Early and late outcomes of 517 consecutive adult patients treated with extracorporeal membrane oxygenation for refractory postcardiotomy cardiogenic shock

Ardawan Julian Rastan, MD, PhD, Andreas Dege, MD, Matthias Mohr, MD, Nicolas Doll, MD, PhD, Volkmar Falk, MD, PhD, Thomas Walther, MD, PhD, and Friedrich Wilhelm Mohr, MD, PhD

Objective: Adult postcardiotomy cardiogenic shock potentially requiring mechanical circulatory support occurs in 0.5% to 1.5% of cases. Risk factors influencing early or long-term outcome after extracorporeal membrane oxygenation implantation are not well described.

Methods: Between May 1996 and May 2008, 517 adult patients received extracorporeal membrane oxygenation support for postcardiotomy cardiogenic shock. Procedures were isolated coronary artery bypass grafting (37.4%), isolated valve surgery (14.3%), coronary artery bypass grafting plus valve surgery (16.8%), thoracic organ transplantation (6.5%), and other combinations (25.0%). Fifty-four preoperative and 42 procedural risk factors concerning in-hospital mortality were evaluated by logistic regression analyses.

Results: Mean age was 63.5 years, 71.5% were male, ejection fraction was $45.9\% \pm 17.6\%$, logistic EuroSCORE was $21.6\% \pm 20.7\%$. Extracorporeal membrane oxygenation was established through thoracic (60.8%) or extrathoracic (39.2%) cannulation. Extracorporeal membrane oxygenation support was 3.28 ± 2.85 days. Intra-aortic balloon pumps were implanted in 74.1%. Weaning from extracorporeal membrane oxygenation was successful for 63.3%, and 24.8% were discharged. Cerebrovascular events occurred in 17.4%, gastrointestinal complications in 18.8%, and renal replacement therapy in 65.0%. Risk factors for hospital mortality were age older than 70 years (odds ratio, 1.6), diabetes (odds ratio, 2.5), preoperative renal insufficiency (odds ratio, 2.1), obesity (odds ratio, 1.8), logistic EuroSCORE greater than 20% (odds ratio, 1.8), operative lactate greater than 4 mmol/L (odds ratio, 2.2). Isolated coronary artery bypass grafting (odds ratio, 0.44) was protective. Cumulative survivals were 17.6% after 6 months, 16.5% after 1 year, and 13.7% after 5 years.

Conclusions: Extracorporeal membrane oxygenation support is an acceptable option for patients with postcardiotomy cardiogenic shock who otherwise would die and is justified by good long-term outcome of hospital survivors. Because of high morbidity and mortality, extracorporeal membrane oxygenation must be decided by individual risk profile. (*J Thorac Cardiovasc Surg* 2010;139:302-311)

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The incidence of refractory postcardiotomy cardiogenic shock (PCS) in adult cardiac surgical patients ranges from 0.5% to 1.5% but depends highly on the surgical case mix.^{1,2} For these patients, the implantation of an extracorporeal membrane oxygenation (ECMO) device is an easily

applicable and widely accepted option for temporary mechanical circulatory support allowing cardiac and pulmonary recovery or bridging until further therapeutic alternatives can be carefully considered.³⁻⁵ During the last 20 years however, ECMO results in these patients have not been satisfactory. Successful ECMO weaning rate ranges from 31% to 60% and corresponds with an in-hospital mortality of 59% to 84%.²⁻¹¹ By indication, acute myocardial failure is the major cause of mortality, although a significant number of other primary causes of death have also been reported.¹²

The perioperative decision for ECMO support in PCS remains difficult and is based on scientific data but also on individual considerations, because ECMO support is associated with a high morbidity that includes bleeding, ischemic or thromboembolic events, and end-organ failures. Surgeons have to carefully balance the high perioperative morbidity, staffing needs, and resource use in ECMO treatment against the probability of survival. Although an unexpected PCS event in a low-risk patient is usually an indicator for

From the Department of Cardiac Surgery, Heart Center, University of Leipzig, Leipzig, Germany.

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Address for reprints: Ardawan Rastan, MD, PhD, University Leipzig, Department of Cardiac Surgery, Struempellstrasse 39, 04289 Leipzig, Germany (E-mail: rastan@rz.uni-leipzig.de).

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Abbreviations and Acronyms

ECMO	= extracorporeal membrane oxygenation
IABP	= intra-aortic balloon pump
OR	= odds ratio
PCS	= postcardiotomy cardiogenic shock
L-VAD	= left ventricular assist device

a more liberal ECMO indication, indications might be more restrictive in high-risk patients and preoperatively foreseeable PCS. The prognostic effects of varying risk factors, including patient characteristics, surgical procedures, and technical ECMO implantation details have not been well considered. The aim of this study was therefore to use univariate and multivariate logistic regression models to identify risk factors that potentially affect hospital and long-term outcomes.

MATERIALS AND METHODS**Patients and Procedures**

Between May 1996 and May 2008, a total of 517 of 40,538 patients (1.28%) received venoarterial ECMO implantation to treat refractory PCS. ECMO was instituted intraoperatively during the primary cardiac procedure or secondarily within 30 minutes of deciding to support a patient with delayed PCS. Secondary indications included progressive univentricular or biventricular forward or backward pump failure, intractable ventricular arrhythmia or fibrillation, or sudden cardiac death of primary unknown reasons.

For all patients with ECMO, multiple preoperative, perioperative, and postoperative clinical variables were prospectively recorded in the hospital database. Fifty-four preoperative and 42 procedural variables were evaluated by univariate and multivariate logistic regression analysis with respect to in-hospital mortality. Follow-up was complete at a mean of 3.2 years for the hospital survivors.

ECMO Device and Management

Arterial cannulation site was central in 60.8% and peripheral in 39.2% (30.3% axillary artery access and 69.7% femoral artery access). The femoral artery was directly cannulated by Seldinger technique, and the axillary artery was approached through a 6- or 8-mm Dacron polyester fabric prosthesis. In 23.4% of femoral artery approaches, a distal leg perfusion cannula (8F or 10F) was introduced. Venous line was inserted by right atrial cannulation in 61.8% and by femoral venous cannulation in 48.2% (42.1% percutaneously, 57.9% by surgical cutdown). In 10% of cases, combined right atrial and femoral venous drainage was established.

The most common indication for ECMO during heart surgery was for patients who could not be weaned from cardiopulmonary bypass. For these patients, the existing right atrial and aortic cannulas were mostly used. In a few cases, central cannulation was converted to peripheral cannulation to allow primary chest closure. In patients receiving ECMO secondary to heart surgery, ECMO was implanted through peripheral cannulation, or, when additional cardiac surgery or cardiac reexploration was indicated, by central insertion. Overall in 50.8% of all cases the chest remained open after ECMO implantation (Table E1).

The institutional ECMO cannulation techniques and management strategies have been previously described.^{2,12} In brief, the ECMO circuit consisted of a centrifugal pump console (in most cases, Biopump PB-80; Medtronic Bio-Medicus, Minneapolis, Minn) in conjunction with an in-

line plasma-tight hollow-fiber microporous membrane oxygenator (Affinity NTTM; Medtronic, Anaheim, Calif; or Hilite 7000 LTTM; Medos Medizin-technik AG, Stolberg, Germany) with integrated heat exchanger. All components were heparin bonded and connected by the shortest possible tubing system. Routinely, no additional left-sided venting or atrial septostomy was performed. The ECMO system was implanted under full heparinization, and activated clotting time was kept longer than 300 seconds. Usually half of the heparin was antagonized with protamine once full ECMO flow was established, aiming for an activated clotting time of 160 seconds. Until the year 2006, aprotinin was routinely administered with a modified Hamer-smith protocol. More recently, aprotinin was replaced by tranexamic acid. Additional coagulation factors, platelets, or coagulant agents were specifically substituted according to the results of laboratory coagulation analysis or thromboelastography. If bleeding was acceptable, the patients were given continuous heparinization as early as possible to maintain an activated clotting time of 160 seconds. If it had not already been done, all patients with coronary artery disease and almost all other patients received intra-aortic balloon pump (IABP) insertion to compensate systemic afterload increase induced by ECMO and to generate pulsatility. With full ECMO support, the goal was to reduce intravenous inotropes and to decrease ventilation to lower positive end-expiratory pressures (5 cm H₂O) and physiologic respiratory minute volumes to allow optimal myocardial and pulmonary recoveries. Fractional inspired oxygen was adjusted to maintain P_O₂ between 85 and 100 mm Hg. The oxygenator was examined twice a day for early detection of thrombus formations. It was exchanged in the event of thrombus detection or if the perfusion pressure started to increase. Platelets were substituted to achieve a platelet count of 50,000 to 100,000 cells/ μ L. Blood clotting factors were analyzed daily and substituted when crossing lower limits. Cardiopulmonary recovery was daily assessed by hemodynamic, clinical, and echocardiographic measurements to define the optimal time of weaning.

Routinely, full ECMO flow was instituted for 48 to 72 hours before the weaning process was started. Weaning was cautiously begun only under stable hemodynamic and metabolic conditions, starting from full flow to approximately 1 L/min during a 36- to 48-hour process of observing intrinsic cardiac output, metabolic status, venous saturation, and end-organ perfusion, allowing medical adjustment when necessary. When signs of malperfusion occurred during ECMO weaning, the flow was increased again to full, allowing prolonged ECMO support and exclusion of cardiac tamponade. During the weaning, all patients underwent at least 1 daily control transesophageal echocardiogram. Before ECMO weaning, bronchoscopy was performed on a routine basis. Even if bridging for recovery was the initial goal, in all cases treatment options including bridging to ventricular assist device implantation and transplantation were considered individually, and preparations were made in case weaning was unsuccessful. When cardiac transplantation was contraindicated in a patient with irreversible ventricular failure, ECMO support was withdrawn with the awareness that survival was unlikely.

Patients with ECMO were managed by the on-shift intensivists and the on-shift cardiac surgeons on a 24-hour basis. Routinely, the patient-to-nurse ratio was reduced from 2:1 to 1:1 during the first 24 hours of the ECMO run. Further personal management depended on the efforts that had to be made for the individual patient with ECMO. Routinely a perfusionist checked the ECMO circuit at least twice a day.

Definitions

Indication for ECMO support included clinical criteria of PCS such as systolic arterial hypotension (<80 mm Hg) and signs of end-organ failure, anaerobic metabolism, and metabolic acidosis (pH <7.3, lactate level >3.0 mmol/L, urinary rate <0.5 mL/kg) despite optimized supportive measures such as IABP, inotropes, nitric oxide, and phosphodiesterase inhibitors. Hemodynamic criteria were cardiac index less than 1.8 L/m² body surface area and pulmonary capillary wedge pressure of at least 20 mm Hg. Cardiac function was reassessed by transesophageal echocardiography in all cases.

Perioperative acute myocardial infarction (AMI) was assumed in cases of creatinine kinase MB fraction release more than 5-fold the upper limit of normal during the perioperative period. According to this definition, an AMI was assumed when creatine kinase MB was higher than 120 units/L. Diabetes was defined as hyperglycemia requiring either insulin or noninsulin treatment, and chronic renal insufficiency was noted for patients with creatinine plasma levels greater than 1.8 mg/dL. Weaning was considered as successful when a patient survived ECMO explantation for longer than 6 hours.

Statistics

Data were 100% complete. Continuous variables are expressed as mean $\pm$ SD for Gaussian distributions and as mean values only otherwise. Categorical data are given as proportions. Categorical variables were compared with the Pearson χ^2 test, and independent continuous variables were compared with 2-tailed Student *t* test or Mann–Whitney *U* test as appropriate. Univariate and stepwise multivariate logistic regression analyses of 54 dichotomous preoperative and 42 perioperative risk factors for in-hospital mortality were performed by calculating the odds ratio (OR) with 95% confidence interval. Risk factors analyzed are listed in Tables 1 through 3 and E1.

Cumulative survivals were calculated by Kaplan–Meier methods with 95% confidence limits. The statistical calculations were performed with the 17.0 SPSS (SPSS, Inc, Chicago, Ill) and Microsoft Excel 2003 (Microsoft Corp, Redmond, Wash) software packages. The study protocol and anonymous data publication were approved by the local ethics committee. There are no disclosures or funding to declare.

RESULTS

For baseline extracardiac and cardiac characteristics of the patients undergoing ECMO and their effects on hospital survival, see Table 1 and Figure E1. The underlying cardiac diseases and corresponding cardiac procedures are presented in Tables 2 and 3. Age ranged from 18 to 84 years.

ECMO was established during the initial cardiac surgery in 41.9% of cases because of circulatory instability during or immediately after weaning from cardiopulmonary bypass. Most of the patients (58.1%) received ECMO secondary to primary cardiac surgery as a consequence of delayed PCS or resuscitation in the postoperative course. Mean interval to primary cardiac procedure in these patients was 62.6 hours, and there was greater postponement among nonsurvivors (71.7 hours) than among hospital survivors (33.3 hours, $P = .031$). Overall delayed ECMO implantation was not associated with a significantly increased in-hospital mortality relative to simultaneous ECMO implantation (OR, 1.20; $P = .404$). In 29.7% of the patients with secondary ECMO implantation, additional cardiac procedures (coronary artery bypass grafting [CABG] or CABG revision in 60%) were performed.

ECMO support lasted 3.3 ± 2.9 days (range, 0–25 days). During that period, surgical ECMO revision for unsatisfactory ECMO flow was required in 12.5% of the patients, and such an event was associated with significantly higher in-hospital mortality (OR, 2.24; $P = .042$). Exchange of the oxygenator was required in 6.1% at a mean of 3.0 days after first ECMO implantation. Arterial cannulation site did not significantly influence hospital outcome, but percutaneous venous femoral cannulation was associated with adverse outcome. For more details, see Table E1.

Successful ECMO weaning was possible in 63.5% of the cases. Overall, 56.4% patients survived ECMO explantation for longer than 24 hours. Overall, in-hospital mortality was 75.2%, with the main reason for death being cardiac in 79.9%. Patients died a mean of 11.1 days after ECMO implantation. As shown in Tables 1 through 3, several preoperative risk factors significantly influenced hospital outcome; of these, however, only age older than 70 years (OR, 1.90; $P = .022$), diabetes (OR, 2.61; $P = .001$), and isolated coronary artery disease (OR, 0.56; $P = .025$) were significant in multivariate analysis. Despite failure to reach statistical significance, there was a strong trend toward worse outcome among patients with additional tricuspid regurgitation greater than 2+, acute type A dissection, and combined aortic and mitral valve disease, whereas preoperative emergency status, preoperative AMI, and active mechanical resuscitation before ECMO implantation were not significant predictors for in-hospital death (Table 2).

In-hospital mortality also depended significantly on the primary cardiac procedure (Table 3). Hospital survival was significantly improved for patients undergoing isolated CABG (34.7%) with surrogates of coronary artery disease and worse for patients undergoing aortic arch repair or total pericardiectomy, indicating that the complexity of the primary cardiac procedure significantly influenced outcome after ECMO implantation.

ECMO outcome was also significantly associated with the severity of pre-ECMO PCS and with circulatory and metabolic recovery during ECMO support, as indicated by lactate level changes. Lactate level greater than 10 mmol/L immediately after ECMO implantation was a significant predictor of mortality (mortality, 83.0%; OR, 2.65; $P < .001$). Persistent lactate values greater than 10 mmol/L after 24 and 48 hours of ECMO support were associated with the highest mortalities of 93.6% (OR, 8.2; $P < .001$) and 97.6% (OR, 22.5; $P < .001$), respectively. Serologic signs of liver necrosis (OR, 3.25; $P < .001$) and acute renal failure (OR, 4.27; $P < .001$) during ECMO were strongly associated with in-hospital mortality.

A total of 54.3% of the patients had AMI according to the definition mentioned previously. Creatine kinase MB levels greater than 120 units/L after 24 and 48 hours of ECMO assistance were also associated with increased mortalities of 78.6% (OR, 1.73; $P < .001$) and 81.0% (OR, 2.36; $P < .001$), respectively.

There was a considerable complication rate among patients undergoing ECMO (Table 4). High blood loss during the first 24 hours of ECMO (survivors 2532 mL vs nonsurvivors 3261 mL, $P = .019$) and the event of acute renal failure (OR, 4.37; $P < .001$) significantly impaired hospital survival, whereas the total amount of blood product transfusion and rethoracotomy did not. Overall hospital stay was 16.2 days, with a mean of 27.2 days among the hospital survivors.

TABLE 1. Patient demographic data and preoperative clinical status with respect to hospital outcomes

Characteristic	All (n = 517)	Hospital survivors (n = 128)	Nonsurvivors (n = 389)	Hospital survival (%)	In-hospital mortality		P value
					OR	95% CI	
Extracardiac characteristics							
Age (y, mean ± SD)	63.5 ± 11.2	60.4 ± 12.3	64.0 ± 10.7				.002
>70 y (%)	29.8%	22.6%	32.2%	18.7%	1.62	1.01–2.69	.049
Sex (% female)	28.5%	27.0%	29.0%	23.5%	1.11	0.69–1.78	.671
BMI >30 (%)	21.8%	14.8%	24.1%	16.8%	1.83	1.04–3.25	.037
Diabetes (%)	32.5%	19.1%	36.9%	14.7%	2.47	1.48–4.13	.001
Hyperlipidemia (%)	47.4%	52.2%	45.8%	27.4%	0.78	0.51–1.18	.238
Arterial hypertension (%)	70.3%	69.6%	70.6%	24.6%	1.05	0.66–1.66	.832
COPD (%)	13.0%	9.6%	14.1%	18.3%	1.55	0.78–3.09	.214
Smoker (%)	27.5%	37.4%	24.2%	33.9%	0.54	0.34–0.84	.006
Renal insufficiency (%)	15.6%	9.2%	17.6%	14.3%	2.11	1.04–4.29	.038
Preop neurologic impairment (%)	7.8%	4.3%	8.9%	13.9%	2.15	0.82–5.67	.121
Peripheral vascular disease (%)	23.5%	17.4%	25.6%	18.3%	1.63	0.95–2.80	.075
Cardiac characteristics							
Preop AF (%)	19.9%	14.8%	21.6%	18.5%	1.58	0.89–2.81	.117
s/p PM/ICD implantation (%)	10.4%	9.6%	10.6%	22.9%	1.12	0.55–2.29	.745
Pulmonary hypertension (%)	14.1%	10.5%	15.3%	18.5%	1.53	0.79–2.98	.209
Previous cardiac surgery (%)	23.8%	18.3%	25.6%	19.1%	1.54	0.91–2.62	.112
s/p AMI (%)	38.0%	46.1%	35.3%	30.3%	0.64	0.42–0.98	.039
s/p PCI (%)	20.3%	29.6%	17.3%	36.2%	0.50	0.31–0.81	.005
Ejection fraction (%; mean ± SD)	45.9% ± 17.6%	46.1% ± 17.2%	45.8% ± 17.8%				.858
<30% (%)	19.0%	15.9%	20.0%	20.9%	1.32	0.75–2.33	.340
CCS angina class IV (%)	15.6%	18.3%	14.8%	29.6%	0.78	0.44–1.36	.375
NYHA functional class IV (%)	23.6%	21.1%	24.4%	22.2%	1.21	0.73–2.02	.464
AMI							
<12 h (%)	16.2%	15.7%	16.4%	22.2%	1.18	0.60–2.32	.636
STEMI	8.5%	7.0%	9.0%	20.5%	1.33	0.59–2.98	.490
NSTEMI	7.7%	8.7%	7.4%	32.3%	0.68	0.31–1.50	.344
Preop cardiogenic shock (%)	17.7%	16.5%	18.1%	23.2%	1.12	0.64–1.96	.700
Preop IABP insertion (%)	9.5%	13.0%	8.3%	34.1%	0.61	0.31–1.18	.139
Preop ventilation (%)	14.9%	14.8%	14.9%	24.6%	1.01	0.56–1.83	.967
Preop inotropic support (%)	19.7%	16.5%	20.7%	20.9%	1.32	0.76–2.30	.311
Emergency indication (%)	39.7%	38.3%	40.2%	25.8%	1.09	0.71–1.67	.708
Urgent indication (%)	23.6%	17.7%	25.6%	18.5%	1.60	0.93–2.74	.089
Resuscitation in operating room (%)	6.0%	3.5%	6.9%	14.3%	2.06	0.70–6.10	.191
Logistic EuroSCORE (%; mean ± SD)	21.6% ± 20.7%	14.7% ± 14.4%	23.9% ± 21.9%				<.001
EuroSCORE >20% (%)	40.0%	29.6%	43.4%	18.4%	1.83	1.16–2.87	.009

AMI, Acute myocardial infarction; BMI, body mass index; CI, confidence interval; CCS, Canadian Cardiovascular Society; COPD, chronic obstructive pulmonary disease; IABP, intra-aortic balloon pump; ICD, implantable cardioverter defibrillator; PM, pacemaker; Postop, postoperative; Preop, preoperative; NSTEMI, Non-ST-segment elevation myocardial infarction; NYHA, New York Heart Association; OR, operation room; s/p, status post; STEMI, ST-segment elevation myocardial infarction.

Five patients with ECMO were bridged to transplantation. Of these, 2 survived. Twelve of 15 patients who received bridge-to-bridge left VAD implantation after a mean of 3.2 ± 1.2 days of ECMO died during the hospital stay.

Overall cumulative survivals were $31.3\% \pm 2.2\%$ after 30 days, $17.6\% \pm 1.8\%$ after 6 months, $16.5\% \pm 1.7\%$ after 1 year, and $13.7\% \pm 1.7\%$ after 5 years (Figure 1). Patients with isolated CABG procedures had the best early ($41.0\% \pm 3.7\%$ after 30 days) and long-term ($22.2\% \pm 3.2\%$ after 1 year and $19.6\% \pm 3.1\%$ after 5 years) survivals. Five-year survival for all hospital survivors was $55.8\% \pm 5.0\%$.

DISCUSSION

ECMO Indication

Patients with persistent PCS despite optimal medical treatment and IABP face almost certain death, and all treatment alternatives have to be assessed in the light of an otherwise dismal prognosis. ECMO is a reasonable treatment option for temporary mechanical circulatory support in these patients and was preferred in our institution relative to other assist devices because of its versatility. ECMO allows rapid restoration of circulation during primary cardiac surgery or active resuscitation, fits with almost all patients and clinical scenarios, is cost saving, offers varying cannulation options,

TABLE 2. Underlying cardiac diseases

Characteristic	All (n = 517)	Hospital survivors (n = 128)	Nonsurvivors (n = 389)	Hospital survival (%)	In-hospital mortality		P value
					OR	95% CI	
CAD							
All	69.1%	77.4%	66.4%	27.8%	0.58	0.35–0.94	.028
1-vessel	12.8%	7.9%	14.7%	17.1%	1.67	0.72–3.88	.232
2-vessel	20.3%	24.7%	18.6%	33.8%	0.60	0.34–1.05	.072
3-vessel	66.9%	67.4%	66.7%	28.0%	0.73	0.48–1.11	.140
Left main disease	27.5%	28.1%	27.3%	28.4%	0.80	0.47–1.34	.390
Isolated CAD	44.1%	56.5%	39.9%	31.9	0.51	0.33–0.79	.002
AV disease	20.3%	15.7%	21.8%	19.1	1.51	0.86–2.65	.155
Isolated AV disease	8.2%	7.0%	8.6%	21.1	1.26	0.56–2.84	.574
CAD and AV disease	7.9%	7.0%	7.8%	22.9	1.12	0.50–2.55	.778
MV disease	19.7%	15.7%	21.0%	19.8	1.43	0.81–2.52	.215
Isolated MV disease	4.1%	3.5%	4.3%	21.1	1.25	0.41–3.85	.617
CAD and MV disease	9.9%	10.4%	9.8%	26.1	0.93	0.46–1.86	.836
Isolated AV and MV disease	1.7%	0.0%	2.3%	0			.210
CAD, AV, and MV disease	2.6%	1.7%	2.9%	16.7	1.67	0.36–7.74	.551
TV regurgitation >2+	3.7%	0.9%	4.6%	5.6	5.95	0.72–41.9	.100
Bacterial endocarditis	4.5%	3.5%	4.9%	19.0	1.43	0.47–4.33	.530
Type A dissection	3.9%	0.9%	4.9%	5.6	5.86	0.77–49.5	.088
Pulmonary embolism	1.5%	1.7%	1.4%	28.6	0.82	0.16–4.30	.818
Thoracic aneurysm	7.3%	7.8%	7.2%	26.5	0.91	0.41–2.01	.819
Other isolated disease	5.4%	4.3%	5.7%	19.3	1.34	0.49–3.66	.566

All figures are percentages of patients. Cardiac diseases are not mutually exclusive and therefore total more than 100%. AV, Aortic valve; CAD, coronary artery disease; CI, confidence interval; MV, mitral valve; OR, odds ratio; TV, tricuspid valve.

and covers biventricular and lung function. The last is of substantial importance in active resuscitation secondary to surgery and emergency operations, where the underlying reason for PCS sometimes cannot be completely fixed. In these cases, ECMO allows bridging of patients for further evaluation and decision making and judgment of neurologic status. From the economic perspective, ECMO also provides circulatory support for older patients with relevant comorbidities, giving them at least the chance for cardiac or respiratory recovery even if VAD implantation or transplantation is not a further option. In this group, termination of ECMO is warranted if no rapid clinical improvement is seen.

A major disadvantage of ECMO is the need for anticoagulation and the requirement of high amounts of transfused blood products, increasing the systemic inflammatory response that is induced by the initial surgery, the ECMO components, and PCS itself. Thus indication for temporary ECMO support for PCS always depends on patient-specific characteristics and center experience, balancing risks and benefits. In our 12-year experience with 517 patients undergoing ECMO for PCS, we evaluated several risk factors for adverse hospital outcome to support decision making in the future.

In-Hospital Mortality

For all our patients with ECMO, native cardiopulmonary recovery was the primary intention, because most patients

were neither transplantation candidates nor candidates for further assist device implantation. Overall, successful weaning from the system was possible for 63.3% of the patients, but more than 50% of the weaned patients died during the hospital stay. Hospital survival thus was limited to 25%, which is comparable to results of smaller series of patients with PCS undergoing ECMO for which early survivals between 16% and 41% have been reported.³⁻¹¹ These data demonstrate that high mortality has continued to plague temporary circulatory ECMO support. They also suggest that despite progress in intensive care management and ECMO hardware components, in-hospital mortality has not significantly changed during the last decade. This finding is indeed supported by our experience that ECMO survival was relatively constant during the 12-year period, except during the last 3 years in which there was an improved survival greater than 30% (data not shown). It can be speculated, however, that there has been an improvement in ECMO results that does not directly translate to mortality reduction but rather reaches the same results for older and sicker patients. This hypothesis is supported by our finding that about 2 thirds of our patients could be successfully weaned from ECMO despite increases in risk scores, patient age, and complexity of cardiac procedures.

Of note, we did not find an improved outcome for 15 patients after early conversion to an implantable left ventricular assist device (L-VAD). This finding contrasts with other

TABLE 3. Cardiac procedures

Characteristic	All (n = 517)	Hospital survivors (n = 128)	Nonsurvivors (n = 389)	Hospital survival (%)	In-hospital mortality		P value
					OR	95% CI	
All CABG (%)	61.8%	70.4%	58.9%	28.3%	0.60	0.38–0.95	.028
Left internal thoracic artery (%)	69.4%	82.0%	64.5%		0.40	0.22–0.73	.003
Bilateral internal thoracic artery (%)	5.0%	10.1%	3.0%		0.28	0.10–0.77	.014
Complete revascularization (%)	82.2%	84.0%	78.0%		0.68	0.35–1.30	.237
Distal anastomoses (no., mean $\pm$ SD)	2.16 $\pm$ 1.27	2.30 $\pm$ 1.24	2.10 $\pm$ 1.27				.202
Isolated CABG (%)	37.4%	52.2%	32.5%	34.7%	0.44	0.29–0.68	<.001
Distal anastomoses (no., mean $\pm$ SD)	2.49 $\pm$ 0.99	2.56 $\pm$ 1.00	2.46 $\pm$ 0.98				.482
AV surgery (%)	32.0%	26.1%	33.9%	20.3%	1.45	0.91–2.33	.120
Isolated AV surgery (%)	7.6%	7.8%	7.5%	25.7%	0.95	0.43–2.09	.901
CABG and AV surgery (%)	5.4%	2.6%	6.3%	12.0%	2.52	0.74–8.58	.139
MV surgery (%)	24.8%	15.7%	27.9%	15.7%	2.08	1.20–3.63	.010
Isolated MV surgery (%)	3.9%	1.7%	4.6%	11.1%	2.72	0.62–12.0	.186
CABG and MV surgery (%)	5.8%	5.2%	6.0%	22.2%	1.17	0.46–2.97	.746
Isolated AV and MV surgery (%)	2.8%	0.9%	3.4%	7.7%	4.07	0.52–31.7	.180
CABG, AV, and MV surgery (%)	2.8%	1.7%	3.2%	15.4%	1.84	0.40–8.45	.430
TV repair (%)	4.3%	2.6%	4.9%	15.0%	1.92	0.55–6.67	.306
Ascending aorta surgery (%)	13.2%	11.3%	13.9%	21.3%	1.26	0.65–2.41	.495
Aortic arch repair (%)	3.7%	0.9%	4.6%	5.9%	5.49	0.72–41.9	.100
Surgical ventricular restoration (%)	1.7%	1.7%	1.7%	25.0%	0.99	0.20–4.98	.991
Ischemic VSD closure (%)	1.1%	0.9%	1.1%	20.0%	1.33	0.15–12.0	.802
Pulmonary embolectomy (%)	1.5%	1.7%	1.4%	28.6%	0.82	0.16–4.30	.818
Pericardiectomy (%)	1.1%	0.0%	1.4%	0.0%			.090
Thoracic transplantation (%)	6.5%	6.1%	6.6%	23.3%	1.09	0.46–2.62	.844
Operative time (min, mean $\pm$ SD)	275 $\pm$ 140	265 $\pm$ 126	279 $\pm$ 144				.342
CPB time (min, mean $\pm$ SD)	179 $\pm$ 106	160 $\pm$ 94	185 $\pm$ 110				.031
Crossclamp time (min, mean $\pm$ SD)	84.6 $\pm$ 51.5	75.6 $\pm$ 50.1	87.4 $\pm$ 52.0				.068
First operating room lactate level >4 mmol/L (%)	13.8%	7.8%	15.8%		2.21	1.06–4.63	.035
Operation end lactate level >4 mmol/L (%)	63.3%	53.0%	66.7%		1.77	1.15–2.72	.009
IABP insertion							
Total (%)	74.1%	77.4%	73.0%		0.79	0.48–1.30	.351
Intraoperative (%)	32.0%	33.9%	31.3%		0.89	0.57–1.39	.606
Postoperative (%)	37.6%	34.8%	38.5%		1.17	0.76–1.82	.475

Cardiac procedures are not mutually exclusive. AV, Aortic valve; CABG, coronary artery bypass grafting; CAD, coronary artery disease; CI, confidence interval; CPB, cardiopulmonary bypass; IABP, intraaortic balloon pump; MV, mitral valve; OR, odds ratio; TV, tricuspid valve; VSD, ventricular septal defect.

experiences, which have reported more than 70% survival after an early switch to long-term L-VAD support.^{5,7,13} This remarkable difference may easily be explained by selection bias; however, it can also be speculated that time of conversion, type of implanted L-VAD, and underlying cardiac disease play critical roles in success of this bridge-to-bridge concept.

Patient and Cardiac Surgery Risks for In-Hospital Death

Patient-specific and procedural predictors for in-hospital death among patients undergoing ECMO are not well defined in the literature. In an analysis of 202 adult patients undergoing ECMO, Smedira and colleagues¹ recently found

that previous cardiac surgery, older age, thoracic aortic operation, and the nonuse of IABP were significant predictors for death. This was particularly confirmed by our findings that age older than 70 years, obesity, and diabetes were independent risk factors for in-hospital mortality, whereas there was only a strong trend for worse survival in thoracic aortic surgery and nonuse of IABP. Advanced age alone, however, cannot serve as an absolute contraindication for ECMO implantation.^{6,14} We additionally found that preoperative critical status itself (eg, mechanical ventilation, inotropic support, active intraoperative resuscitation) was not associated with increased in-hospital mortality, whereas severity of PCS as measured by preoperative lactate values was.

TABLE 4. Postoperative complications

Rethoracotomy	
Total (no.)	425 (82.2%)
For bleeding (no.)	300 (58.0%)
For sternal wound revision (no.)	20 (3.9%)
IABP support (d, mean $\pm$ SD)	5.93 $\pm$ 5.31
Ventilation	
Total ventilation time (h, mean)	339
Reintubation (no.)	119 (23.2%)
Tracheostomy (no.)	95 (18.4%)
Pneumonia (no.)	111 (21.5%)
Adult respiratory distress syndrome (no.)	48 (9.3%)
Postoperative drainage loss (mL)	
First 24 h	3080
First 48 h	4245
Blood product transfusion in first 48 h	
Total (units, mean $\pm$ SD)	29.4 $\pm$ 25.6
Red blood cells (units, mean $\pm$ SD)	13.6 $\pm$ 12.1
Fresh-frozen plasma (units, mean)	14.0 $\pm$ 13.0
Platelets (units, mean $\pm$ SD)	1.72
Renal replacement therapy	
Use (no.)	336 (65.0%)
Duration (d)	9.7
ECMO leg complications	
Leg ischemia (no.)	28/141 (19.9%)
With distal leg perfusion cannula (no.)	3/33 (9.1%)
Without distal leg perfusion cannula (no.)	25/108 (23.1%)
Leg fasciotomy (no.)	13/141 (9.2%)
With distal leg perfusion cannula (no.)	1/33 (3.0%)
Without distal leg perfusion cannula (no.)	12/108 (11.1%)
Gastrointestinal complication (no.)	97 (18.8%)
Laparotomy (no.)	28 (5.4%)
Cerebrovascular events	
Total (no.)	90 (17.4%)
Cerebral bleeding (no.)	19 (3.7%)
Cerebral stroke (no.)	28 (5.4%)
New atrial fibrillation (no.)	103 (19.9%)

ECMO, Extracorporeal membrane oxygenation; IABP, intra-aortic balloon pump.

We also demonstrated that the underlying cardiac disease and the corresponding cardiac procedure had significant effects on hospital survival after ECMO for PCS. One important finding was that isolated CABG had the best prognosis of all operative procedures, with an in-hospital survival of 44%. Internal thoracic artery use provided supplementary protection. This is consistent with the findings of Magovern and Simpson,⁸ who demonstrated increased survival for patients with ECMO after isolated CABG. In contrast to CABG, we found that patients with mitral valve surgery had a significantly worse prognosis after ECMO implantation. Moreover, there was a clear trend for aortic arch surgery (5.9% survival) and pericardiectomy (no survival) to be associated with bad prognosis, probably because of intractable bleeding complications from the large wound surface. It would be of utmost interest to know a critical combination of underlying diseases or surgical procedure that makes risk of ECMO implantation prohibitively high.

FIGURE 1. Cumulative survival curve indicating freedom from death of any cause after extracorporeal membrane oxygenation implantation for postcardiotomy cardiogenic shock. Mean follow-ups were 0.82 years for all patients and 3.2 years for hospital survivors.

We cannot recommend absolute refusal ECMO in any particular case; however, our results demonstrate that prognosis for patients with ECMO after type A dissection, constrictive pericarditis, or double-valve disease is extremely limited.

ECMO Management

On the basis of our results, implementation of ECMO should be considered early in the face of cardiac pump failure. If a general decision for ECMO support is made, it is reasonable not to wait until secondary organ damage, resuscitation, or profound metabolic acidosis has occurred.

There was no advantage of a central arterial cannulation site relative to a peripheral site or to an axillary artery approach relative to a femoral artery approach. In contrast, percutaneous femoral vein drainage was associated with a worse prognosis and may be a surrogate for suboptimal venous drainage and compromised ECMO flow. Like others, we found that any ECMO revision was associated with poor prognosis.¹⁴

We also found no difference between simultaneous and secondary ECMO implantations. Among cases of secondary indications, however, nonsurvivors had a significant longer interval between primary cardiac surgery and ECMO implantation. This group represents more patients with sudden cardiac death receiving ECMO as a last resort, with comparably worse prognosis.

ECMO Predictors for In-Hospital Death

Like others, we found several significant predictors for in-hospital mortality during ECMO support, including acute liver and renal failure.⁴ Findings of persistent anaerobic metabolism after 24 and 48 hours of ECMO support, as

measured by persistent high lactate values, were the strongest predictors for mortality. On the basis of these findings, we recently started to use bicarbonate dialysis in the very early post-ECMO period to prevent severe metabolic acidosis when ECMO flow was appropriate.

AMI was a common finding among patients undergoing ECMO and was associated with poor outcome. This is in accordance with Zhang and colleagues,¹⁰ who demonstrated a strong relationship between creatine kinase MB release during ECMO and in-hospital mortality. In contrast to our measurement, Zhang and colleagues¹⁰ used the ratio of creatine MB to total creatine kinase.

Complication Rate

ECMO was associated with significant morbidity. Leg ischemia occurred in our series in a total of 5.4% patients, and in 19.9% of legs with femoral artery ECMO cannulation. This is comparable with limb ischemia rates reported by others.^{1,4} We found that the use of a distal leg perfusion cannula reduced leg ischemia and fasciotomy to less than 40%, and we therefore recommend this whenever the femoral artery is used for ECMO implantation.

Despite the administration of antifibrinolytic agents, selective coagulation factors, and blood product transfusions, postoperative bleeding was among the major problems in postoperative ECMO care. Reasons for excessive bleeding in these patients included the surgical trauma, thrombocytopenia, activation of leucocytes, and anticoagulation treatment. Excessive bleeding led to rethoracotomy in more than half of the patients. Mean perioperative red blood cell transfusion rate was 13 units/patient during the first 48 hours of ECMO support. Golding and coworkers¹⁵ reported a mean transfusion rate of 53.2 packed red blood cell units/patient and a rethoracotomy rate of 87.3% among 91 patients undergoing ECMO. In other studies of ECMO for PCS, rethoracotomy for bleeding was required in 40.0% and 53.2% of patients, respectively.^{4,16}

Cerebrovascular events occurred in 17.4% of all our patients. Smedira and colleagues¹ reported that 33% of 202 patients had significant neurologic injury. In previous studies, others found neurologic complications among 10.0% to 16.0% of adult patients undergoing ECMO^{4,15,16}; however, we demonstrated by autopsy studies that 51.9% of all cerebral pathologic conditions in patients undergoing ECMO were clinically undetected.¹² Even if it is difficult to assign the cerebral event to the operative procedure, the critical pre-ECMO circulatory state, or the ECMO run itself, the overall risk of neurologic events must be kept in mind and should lead to morphologic diagnostic evaluation before further major therapy is considered.

Follow-up

Despite the high in-hospital mortality, we should keep in mind that the overall long-term survival of patients after

ECMO for PCS is comparable to data known from lung cancer. Recently, a Finnish group demonstrated an overall 5-year survival with lung cancer of 12% in 602 patients of comparable age.¹⁷ The long-term-survival of hospital survivors after ECMO for PCS is good, however, demonstrating that the early mortality is the Achilles heel in ECMO therapy. We found a 56% 5-year survival for hospital survivors. These data are comparable to the Cleveland Clinic experience with an unselected ECMO population, in which patients surviving 30 days had a 63% chance of being alive after 5 years.¹ Smith and colleagues¹⁸ from Melbourne also found an excellent long-term survival and satisfactory quality of life in an older population of hospital survivors after ECMO. The finding regarding quality of life was recently confirmed by detailed measurements of mental health and vitality in 28 long-term survivors after ECMO.¹⁸

Limitations

Even though the data collection was performed prospectively, this study is subject to all limitations inherent in a non-randomized study.

CONCLUSIONS

This study was performed to analyze the outcome of temporary ECMO support for the indication of PCS. In this series, overall hospital survival was 24.8%. Patients with isolated CABG had the best outcome, whereas high extracardiac morbidity and profound and ECMO-resistant PCS were significant risk factors for in-hospital mortality. Because prognosis of patients undergoing ECMO for PCS depends significantly on the depth of PCS at implantation, it is wise not to wait too long when ECMO is a reasonable option.

Long-term outcome of hospital survivors was relatively good. Because of the high morbidity, however, ECMO has to be considered on the basis of individual risk profile and underlying cardiac disease. Because of the high device-related morbidity, further efforts have to be made to develop less traumatic devices, allowing fast and easy application for temporary circulatory support.¹⁹

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Discussion

Dr R. Duane Davis (Durham, NC). Dr Rastan and colleagues have reported on a large cohort of patients with PCS supported by ECMO. Not surprisingly, for this difficult group of patients, this experience featured substantial mortality and morbidity, particularly bleeding and thromboembolic complications. The hospital survival of approximately 25% is similar to numerous previous reports as well as to registry data, which are approximately in the 30% to 35% range. So their results are well within the range of what we would expect. My questions are going to be related first to technical issues, second to patient selection issues, and third to overall strategic issues.

First, Dr Rastan, you have suggested that ongoing shock, as manifested by lactate levels that are increasing or high at the beginning, is associated with worse outcomes in terms of mortality. Is this an opportunity? That is, do you have data to suggest that if you are able to increase the performance while on ECMO by increasing ECMO flow rates or improving the blood pressure that you can actually improve outcomes? From that standpoint, is there a strategy when you have ongoing higher lactate levels or shock of

altering cannula positions or other things to try to improve ECMO performance?

Dr Rastan. This is an important point. What we sometimes found in our experience is that we had some problems with the venous backflow to the ECMO system if we used femoral cannulation sites. As a consequence, this was one of the main reasons for ECMO revision. In these patients, we found an ongoing high lactate level during the first 24 hours because we had a flow of only 80% to 90% of the cardiac output. This was in a few patients an indication for reopening the chest to put in a right atrial cannulation. So in addition to bleeding, compromised ECMO flow was indeed one of the most important reasons for ongoing high lactate levels, and we could show that this was associated with extremely high mortality.

Dr Davis. Let me follow up on that. Have you changed your strategy during the years—earlier implantation, more open-chest procedures, more central cannulation—or is it still a kind of mish-mash of approaches to these patients?

Dr Rastan. Yes, we changed our policy twice. With the introduction of long venous femoral cannulas, our policy changed to close the chest and to use peripheral cannulation—axillary or femoral arterial cannulation—to reduce bleeding complications. In our experience, however, some of these patients had suboptimal ECMO flow, so we changed the strategy again and used thoracic cannulation more liberally to allow an optimal ECMO flow.

The latter strategy is also supported by the experience that even with peripheral cannulation and a closed chest, most of the patients required rethoracotomy because of hematoma, which compromised the cardiac function, whereas there was bleeding and a low infection rate in open-chest patients. So we think that closing the chest is not the primary goal for every patient undergoing ECMO.

Dr Davis. My second question really regards patient selection. When is the use of ECMO really going to be futile? You have shown a statistical analysis, which basically assumes a linear relationship with a number of variables, but we all know that for age, for instance, the relationship may be linear for a long time, but as you approach the 70s and 80s it actually becomes more of an exponential relationship. That is, would you put an 80-year-old patient on ECMO after dissection repair in your institution? Whom do you exclude?

Dr Rastan. This is a difficult point. Our policy was to use ECMO liberally in PCS situations. We put not all but almost all patients in PCS on ECMO. This included older patients, allowing them cardiac recovery for at least 2 to 3 days. If this failed and the cardiac failure persisted, we withdrew ECMO therapy in consensus with the families.

I think that especially in unexpected PCS, that is, for patients with primary good cardiac function or after uneventful early post-operative course, there is a good chance for cardiopulmonary recovery. This is why we do not reject implantation of ECMO even for an older patient. What we have to rethink, however, on the basis of these data is whether after complex valve or aortic procedures with a high bleeding rate we should decide to turn down ECMO or withdraw it earlier.

Dr Davis. My final question regards the appropriate strategy in 2009 or 2010 for the support of a patient after PCS? In this series, you didn't have a substantial improvement during the 12-year period. If you look at the literature, there also doesn't appear to be much of an improvement during that period. Your 6-month survival

is only 16% or 17%, which may be acceptable versus the alternative, but is that really where we should be headed? Can't we do better?

Now, this question is kind of multiphase. It has to do with some institutional bias in that we try to direct our therapy to what is failing. That is, if it is a left ventricular failure, we'll put an L-VAD in; if it is a left ventricular failure, if it is a right ventricular failure, we'll put a right VAD in; if it is just pulmonary, parenchymal, or gas exchange, then we use venovenous ECMO. We use venoarterial ECMO more along the lines of 2 or 3 failures, right ventricle, left ventricle, lung. Do you have an approximation of how many of the patients had right ventricular failure, left ventricular failure, parenchymal failure, or a combination? And are you moving away from using venoarterial ECMO to some of the other treatment modalities? You may actually have more tools in your chest than we have in the United States.

Dr Rastan. First, our data revealed an improved survival gain during the last 3 years in our institution, which I didn't show here. We all know that the survival and the success of ECMO depends heavily on patient selection. In other words, if you include unfavorable patients in your cohort and implant ECMO, you will have a bad outcome. So the results depend strongly on the indication and the selection before the ECMO implantation. As I demonstrated, we used ECMO liberally and included some very poor candidates. Surprisingly, a significant number even of these patients survived.

The reasons we preferentially used ECMO rather than other life-saving systems, especially for the postoperative indications, were that we can implant it quickly, that ECMO fits all patients, and that ECMO covers both right and left ventricular as well as pulmonary failure, which sometimes is difficult to distinguish in an emergency situation. I agree with you that if you can fix left ventricular failure, maybe a centrifugal pump just for support of the left ventricle might be the better option to reduce systemic inflammatory response syndrome or the high bleeding rate. This is difficult to fix in

an individual situation or under resuscitation, however, so our policy is to use ECMO more often than isolated centrifugal pumps.

Not surprisingly, we found left ventricular failure in most of our patients. For patients with right ventricular failure, we had the experience that cardiac recovery was more prolonged or failure more frequent. Thus patients with right heart failure had worse outcome than patients with left ventricular failure.

In a total of 15 younger patients, we implanted an L-VAD as a bridge-to-bridge therapy. To be honest, though, these data were unsatisfactory. We lost 12 of these 15 patients in the postoperative course. Maybe the concept is to fix the problem as fast as possible under ECMO and then to switch as early as possible to a more durable system if the patient is a transplantation candidate. Most of our patients were not transplantation candidates, or were poor candidates, as I could demonstrate to you. A lot of our patients had emergency or urgent indications for surgery.

Dr Davis. I guess my comment with regard to ECMO and trying to get left ventricular recovery is it is really not an unloading strategy. It is, rather, a loading strategy, and then you throw in all the thromboembolic complications that run with having essentially a membrane oxygenator and circuit, it seems to be a bit problematic. But my congratulations on an excellent presentation.

Dr Thorsten Hanke (*Lübeck, Germany*). I have a single question. There was a difference between patients in whom you implanted the ECMO early in the operating room and those in whom you did it after 2 or 3 days. Has there been a difference in the outcome between those patient groups?

Dr Rastan. No. Just a short answer. This was interesting, because there might be a difference in patient characteristics between patients who received ECMO because they were not able to be weaned from cardiopulmonary bypass and other patients who had primarily good or acceptable condition with an IABP and low catecholamines and then had PCS. But this event per se was not an indicator for hospital mortality in univariate analysis.

FIGURE E1. Univariate and multivariate analyses of in-hospital mortality, including 54 preoperative and 42 procedural variables. Only significant variables are demonstrated. Odds ratios are depicted with 95% confidence intervals, indicating significance when not crossing midline bar. Variables labeled with *asterisk* were also significant in multivariate logistic regression analysis. *CAD*, Coronary artery disease; *s/p*, status post; *AMI*, acute myocardial infarction; *PCI*, percutaneous coronary intervention.

TABLE E1. Extracorporeal membrane oxygenation implantation details and outcomes

Characteristic	All (n = 517)	Hospital survivors (n = 128)	Nonsurvivors (n = 389)	In-hospital mortality		
				OR	95% CI	P value
Simultaneous ECMO implantation (%)	41.9%	45.2%	40.8%	0.84	0.55–1.28	.406
Secondary ECMO implantation (%)	58.1%	54.8%	59.2%	1.20	0.78–1.83	.406
Time after primary surgery (h)	62.6	33.3	71.7			.031
Optimal time of ECMO implantation (h, mean ± SD)	111 ± 79	104 ± 70	113 ± 82			.420
Additional cardiac surgery (%)	29.7%	30.2%	29.6	0.97	0.64–1.48	.892
Arterial cannulation						
Central (%)	60.8%	62.2%	60.3%	0.91	0.59–1.40	.666
Peripheral (%)	39.2%	37.8%	39.7%	1.05	0.68–1.62	.831
Axillary (%)	11.9%	9.6%	12.6%	1.37	0.68–2.75	.378
Femoral (%)	27.3%	28.2%	27.1%	1.00	0.62–1.63	.998
Leg perfusion (% of femoral)	23.4%	29.1%	21.4%	0.65	0.23–1.78	.399
Venous cannulation*						
Central (%)	61.8%	62.6%	61.5%	0.95	0.62–1.47	.831
Femoral (%)	48.2%	40.0%	50.9%	1.55	1.01–2.38	.044
Percutaneous (%)	20.3%	13.9%	22.4%	1.79	0.99–3.21	.052
Open (%)	27.9%	26.1%	28.4%	1.13	0.70–1.81	.624
Open chest (%)	50.8%	53.9%	49.7	0.85	0.59–1.29	.435
Surgical ECMO revision (%)	12.5%	7.0%	14.4	2.24	1.03–4.89	.042
Oxygenator exchange (%)	6.9%	3.5%	8.0	2.42	0.83–7.08	.104
ECMO support						
Duration (d, mean ± SD)	3.28 ± 2.85	2.99 ± 1.93	3.38 ± 3.09			.210
>5 d (%)	20.1%	14.8%	21.8	1.61	0.91–2.86	.104

OR, Odds ratio; CI, confidence interval; ECMO, extracorporeal membrane oxygenation. *Venous central and femoral cannulations are not exclusive because of revisions for insufficient venous drainage.