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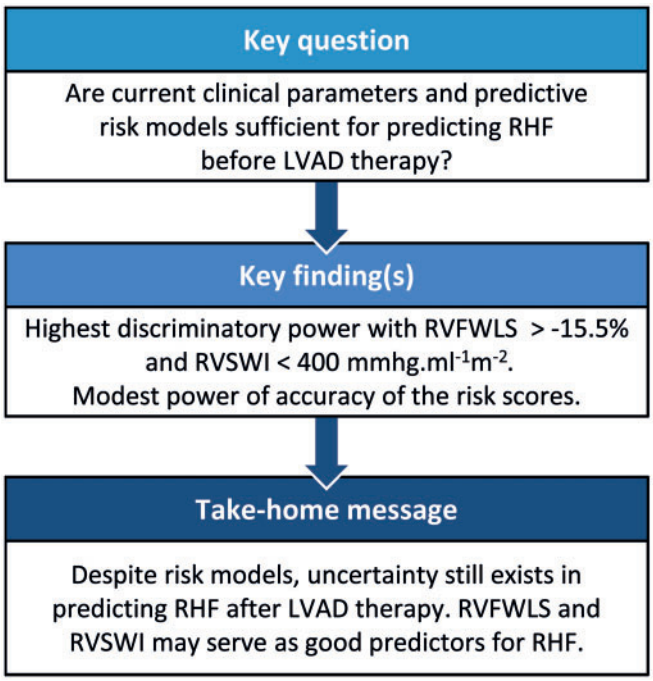
Right ventricular free wall longitudinal strain and stroke work index for predicting right heart failure after left ventricular assist device therapy

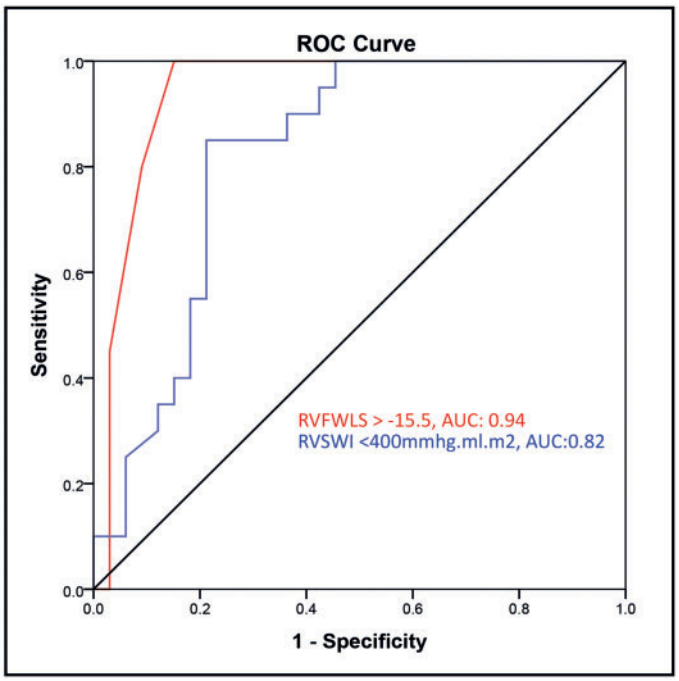
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Abstract

OBJECTIVES: Right heart failure (RHF) is an important prognostic factor in continuous-flow left ventricular assist device (LVAD) therapy. We aimed to assess the clinical variables associated with RHF after LVAD implantation and to compare their performance against currently available RHF predictive scoring systems.

METHODS: The study cohort comprised 57 patients who underwent LVAD therapy between January 2012 and May 2018 in our centre. The mean age of the patients was 39.9 ± 18.3 years, and 43 (81.1%) of them were men. Thirty-eight patients (66.6%) were in the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) profile I or II. The study cohort was divided into the patients with RHF postoperatively ($n = 20$, 35.1%) and without RHF ($n = 37$, 64.9%).

RESULTS: Independent predictors for RHF were preoperative right ventricular ejection fraction <25% [odds ratio (OR) 4.68, 95% confidence interval (CI) 1.41–15.5; $P = 0.01$], right ventricular stroke work index <400 mmHg ml^{-1} (OR 3.73, 95% CI 1.01–13.7; $P = 0.04$), right ventricular outflow tract systolic excursion <7 mm (OR 1.55, 95% CI 0.31–0.84; $P = 0.002$), right ventricular outflow tract fractional shortening <15% (OR 1.62, 95% CI 0.34–0.78; $P = 0.02$), right ventricular free wall longitudinal strain ≤19% (OR 3.13, 95% CI 1.01–2.43; $P = 0.003$), right

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ventricular fractional area change <27% (OR 3.71, 95% CI 1.15–11.9; $P = 0.02$) and prealbumin <14 mg/dl (OR 3.45, 95% CI 1.07–11.03; $P = 0.03$). Modest diagnostic performance for RHF was detected in 4 of 7 validated scoring systems with resulting area under the curve values of 0.70 (95% CI 0.55–0.84; $P = 0.001$) for the Seattle Heart Failure Model; 0.68 (95% CI 0.49–0.81, $P = 0.03$) for the Fitzpatrick's; 0.68 (95% CI 0.53–0.83, $P = 0.028$) for the acute physiology and chronic health evaluation (APACHE) II; and 0.66 (95% CI 0.50–0.82, $P = 0.04$) for the model for end-stage liver disease scoring systems. However, we found best discrimination performance of the score with a resulting area under the curve value of 0.94 (95% CI 0.55–0.89, $P = 0.03$) for right ventricular free wall longitudinal strain ≥-15.5% and 0.82 for right ventricular stroke work index <400 mmHg ml^{-1} m^{-2} in predicting RHF.

CONCLUSIONS: Right ventricular free wall longitudinal strain ≥-15.5% and right ventricular stroke work index <400 mmHg ml^{-1} m^{-2} were independent predictors of RHF following LVAD implantation. Currently available prediction risk scores had the modest power of accuracy in the low INTERMACS profile Turkish population.

Keywords: Left ventricular assist device • Right heart failure • Right ventricular longitudinal strain • Echocardiography • Right ventricular failure risk scoring

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INTRODUCTION

Advances in durable mechanical circulatory support have increased survival among patients with advanced heart failure and continuous-flow left ventricular assist device (LVAD) implantation is an established therapy as a bridge-to-transplantation (BTT) or destination therapy [1]. However, despite technological advances and evolving surgical experience the incidence of right heart failure (RHF) still varies over a range from 9.4% to 44% after LVAD therapy with an associated high perioperative mortality [2–7].

Previous studies [3–5, 8–11] have identified several clinical factors, biochemical markers, haemodynamic parameters and echocardiographic predictors for RHF after LVAD implantation.

The aim of our study was to identify new parameters which contribute to the prediction of post-LVAD RHF and to investigate the accuracy of previously published scoring systems to predict RHF.

MATERIALS AND METHODS

Study population

We conducted a retrospective cohort study, including all consecutive patients who received the LVAD therapy as a BTT ($n = 57$) between January 2012 and May 2018. Exclusion criteria were biventricular assist device or total artificial heart implantation. Follow-up interventions and clinical events were captured for all patients. Cases with ($n = 20$) and without ($n = 37$) RHF were identified, and possible risk factors were then retrospectively compared between the 2 groups.

The implanted devices were the HeartMate II (Abbott, Chicago, IL, USA) ($n = 17$), the HeartWare HVAD (Medtronic Inc., Framingham, MA, USA) ($n = 28$) and the HeartMate 3 (Abbott, Chicago, IL, USA) ($n = 8$). The study protocol was approved by the Ankara University School of Medicine, Ethics Committee (05-304-18, 12 March 2018).

Definition of right heart failure

Definition of postoperative RHF after LVAD implantation has been inconsistent in several clinical studies [5, 12–15]. RHF after LVAD implantation in the current study was defined as in the updated definition of the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) database [16] including the following criteria in the absence of cardiac tamponade within the first 48 h after surgery:

- The mean arterial pressure <55 mmHg
- Central venous pressure or right atrial pressure >16 mmHg
- Cardiac index <2 l/min/m^2
- Requirement of prolonged postimplant inotropes (inotropic score >20 units)
- Inhaled nitric oxide or intravenous vasodilators continued beyond postoperative day 14 following LVAD implant or requiring right ventricular assist device (RVAD) or extracorporeal membrane oxygenation support.

Echocardiographic assessment and right heart catheterization

Routine echocardiographic measurements of the right ventricle were obtained in accordance with current guidelines [17]. All preoperative transthoracic echocardiography and transoesophageal echocardiography data used in the study were obtained between 24 and 48 h before surgery. Intraoperative transoesophageal echocardiography was also performed before and after cardiopulmonary bypass to set-up the device and perform deairing. We advocated transoesophageal echocardiography-guided management at least 24 h postoperatively.

Standard haemodynamic measurements were made at least twice a year preoperatively including cardiac output, cardiac index, pulmonary capillary wedge pressure, systemic and pulmonary vascular resistance, transpulmonary pressure gradient, central venous pressure and right ventricular stroke work index (RVSWI). In addition to these parameters, simplified right ventricular contractility pressure index was derived as tricuspid annular plane systolic excursion × (RV-RA pressure). The mPAP, central venous pressure, cardiac output and cardiac index were obtained using a rapid-response thermistor pulmonary artery catheter intraoperatively and after surgery every 2 h in the intensive care unit for a maximum of 7 postoperative days (Swan-Ganz catheter, Edwards Lifesciences, Irvine, CA, USA).

Risk scoring algorithms

We applied 4 RHF predictive scoring systems to our patient population namely Matthews' [8], Fitzpatrick's [3], Drakos' [4] and ARVADE scoring systems [18] and assessed their predictivity of these scores for RHF in our study cohort.

Statistical analysis

Data analysis was performed using the SPSS version 15.0 (SPSS Inc., Chicago, IL, USA). Continuous data were evaluated for normality using the Shapiro–Wilk and graphical methods (histogram, Q–Q plots), and between-group comparisons were performed using either the Student's *t*-test or the Mann–Whitney *U*-test for normal and non-normal data, respectively. Categorical data were compared using either the Pearson χ^2 test or the Fisher's exact test, in case the minimum expected number in each cell is less than 5. Univariable significant variables were categorized according to the clinical cut-off values, then stepwise forward multiple logistic regression analyses were performed on univariable predictors of RHF (entry criterion $P < 0.05$). Correlation curves of related parameters were calculated with Spearman's Rho or the Pearson correlation test. Receiver-operating characteristic curves of the predictors of RHF found significant in the multiple logistic regression analysis were created. A Kaplan–Meier curve was used to represent the actuarial survival of 2 groups.

RESULTS

Population characteristics

As shown in Table 1, the mean age of the patients at operation was 39.9 ± 18.3 years (range 12–69 years), and 43 (81.1%) patients were men. Approximately 67% (38 patients) were in INTERMACS profile I and II. After LVAD implantation, 20 patients (35.1%) developed RHF and 11 of them required a Levitronix Centrimag

Table 1: Clinical characteristics

Variables	Study cohort (*n* = 57)	No RHF (*n* = 37)	RHF (*n* = 20)	*P*-value
Age	39.8 ± 18.3	39.97 ± 15.01	39.77 ± 22.6	0.97
Gender (male), *n* (%)	47 (82.4)	34 (91.8)	13 (65)	0.06
Diagnosis, *n* (%)				
ICMP	19 (33.3)	13 (35.1)	6 (30)	0.24
DCMP	37 (64.9)	23 (62.1)	14 (70)	0.18
PPCMP	1 (1.7)	1 (2.7)	0	
BSA (m^2)	1.81 ± 0.09	1.92 ± 0.08	1.82 ± 0.01	0.76
DM, *n* (%)	15 (26.3)	9 (24.3)	6 (20)	0.9
Hypertension, *n* (%)	21 (36.8)	15 (40.5)	6 (20)	0.2
Hyperlipidaemia, *n* (%)	23 (40.3)	13 (35.1)	10 (50)	0.16
Chronic lung disease, *n* (%)	23 (40.3)	16 (43.2)	7 (35)	0.24
CVO, *n* (%)	2 (3.5)	2 (5.4)	0 (0)	0.62
PAD, *n* (%)	5 (8.7)	4 (10.8)	1 (5)	0.58
Obesity (BMI ≥30 kg/m^2), *n* (%)	9 (15.7)	6 (16.2)	3 (15)	0.86
Ascites, *n* (%)	12 (21)	5 (13.5)	7 (35)	0.18
Hepatomegaly, *n* (%)	10 (17.5)	5 (13.5)	5 (25)	0.28
Pacemaker requirement, *n* (%)				
ICD	28 (49.1)	15 (40.5)	13 (65)	0.62
CRT	18 (31.5)	12 (32.4)	6 (30)	0.56
IABP, *n* (%)	3 (5.2)	1 (2.7)	2 (10)	0.06
ECMO, *n* (%)	15 (26.3)	6 (16.2)	9 (45)	0.16
Resternotomy, *n* (%)	20 (35)	8 (21.6)	12 (60	0.059
INTERMACS profile, *n* (%)				
I–II	38 (66.6)	20 (54)	18 (90)	0.27
III–IV	15 (26.3)	13 (35.1)	2 (10)	0.051
VO_2 max (ml/kg/dk)	12.1 ± 2.2	15.1 ± 1.26	11.8 ± 1.91	0.45
6-min walk distance (m)	431 ± 91.8 (*n* = 41)	498.1 ± 31.9 (*n* = 28)	337.3 ± 60.04 (*n* = 13)	0.16
Mechanical ventilation, *n* (%)	23 (40.3)	9 (24.3)	14 (70)	0.23
Operative data, *n* (%)				
Type of LVAD				
HeartWare (HVAD)	28 (49.1)	21 (56.7)	7 (35)	0.06
HeartMate II	17 (29.8)	6 (16.2)	11 (0.55)	0.76
HeartMate 3	8 (14)	4 (10.8)	4 (20)	0.1
Concomitant tricuspid valve repair	6 (10.5)	3 (8.1)	3 (15)	0.78
Postoperative data				
Haemorrhage, *n* (%)	16 (28)	7 (18.9)	9 (45)	0.6
Transfusion (unit/blood)	4.3 ± 1.3	3.4 ± 0.18	5.1 ± 1.1	0.13
Inotrope infusion, *n* (%)				
Dobutamine	21 (36.8)	5 (13.5)	16 (80)	0.2
Milrinone	13 (22.8)	5 (13.5)	8 (40)	0.9
Dopamine	10 (17.5)	5 (13.5)	5 (25)	0.8
Nitric oxide, *n* (%)	29 (50.8)	10 (27)	19 (95)	0.13
Sildenafil, *n* (%)	32 (56.1)	20 (54)	12 (60)	0.95

Continuous data are presented as the mean ± standard deviation and categorical data are presented as percentage. *P*-value <0.05 for comparison between LVAD patients with and without RHF.

BMI: body mass index; BSA: body surface area; CRT: cardiac resynchronization therapy; CVO: cerebrovascular occlusion; DCMP: dilated cardiomyopathy; DM: diabetes mellitus; ECMO: extracorporeal membrane oxygenation; IABP: intra-aortic balloon pump; ICD: implantable cardioverter defibrillator; ICMP: ischaemic cardiomyopathy; INTERMACS: Interagency Registry for Mechanically Assisted Circulatory Support; LVAD: left ventricular assist device; PAD: peripheral arterial disease; PPCMP: postpartum cardiomyopathy; RHF: right heart failure.

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device (Thoratec Corporation, Pleasanton, CA, USA). We identified 3 patients in the RHF group with RVAD support who successfully underwent BTT at 15th day, 11th and 15th months, respectively. Among these 3 patients, 2 of them were still alive; however, 1 patient with early RHF died of multiorgan failure 8 days after heart transplantation. In addition, 2 patients were successfully weaned from right ventricular support within 2 weeks; however, they were lost in the following days due to stroke and infection. The remaining patients with the RVAD support, not mentioned above ($n = 6$), died as a result of persistent RHF ($n = 2$) due to insufficient support despite the maximum flow rates and the lack of a suitable donor or sepsis ($n = 4$). In contrast, we had 4 patients who underwent BTT at the 1st, 3rd, 6th and 7th months in the group of patients with no RHF. Only 1 patient died of sepsis 14 days after the surgery. In our study, 38 patients were in the INTERMACS profile I or II. Of them, 18 (47.3%) patients developed RHF, whereas only 2 patients (13.3%) in the INTERMACS III or IV profile developed RHF.

Laboratory parameters

Univariable analysis of laboratory data, as demonstrated in Table 2, such as serum creatinine ($P = 0.04$), prealbumin ($P = 0.004$), aspartate transaminase ($P = 0.045$), lactate dehydrogenase ($P = 0.021$) and total bilirubin ($P = 0.03$) were significantly different between 2 groups.

Echocardiography and right heart catheterization

The univariate analysis of preoperative echocardiographic data as shown in Table 3 identified right ventricular ejection fraction (RVEF) ($P = 0.009$), right ventricular free wall longitudinal strain (RVFWLS) ($P = 0.003$), right ventricular global longitudinal strain ($P = 0.001$), right ventricular septum longitudinal strain ($P = 0.007$), RV-FAC ($P = 0.025$), right ventricular outflow tract (RVOT) systolic excursion (RVOT-SE) ($P = 0.001$) and RVOT fractional shortening ($P = 0.001$) as the echocardiographic risk factors for RHF. The univariate analysis of right heart catheterization data as presented in Table 3 identified right atrial pressure ($P = 0.02$), right atrial pressure/pulmonary capillary wedge pressure ($P = 0.009$), right ventricular contractility pressure index ($P = 0.02$) and RVSWI ($P = 0.002$) as risk factors for RHF.

Multivariate regression analysis identified RVEF <25% [odds ratio (OR) 4.68], RVSWI <400 mmHg ml^{-1} m^{-2} (OR 3.73), RVOT-SE <7 mm (OR 1.55), RVOT fractional shortening <15% (OR 1.62), prealbumin <14 mg/dl (OR 3.45), RV-FAC <27% (OR 3.71), RVFWLS ≥19% (OR 2.65) as independent predictors for RVF following LVAD therapy (Table 4). Receiver-operating characteristic curves for the independent risk factors were drawn and RVFWLS and RVSWI had the best area under the curve (AUC) (0.94 and 0.82) for the cut-off values of -15.5% and 400 mmHg ml/m^2, respectively (Fig. 1). RVFWLS had the highest sensitivity (86.4%) and specificity (95.2%) in predicting RHF.

Correlation between the independent predictors

Positive correlations were observed between RVOT-SE and RVOT fractional shortening ($r = 0.407$, $P = 0.002$); RVSWI and fractional area change (FAC) ($r = 0.467$, $P = 0.000$); RVEF and FAC ($r = 0.429$, $P = 0.001$); and RVOT-SE and FAC ($r = 0.41$, $P = 0.002$); in contrast, no significant correlation was detected among other parameters (Fig. 2).

Table 2: Preoperative laboratory data

Variables	Study cohort ($n = 57$)	No RHF ($n = 37$)	RHF ($n = 20$)	P-value
Haemoglobin (g/dl)	13.4 ± 1.72	13.6 ± 1.9	13.3 ± 1.46	0.16
Haematocrit (%)	38.6 ± 4.5	40.5 ± 4.9	38.3 ± 4.51	0.242
Leucocyte (K/mm^3)	7.53 ± 2.34	7.1 ± 2.44	8.1 ± 2.1	0.112
Platelets (K/mm^3)	333 ± 74.4	344, 4 ± 72	316.9 ± 76.6	0.187
Blood urea nitrogen (mg/dl)	40.3 ± 23.4	24.23 ± 6.2	33 ± 19.5	0.058
Creatinine (mg/dl)	1.28 ± 0.48	0.93 ± 0.15	1.57 ± 0.34	0.04
Sodium (mEq/l)	136.8 ± 4.84	140.1 ± 3.3	145.2 ± 2.7	0.21
Potassium (mEq/l)	4.21 ± 0.68	3.75 ± 0.35	4.1 ± 0.04	0.15
Magnesium (mEq/l)	2.01 ± 0.07	2.01 ± 0.2	2.02 ± 0.8	0.63
Calcium (mEq/l)	1.02 ± 0.013	1.04 ± 0.02	1.05 ± 0.2	0.57
Albumin (g/dl)	2.71 ± 0.31	2.93 ± 0.2	2.41 ± 0.17	0.655
Prealbumin (mg/dl)	14.6 ± 3.46	16.5 ± 2.8	11.8 ± 2.2	0.004
INR	1.26 ± 0.35	1.04 ± 0.17	1.3 ± 0.3	0.18
ALT (IU/l)	108.1 ± 65.4	80 ± 23.3	161.3 ± 46.6	0.32
AST (IU/l)	119.7 ± 82.5	80.3 ± 27.9	195.2 ± 45.8	0.045
GGT (IU/l)	74.1 ± 25.1	72.2 ± 27.7	116.4 ± 37.5	0.537
LDH (IU/l)	209.2 ± 75.6	171.1 ± 35.1	299.05 ± 67.3	0.021
Pro-BNP (pg/ml)	3745 (898–4456)	1289 (554–1451)	1668 (882–2916)	0.2
Troponin I (ng/ml)	76.5 (37.1–88.2)	48.5 (31.1–65.3)	123 (81.1–153.2)	0.227
Total bilirubin (mg/dl)	2.41 ± 0.82	1.66 ± 0.31	2.9 ± 0.7	0.03
Direct bilirubin (mg/dl)	1.48 ± 0.54	1.28 ± 0.18	1.5 ± 0.2	0.154
Uric acid (mg/dl)	7.5 (3.4–9.8)	7.5 (3.4–8.8)	8 (4.3–10.2)	0.873
Mixed venous SO_2 (%)	62 (43–76)	66.4 (41–81)	56 (38–69)	0.061

Continuous variables with normal distribution were given as mean ± standard deviation, with non-normal distribution were given as median and the interquartile range (IQR) and categorical data as percentage. P-value <0.05 for comparison between LVAD patients with and without RHF.

ALT: alanine transaminase; AST: aspartate transaminase; GGT: gamma-glutamyl transferase; INR: international normalized ratio; LDH: lactate dehydrogenase; Pro-BNP: prohormone of brain natriuretic peptide; SO_2: Saturation.

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Table 3: Preoperative echocardiographic and right heart catheterization measurements

Variables	Study cohort ($n = 57$)	No RHF ($n = 37$)	RHF ($n = 20$)	P-value
LA (mm)	49.8 ± 4.3	49.6 ± 4.4	50.3 ± 4.4	0.876
SPAP (mmHg)	57.2 ± 8.4	56.8 ± 8.2	57.3 ± 8.9	0.805
RV (mm)	27.8 ± 4.1	25.1 ± 1.5	32.3 ± 2.5	0.042
LVESD (mm)	60.4 ± 2.1	60.3 ± 2.04	60.7 ± 2	0.28
LVEDD (mm)	64.4 ± 2.9	64.1 ± 2.9	64.9 ± 2.8	0.15
RVESD (mm)	30.4 ± 3.9	30.9 ± 3.7	29.7 ± 4.1	0.36
RVEDD (mm)	40.2 ± 4.1	40.2 ± 4.3	40.3 ± 3.9	0.80
RVEDD/LVEDD	0.79 ± 0.1	0.77 ± 0.12	0.74 ± 0.1	0.139
LVESV	211.9 ± 11.5	212.1 ± 12.08	211.5 ± 10.9	0.343
LVEDV	248.6 ± 13	247.7 ± 13.1	250.1 ± 13.1	0.555
LVEF (%)	21.1 ± 3.8	21.6 ± 3.9	20.3 ± 3.7	0.782
RVEF (%)	31.3 ± 3.6	33.4 ± 1.6	27.9 ± 3.4	0.009
MR (3° or 4°) (%)	35.8	33.3	40	0.121
TR (3° or 4°) (%)	11.3	3	25	0.08
RAA (cm^2)	28.2 ± 3.4	27.3 ± 3.4	29.6 ± 4.5	0.576
RVFWLS	-18.6 ± 2.7	-19.5 ± 2.2	-15.6 ± 0.1	0.003
RVSLS	-13.2 ± 3.3	-15.5 ± 1.1	-9.4 ± 2.1	0.001
RVGLS	-14.8 ± 3.1	-17 ± 1.2	-11.3 ± 1.7	0.007
FAC (%)	27.6 ± 5.5	31.6 ± 1.8	20.9 ± 1.7	0.025
RVMPI	0.32 ± 0.08	0.28 ± 0.07	0.38 ± 0.4	0.143
TAPSE (mm)	14.7 ± 2.4	16.09 ± 1.5	12.4 ± 1.8	0.209
S′	11.9 ± 1.9	13 ± 1.4	10.2 ± 1.2	0.06
E	9 ± 1.38	9.06 ± 1.4	8.9 ± 1.3	0.843
A	16.1 ± 3.3	18.4 ± 1.8	12.4 ± 1.1	0.741
E/*A*	0.53 ± 0.18	0.49 ± 0.1	0.7 ± 0.1	0.18
IVC (mm)	20.6 ± 1.7	20.7 ± 1.6	20.6 ± 1.9	0.933
IV SEPTUM (mm)	0.78 ± 0.03	0.8 ± 0.1	0.88 ± 0.13	0.306
RVOT-SE (mm)	6.2 ± 1.9	7.2 ± 1.4	5.4 ± 1.8	0.001
RVOT-FS (%)	15.2 ± 4.6	18.5 ± 1.5	9.7 ± 1.7	0.001
RVD 1 (mm)	39.9 ± 2.6	39 ± 2.1	41.4 ± 2.6	0.002
RVD 2 (mm)	33.6 ± 2.9	33.6 ± 2.8	34.7 ± 2.7	0.086
RVD 3 (mm)	79.3 ± 5.6	77.2 ± 5.7	82.8 ± 3.5	0.051
Tricuspid annular diameter (mm)	39.9 ± 2.02	39.8 ± 2.1	39.9 ± 1.9	0.89
CO (l/min)	3.2 ± 0.3	3.3 ± 0.3	3.2 ± 0.2	0.102
CaI (l/min/m^2)	1.6 ± 0.1	1.6 ± 0.12	1.63 ± 0.1	0.443
PCWP (mmHg)	24.3 ± 1.5	23.6 ± 1.3	25.3 ± 1.2	0.08
SPAP (mmHg)	54.3 ± 2.9	54.2 ± 3.06	54.5 ± 2.9	0.805
DPAP (mmHg)	35.9 ± 6.03	35.7 ± 6.4	36.2 ± 5.4	0.579
PVR (Wood U/m^2)	4.01 ± 0.8	3.9 ± 0.8	4.2 ± 0.7	0.11
SVR (Wood U/m^2)	19.8 ± 1.40	20.2 ± 1.5	19.7 ± 1.2	0.23
TPG (mmHg)	11.6 ± 2.6	11.1 ± 2.6	12 ± 2.6	0.559
RAP (mmHg)	12.3 ± 2.5	11.5 ± 2.2	13.2 ± 2.6	0.02
RAP/PCWP	0.5 ± 0.1	0.47 ± 0.08	0.5 ± 0.1	0.009
RVCPI	552.8 ± 105.2	586.8 ± 107.8	496.8 ± 75.2	0.02
RVSWI (mmHg ml^{-1} m^{-2})	410.5 ± 112.9	452.3 ± 106.3	342 ± 88.8	0.002
CVP (mmHg)	11.9 ± 3.4	10 ± 2.8	14.5 ± 2.3	0.03

Continuous data are presented as mean ± standard deviation, and categorical data are presented as percentage. P-value <0.05 for comparison between LVAD patients with and without RHF.

A: late transmitral filling velocities; CaI: cardiac index; CO: cardiac output; CVP: central venous pressure; DPAP: diastolic pulmonary arterial pressure; *E*: early transmitral filling velocities; FAC: fractional area change; IV: interventricular septum; IVC: inferior vena cava; LA: left atrium; LVEDD: left ventricular end-diastolic diameter; LVEDV: left ventricular end-diastolic volume; LVEF: left ventricular ejection fraction; LVESD: left ventricular end-systolic diameter; LVESV: left ventricular end-systolic volume; MR: mitral regurgitation; PCWP: pulmonary capillary wedge pressure; PVR: pulmonary vascular resistance; RAA: right atrium area; RAP: right atrial pressure; RHF: right heart failure; RV: right ventricle; RVCPI: right ventricular contractility pressure index; RVD: right ventricular dimension; RVEDD: right ventricular end-diastolic diameter; RVEF: right ventricular ejection fraction; RVESD: right ventricular end-systolic diameter; RVFWLS: right ventricular free wall longitudinal strain; RVGLS: right ventricular global longitudinal strain; RVMPI: right ventricular myocardial performance index; RVOT-FS: right ventricular outflow tract fractional shortening; RVOT-SE: right ventricular outflow tract systolic excursion; RVSLS: right ventricular septum longitudinal strain; RVSWI: right ventricular stroke work index; SPAP: systolic pulmonary arterial pressure; SVR: systemic vascular resistance; TAPSE: tricuspid annular plane systolic excursion; TPG: transpulmonary gradient; TR: tricuspid regurgitation.

Predictive scores

We compared 7 different scoring models for our study population in terms of mean scores of each model (Table 5). Among them, the Fitzpatrick's scoring system ($P = 0.03$) had the highest accuracy for prediction of RHF, whereas the scores of Matthews', Drakos' and ARVEDE (assessment of right ventricular dysfunction predictors before the implantation of a left ventricular assist device in end-stage heart failure patients using echocardiographic measures) models demonstrated modest accuracy with AUC values that varied from 0.45 to 0.51. Although the acute physiology and chronic health evaluation (APACHE) II, the Seattle Heart

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Table 4: Independent predictors of postimplantation RHF

Variables	*P*-value	Odds ratio	95% CI
RVEF (<25%)	0.011	4.68	1.41–15.5
RVSWI (<400 mmHg ml^{-1} m^{-2})	0.048	3.73	1.01–13.7
RVOT-SE (<7 mm)	0.002	1.55	0.31–0.84
RVOT-FS (<15%)	0.02	1.62	0.34–0.78
Prealbumin (<14 mg/dl)	0.037	3.45	1.07–11.03
FAC (<27%)	0.028	3.71	1.15–11.9
RVFWLS (≥19%)	0.003	2.65	1.01–2.43

CI: confidence interval; FAC: fractional area change; RHF: right heart failure; RVEF: right ventricular ejection fraction; RVOT-FS: right ventricular outflow tract fractional shortening; RVOT-SE: right ventricular outflow tract systolic excursion; RVFWLS: right ventricular free wall longitudinal strain; RVSWI: right ventricular stroke work index.

Failure Model (SHFM) and the model for end-stage liver disease (MELD) scoring systems were not designed to predict RHF, they showed similar predictive accuracy. After the receiver-operating characteristic analysis, the SHFM score of 2.5 had the best AUC [AUC 0.70, 95% confidence interval (CI) 0.55–0.84] to predict RHF, whereas the MELD, the APACHE II and the Fitzpatrick's scoring systems had lower AUC values.

Survival

As shown in Fig. 3, survival was evaluated for all patients at 1, 5, 10, 15, 20 and 25 months. The survival rates of all patients with RHF versus without RHF were 25% (95% CI 15.4–34.6%) vs 72.9% (95% CI 61.9–83.9%) at 5 months, 20% (95% CI 1.3–38.7%) vs 62.1% (95% CI 45.1–79.1%) at 10 months, 10% (95% CI 7.9–12.1%) vs 54% (95% CI 37.2–70.8%) at 15 months and 10% (95% CI 7.9–12.1%) vs 45.9% (95% CI 30.7–61.1%) at 20 months and 25 months, respectively. Survival was significantly different for 2 groups ($P = 0.0001$).

DISCUSSION

Depending on the definition of RHF, the incidence widely varies in different studies. In some series, RHF was defined as the abrupt insertion of an RVAD alone and reported 8–15% incidence of RHF [9, 19]. In other studies, the incidence of RHF was between 20% and 50% in which RHF was defined as the use of an intravenous inotrope for more than 14 days after surgery or unplanned insertion of an RVAD or extracorporeal membrane oxygenation. A recent study comparing INTERMACS level I and level II to level III and level IV patients predicted higher complication rates and mortality but did not significantly predict postoperative RHF [20]. Thirty-eight (66.6%) patients in our study cohort were in the INTERMACS I or II profile preoperatively; consequently, the mortality, morbidity and the incidence of RHF were relatively higher.

In this study, we included the RHF predictive scores derived from the Matthews' [8], the Drakos' [4], the Fitzpatrick's [3] and the ARVEDE [18] models and the heart failure mortality models such as the SHFM [21], the MELD [22] and the APACHE II [23] used in intensive care units for predicting mortality. Although the scoring systems developed for RHF prediction (Matthews', Drakos', Fitzpatrick's and ARVEDE models) seemed to be accurate in their populations, the only scoring system that appeared to be

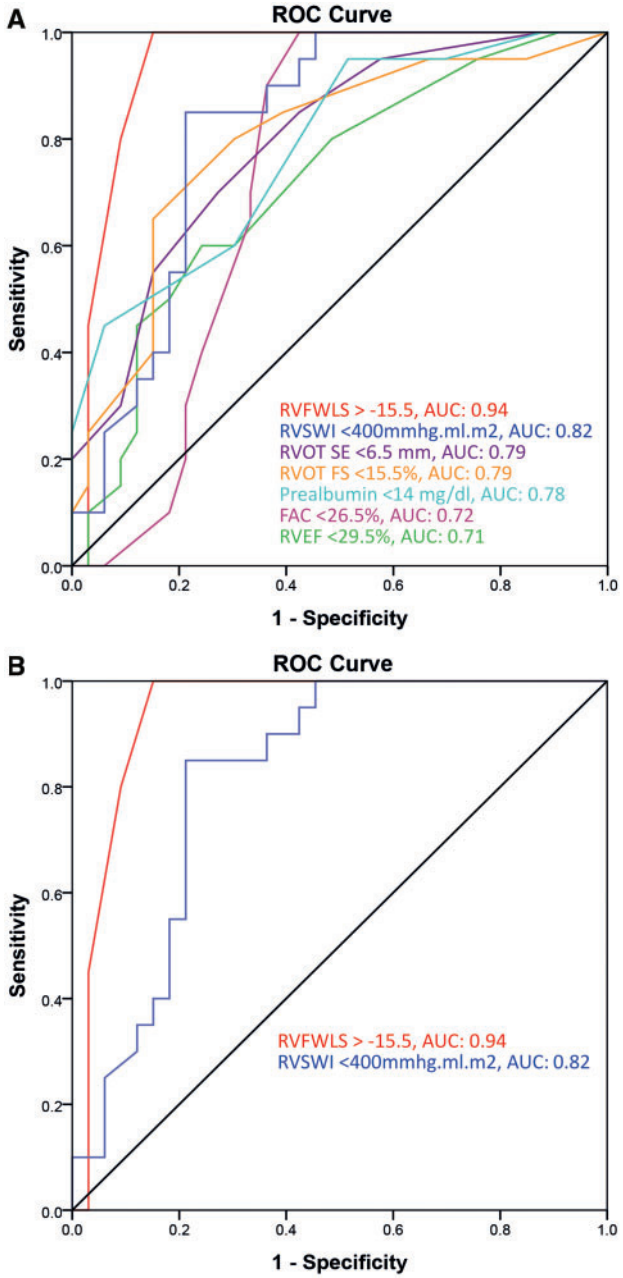


Figure 1: (**A**) ROC curves for the independent right heart failure predictors with their specific cut-off values. (**B**) ROC curves for two independent risk factors having the highest AUC. The line of unity is representing right heart failure with an AUC of 50%. AUC: area under the curve; FAC: fractional area change; ROC: receiver-operating characteristic; RVEF: right ventricular ejection fraction; RVFWLS: right ventricular free wall longitudinal strain; RVOT-FS: right ventricular outflow tract fractional shortening; RVOT-SE: right ventricular outflow tract systolic excursion; RVSWI: right ventricular stroke work index.

significantly correlated with RHF was the model of Fitzpatrick *et al.* in our study population. Several factors should be considered for the limitations of these models. Firstly, these scores have been derived from a limited population in a retrospective manner. Secondly, the parameters used in the scoring models have been mostly already the markers of RHF, and this might weaken the prediction power of systems. To minimize these mispredictions, Loghmanpour *et al.* [24] designed a Bayesian analysis which showed great promise as a reliable and accurate risk stratification

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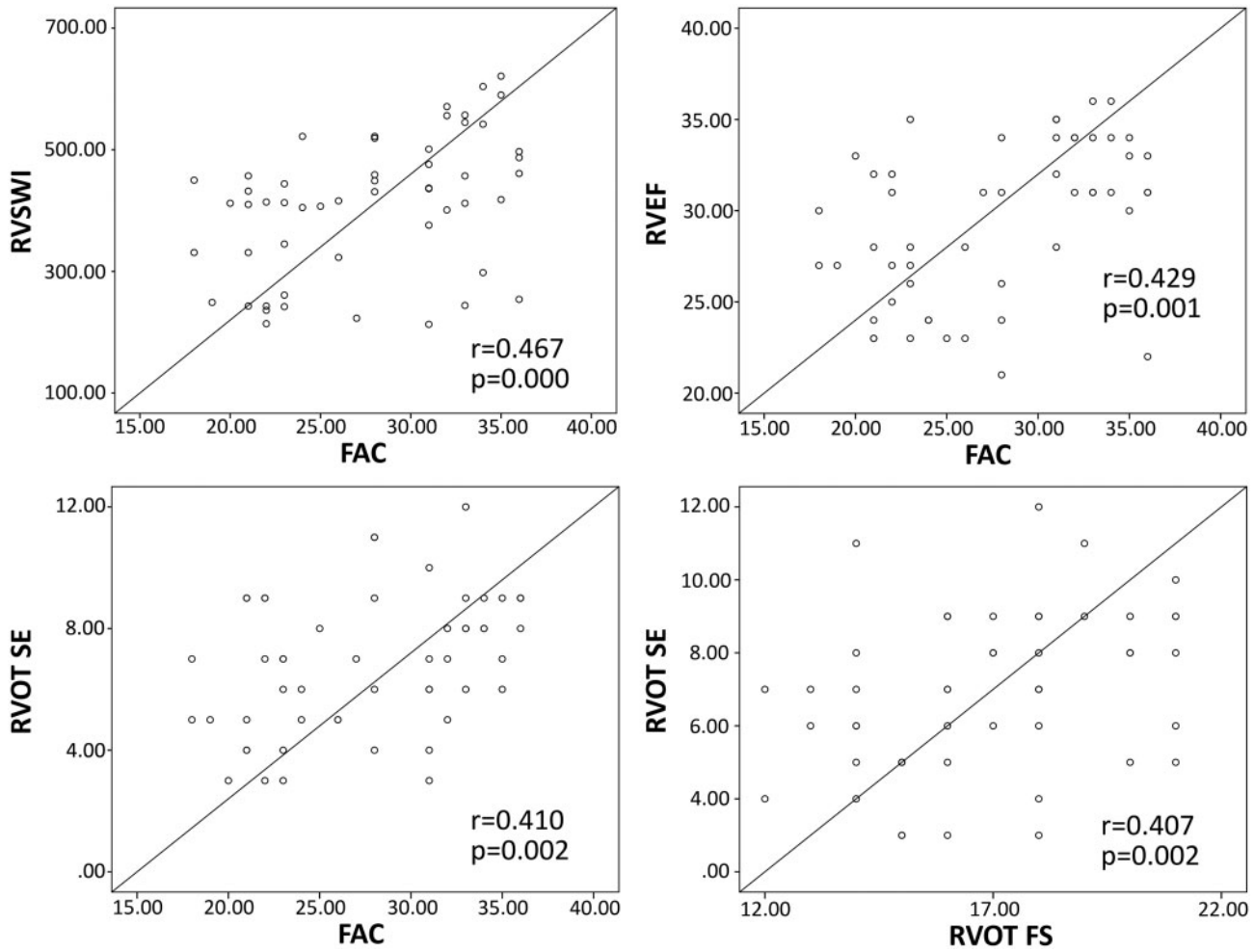


Figure 2: The Spearman correlations of significant independent risk factors. FAC: fractional area change; ROC: receiver-operating characteristic; RVEF: right ventricular ejection fraction; RVOT-FS: right ventricular outflow tract fractional shortening; RVOT-SE: right ventricular outflow tract systolic excursion; RVSWI: right ventricular stroke work index.

Table 5: Preoperative clinical scores of population

Variables	Total cohort ($n = 57$)	No RHF ($n = 37$)	RHF ($n = 20$)	*P*-value
Matthews'	3.43 ± 1.57	3.46 ± 1.73	3.36 ± 1.31	0.98
Fitzpatrick	46.5 ± 5.34	45.3 ± 5.25	48.6 ± 4.96	0.03
Drakos'	12.5 ± 2.17	12.06 ± 1.67	13.4 ± 2.66	0.08
ARVEDE	2.3 ± 1.02	2.9 ± 0.88	3.16 ± 0.12	0.18
SHFM	2.47 ± 1.01	2.03 ± 0.88	3.2 ± 0.76	0.001
MELD	12.59 ± 4.11	11.2 ± 2.68	14.9 ± 5.02	0.04
APACHE II	17.4 ± 3.36	16.3 ± 3.2	19.1 ± 2.96	0.028

Continuous data are presented as mean ± standard deviation.

P-value <0.05 for comparison between LVAD patients with and without RHF.

APACHE II: acute physiology and chronic health evaluation; ARVEDE: assessment of right ventricular dysfunction predictors before the implantation of a left ventricular assist device in end-stage heart failure patients using echocardiographic measures; MELD: model for end stage liver disease; RHF: right heart failure; SHFM: Seattle Heart Failure Model.

tool for clinical decision-making to predict the risk of RHF in a large, multicentre LVAD cohort using the INTERMACS registry. They also evaluated the accuracy of existing scoring systems (Matthews' and Drakos' scoring systems) which were used for predicting RHF and found that the accuracy of them was virtually equivalent to the flip of a coin. In our study, the scoring systems (the SHFM, APACHE II and MELD scoring systems) not developed for predicting RHF originally had better accuracy than the RHF prediction models. Wang *et al.* [2, 25] also created a model using a decision tree classifier, but it was also limited to a single centre

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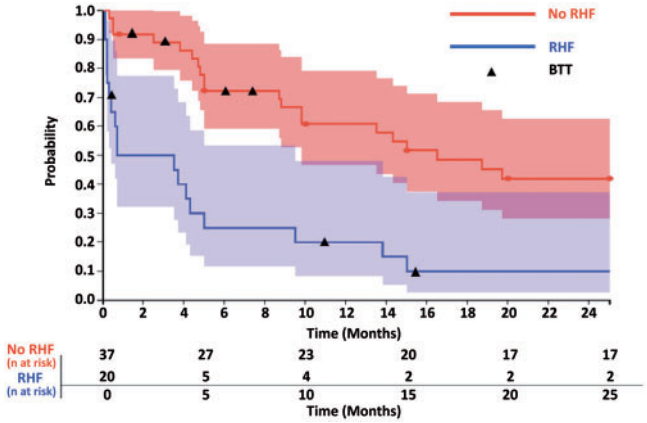


Figure 3: Survival probability for patients after left ventricular assist device with or without right heart failure. The patients bridged to transplantation were marked in the survival curve with '▲'. BTT: bridge to transplantation; RHF: right heart failure.

and continuous-flow LVADs even though it provided promising results in related individuals. Consequently, RHF occurring after LVAD is multifactorial, including patient characteristics, biomarkers, haemodynamic and echocardiographic parameters. New scoring models developed with multicentre, prospective studies may facilitate a clinical decision, while screening candidates for RHF before LVAD implantation in the future.

Despite the opportunity for the detailed evaluation of the right ventricle with the development in echocardiographic techniques, incorporated echocardiographic parameters are very limited in current scoring systems. Tricuspid annular plane systolic excursion, RVEF, FAC, right ventricular end-diastolic diameter, RVEDS and RVSWI are the most commonly used parameters. We also demonstrated that commonly used measurements, RVSWI, RVEF and FAC were valuable in predicting post-LVAD RHF, but surprisingly tricuspid annular plane systolic excursion, RVEDS, right ventricular end-diastolic diameter and RVD were not significantly associated with RHF in our study.

A relatively new approach, speckle-tracking echocardiography, which has the advantage of differentiating active motion from passive motion, uses the strain imaging to assess the ventricular function [26–28]. Fukuda *et al.* [29] reported that the RVFWLS was significantly correlated with mPAP and pulmonary vascular resistance in patients with pulmonary hypertension. Grant *et al.* [6] also emphasized that global longitudinal strain of the right ventricular free wall represents a new parameter to predict RHF, and this parameter may assist in making clinical decisions in the future. RVOT-SE is another novel parameter used in right ventricular performance. Asmer *et al.* showed that RVOT-SE > 6 mm had 100% sensitivity and specificity in patients with reduced right ventricular function and also found the significant difference in survival between the patients with RVOT-SE < 6 mm vs > 6 mm [30]. This study confirms to show the utility of RVLS and RVOT-SE significantly; furthermore, RVFWLS demonstrated the highest diagnostic accuracy (AUC 0.94) and good sensitivity and specificity of 86% and 84%, respectively, using a cut-off value of greater than -15.5%. To the best of our knowledge, the current study is the first, which used the RVFWLS and RVOT-SE concomitantly in patients who will undergo LVAD implantation and showed the usefulness of these parameters for the prediction of right ventricular performance after implantation.

In particular, among the independent risk factors obtained in our study, we found the strongest and significant correlation between RVEF and FAC, whereas no significant correlation was obtained for RVFWLS with other risk factors. These results can be explained by the fact that these measurements may guarantee only a regional evaluation and are affected by several different conditions.

Limitations

The case series retrospectively organized in a single centre are susceptible to reporting bias. The limitations of the present study are single-centre design and small sample size. Including the high number of patients with INTERMACS I or II profiles in our institution may affect the present analysis.

CONCLUSION

Predictive performance of single and easily determined echocardiography parameter, RVFWLS ≥-15.5% and RVSWI <400 mmHg ml^{-1} m^{-2} were confirmed as the highest discriminatory power in low INTERMACS profile Turkish population who underwent LVAD therapy. However, both RVFWLS and RVSWI should be regarded as additional predictive factors for RHF in the preoperative decision-making process of the Heart Team. Previously described prediction risk scores had the modest power of accuracy in our population. Independent validation, multicentre prospective studies with larger cohorts, the use of machine learning systems to have the intuitive structure and tolerance of missing or erroneous data elements such as the Bayesian prognostic models [2, 24] are warranted to predict and avoid RHF following LVAD implantation.

Conflict of interest: none declared.

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