Impact of Right Ventricular Performance in Patients Undergoing Extracorporeal Membrane Oxygenation Following Cardiac Surgery

ORIGINAL RESEARCH

Impact of Right Ventricular Performance in Patients Undergoing Extracorporeal Membrane Oxygenation Following Cardiac Surgery

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***Background*—**Extracorporeal membrane oxygenation following cardiac surgery safeguards end-organ oxygenation but unfavorably alters cardiac hemodynamics. Along with the detrimental effects of cardiac surgery to the right heart, this might impact outcome, particularly in patients with preexisting right ventricular (RV) dysfunction. We sought to determine the prognostic impact of RV function and to improve established risk-prediction models in this vulnerable patient cohort.

***Methods and Results*—**Of 240 patients undergoing extracorporeal membrane oxygenation support following cardiac surgery, 111 had echocardiographic examinations at our institution before implantation of extracorporeal membrane oxygenation and were thus included. Median age was 67 years (interquartile range 60-74), and 74 patients were male. During a median follow-up of 27 months (interquartile range 16-63), 75 patients died. Fifty-one patients died within 30 days, 75 during long-term follow-up (median follow-up 27 months, minimum 5 months, maximum 125 months). Metrics of RV function were the strongest predictors of outcome, even stronger than left ventricular function ($P<0.001$ for receiver operating characteristics comparisons). Specifically, RV free-wall strain was a powerful predictor univariately and after adjustment for clinical variables, Simplified Acute Physiology Score-3, tricuspid regurgitation, surgery type and duration with adjusted hazard ratios of 0.41 (95%CI 0.24-0.68; $P=0.001$) for 30-day mortality and 0.48 (95%CI 0.33-0.71; $P<0.001$) for long-term mortality for a 1-SD (SD=−6%) change in RV free-wall strain. Combined assessment of the additive EuroSCORE and RV free-wall strain improved risk classification by a net reclassification improvement of 57% for 30-day mortality ($P=0.01$) and 56% for long-term mortality ($P=0.02$) compared with the additive EuroSCORE alone.

***Conclusions*—**RV function is strongly linked to mortality, even after adjustment for baseline variables and clinical risk scores. RV performance improves established risk prediction models for short- and long-term mortality. **(*J Am Heart Assoc*. 2017;6: e005455. DOI: 10.1161/JAHA.116.005455.)**

Key Words: extracorporeal circulation • extracorporeal membrane oxygenation • right ventricle • right ventricular dysfunction • right ventricular function

Extracorporeal membrane oxygenation (ECMO) is a life-saving method for critically ill patients following cardiovascular surgery.[1] Despite growing evidence supporting the use of ECMO therapy,[2-4] outcome remains poor, and accurate risk stratification challenging: successful weaning probabilities are as low as 31% depending on the series, and in-hospital fatal events are frequent, resulting in short-term mortalities of up to 84%.[3,5-13] Prior studies have focused on

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An accompanying Figure S1 is available at http://jaha.ahajournals.org/content/6/8/e005455/DC1/embed/inline-supplementary-material-1.pdf

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Clinical Perspective

What Is New?

- Right ventricular function is a powerful predictor of mortality and improves risk stratification in patients who need veno-arterial extracorporeal membrane oxygenation after cardiovascular surgery.

What Are the Clinical Implications?

- Although left ventricular function might have only minor impact on outcome, prognosis seems limited if right ventricular performance is already affected preoperatively.
- Further studies are needed to test whether the dismal course can be improved by therapies tailored specifically to the failing right heart.

clinical variables, comorbidities, and renal function for risk stratification before ECMO initiation.[1-3,9,10,14-17] However, data on cardiac physiology and myocardial mechanics before therapy—easily assessable by echocardiography—and their predictive value are scarce.

Pre-, and postcardiotomy right ventricular (RV) dysfunction is strongly linked to outcome.[18-22] The etiology of RV failure is multifactorial: pericardiotomy results in loss of pericardial support and a decline of myocardial blood flow.[23,24] Cardiopulmonary bypass itself may cause an inflammatory response.[25] Furthermore, ECMO initiation results in rising afterload increasing left ventricular (LV) end-diastolic pressure and consequently RV pressure load.[20,26-28] In the absence of preexisting RV dysfunction, the compensatory reserve is sufficient to outbalance those stressors, resulting in a low incidence of postoperative right heart failure.[29] In patients requiring mechanical circulatory support the compensatory reserve might be exhausted, and the alteration of the hemodynamic load opposed to the heart might set in counterproductively. Metrics of RV function are powerful predictors of outcome in patients with pulmonary hypertension, valvular heart disease, patients undergoing cardiac surgery[19,30-32] as well as patients receiving LV assist devices.[33,34] Complemental imaging techniques such as speckle-tracking imaging allow detection of even subclinical changes of myocardial function and are readily available. Recent studies suggest that speckle tracking of strain more accurately quantifies RV function as opposed to traditional metrics and improves risk stratification.[35,36]

We therefore set out to investigate the prognostic significance of preoperative right heart function assessed by standard echocardiography and speckle-tracking strain imaging, a novel method better reflecting myocardial mechanics. Furthermore, we aimed to refine established risk-prediction models by implementation of RV function.

Methods

Study Population

Between September 2003 and June 2014, adult patients undergoing venoarterial ECMO therapy after cardiovascular surgery were enrolled in our registry. All patients were recruited at the Vienna General Hospital, a university-affiliated tertiary care center. The study was approved by the Ethics Committee of the Medical University of Vienna and is in line with the Declaration of Helsinki. All patients admitted to the Medical University of Vienna provided written consent at hospital admission. For the echocardiographic analysis only patients who underwent a comprehensive preoperative echocardiographic exam at our institution were selected. Patients undergoing a heart transplant were excluded from further analysis (Figure S1).

Echocardiographic Assessment

Standard echocardiograms were performed using commercially available equipment (Vivid 7 and Vivid 9, GE Healthcare, Chicago, IL; Acuson Sequoia, Siemens, Berlin, Germany). Cardiac morphology was assessed using diameters and areas as well as volumetric measurements in standard 4- and 2-chamber views.[37]

LV volumes and ejection fraction (EF) were calculated using the biplane Simpson method. RV function was quantified by fractional area change, tricuspid annular peak systolic excursion (TAPSE), and RV longitudinal free-wall strain (RVLS).[37,38] Right-to-left ventricle diameter ratio and RV contraction pressure index were calculated as previously reported.[39,40] Semiquantitative assessment of right heart function was performed by experienced readers using multiple acoustic windows and graded as normal, mild, mild to moderate, moderate, moderate to severe, and severe. Valve stenosis and regurgitation were quantified using an integrated approach and graded as none, mild, mild to moderate, moderate, moderate to severe, and severe according to current guidelines.[41,42] Systolic pulmonary artery pressures were calculated by adding the peak tricuspid regurgitation (TR) systolic gradient to the estimated central venous pressure.

Left- and Right-Ventricular Longitudinal Strain

LV and RV longitudinal shortening (strain) were measured by tracking the displacement of speckles from 2-dimensional images using an automated algorithm (Speckle tracking).[43,44] Longitudinal strain is the percentage shortening of a region of interest relative to its original length.[45] This method has been previously shown to provide angle independent and objective quantification of myocardial systolic mechanics.[37,38] LV and

RV strain were measured using commercially available software (2D Cardiac Performance Analysis; TomTec Imaging Systems, Munich, Germany) that allows standardized quantification of myocardial strain within 1 platform independently of the echo machine vendor. Files with poor frame rates (<40 fps) and inadequate image quality were excluded from the analyses. Left ventricular longitudinal strain was calculated in standard 4-, 2-, and 3-chamber views as described previously.[43] RVLS strain was assessed in a standard 4-chamber view as described previously.[44] Strain data are expressed as the percentage of systolic shortening, where negative longitudinal deformation corresponds to shortening (contraction) during systole.

ECMO Management

Venoarterial ECMO support was initiated in patients with systolic arterial hypotension (<80 mm Hg) or other clinical signs of cardiogenic shock, end-organ failure, or anaerobic metabolism despite optimized supportive therapeutic measures (fluid, inotropes, intra-aortic balloon pump). The ECMO system consisted of a pump console (Bio-Console560, Medtronic, Fridley, MN; or Cardiohelp system, Maquet, Germany) and an inline plasma-tight hollow-fiber microporous membrane oxygenator (Affinity-NTTM, Medtronic, Fridley, MN; or HLS module advanced, Maquet, Germany). All parts of the system were routinely checked every 24 hours by the on-shift intensive care physician or an experienced perfusionist. The complete system was coated with heparin to prevent clotting. If any signs of fibrin deposits or blood clots were present or if blood oxygenation levels declined drastically, the circuit was changed. Ventilator settings were adapted to ensure lung-protective ventilation with peak airway pressures below 25 cm H_2O and respiratory tidal volumes between 6 and 8 mL/kg. The fraction of inspired oxygen on the oxygenator was adjusted to maintain a target partial pressure of oxygen of 80 to 100 mm Hg.

Clinical Definitions and End Points

The Simplified Acute Physiology Score-3 was recorded; and the European System of Cardiac Operative Risk Evaluation (EuroSCORE) was assessed in every patient at intensive care unit admission. All-cause 30-day mortality was selected as primary end point, and all-cause long-term mortality was defined as death occurring throughout the entire follow-up duration of a median of 27 months (minimum 5 months, maximum 125 months) as a secondary end point. Mortality data were obtained by screening the national registry of deaths including screening for the cause of death (according to the International Classification of Diseases, 10th Revision).

Statistical Methods

Discrete data were presented as count and percentage and analyzed by using chi-squared tests. Continuous data were presented as median and interquartile range (IQR) and compared using Kruskal-Wallis tests. Cox proportional hazard regression analysis was applied to assess the effect of the respective echocardiographic parameters on survival. Results were expressed as the hazard ratio (HR) for a 1-SD change with the respective 95%CIs. To account for potential confounders, we adjusted for age, sex, Simplified Acute Physiology Score-3, TR, type of cardiovascular surgery, and procedure duration. Statistical significance was given if 2-sided $P<0.05$. Kaplan-Meier analysis was applied to evaluate the effect of RV free-wall strain and TAPSE on survival and compared them using a log-rank test. The respective variables were divided into 2 groups using the median of the respective variable as a cutoff value. The discriminatory power of the respective variables was assessed using receiver operating characteristic analysis and Harrell C-statistic. Receiver operating characteristic analysis was used to assess the predictive accuracy of the parameters to predict short- and long-term survival. An improvement in individual risk prediction was examined by the net reclassification improvement. Intraobserver, and interobserver variability for RVLS and TAPSE were assessed in 20 randomly selected patients. Interobserver agreement and intraobserver consistency were presented by using interclass correlation coefficients and a 95%CI. All statistical analyses were computed using the STATA11 software package and SPSS 23.

Results

General Characteristics

Between September 2003 and June 2014, we included 240 consecutive patients undergoing venoarterial ECMO support following cardiovascular surgery as previously described.[14-16] Of these, 51 patients underwent cardiac transplantation and were therefore not eligible for study inclusion. A total of 111 patients had preoperative echocardiographic exams at our institution before ECMO therapy and were therefore included in our analysis (Figure S1). The median EuroSCORE of the echocardiographic study population was 11 points (8-13), and the median age was 67 years (IQR 60-74), respectively. Detailed baseline characteristics for the entire study population as well as the echocardiographic study population are displayed in Table 1. Valve surgery was performed in 44 (40%) patients, coronary artery bypass graft surgery in 14 (13%), combined coronary artery bypass graft and valve surgery in 36 (32%), ventricular assist device implantation in 8 (7%), aortic reconstruction in 3 (3%), and other cardiovascular surgeries in 6 (5%) patients. Patients undergoing isolated

Table 1. Baseline Characteristics of the Total ECMO Study Population (n=240) and the Echocardiographic Substudy Population (n=111)

Baseline Characteristics at Hospital Admission	Total Study (n=240)	Echocardiographic Study Population (n=111)
Age, y (IQR)	65 (55-72)	67 (60-74)
Body-mass index, n (IQR)	27 (24-30)	27 (24-31)
Male sex, n (%)	172 (72)	74 (67)
EuroSCORE (additive), points (IQR)	10 (8-13)	11 (8-13)
Procedure duration, h (IQR)	8.0 (6.1-9.4)	7.2 (5.3-9.3)
Hypertension, n (%)	169 (70)	83 (75)
Diabetes mellitus, n (%)	66 (28)	37 (33)
Hypercholesterolemia, n (%)	125 (52)	60 (54)
Coronary artery disease, n (%)	124 (52)	58 (52)
Glucose, mg/dL (IQR)	109 (92-142)	112 (93-148)
Total cholesterol, mg/dL (IQR)	143 (104-182)	146 (105-182)
Triglycerides, mg/dL (IQR)	109 (81-156)	111 (74-172)
Creatinine, mg/dL (IQR)	1.3 (1.1-1.8)	1.3 (1.0-1.9)
Estimated GFR, mL/min per 1.73 m^2 (IQR)	51 (39-69)	49 (36-70)
Total bilirubin, mg/dL (IQR)	1.1 (0.6-1.6)	0.9 (0.6-1.4)
ASAT, U/L (IQR)	33 (23-67)	34 (25-56)
ALAT, U/L (IQR)	33 (23-67)	26 (18-40)
γ-GT, U/L (IQR)	54 (32-105)	54 (29-102)
Hemoglobin, mg/dL (IQR)	12.0 (10.1-13.6)	11.2 (9.9-13.0)
Platelets, 1000/μL (IQR)	188 (134-241)	186 (136-243)
C-reactive protein, mg/dL (IQR)	1.0 (0.3-4.3)	1.3 (0.3-7.6)
Leukocytes, 1000/μL (IQR)	8.0 (6.1-11.1)	8.2 (6.0-12.1)
Post-ECMO implantation (first 24 h)		
SAPS-3 at ICU admission, n (%)	43 (36-51)	43 (36-51)
ECMO flow, L/min (IQR)	3.4 (2.5-4.3)	3.0 (2.5-4.0)
ECMO rotation, rpm (IQR)	3000 (2485-3500)	2740 (2270-3420)
ECMO gas flow, L/min (IQR)	2.5 (2.0-3.0)	2.0 (2.0-3.0)
ECMO FiO_2, % (IQR)	70 (60-100)	68 (60-80)
ECMO duration, median days (IQR)	4 (3-7)	5 (2-7)

Counts are given as numbers and percentages. Continuous variables are given as median and interquartile range. ALAT indicates alanine aminotransferase; ASAT, aspartate aminotransferase; ECMO, extracorporeal membrane oxygenation; FiO_2, fraction of inspired oxygen; GFR, glomerular filtration rate; γ-GT, γ-glutamyl transferase; IQR, interquartile range; SAPS-3, simplified acute physiology score 3.

valve procedures had single-valve procedures done in 52%, 2-valve procedures in 32%, and 3-valve procedures in 16% of the cases. In patients undergoing valve and CABG, single-valve procedures were done in 69%, 2-valve procedures in 22%, and 3-valve procedures in 8% of the cases. ECMO cannulation was femoral (arterial)-femoral (venous) in 47% of patients, subclavian (arterial)-femoral (venous) in 39% of patients, and central (arterial)-femoral (venous) in 14% of patients. ECMO support was initiated due to weaning failure from cardiopulmonary bypass (60%), immediate postoperative cardiogenic shock in the operating room (26%), postoperative bleeding/tamponade with cardiogenic shock (7%), immediate postoperative respiratory failure in the operating room (3%), and miscellaneous conditions (4%). Of the 111 patients included in this analysis, 95 (86%) were (primarily) successfully weaned from VA-ECMO, and 16 (14%) died on VA-ECMO support. Fifty-one (46%) patients died within 30 days after VA-ECMO implantation, and 75 (68%) during long-term follow-up.

Preoperative Echocardiographic Assessment of the RV

Median RV diameter measured 35 mm (IQR 30-42 mm), and the RV end-diastolic area was 19 cm^2 (IQR 14-24 cm^2). The median systolic pulmonary pressure was estimated as 56 mm Hg (IQR 41-64 mm Hg). RV function was assessed semiquantitatively and using TAPSE (15 mm, IQR 11-18 mm), fractional area change (35%, IQR 27% to 42%), and RV free-wall strain (−14%, IQR −11% to −20%). Detailed results of the echocardiographic subanalysis are presented in Table 2. RV free-wall strain demonstrated good reproducibility with an interclass correlation coefficient for intraobserver variability of 0.98 (95%CI 0.95-0.99) and for interobserver variability of 0.98 (95%CI 0.94-0.99). Comparable results were observed for TAPSE (intraobserver 0.98, 95%CI 0.95-0.99; interobserver 0.97, 95%CI 0.93-0.99).

Table 2. Echocardiographic Characteristics of the Substudy Population (n=111)

	Echocardiographic Study Population (n=111)
Left atrial/ventricular parameters	
LA diameter, mm (IQR)	60 (55-68)
IVS thickness, mm (IQR)	14 (12-16)
LVEDD, mm (IQR)	46 (43-54)
LVEDV, mL (IQR)	125 (84-161)
LVESV, mL (IQR)	58 (38-95)
EF, % (IQR)	48 (37-55)
LV function (semiquantitative)	
Moderately reduced, n (%)	10 (9)
Severely reduced, n (%)	18 (16)
LV global longitudinal strain, % (IQR)	−12 (−9 to −15)
Aortic stenosis (≥moderate), n (%)	31 (28)
Aortic regurgitation (≥moderate), n (%)	19 (15)
Mitral stenosis (≥moderate), n (%)	7 (5)
Mitral regurgitation (≥moderate), n (%)	51 (40)
Right atrial/ventricular parameters	
RA diameter, mm (IQR)	58 (52-67)
RVEDD, mm (IQR)	35 (30-42)
RVEDA, cm^2 (IQR)	19 (14-24)
RVSA, cm^2 (IQR)	12 (9-16)
RV-LV diameter ratio, n (IQR)	0.71 (0.64-0.81)
RVCPI, mm×mm Hg (IQR)	501 (348-700)
FAC, % (IQR)	35 (27-42)
RV function (semiquantitative)	
Moderately reduced, n (%)	28 (25)
Severely reduced, n (%)	17 (15)
TAPSE, mm (IQR)	15 (11-18)
RV free-wall longitudinal strain, % (IQR)	−14 (−11 to −20)
sPAP, mm Hg (IQR)	56 (41-64)
Tricuspid regurgitation (≥moderate), n (%)	43 (39)

FAC indicates fractional area change; IQR, interquartile range; IVS, interventricular septum; LA, left atrium; LV, left ventricle; LVEDD, left ventricular end-diastolic diameter; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; RA, right atrium; RV, right ventricular; RVCPI, right ventricular contraction pressure index; RVEDA, right ventricle end-diastolic area; RVEDD, right ventricular end-diastolic diameter; RVSA, right ventricular systolic area; sPAP, systolic pulmonary artery pressure; TAPSE, tricuspid annular plane systolic excursion.

RV Function and Outcome

During a median follow-up time of 27 months (IQR 16-63 months), 75 patients (68%) died. RV function assessed semiquantitatively by TAPSE and by RVLS were significantly associated with 30-day as well as long-term mortality (Tables 3 and 4). The strongest association was found for RVLS with a crude HR of 0.44 (95%CI 0.30-0.66; $P<0.001$) for 30-day mortality and of a HR of 0.50 (95%CI 0.36-0.69; $P<0.001$) for long-term mortality. The area under the curve (AUC) for 30-day mortality was 0.76 for RV free-wall strain, 0.75 for TAPSE, and 0.73 for semiquantitative assessment of RV function and remained persistent for long-term mortality with AUCs of 0.74, 0.72, and 0.68, respectively. AUCs for RV free-wall strain indicated significantly stronger risk prediction for 30-day and long-term mortality compared with metrics of LV function ($P<0.001$ for RV free-wall strain AUCs and LV ejection fraction (LVEF) for both 30-day and long-term mortality, $P<0.001$ for RV free-wall strain AUCs and left ventricular GLS (global longitudinal strain) for 30-day mortality and $P<0.01$ for long-term mortality). The effect was even more pronounced after multivariate adjustment with an adjusted HR of 0.41 (95%CI 0.24-0.68; $P=0.001$) for 30-day mortality and of a HR of 0.48 (95%CI 0.33-0.71; $P<0.001$) for long-term mortality. Kaplan-Meier analysis confirmed a significant increase of mortality with decreasing RVLS (30-day $P=0.001$; Figure Panel A; long-term $P=0.001$) and decreasing TAPSE (30-day $P<0.001$; Figure Panel B; long-term $P<0.001$). No association between mortality and parameters of LV function including LV longitudinal strain were observed (Tables 3 and 4).

RV Free-Wall Longitudinal Strain and Risk Prediction

Combined assessment of the additive EuroSCORE and RV free-wall strain led to a substantial improvement of the discriminatory power measured by the Harrel C-statistic of the EuroSCORE for 30-day mortality (EuroSCORE: 0.59 versus EuroSCORE and RV free-wall strain 0.71; $P=0.03$) and for long-term mortality (EuroSCORE: 0.59 versus EuroSCORE +

Table 3. Univariable Cox Proportional Hazard Model of Preoperative Echocardiographic Parameters

		30-Day Mortality			Long-Term Mortality		
	SD	HR (95%CI)	*P* Value	AUC	HR (95%CI)	*P* Value	AUC
LVEDV, mL	57	0.84 (0.59-1.20)	0.34	0.59	0.88 (0.66-1.17)	0.37	0.55
LV function	···	0.84 (0.67-1.05)	0.13	0.59	0.92 (0.77-1.11)	0.40	0.52
EF, %	13	1.37 (0.98-1.92)	0.06	0.60	1.19 (0.92-1.55)	0.19	0.55
LV global longitudinal strain, %	−5	1.21 (0.88-1.66)	0.25	0.61	1.01 (0.81-1.40)	0.64	0.51
RVEDA, cm^2	9	0.88 (0.60-1.28)	0.50	0.54	0.88 (0.66-1.18)	0.39	0.55
RV-LV diameter ratio, n (IQR)	0.23	1.01 (0.82-1.39)	0.63	0.55	0.78 (0.49-1.25)	0.31	0.53
RVCPI, mm×mm Hg (IQR)	310	0.78 (0.49-1.25)	0.31	0.60	0.76 (0.53-1.10)	0.16	0.56
FAC, %	10	0.77 (0.53-1.10)	0.15	0.60	0.82 (0.61-1.10)	0.18	0.57
RV function	···	1.60 (1.25-2.04)	<0.001	0.73	1.49 (1.22-1.83)	<0.001	0.68
TAPSE, mm	5	0.51 (0.35-0.73)	<0.001	0.75	0.54 (0.40-0.72)	<0.001	0.72
RV free-wall strain, %	−6	0.44 (0.30-0.66)	<0.001	0.76	0.50 (0.36-0.69)	<0.001	0.74
sPAP, mm Hg	19	1.27 (0.94-1.72)	0.12	0.59	1.27 (0.97-1.68)	0.09	0.64

Hazard ratios (HR) refer to a 1-SD increase/decrease in continuous variables and to a reduction in 1 category of left ventricular/right ventricular function. Additionally, receiver operating characteristics for the respective values are presented. AUC indicates area under the curve; EF, left ventricular ejection fraction; FAC, fractional area change; IQR, interquartile range; LV, left ventricular; LVEDV, left ventricular end-diastolic diameter; RV, right ventricular function; RVCPI, right ventricular contraction pressure index; RVEDA, right-ventricular end-diastolic area; sPAP, estimated systolic pulmonary artery pressure; TAPSE, tricuspid annular plane systolic excursion.

RV free-wall strain 0.70; *P*=0.03). Simultaneous Cox proportional hazards model yielded a crude HR of 0.46 (95%CI 0.31-0.69, *P*<0.001; adjusted HR 0.42, 95%CI 0.25-0.69, *P*=0.001) for RV-free-wall strain and a crude HR of 1.06 (95%CI 0.74-1.53, *P*=0.75; adjusted HR 0.79, 95%CI 0.44-1.42, *P*=0.43) for the EuroSCORE for 30-day mortality. For long-term mortality, we observed a crude HR of 0.51 (95%CI 0.36-0.71, *P*<0.001; adjusted HR 0.48, 95%CI 0.33-0.71, *P*<0.001) for RV-free-wall strain and a HR of 1.19 (95%CI 0.90-1.57, *P*=0.23; adjusted HR 0.90, 95%CI 0.59-1.36, *P*=0.61) for the EuroSCORE for

Table 4. Multivariate Cox Proportional Hazard Model of Preoperative Echocardiographic Parameters

		30-Day Mortality		Long-Term Mortality	
	SD	Adjusted HR (95%CI)	*P* Value	Adjusted HR (95%CI)	*P* Value
LVEDV, mL	57	1.09 (0.68-1.74)	0.74	0.72 (0.63-1.37)	0.93
LV function	···	0.80 (0.58-1.12)	0.17	0.81 (0.62-1.04)	0.10
EF, %	13	1.58 (0.98-2.55)	0.06	1.35 (0.92-1.98)	0.13
LV global longitudinal strain, %	−5	1.44 (0.87-2.39)	0.16	1.24 (0.82-1.87)	0.31
RVEDA, cm^2	9	0.93 (0.79-0.93)	0.79	0.84 (0.57-1.25)	0.82
RV-LV diameter ratio, n (IQR)	0.23	1.02 (0.75-1.02)	0.89	1.29 (0.43-3.81)	0.65
RVCPI, mm×mm Hg (IQR)	310	0.96 (0.55-1.57)	0.87	0.82 (0.55-1.23)	0.34
FAC, %	10	0.85 (0.55-1.31)	0.46	0.56 (0.62-1.30)	0.56
RV function	···	1.51 (1.21-2.03)	0.007	1.64 (1.26-2.13)	<0.001
TAPSE, mm	5	0.56 (0.36-0.86)	0.008	0.51 (0.34-0.75)	0.001
RV free-wall longitudinal strain, %	−6	0.41 (0.24-0.68)	0.001	0.48 (0.33-0.71)	<0.001
sPAP, mm Hg	19	1.25 (0.86-1.81)	0.25	1.20 (0.89-1.68)	0.29

Hazard ratios (HR) refer to a 1-SD increase/decrease in continuous variables and to a reduction in 1 category of left ventricular/right ventricular function. HRs are adjusted for all variables in the clinical confounder model, ie, age, sex, SAPS-3 score, tricuspid regurgitation, type of cardiovascular surgery, and procedure duration. EF indicates left ventricular ejection fraction; FAC, fractional area change; IQR, interquartile range; LV, left ventricular; LVEDV, left ventricular end-diastolic diameter; RV, right ventricular function; RVCPI, right ventricular contraction pressure index; RVEDA, right-ventricular end-diastolic area; SAPS-3, simplified acute physiology score-3; sPAP, estimated systolic pulmonary artery pressure; TAPSE, tricuspid annular plane systolic excursion.

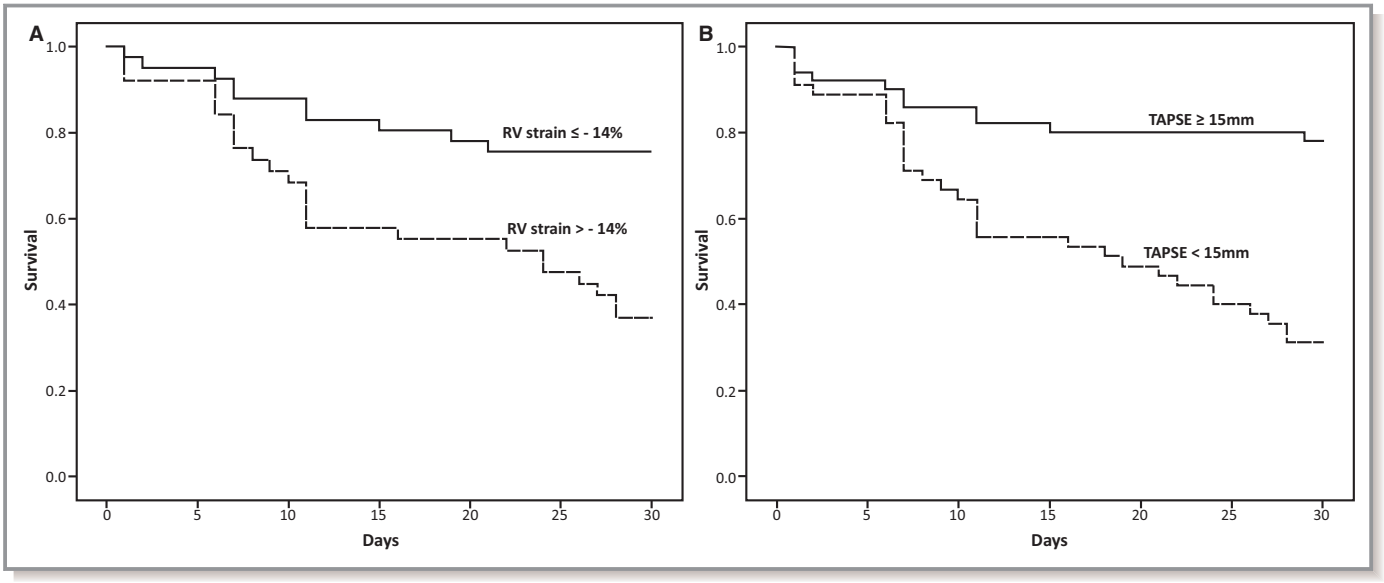

Figure. Kaplan-Meier estimates of 30-day mortality according to right ventricular (RV) free-wall strain (A, P=0.001) and tricuspid annular plane systolic excursion (TAPSE) (B, P<0.001).

long-term mortality. Furthermore, an improvement in individual risk stratification with combined assessment of the additive EuroSCORE and RV free-wall strain with a net reclassification improvement of 57% for 30-day mortality (P=0.01) and 56% for long-term mortality (P=0.02) were observed.

Discussion

In this study we show the vital importance of RV function in patients undergoing ECMO support following cardiovascular surgery. Metrics of RV function are strong predictors of short-term and long-term mortality in this vulnerable patient population. These strong associations persist even after adjustment for baseline clinical variables, surgical or ICU admission scores, and careful consideration of confounders, eg, severity of TR and type of surgery. Furthermore, surrogates of RV function improve established risk prediction models reflected by a substantial improvement of the discriminatory power and individual risk stratification for both short-term and long-term mortality.

Prognostic Value of LV Morphology and Function

The prognostic importance of LVEF before cardiac surgical procedures has been shown in several studies for a variety of cardiac diseases and has therefore been incorporated in risk stratification tools such as the EuroSCORE.[46] Thus, several studies have investigated the impact of LV function before ECMO initiation on outcome. Most recently only 1[17] out of 4 studies[2,8,9] that investigated EF before postcardiotomy ECMO initiation found a significant difference in EF between survivors and nonsurvivors. Interestingly, in this study, the predominant surgical procedure before ECMO initiation was isolated coronary artery bypass graft surgery as opposed to others where valve procedures were more prevalent. A major limitation of EF is the diversity of pathologies that influence this parameter. It grossly underestimates the extent of myocardial impairment, particularly in patients with concomitant left-sided regurgitant valve lesions. Indeed, for a given contractility a significantly increased preload and reduced afterload (a common finding in mitral and aortic regurgitation) will yield a normal-appearing EF despite intrinsic myocardial damage, dysfunction, and reduced output.[47,48] The heterogeneity of the cohort in the present and other studies therefore makes it almost impossible to predict outcomes by preoperative EFs. Furthermore, the sample size in the study by Hsu et al was relatively small (n=51), and the regression analysis was adjusted only for the chronic heart failure stage and preoperative hypotension. Rastan and co-workers also detected no difference in EF between survivors and nonsurvivors in a large cohort (n=517) of patients who were in need of ECMO after cardiac surgery.[2] Other contemporary studies that investigated precardiotomy EF as a predictor of outcome were underpowered and lacked multivariable regression analyses.[8,9,17] A probable limitation of the EF is its operator dependency and mistakes due to endocardial delineation errors. We therefore also investigated a new index of LV function—peak systolic LV strain—measured by an automated speckle-tracking algorithm, which previously has been shown to be a more sensitive marker of intrinsic myocardial dysfunction, albeit subject to similar limitations as EF such as

load dependence.[43,49] Accordingly, we also found the LV longitudinal strain to be an insignificant predictor of outcome in this subset of patients. Venoarterial ECMO support ultimately is an intervention to maintain end-organ perfusion, and the ECMO initiation should not be withheld from patients based on preoperative LV dysfunction.

Prognostic Value of RV Function

RV function may be impaired in a variety of cardiovascular and pulmonary disease states with chronic left-sided heart failure being the most common.[50,51] Both pathophysiological and prognostic significance of the right heart and pulmonary circulation have been underestimated in the past but more recently have been recognized to be of crucial prognostic significance.[52] The same is true in postcardiotomy ECMO support: although preoperative LV function has been studied extensively, the role of RV function and pulmonary circulation remains unknown. The incidence of right heart failure following cardiotomy is relatively low, ranging from 0.04% to 1% depending on the study.[29] However, with more heterogeneous cohorts, a relative increase can be observed. In particular, recipients of LV assist devices are susceptible to refractory right heart failure, which occurs in up to 30%.[29] Similar hemodynamic concepts apply to patients receiving ECMO support after pericardiotomy: altered interventricular balance introduces a hemodynamic load shift toward the pulmonary circulation and the right heart. We show—for the first time—a high incidence of RV impairment in this vulnerable patient cohort and its prognostic significance. Of note, metrics of RV function were strong predictors of outcome, univariate and after comprehensive adjustment for clinical variables and confounders. The major advantage of RV strain and TAPSE, as opposed to fractional area change is that they purely reflect the RV function without integrating the interventricular septum. Furthermore, there is less likelihood of endocardial delineation error, a common source of error in volumetric or area measurements. Anatomic features, eg, prominent trabeculation of the right heart, add complexity to endocardial border delineation. TAPSE is a powerful, fast, and easily obtainable measurement. However, a major limitation of this measure is that it is obtained at only 1 single region of interest—the lateral tricuspid annulus. In contrast, RV strain tracks speckles throughout the entire lateral wall of the right heart, reflecting more specifically the myocardial fiber contractility. Our results suggest that ideally RVLS should be used to predict outcome and improve currently established risk prediction model scores. However, given the limitations of nonavailability of speckle-tracking software in some hospitals and the lack of standardization between vendors, alternative surrogate markers of RV function such as TAPSE, semiquantitative assessment by an experienced reader, or an integrated approach seem to be valid alternatives to estimate RV function and enhance risk stratification.

We also investigated more experimental metrics of RV function that have shown to be predictive in mechanical circulatory support patients. We calculated the RV contraction pressure index as a surrogate for the RV stroke-work index and the RV to LV diameter ratio. Those parameters were not significantly predictive of outcome. The major limitations of the calculated values are their susceptibility to measurement errors. Ratios introduce an additional possible error by combining 1 or more measurements. This might particularly bias the RV to LV diameter ratio as well as area measurements of the right heart. The right heart is a complex 3-dimensional structure, and a single diameter might not adequately reflect the size. The estimated pulmonary pressures from the tricuspid regurgitation velocities that are incorporated into the RV contraction pressure index to estimate RV stroke-work index might bias this particular measurement because they are dependent on right heart function and on the gradient between the RV and the right atrium, which might lead to gross underestimations of systolic pulmonary pressures and hence bias of the calculated measurements.

The presence of TR may mask reduced RV function just as mitral regurgitation may mask reduced LV performance. Indeed, significant TR was highly prevalent in this series (TR $\geq$moderate in 39% of the patients). Kammerlander and coworkers recently proved that there was no significant association between TR and outcome in a prospective cohort late after left-sided heart valve surgery and pointed out the prognostic importance of RV function.[53] Similarly, in the present study, TR is rather a consequence of RV dysfunction and increased afterload than the primary culprit.

In this series we show the crucial role of RV function in patients receiving ECMO support after pericardiotomy. Our data indicate that patients in need of ECMO after pericardiotomy have a limited prognosis if RV function is already impaired preoperatively. Whether the dismal clinical course can be altered by specific interventions remains to be demonstrated. Potential strategies to alleviate the impact of reduced RV function on outcome might include (1) avoiding open heart surgery—eg, showing a preference for minimally invasive/transcatheter approaches; (2) optimizing inotropic treatment[54]; (3) use of pulmonary vasodilators; (4) early use of biventricular assist devices; and (5) prompt evaluation of candidates for high-urgency heart transplant.

Strengths and Limitations

Echocardiographic data were available for only a relatively small subset of patients. However, there were no significant differences in baseline characteristics between patients who

underwent comprehensive exams at our institution before ECMO therapy and those with extramural reports, and so far, this is the first study with thorough analyses of biventricular morphology and function in patients subsequently receiving ECMO support. Although comparable mortality rates suggest similar morbidity, we cannot rule out some degree of selection bias. There is always an element of inter- and intraobserver variability, but we demonstrate it to be within an acceptable range given the presence of experienced readers.

Conclusions

In this series of patients on ECMO support, RV function before cardiac surgery is a strong and independent predictor of both short-term and long-term mortality. The results suggest that RV function assessed by echocardiography improves the predictive power of the currently used risk prediction models. Finally, peak systolic strain of the lateral RV free-wall might best reflect intrinsic RV contractile fiber dysfunction, but TAPSE or semiquantitative assessment by experienced readers might be valid alternatives if speckle-tracking software is not available. Further studies are needed to assess the possible treatment strategies to support the right heart in patients in need of ECMO support.

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Disclosures

None.

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SUPPLEMENTAL MATERIAL

Figure S1. Flow diagram. Of 240 patients who received a VA-ECMO after cardiotomy at the Vienna General Hospital, 56 were excluded because they underwent cardiac transplantation. In the remaining cohort of 189 patients echo images were available in 111 patients.