested by elevated blood urea nitrogen influenced neither the ability to wean off ECMO nor survival to discharge. Temporary renal insufficiency on ECMO developed in 28 (42.4%) patients. Significant hemorrhagic complications occurred in the majority of patients (Table 5). These complications were mainly related to hemorrhage (cannulation site, cerebral, consumption coagulopathy). This was usually managed by repeated bedside surgical exploration with treatment of coagulopathy along with ACT control. Circuit thrombus formation, mainly in the gas-exchange connectors, was found to be the most common mechanical complication occurring in 13 (19.7%) patients. Circuit replacement was required in 8 (12.1%) of these patients. Cerebral hemorrhage and persistent myocardial failure occurred in 25 (37.8%) and 13 (19.7%) patients, respectively, of whom none survived.

Therefore, there was no statistically significance difference in outcome (type of complications) by comparing survivors and non-survivor populations.

4. Discussion

The increasing complexity of congenital cardiac surgery has resulted in the increased use of ECMO support for children who cannot be weaned off CPB despite maximal inotropic therapy and optimal operative repair [1–11]. The results of our experience with ECMO had been previously partially studied and published [12–14]. In the last years, the development of a team of surgeons, anesthetists, perfusionists, pediatric cardiologists, and nurses who have been more and more trained for ECMO system care and management provided a big support for good results in such a delicate population of patients.

In our institution, the majority of patients are placed on intraoperative ECMO due to inability to wean from CPB. The mechanical support is maintained via the original bypass cannulae and converted to a closed system [12].

Cardiac output is not readily determined in infants and small children because thermodilution catheters may not be placed and patients often have systemic-to-pulmonary

Table 6
Analysis of possible risk factors for hospital death in ECMO population

Variable	Survivors (*n*=36)	Non-survivors (*n*=30)	*P*-value
Age (years)	3.9±5	7.4±6	0.82
Weight (kg)	12.7±5.1	10.3±4.3	0.21
Male gender *n* (%)	14 (46.7%)	24 (66.7%)	0.05
Duration of CPB (min)	53.2±27	51.5±29	0.36
Arterial pH at ECMO initiation	7.32±0.13	7.29±0.16	0.05
Arterial lactate level at ECMO initiation (mmol/l)	10.3±5.2	14.4±7.5	0.004
Blood urea nitrogen level at ECMO initiation (mg/dl)	40.1±27.8	45.7±27.7	0.39
Duration of ECMO (days)	2.9±1.8	5.3±2.7	0.003

CPB, cardiopulmonary bypass; ECMO, extracorporeal membrane oxygenation.

shunts. Therefore, the indications for postcardiotomy ECMO must often be based on clinical judgment, according to the evidence of isolated right or left heart failure, pulmonary hypertension, or poor peripheral perfusion and systemic acidosis (LCOS) even if immediately after weaning from CBP (Tables 2 and 3).

LCOS, as defined by a progressive decrease in urine output to <1 ml/kg/h despite increasing inotropic and diuretic therapy, in association with poor peripheral perfusion, low systemic venous oxygen saturations, or progressive elevation of myocardial filling pressures, is generally considered an indication for ECMO support. In addition, refractory atrial or nodal arrhythmias resulting in or contributing to LCOS are also relative indications for ECMO.

Prompt initiation of ECMO may result in rapid return of peripheral perfusion and an increase in urine output and may obviate the need for hemodialysis or ultrafiltration in many patients who sustain a low cardiac output state after cardiac repair. No objective criteria to predict the need for ECMO support in the postoperative period have yet been determined [15].

According to our policy, ECMO support is preferable in children with post-cardiotomy heart failure in whom myocardial recovery in a matter of days is anticipated. If myocardial recovery is delayed or absent, switching to a the pediatric Berlin Heart ventricular assist device (VAD) should be performed without delay [8, 9, 15, 16].

Following our algorithm for ECMO placement [8, 12, 15], none of the patients of this study could be bridged to pediatric VAD support due to the complexity of the congenital anomalies even if corrected but with presence of temporary shunts, still intracardiac defects or respiratory problems. Therefore, during the studied period we had no experience in VAD placement in single ventricle repair patients or in the case of too low weight of infants. In the remainder of cases, the recovery was expected to be within two weeks, thus forcing us to go on with ECMO support.

Since the beginning of our experience and according to surgeon's preference, we established a cut-off time ECMO support of 10 days before going to other eventual solutions (VAD or transplantation, when possible) as well described elsewhere [12]. Actually, according to the last results we clearly advise to switch to other therapies earlier.

ECMO system was established immediately after surgery in case of weaning from CBP or within 1 h since the end of primary surgery time. In these cases the weaning from CBP appeared not risky with satisfactory hemodynamics but we had a sudden failure particularly in case of non-complete cardiac correction [12]. Above all, we do not do prophylactic placement of ECMO support as described by other authors since it is still not well established when or in which congenital cardiac disease treatment.

Patients with hypoplastic left heart syndrome (HLHS) after Norwood stage I palliative repair presented a particular problem. Use of the standard venoarterial ECMO circuit is associated with overperfusion of the lungs through the systemic-to-pulmonary shunt. This increase in pulmonary blood flow is not well tolerated by the single right ventricle and has not, in our experience, been associated with significant myocardial recovery. Recent reports suggest that ECMO can be used in patients after the Norwood procedure if pulmonary blood flow is limited by temporarily occluding the systemic-to-pulmonary shunt with a vascular clip as we did in the past [12, 17]. This clip is removed before weaning from ECMO. Actually, we apply this approach to all situations of a single ventricle physiology and aorto-pulmonary shunts thus probably going against Jaggers et al. who demonstrated the benefits of the contrary as well [7].

Further studies seem to be necessary to better understand how to manage in the right way such kind of physiology.

4.1. Complications of ECMO support

In this study, the major complication of postcardiotomy ECMO in pediatric patients is hemorrhage [13]. A large proportion of children, approaching 50%, require reexploration for hemorrhage at some point during the period of ECMO perfusion. In our experience, the primary determinant of significant hemorrhage is duration of ECMO; reexploration is unusual in the first 72 h, but is increasingly required thereafter. In our experience (25 cases, Table 5), once reexploration is required, additional attempts to control hemorrhage are usually necessary at decreasing intervals. Mediastinal reexploration is generally performed in the intensive care unit, while ECMO continues, to avoid the risk of cannula dislodgment or tamponade, with transport to the operating room.

Cerebral hemorrage has been our main cause of death. The result actually forced us to use more heparin-coated circuits and to perform a better anticoagulation management, actually by means of thromboelastography and platelet aggregation tests and an ECMO running with lower levels of ACT as well [13, 18].

An additional complication of ECMO is renal insufficiency. In our experience, however, this has been uncommon [1–11]. If ECMO is initiated promptly on discovery of progressive LCOS, ultrafiltration or dialysis is rarely necessary. Initiation of ECMO prior to complete anuria has resulted in rapid improvement in renal function in our patients.

An additional risk or prolonged use of ECMO is sepsis or mediastinitis [1–11]. The multiple cannulae and intravascular catheters in patients who required prolonged ECMO perfusion, in association with low cardiac output and renal insufficiency, predispose towards a significant incidence of infection. Reexploration of the mediastinum, continued bleeding from the mediastinal structures, and the exit of cannulae through the mediastinal wound can contribute to a significantly increased risk of mediastinal infection. Pneumonia and intravascular sepsis have not been seen in our series of patients and mediastinitis requiring drainage has not been encountered.

In our previous report, we found out that there was no significant difference in survival and mortality rates whether ECMO support was used preoperatively, intraoperatively or postoperatively [12]. However, the best overall recorded survival is recorded in patients with tetralogy of Fallot (TOF), truncus arteriosus, atrioventricular canal, and total anomalous pulmonary venous return. These may suggest that, as expected, complete operative repair is associated with improved survival; more palliative operations, such as for single ventricle or hypoplastic heart syndrome with shunt-dependent pulmonary blood flow, are associated with

a lower recovery rate. In addition, Fontan operation without early achievement of optimal hemodynamics is not associated with good survival despite ECMO, suggesting that in the majority of these patients ventricular function does not improve sufficiently with time or that pulmonary resistance remains elevated. Therefore, there was no statistical significance difference in outcome (complications or mortality) by comparing single ventricle palliations vs. two ventricle repairs. A consistent finding in all reported series [12], as in our study, is a decreased survival rate if ECMO is required to wean the patient from bypass in the operating room, suggesting a greater level of myocardial damage in these patients. In the majority of patients who did not survive late after ECMO in the Deutsches Herzzentrum Berlin series, significant myocardial dysfunction persisted or pulmonary hypertensive events occurred after weaning from ECMO. Nevertheless, an acceptable number of patients who were successfully weaned from ECMO ultimately survived to leave the hospital.

5. Conclusions

Mechanical circulatory support in the form of ECMO can be effective in pediatric patients during palliative or corrective surgery of congenital heart diseases when weaning off CPB proved to be difficult. It saves the lives of those who otherwise would not have survived the surgery. Likewise, ECMO has the advantage of being applicable over a wide range of ages and weights and of providing biventricular cardiovascular and pulmonary support. The overall mortality rate remains high, but ECMO success can be achieved in most patients with congenital heart defects.

6. Limitations

The first limitation of this study is the retrospective nature of the analysis. There was not the same protocol-driven management of hemodynamics before mechanical support during all of this long period of study. The population sample was not adjusted according to any established severity score in order to evaluate any eventual preoperative predictor to eventually address the topic of a 'prophylactic' ECMO support. Further studies are also necessary to better understand how to manage the physiology of single ventricle repair while on ECMO.

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eComment: Outcome of extracorporeal membrane oxygenation in pediatric cardiac surgery – impact of residual lesions

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The report of Loforte and colleagues [1] shows the increasing use of extracorporeal membrane oxygenation (ECMO) in postcardiotomy pediatric patients. As their work shows, significant morbidity and mortality, with an overall survival rate of 40% can be expected in this patient population. The cost of ECMO use and relatively poor outcomes make appropriate patient selection a desirable goal. But as the authors [1] observe, the indications for postcardiotomy ECMO must often be based on clinical judgment, and thus uniform selection criteria for postcardiotomy pediatric patients being considered for ECMO salvage remain elusive.

Nevertheless, the primary aim of cardiac ECMO remains unchanged – unloading the heart to decrease its work so as to allow recovery of cardiac function from injury within a short time frame. ECMO is thus best used in the patient with a good potential for myocardial recovery in a matter of days. Hemodynamically significant residual lesions unresolved by the cardiac repair profoundly undermine this potential for recovery. The most common residual lesions after congenital heart surgery are residual shunts, obstructed ventricular outflow pathways, and atrioventricular valve regurgitation. These may be the result of incomplete/imperfect repairs or undiagnosed but hemodynamically significant lesions existing preoperatively. Residual lesions may be present in as many as 15% of pediatric postcardiotomy patients placed on ECMO; a third of these residual lesions may not be diagnosed preoperatively [2]. In the presence of such residual lesions, the likelihood of recovery of cardiac function on ECMO is slim; an already compromised myocardium stands little chance of recovering from the additional hemodyn-

amic burden imposed by significant residual lesions. Not surprisingly, the presence of residual lesions has been found to be an important adverse factor for ECMO survival [2, 3]. On this basis, complete surgical repair must be ensured before ECMO is applied. Every effort must be made to rule out hemodynamically significant residual lesions before ECMO salvage is contemplated. Postcardiotomy residual defects must be considered contraindications to ECMO. From the study of Black and colleagues [3], excluding children with residual defects resulted in successful weaning from ECMO in almost 70% of cases, with almost all recovery occurring within the first six days of ECMO.

Summarily, a complete preoperative diagnosis ensures that all hemodynamically significant lesions are addressed intraoperatively to facilitate a complete repair. When patients cannot be separated from bypass, a thorough search must be made for residual lesions which must be addressed to improve ECMO outcomes.

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