Clinical Investigation

Comparative Analysis of Established Risk Scores and Novel Hemodynamic Metrics in Predicting Right Ventricular Failure in Left Ventricular Assist Device Patients

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ABSTRACT

Background: Right ventricular failure (RVF) portends poor outcomes after left ventricular assist device (LVAD) implantation. Although numerous RVF predictive models have been developed, there are few independent comparative analyses of these risk models.

Methods and Results: RVF was defined as use of inotropes for >14 days, inhaled pulmonary vasodilators for >48 hours or unplanned right ventricular mechanical support postoperatively during the index hospitalization. Risk models were evaluated for the primary outcome of RVF by means of logistic regression and receiver operating characteristic curves. Among 93 LVAD patients with complete data from 2011 to 2016, the Michigan RVF score (C = 0.74 [95% CI 0.61−0.87]; $P = .0004$) was the only risk model to demonstrate significant discrimination for RVF, compared with newer risk scores (Utah, Pitt, EuroMACS). Among individual hemodynamic/echocardiographic metrics, preoperative right ventricular dysfunction (C = 0.72 [95% CI 0.58−0.85]; $P = .0022$) also demonstrated significant discrimination of RVF. The Michigan RVF score was also the best predictor of in-hospital mortality (C = 0.67 [95% CI 0.52−0.83]; $P = .0319$) and 3-year survival (Kaplan-Meier log-rank 0.0135).

Conclusions: In external validation analysis, the more established Michigan RVF score—which emphasizes preoperative hemodynamic instability and target end-organ dysfunction—performed best, albeit modestly, in predicting RVF and demonstrated association with in-hospital and long-term mortality. (*J Cardiac Fail 2019;25:620−628*)

Key Words: Right heart failure, prediction models, mechanical circulatory support, preoperative end-organ dysfunction.

Left ventricular assist devices (LVADs) have become an important cornerstone in the management of advanced heart failure (HF) patients. These devices have alleviated the unacceptable mortality that was previously observed in advanced HF, particularly in those waiting on the heart transplant list.[1] Despite the widespread adoption and success of LVADs for bridge-to-transplant or destination-therapy (DT) indications, several attendant complications continue to limit the efficacy of LVADs.[2,3] The prevention and management of certain complications, such as bleeding, hemolysis, stroke, and driveline infections, have fortunately improved, particularly with the newer generation LVADs.[4−7] Conversely, postoperative right ventricular failure (RVF) has persisted as a perennial challenge to LVAD success. RVF in the postoperative period is not only difficult to predict but is also a management conundrum. In the current era of continuous-flow LVADs, RVF affects ∼15%−40% of LVAD implants.[8−15] It is an ominous and often

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intractable complication that is highly associated with increased mortality and morbidity.[8,16,17]

The pathophysiology of RVF after LVAD implantation is complex and heterogeneous, thus making risk stratification and prediction a challenging task.[17] Accordingly, numerous preoperative factors have been studied and several models developed in an effort to predict postoperative RVF.[13,18–22] More recently, several advanced hemodynamic metrics and echocardiographic findings have also been explored as predictors of RVF.[14,23–26] Despite the ubiquity of RVF predictors and scores, there have been few independent comparative analyses of these models in the modern era of continuous-flow LVADs.[27,28] We therefore performed a comparative analysis of commonly used RVF predictive models in our cohort of LVAD patients undergoing primary implants.

Methods

Study Design and Patient Cohort

Patients implanted with LVADs at a single academic center (University of Virginia Health System) from March 2011 through September 2016 were retrospectively reviewed. Baseline characteristics and hospitalization data were obtained through the Clinical Data Repository. Patient charts were individually reviewed from the electronic medical record system. We abstracted data that included clinical information, preoperative laboratory data, medications, hemodynamic data, echocardiographic assessments, HF etiology, and requirement for temporary mechanical circulatory support. Data points and echocardiographic measurements closest to the time of LVAD surgery were recorded, typically from the morning of surgery, but up to 14 days before surgery if necessary. Hemodynamic data were collected from right heart catheterizations closest to the time of surgery with a median of 8 days before the implantation date (79% within 14 days before implantation, range 0−303 days before implantation). Preoperative right ventricular dysfunction was abstracted from echocardiography reports as none, mild, moderate, or severe. Preoperative tricuspid regurgitation (TR) was abstracted from echocardiography reports as none, mild, mild-moderate, moderate, moderate-severe, or severe. Patients in this study underwent device implantation with Heartmate II, Heartmate 3, (both manufactured by Thoratec Corp, now Abbott Laboratory, Pleasanton, California) or Heartware (HVAD, manufactured by Heartware Corp, now Medtronic, Framingham, Massachusetts). The study was approved by the University of Virginia Institutional Review Board.

Right Ventricular Failure and Predictive Models

The respective RVF predictive models were calculated as specified in the original studies (Table 1).[18–20,22] For the Pitt algorithm, there was no range of "score" outcomes provided, so the score was recorded as binary (1 for patients who required a RVAD and 0 for those who did not). RVF was defined as use of inotropes for >14 days, inhaled pulmonary vasodilators for >48 hours, or unplanned need for right ventricular mechanical support postoperatively during the index hospitalization.[18,19,22,27]

Hemodynamic and echocardiographic metrics, including pulmonary artery pulsatility index (PAPi, calculated as [systolic pulmonary artery pressure − diastolic pulmonary artery pressure]/right atrial pressure), preoperative RV dysfunction, preoperative TR, right atrial pressure (RAP), pulmonary vascular resistance (PVR), RV stroke work index (RVSWI), and RA to pulmonary capillary wedge pressure ratio (RA:PCW), were abstracted or calculated.

Study End Points and Statistical Analysis

Comparisons of categoric and continuous variables were performed with the use of chi-square and Wilcoxon rank-sum tests, respectively. The Fisher exact test was used for categoric variables with small (<5) expected values. The respective RVF models were evaluated for the association with the primary outcome of incident postimplantation RVF during the implant hospitalization. RVF models were assessed by putting the respective model scores into a logistic regression model with RVF as the binary outcome. Receiver operating characteristic (ROC) curves were computed to generate C-statistics for model comparison. Individual hemodynamic and echocardiographic metrics were initially compared in a separate logistic regression with RVF as the primary outcome. Based on the pattern of association with RVF, the best-performing individual echocardiographic and hemodynamic metrics (preoperative RV dysfunction and PAPi, respectively) were added to the ROC analysis.

To assess for the incremental value of using multiple predictors, we combined the best-performing model (Michigan RVF score) with the best-performing hemodynamic (PAPi) and echocardiographic (preoperative RV dysfunction) metrics. The optimal cutoff value for PAPi was identified as <1.5, generating 2 categories with lower PAPi associated with unfavorable outcomes (2 points for <1.5, 0 points for ≥1.5). Of note, previous studies have demonstrated optimal cutoff values of 1.85 and 2.0.[23,24] Optimal weighting of preoperative RV dysfunction was identified as 0 points for none-mild, 1 point for moderate, and 4 points for severe. A combination score was constructed by adding categorized PAPi and preoperative RV dysfunction to the Michigan RVF score. The incremental value of this combination score was assessed by integrated discrimination index and Akaike information criterion (AIC).[29]

Best-performing RVF predictors were also examined for association with in-hospital mortality using logistic regression and long-term, three-year survival using Kaplan-Meier analyses. All statistical analysis was performed using SAS, version 9.4 (Cary, North Carolina).

Results

Study Cohort and Outcomes

There were 128 LVAD consecutive patients reviewed from March 2011 to June 2016. Of these patients, 93 had complete hemodynamic and echocardiographic data

Table 1. Established Models for Right Ventricular Failure Prediction in LVAD Patients

Study	Patient Population	RVF Rate (%)	C-Statistic	Score Components (Points)
Michigan RVF risk score[18] (2008)	• 197 • 14% CF • 6% DT	35	0.73	• Vasopressor requirement (4) • AST ≥ 80 IU/L (2) • Bilirubin ≥2.0 mg/dL (2.5) • Creatinine ≥2.3 mg/dL (3)

Utah RVF risk score[19] (2010)	• 175
	• 14% CF
	• 42% DT
		44	0.74	• Destination therapy (3.5)
				• IABP (4)
				• Pulmonary vascular resistance:
				  • ≤1.7 Wood units (1)
				  • 1.8−2.7 Wood units (2)
				  • 2.8−4.2 Wood units (3)
				  • ≥4.3 Wood units (4)
				• Inotrope dependency (2.5)
				• Obesity (2)
				• ACEi/ARB (−2.5)
				• Beta-blocker (2)

Pittsburgh Decision Tree[20] (2012)*	• 183 • 21.9% CF • DT % not reported	15†	0.87	• Transpulmonary gradient • Age • Right atrial pressure • International normalized ratio • Heart rate • White blood cell count • ALT • No. of inotropic agents
EuroMACS-RHF risk score[22] (2017)	• 2000‡ • 100% CF • 17% DT	21.7	0.70‡	• INTERMACS class 1−3 (2) • Use of multiple inotropes (2.5) • Severe RV dysfunction on echocardiography (2) • Ratio of right atrial to pulmonary capillary wedge pressure >0.54 (2) • Hemoglobin ≤10 (1)

CF, continuous-flow left ventricular assist device; DT, destination therapy; AST, aspartate transaminase; ALT, alanine transaminase; IABP, intra-aortic balloon counterpulsation; ACEi, angiotensin-converting enzyme inhibitor; ARB, angiotensin II receptor blocker.

*No point system used in the Pittsburgh Decision Tree model.

†Defined only as RVAD requirement; all other reviewed models used the RVF definition described in the Methods section.

‡2000 patients were included in the derivation cohort. The validation cohort included an additional 988 patients, with C-statistic of 0.67.

(Table 2) and composed the final cohort. RVF was identified in 16 patients (17.2%), of which 14 (15.1% of total) were treated with inotropes for >14 days, 3 (3.2% of total) had right ventricular mechanical support postoperatively, and 3 (3.2% of total) were treated with inhaled pulmonary vasodilators for >48 hours. Baseline clinical and demographic characteristics of the study cohort are presented in Table 2. The median age was 60 years (interquartile range 53−65), 77 (82.8%) of the patients were white, 13 (14.0%) black, 3 (3.2%) Hispanic, and 20 (21.5%) were women. The implantation strategy was DT in 44 patients (47.3%; 50.0% of patients with RVF and 46.8% of patients without RVF; $P = .81$). The etiology for HF was primarily ischemic in 39 patients (41.9%; 43.8% of patients with RVF and 41.6% of patients without RVF; $P = .87$).

Table 2. Baseline Demographics and Preoperative Comorbidities

Variable	RV Failure	
	Yes (n = 16)	No (n = 77)
Age (y)	60 (52.5−65.5)	60 (54−65)
Sex female	1 (6.3%)	19 (24.7%)
Race/ethnicity		
White	12 (75.0%)	65 (84.4%)
African-American	3 (18.8%)	10 (13.0%)
Hispanic	1 (6.3%)	2 (2.6%)
Body mass index (kg/m^2)	25.3 (20.6−29.7)	26.8 (23.3−30.2)
Coronary artery disease	9 (56.3%)	43 (55.8%)
Hypertension	7 (43.8%)	37 (48.1%)
Diabetes	7 (43.8%)	39 (50.7%)
Chronic kidney disease	10 (62.5%)	42 (54.6%)
Chronic obstructive pulmonary disease	3 (18.8%)	11 (14.3%)
Charlson comorbidity ndex	3.5 (2−5)	4 (2−5)
Device		
Heartmate II	14 (87.5%)	69 (89.6%)
Heartware HVAD	2 (12.5%)	5 (6.5%)
Heartmate 3	0 (0%)	3 (3.9%)

Values are presented as median (interquartile range) or n (%).

Preoperative RVF predictors and model scores are compared in Table 3. Patients who developed RVF had significantly higher preoperative creatinine and bilirubin as well as more preoperative RV dysfunction based on echocardiography. There was a trend toward greater preoperative vasopressor requirement, lower PAPi, and higher-acuity INTERMACS profiles in patients with RVF. Patients with RVF had a significantly longer length of stay: median 36.5 days (interquartile range 27.5−53) versus 29 days (interquartile range 24−38; $P = .040$). All-cause in-hospital death occurred in 11 patients (11.8%), with mortality rates of 37.5% (n = 6) in the RVF group and 6.5% (n = 5) in patients without RVF ($P = .003$).

Table 3. Preoperative RV Failure Predictors and Model Scores

Predictor	RV Failure		*P* Value*
	Yes (n = 16)	No (n = 77)	
Heart rate	84.5 (78–91.5)	84 (76–96)	.96
Hemoglobin	11.1 (9.3–13.2)	11.4 (10.2–12.8)	.70
White blood cell count	9.4 (6.3–12.0)	8.1 (6.3–10.0)	.33
Creatinine	1.7 (1.4–2.0)	1.4 (1.0–1.5)	.028*
AST	33.0 (24.5–54.5)	33.0 (22.0–46.0)	.52
ALT	31.5 (17.0–54.5)	32.0 (19.0–68.0)	.59
Bilirubin	1.6 (1.1–2.4)	1.0 (0.8–1.5)	.026*
INR	1.2 (1.1–1.4)	1.2 (1.1–1.3)	.76
Vasopressor requirement	4 (25.0%)	6 (7.8%)	.066
Inotrope requirement	13 (81.3%)	64 (83.1%)	1.00
Mechanical circulatory support before implantation‡	5 (31.3%)	14 (18.2%)	.31
Mechanical ventilation before implantation	3 (18.8%)	7 (9.1%)	.37
Severe RV dysfunction†	4 (25.0%)	3 (3.9%)	.016*
Severe TR†	2 (12.5%)	7 (9.1%)	.65
Right atrial pressure	15.0 (12.0–19.5)	12.0 (9.0–17.0)	.10
Transpulmonary gradient	10.0 (7.5–15.0)	11.0 (7.0–14.0)	.98
Pulmonary vascular resistance	2.7 (2.3–3.7)	2.5 (1.9–3.4)	.24
PAPi	1.7 (1.2–2.7)	2.3 (1.7–3.2)	.078
RA:PCW	0.5 (0.4–0.7)	0.5 (0.4–0.7)	.78
RVSWI	0.5 (0.3–0.7)	0.6 (0.4–0.8)	.23
Preoperative ACEi/ARB	3 (18.8%)	24 (31.2%)	.38
Preoperative BB	9 (56.3%)	60 (77.9%)	.11
Destination therapy	8 (50.0%)	36 (46.8%)	.81
INTERMACS	2.5 (2.0–3.0)	3.0 (2.0–3.0)	.099
Michigan RVF risk score	2.5 (0–4.0)	0 (0–0)	.0002*
Pittsburgh RVF decision tree	2 (12.5%)	7 (9.1%)	.65
Utah RVF risk score	8.0 (7–11.3)	7.5 (6.0–10.5)	.41
EuroMACS RHF risk score	4.0 (2.0–5.0)	3.0 (2.0–4.0)	.054

Values are presented as median (interquartile range) or n (%). INR, international normalized ratio; TR, tricuspid regurgitation; PAPi, pulmonary artery pulsatility index; RA:PCW, ratio of right atrial to pulmonary capillary wedge pressure; RVSWI, right ventricular stroke work index; BB, beta-blockers; other abbreviations as in Table 1.

*p-values.

†Compared with none, mild, or moderate RV dysfunction/tricuspid regurgitation.

‡Includes IABP (n = 10), Tandemheart (n = 8), and extracorporeal membrane oxygenation (n = 1).

Right Ventricular Failure and Risk Models

The Michigan RVF score (C = 0.74 [95% CI 0.61–0.87]; $P = .0004$) compared favorably with newer RVF risk scores: Utah (C = 0.57), Pitt (C = 0.52), and EuroMACS (C = 0.65; Table 4 and Fig. 1). The unadjusted C-statistics for individual hemodynamic/echocardiographic metrics were as follows: preoperative RV dysfunction 0.71, preoperative TR 0.64, PAPi 0.64, right atrial pressure 0.63, pulmonary vascular resistance 0.59, PA mean pressure 0.61, RVSWI 0.60, and RA:PCWP 0.52. Among individual hemodynamic/echocardiographic metrics, only preoperative RV dysfunction (C = 0.71 [95% CI 0.58–0.85]; $P = .0022$) demonstrated statistically significant, albeit modest, discrimination of RVF (Table 4). The established models and best-performing metrics (categorized preoperative RV dysfunction and categorized PAPi) are compared by ROC curve in Fig. 1. Adding the categorized and weighted PAPi and preoperative RV dysfunction to the Michigan RVF score in order to develop a combination score modestly improved predictive value (C = 0.79 [95% CI 0.65–0.92]; $P < .0001$). Compared with the Michigan score alone, this combination score demonstrated integrated discrimination improvement of 0.0812 [95% CI 0.0034–0.159] with $P = .0409$, indicating statistically significant improvement in RVF prediction. The AIC of the combination score was 73.95, representing ΔAIC of −7.05 in AIC from the Michigan score alone.

The Michigan RVF score also performed favorably (C = 0.67 [95% CI 0.52–0.83]; $P = .0319$) in predicting all-cause in-hospital mortality compared with the newer RVF prediction scores and metrics (only model or metric to reach significant discrimination; Table 4 and Fig. 2). In comparison, the Heartmate II Risk Score demonstrated a C-statistic of 0.61 [95% CI 0.42–0.81] with $P = .25$ for all-cause in-hospital mortality (among the 92 patients with complete data for the score). Compared with other top performing scores and metrics (EuroMACS and RV dysfunction), the Michigan RVF score was also more closely associated with long-term 3-year survival (Kaplan-Meier log-rank 0.0135; Fig. 3).

Discussion

In this contemporary cohort of patients undergoing primary implantation of continuous-flow LVADs, we found that the more established Michigan RVF score performed best in predicting RVF among newer RVF predictive scores and metrics. Furthermore, the Michigan RVF score was associated with in-hospital and long-term survival. Overall, we also noted that preoperative metrics and scoring systems

Table 4. Comparison of Risk Models and Metrics for RVF Prediction and In-Hospital Mortality

	RVF			In-Hospital Mortality		
Model or Metric	C	95% CI	*P* Value	C	95% CI	*P* Value
Michigan[18]	0.74	0.61–0.87	.0004*	0.67	0.52–0.83	.0319*
Utah[19]	0.57	0.41–0.73	.41	0.57	0.39–0.75	.45
Pittsburgh[20]	0.52	0.43–0.61	.71	0.60	0.46–0.74	.17
EuroMACS[22]	0.65	0.48–0.82	.085	0.60	0.38–0.83	.36
Preoperative RVD	0.71	0.58–0.85	.0022*	0.62	0.45–0.78	.16
Categorized RVD†	0.72	0.59–0.85	.0008*	0.59	0.42–0.77	.30
Preoperative TR	0.64	0.48–0.81	.096	0.67	0.49–0.85	.065
PAPi	0.64	0.48–0.80	.086	0.52	0.35–0.69	.81
Categorized PAPi†	0.67	0.54–0.81	.011*	0.52	0.39–0.65	.77
RAP	0.63	0.49–0.77	.068	0.48	0.31–0.65	.82

RVD, right ventricular dysfunction; RAP, right atrial pressure; other abbreviations as in Tables 1 and 3.
*$P < .05$.
†See Methods section for categorization process.

for RVF demonstrated modest predictive ability, with C-statistics not greater than 0.74.

As the use of mechanical circulatory support for the treatment of advanced HF has increased over the past decade, RVF has remained a troubling challenge in the patient selection process for LVAD implantation. RVF continues to be a leading cause of morbidity and mortality after LVAD surgery. Patients who develop RVF also have a greater risk of developing concomitant complications remote from the failing ventricle. For example, patients with pre- or postoperative RV dysfunction or failure have significantly higher rates of adverse events such as multiorgan system failure, gastrointestinal and postoperative bleeding, pulmonary complications, and thromboembolic events.[8,30–32] Importantly, forecasting which patient subsequently develops RVF after LVAD implantation can be a challenging undertaking, even for the most experienced clinicians.

The scope of the problem of RVF risk prediction is underscored by the numerous risk scores that have been proposed in the risk stratification process. A number of these risk scores were developed from small single-center studies with significant heterogeneity in the definitions of RVF, device type (pulsatile vs continuous flow), and the era of derivation of the risk score. Moreover, there is a paucity of external validation studies of these risk prediction models.[27] The well known risk scores include the Michigan RVF score,[18] Penn RVAD risk score,[33] Heartmate II bridge-to-transplantation RVF analysis,[8] Utah RVF risk

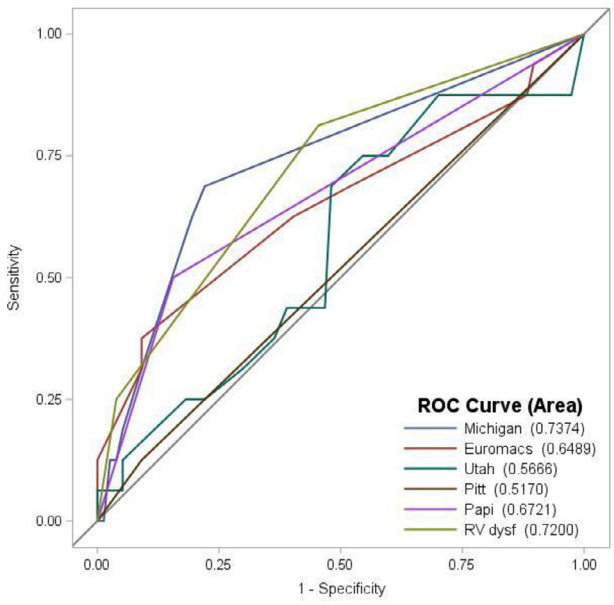

Fig. 1. Receiver operating characteristic (ROC) curves for right ventricular failure (RVF) according to logistic regression modeling. The areas under the ROC curves (AUCs) are 0.74 ($P = .0004$) for the Michigan RVF score, 0.67 ($P = .011$) for PAPi, and 0.71 ($P = .0022$) for preoperative RV dysfunction. No other model or metric reached statistical significance.

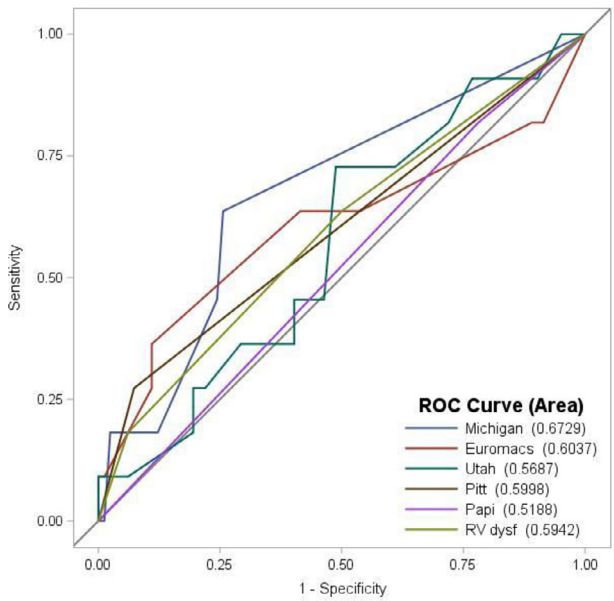

Fig. 2. ROC curves for all-cause in-hospital mortality according to logistic regression modeling. The AUC for the Michigan RVF score is 0.67 ($P = .0319$). No other model or metric met statistical significance. Abbreviations as in Fig. 1.

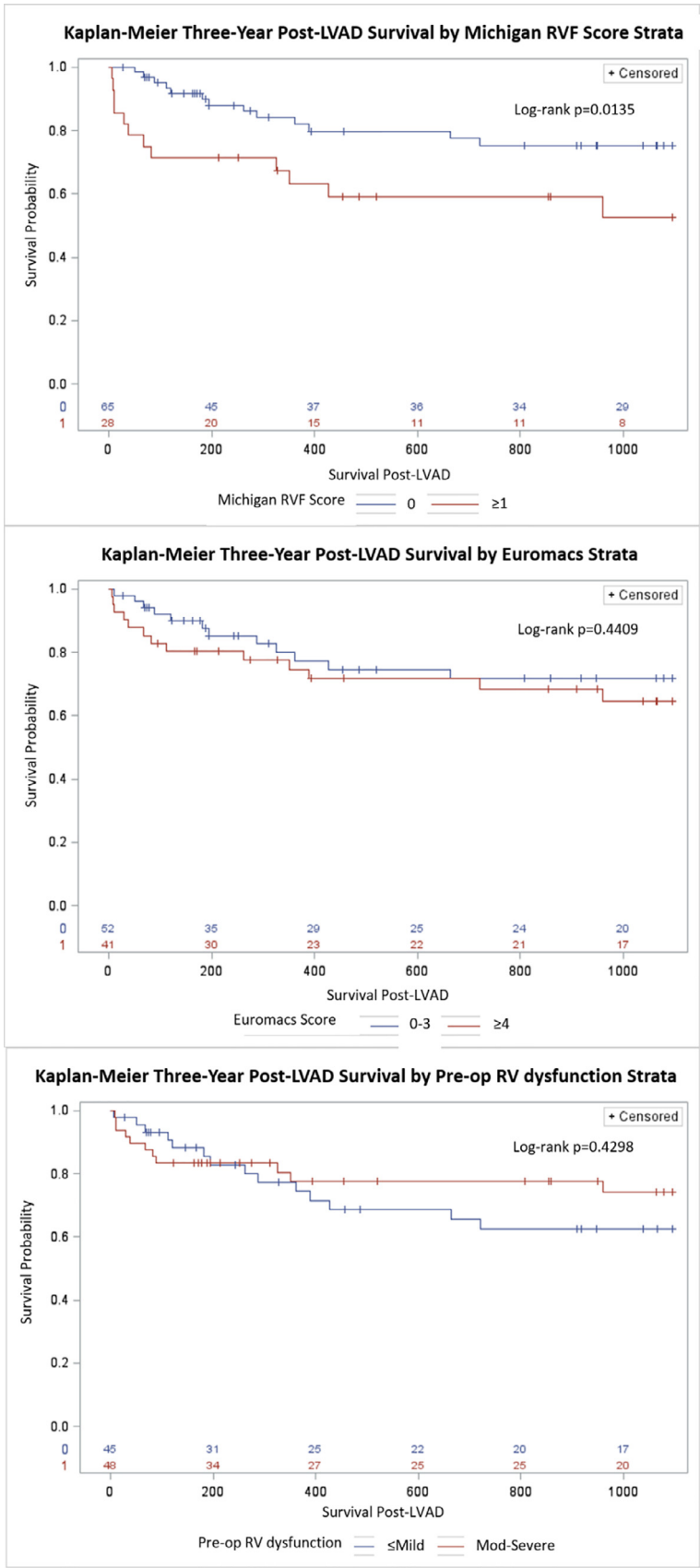

Fig. 3. Three-year survival based on stratification by best-performing models and metrics. The Kaplan-Meier survival curves are shown with stratification based on Michigan RVF score (log rank $P = .0135$), EuroMACS score (log rank $P = .44$), and preoperative RV dysfunction (log rank $P = .43$). Abbreviations as in Fig. 1.

score,[19] Pittsburgh decision tree,[20] Penn CRITT score,[13] EuroMACS score,[22] and Pittsburgh bayesian models.[21] These models have included PVR, RV dysfunction, TR, RAP, RA:PCW, and RVSWI as echocardiographic and hemodynamic predictors of RVF. In addition, other metrics have been explored, including PAPi, RV-to-LV end-diastolic diameter ratio, RV free wall peak longitudinal strain, RV fractional area change, RV end-systolic and end-diastolic volume indexes, left atrial volume index, and LV volume and function.[9,10,14,23,24,34,35] Results from these studies have reported varying predictive ability of RVF, with C-statistics ranging mostly from 0.6 to 0.8 and in some studies to >0.9.[24,35] Reproducibility of these findings has been disappointing. For example, several studies have found substantially lower predictive ability for the Michigan RVF score (C = 0.54−0.61)[13,20,21] compared with the original Michigan study (C = 0.73)[18]; these discrepancies underscore the need for further validation studies. Unsurprisingly, many of these studies also demonstrated a close association between RVF and mortality in LVAD patients, emphasizing the importance of identifying patients at risk for RVF.

Compared with the original studies, the present analysis demonstrated lower predictive ability for the Utah risk score, the Pittsburgh decision tree, and the EuroMACS score. Conversely, the Michigan risk score retained its strength of prediction in this analysis compared with the original derivation study. In assessing the differences between the risk models, it is evident that the Michigan score exclusively emphasizes severity of preoperative hemodynamic instability and clinical end-organ injury. On the other hand, the Pitt, Utah, and EuroMACS models include a range of variables that include cardiopulmonary hemodynamic metrics, patient characteristics, and preoperative medical management. Notably, previous work has shown that clinical variables reflecting hemodynamic instability and end-organ dysfunction (and thereby severity of RV dysfunction) drive much of the ability of scores to predict RVF.[36,37] As one would expect, preoperative mechanical ventilation and intubation status has been associated with RVF in previous studies[13]; our findings, however, did not show a statistically significant relationship between preoperative mechanical ventilation status and RVF. These findings were likely due to relatively lower numbers (n = 10) of patients with mechanical ventilation before LVAD surgery.

Of note, the incidence of RVF in our study was lower than that reported in some other published studies,[18,19,27] but was similar to the recently published EuroMACS study.[22] The wide variation in the reported incidence of RVF in previous studies has been attributed to heterogeneities in RVF definitions.[15] Our definition of RVF was limited to the immediate postoperative period of the index hospitalization. Other studies have included RVF up to 90 days after LVAD implantation, a definition that may include late-onset RVF.[27] The phenomenon of late-onset RVF that occurs weeks to months after the initial postoperative period is well documented in the literature.[38] Even so, our findings are concordant with the only other large independent comparison of RVF predictive models in which the Michigan score outperformed the Utah risk score, Pittsburgh decision tree, and Penn CRITT score, among others.[27] The present study validates this finding in a modern LVAD population and expands the comparative analysis to include newer predictive models and metrics. Furthermore, this study demonstrates that combining the Michigan risk score (reflective of preoperative hemodynamic instability and clinical end-organ injury) with preoperative echocardiographic and hemodynamic RV dysfunction (ie, PAPi) provides modest, but statistically significant, incremental prognostic yield. Taking these together, our study further underscores the challenges of RVF prediction with current scores and metrics which provide modest discrimination at best.

Judicious patient selection is vital to preventing RVF in patients undergoing LVAD surgery. This is even more pertinent among patients whose treatment strategy is DT, in whom biventricular support is practically tenuous. Considering that RVF after LVAD remains a common and significant driver of morbidity and mortality,[8−15] robust risk stratification tools are needed to mitigate this complication. At a bare minimum, risk stratification for patients undergoing LVAD implantation provides prognostic information that may be valuable in guiding the shared decision-making process between patients and clinicians before the LVAD surgery. Furthermore, RVF risk modeling identifies patients that may benefit from a planned up-front biventricular support strategy—either as bridge-to-transplant or as temporary perioperative RV support—both of which may be associated with favorable outcomes.[39−41] In the present study, the predictive strength of the Michigan risk score highlights the importance of preoperative target end-organ dysfunction in forecasting the risk of developing RVF after LVAD implantation. Admittedly, a clinical profile of multiple end-organ damage does not uniquely signal impending RVF, but rather may also be a reflection of a more global critical illness (such as severe sepsis). In this regard, risk modeling that focuses on the right ventricle itself may be more specific and attractive. To this end, advanced imaging of the right ventricle with the use of cardiovascular magnetic resonance imaging and speckle tracking imaging are promising modalities that may enhance patient selection.[42,43] Unfortunately, these modalities are yet to achieve wider adoption in routine patient care, because they require specialized skills and may not be widely available. In the present study, preoperative RV dysfunction based on echocardiography alone provided nearly as much predictive power for RVF as the Michigan score (although notably less association with survival). To increase the strength and precision of RVF prediction, further investigation of the combination of proven risk models with newer hemodynamic/echocardiographic metrics is warranted.

Study Limitations

This study carries the inherent limitations of a single-center retrospective study. The sample size is fairly modest and the analyzed population was further reduced by missing hemodynamic variables in some of the patients. If there were systematic differences between the patients with and without complete data, that could limit generalization of the results to all HF patients undergoing primary implants. Another potential limitation of this study was the wide range in the timing of hemodynamic data collected before implantation. Previous studies have used varied methodologies ranging from restricting hemodynamic data to ≤24 hours before implantation[24] to including data anywhere from 1 to 180 days before implantation.[23] Other studies have not clearly defined the time frame for preoperative hemodynamic data.[22,27] We included a broad range of preoperative hemodynamic data to reflect this variability in previous studies and to mirror real-world applicability, but this could have contributed to more heterogeneous hemodynamic data. In addition, this study was unable to compare the CRITT model owing to the nonavailability of reliable pertinent variables. This study focused primarily on acute RVF during the index hospitalization rather than late-onset RVF which occurs in the weeks to months after LVAD implantation at an estimated rate of 10%−35%.[8,38,44–46] Also, we were not able to characterize the severity of acute RVF (ie, extended but transient inotrope requirement vs RVAD dependency) owing to small event rates.

Conclusion

In external validation analysis of risk models and metrics for predicting RVF in patients undergoing LVAD implantation, the more established Michigan RVF score—which emphasizes preoperative hemodynamic instability and target end-organ dysfunction—performed best, albeit modestly, in predicting RVF and demonstrated association with in-hospital and long-term mortality.

Disclosures

None.

Supplementary Materials

Supplementary material associated with this article can be found in the online version at https://doi.org/10.1016/j.cardfail.2019.02.011.

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