Pressure-dimension index: A novel "morphologic-functional" index of right ventricle that predicts short-term survival after left ventricular assist device implantation

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Abstract

Background: Right ventricular failure (RVF) after left ventricular assist device (LVAD) implantation is a major cause of postoperative morbidity and mortality. Despite the availability of multiple imaging parameters, none of these parameters had adequate predictive accuracy for post-LVAD RVF. Aim: To study whether right ventricular pressure-dimension index (PDI), which is a novel echocardiographic index that combines both morphologic and functional aspects of the right ventricle, is predictive of post-LVAD RVF and survival. Methods: 49 cases that underwent elective LVAD implantation were retrospectively analyzed using data from an institutional registry. PDI was calculated by dividing systolic pulmonary artery pressure to the square of the right ventricular minor diameter. Cases were categorized according to tertiles. Results: Patients within the highest PDI tertile (PDI>3.62 mmHg/cm2) had significantly higher short-term mortality (42.8%) and combined short-term mortality and definitive RVF (50%) compared to other tertiles ($p<0.05$ for both, log-rank p for survival to 15th day 0.014), but mortality was similar across tertiles in the long-term follow up. PDI was an independent predictor of short-term mortality (HR:1.05–26.49, p=0.031) and short-term composite of mortality and definitive RVF (HR:1.37–38.87, p=0.027). Conclusions: Increased PDI is a marker of an overburdened right ventricle. Heart failure patients with a high PDI is at risk for short-term mortality following LVAD implantation.

1. Introduction

Despite improvements in patient selection and management algorithms, right ventricular failure (RVF) remains as a major cause of postoperative morbidity and mortality following left ventricular assist device (LVAD) implantation and seen in up to 13% - 51% of patients, depending on the definition of RVF (1,2). Several clinical, imaging, laboratory and catheterization parameters are available to predict postoperative RVF with variable diagnostic accuracy (3). Of those, transthoracic echocardiography (TTE) plays a pivotal role for preoperative evaluation of the right ventricle (RV) as this is a widely available modality that could be easily utilized at bedside and it allows a comprehensive evaluation for the structural and functional alterations in the RV (3). Numerous echocardiographic parameters were studied as a possible "gold-standard" method to predict post-LVAD RVF, though these variables rarely performed well beyond their initial study cohort. A recent meta-analysis that included available echocardiographic parameters has concluded that a qualitative analysis of the RV remains as the best predictor of postoperative outcomes (3).

A major shortcoming of all available standalone parameters is that the variable in question either evaluates structural (i.e. RV diameter or RV to left ventricle (LV) ratio) or hemodynamic / functional (tricuspid annular excursion, pulmonary artery pressure) changes in the RV. As a result, other aspects of the RV structure or function is omitted and therefore the parameter studied does not fully reflect alterations in the RV. As such, an index that combines both structural and hemodynamic/functional changes in the RV could theoretically be more useful over existing parameters to predict post-LVAD RVF.

In the present analysis, we aimed to investigate the usefulness of RV pressure-dimension index (PDI), a novel index that reflects both the structural and functional changes in the RV, to predict post-LVAD short-term and long-term mortality and RV failure. In addition, correlation of PDI with available parameters of RV structure and function was also investigated.

2. Materials and Methods

Data for the present study was obtained from an institutional advanced heart failure registry that prospectively collected demographic, clinical, echocardiography, invasive and outcome data from patients with advanced heart failure that are candidates for LVAD implantation or cardiac transplantation. All patients that were aged 18 years and older, had complete pre-implantation and follow-up records and had an LVAD implanted in a non-emergent setting were considered eligible for the present analysis. Per registry protocol, all patients have offline echocardiographic images recorded and stored prior to LVAD implantation. Patients with missing echocardiographic or catheterization data that would prevent calculating PDI or other parameters used in statistical analyses were excluded. No other exclusion criteria were used. Out of 54 patients that were initially assessed for eligibility, 49 were included to the final analysis after applying these criteria.

Demographic, clinical, laboratory and catheterization data were obtained using registry data. Echocardiographic measurements and analyses were done using stored offline images as detailed below. No specific written consent was sought for the present study, but a written consent from all patients were obtained prior to inclusion to the institutional registry. Present study was carried out according to the principles of the Declaration of Helsinki in 1975, and a local ethic committee approval was obtained.

2.1 Definitions

Right ventricular failure was defined as probable or definite if the patient needed inotropic drugs with/without pulmonary vasodilators for at least 7 days and 14 days, respectively. For both definitions, there should be no other coexisting condition (i.e. hypovolemia or pericardial tamponade) that would necessitate inotropic use, central venous pressure should be 16 mmHg or higher and postoperative echocardiographic findings should be compatible with right heart failure. In addition, patients who needed temporary right heart support via a short-term mechanical assist device or extracorporeal membrane oxygenator were automatically considered as having definite right ventricular failure (4). Mortality was defined as death from any cause.

2.2 LVAD implantation

All patients included to the present study underwent surgery on an elective basis, and received either a Heartmate II, Heartmate III (Thoratec Inc., Pleasanton, CA, USA) or a Heartware HVAD (HeartWare Inc., Framingham, MA, USA). Per institutional protocol, dobutamine (5 mcg/kg/min) and levosimendan (no bolus, starting with a dose of 0.05 mcg/kg/min titrated up to 0.02 mcg/kg/min as tolerated) were administered prior to implantation. Device implantation was performed by midline sternotomy. Due to regulatory reasons, all patients underwent implantation with a bridge-to-transplant (BTT) or bridge-to-candidacy (BTC) indications, though none of the patients actually underwent transplantation during the follow-up period.

2.3 Cardiac catheterization

Preoperative right heart (with or without left heart) catheterization procedures were done from femoral or right internal jugular veins by an interventionalist experienced in hemodynamic measurements. Indirect Fick method was used to calculate cardiac output, and Bergstra's formula was used to estimate minute oxygen consumption (5,6). Right ventricular stroke work index was calculated by subtracting right atrial pressure from mean pulmonary artery pressure and multiplying the result with stroke volume index.

2.4 Echocardiography

All echocardiographic procedures were performed using an echocardiography platform equipped with a 2.5 MHz phased-array transducer (Vivid 3, GE Healthcare, Piscataway, NJ). Per heart failure clinic protocol, all examinations were performed by the members of advanced heart failure team that are competent in echocardiographic procedures. Stored images and 3-beat loops that were acquired from parasternal long-axis, parasternal short-axis and apical views were analyzed to repeat all measurements and calculations. Right ventricular PDI was calculated using the following equation:

Eq 1. PASP / $RVMD^2$

where RVMD is right ventricular minor diameter as measured immediately above the tricuspid valve at end-diastole and PASP is the systolic pulmonary artery pressure (Figure 1). Echocardiographic PASP was calculated according to relevant guidelines (7). Right ventricular contraction pressure index was calculated as defined before (8). For the purposes of the present study, images were used from the echocardiographic examination that immediately preceded left ventricular assist device implantation, and this is done two days before planned implantation date. None of the patients were on inotropes or vasoactive drugs when echocardiographic examination was performed. All measurements and calculations were performed according to relevant guidelines.

2.5 Statistical methods

For the purposes of this study, patients were divided into tertiles according to their PDI and the data was analyzed accordingly. Continuous variables were given as mean ± SD or median and IQR depending on the pattern of distribution. Categorical variables were presented as number and percentages. Patterns of distribution and equality of variances for continuous variables were tested using Shapiro-Wilk and Levene's tests, respectively. For continuous variables, either one-way ANOVA with post-hoc Tukey test or Kruskal-Wallis test were used as appropriate to determine significant differences between groups. For variables with a skewed distribution, Mann-Whitney U test was used to find the exact difference between groups if Kruskal-Wallis test suggested a significant difference. Categorical variables were analyzed using χ^2 test and standardized residuals were calculated to determine deviations from expected values. Correlations between echocardiographic and catheterization variables with PDI were analyzed using Spearman's Rho. Kaplan-Meier curves were drawn to analyze*i)* survival to postoperative day 15, *ii)* survival free of RVF at postoperative day 15, *iii)* total long-term survival for PDI tertiles. Log-rank test was used to determine significant differences between PDI tertiles in terms of survival. Cox proportional hazards models were built to analyze the association of demographic, clinical, laboratory and echocardiographic with short-term survival and RVF-free survival. A univariate analysis was initially done to select parameters that were associated with events, and parameters with a p value less than <0.1 were included in the final multivariate Cox regression analysis. These models did not include echocardiographic systolic pulmonary artery pressure and right ventricular end-diastolic minor diameters due to collinearity of these parameters with PDI.

All statistical analyses were performed using SPSS 17.0 for Windows (IBM Inc, USA). For all comparisons, a p value below 0.05 was accepted as statistically significant.

3. Results

Mean age of the study sample was 50.57 ± 7.33 and 40 patients (81.6%) were male. Approximately half of the patients had ischemic cardiomyopathy (n=25, 51%). 69.4% (n=34) had symptoms compatible with an INTERMACS profile between IV-VII, while the remaining 30.6% (n=15) were classified as INTERMACS II or III. Preoperative visual echocardiographic assessment indicated RVF in 17 (34.7%) of patients. At postoperative day 15, 13 (26.5%) patients had probable and 4 (8.2%) patients had definitive RVF and a total of 10 patients (20.4%) died. Patients with a PDI [?] 2.41 $mmHg/cm^2$, 2.41 $mmHg/cm^2$ < PDI [?]3.62 $mmHg/cm^2$ and PDI >3.62 $mmHg/cm^2$ were assigned to the PDI tertiles.

3.1 Clinical characteristics according to pressure-dimension index tertiles

Clinical and laboratory characteristics of patients within the three PDI groups were summarized in Table 1. The only remarkable difference between groups in terms of clinical and demographic variables was that the number of patients with an ischemic cardiomyopathy was significantly higher in the second tertile. As expected, RVMD and PASP on echocardiography were significantly different between groups, although catheter-measured mean pulmonary artery pressure did not differ among groups. Instead, right atrial pressure (RAP) and pulmonary vascular resistance (PVR) were significantly different, with the former being lowest and the latter being highest in the third tertile (Table 2).

3.2 Correlation of pressure-dimension index with echocardiographic and catheterization parameters

As expected, PDI had significant correlations with right ventricular end-diastolic diameter ($p<0.001$, r=-0.626) and echocardiographic systolic pulmonary pressure (p=0.001, r=0.442). No other echocardiographic parameter correlated with PDI, including visual assessment of RV and tricuspid regurgitation velocity. Of catheterization parameters, PDI had shown a significant correlation with RAP (r=-0.402, p=0.007), RAP/wedge pressure ratio (r=-0.369, p=0.014) and PVR (r=0.447, p=0.002) (Figure 2). To note, the association between PDI and PVR was in part related to the correlation between PASP and PVR (r=0.297, p=0.05).

3.3 Relationship of pressure-dimension index with short and long term outcomes

There were no significant differences between the tertiles in terms of probable or definitive RVF, but patients with a higher PDI had a significantly higher short-term mortality or the composite of mortality and definitive RVF a postoperative day 15 as compared to other PDI tertiles (Table 2). Accordingly, survival to postoperative day 15 (log-rank p=0.014) and survival free of definitive RVF to postoperative day 15 (log-rank p=0.021) were significantly different between groups, with the latter mainly driven by mortality (Figure 2A and 2B). On multivariate analysis, PDI was an independent predictor of short-term mortality or composite short term mortality or definitive right ventricular failure (Table 3). PDI was not found as a significant determinant of long-term mortality (log-rank p=0.08), although the lowest mortality rate as well as highest mean survival was seen in the second tertile (mortality 29.7%, mean estimated survival 1289 days) (Figure 3).

4. Discussion

Present study was an exploratory analysis that assessed PDI as a potential tool for predicting short and long-term mortality following continuous-flow LVAD implantation. Key findings from this study were as follows: i) patients with the highest PDI values were significantly more likely to have a higher mortality within 15 days of LVAD implantation, ii) PDI was not useful to predict long term mortality, though patients with intermediate PDI values had better survival and iii) a high PDI reflects lower RAP and elevated PVR. While a higher PDI also indicated a lower short-term survival free of RVF, this was driven mainly by mortality rather than RVF.

4.1 Imaging predictors of right ventricular failure after left ventricular assist device implantation

Echocardiographic parameters that have been studied as possible predictors of RVF can be broadly classified into two subgroups; those that represent geometric changes in the right ventricle (9,10) and those that reflect RV performance, hemodynamic changes, or both (8,11,12). A shortcoming of these parameters is that they usually do not fully reflect adaptive or maladaptive changes in the RV that occurs as heart failure progresses. Postoperative RVF has many causes, including but not limited to right ventricular volume overload, ventricular interdependence, high right ventricular afterload and inherent abnormalities in the right ventricular contractility (13). A single measurement that provides only one "dimension" of RV morphology or function could hardly predict occurrence of RVF in all patients when the causes of RVF differ among patients, which could also explain why singular echocardiographic measurements perform poorly when they are used in cohorts other than original derivation cohort.

4.2 Right ventricular geometry and afterload

Pressure-dimension index classifies patients according to the morphology and afterload of the RV. Previous observations have found that low RV systolic pressure (RVSP) and RV dilation identify a subset of patients with vulnerable RV that is more prone to have postoperative RVF (9,10,14), though high RV afterload also appears as a marker in other studies (15). In that sense, patients within the lower spectrum of PDI would be more likely to have an "exhausted" RV phenotype while those with higher PDI would be more likely to have "overburdened" (i.e., high RVSP) RVs. Contrary to our initial predictions, our findings indicated that patients with an "overburdened" RV have a much higher short-term mortality as compared to other tertiles, including those within the first tertile. A possible explanation of this finding is that the patients with a true exhausted RV phenotype might have been excluded as the analyzed data was obtained from an institutional registry and patients that were deemed to have a high risk of postoperative RV failure were not considered for LVAD implantation. Another possible explanation is that some patients with a low PDI might not have an exhausted RV phenotype (i.e. those with a low RV afterload and moderately dilated RV), thus creating a mixed group of patients with normal and dysfunctional RV's. As such, in the first tertile neither visual assessment nor conventional echocardiographic findings suggested that RV dysfunction was as prevalent as could be expected from patients with a true exhausted RV phenotype. It can be assumed that those with a lower PDI that is found for the first tertile (x=1.94) could identify a group of patients that have a true exhausted RV and therefore at high risk for post-LVAD RV failure, though this assumption needs further studies to verify whether it could be useful in clinical practice.

In contrast, patients with an overburdened RV phenotype have an excess short-term mortality following LVAD implantation and therefore a high PDI can be a useful tool to identify those at high risk for post-LVAD mortality. These patients had a small RV with high PASP, high PVR and a lower RAP, but parameters associated with RV systolic function were preserved (Tables 1 and 2). Although evidence suggest that LVADs could reduce PVR in the long-term, a beneficial effect of unloading is less likely in the immediate postoperative period due to structural pulmonary remodelling, thus making these patients more susceptible to RVF (17,17). Moreover, a smaller RV cavity would be less likely to handle volume overload caused by an LVAD, which could be an additional factor that facilitates RVF (18). It should be emphasized that our data does not indicate an excess RVF in patients surviving to postoperative days 7 and 14 and the present study could not establish whether the cause of death was RVF in patients within the third tertile. It is equally difficult to suggest that a high PDI is not related to RVF given that there are no other reasons for PDI to predict mortality since this novel parameter only reflects alterations in RV. However, a cause-and-effect mechanism cannot be established with available data and as such, a high PDI should only be regarded as a marker of short-term mortality until more data becomes available.

4.3 Clinical usefulness of pressure dimension index and future perspectives

Predicting RVF is a major goal to reduce postoperative morbidity and/or mortality, but available evidence suggests that available parameters, indices or algorithms are insufficient to reach this goal (3). Since present data is obtained from a small sample of subjects enrolled from a single centre, it would not be reasonable to suggest that PDI could be incorporated in routine echocardiographic practice before LVAD implantation. Rather, PDI can be useful in selected cases to help clinicians identifying patients that would be at-risk for short term mortality who could benefit from intensive hemodynamic support in the postoperative period. However, we consider that the real value of the present "pilot" study is that a index combining both the functional and structural aspects of the RV could be more useful than traditional parameters that capture only one "dimension" of the RV. PDI or other similar "multidimensional" indices could be tested in future studies, which would allow a more precise classification of the right ventricular alterations in heart failure patients that are candidates for an LVAD.

5. Limitations

Present data was obtained from a single centre and from a limited number of patients, so it should be regarded as a "hypothesis-generating" study. This limited sample size also drastically reduces the power of the study and therefore limits the reliability of the results. The retrospective design of the study prevents making detailed analyses on the causes of death for patients within the third PDI tertile to ascertain whether these cases had RVF immediately before their death. The sample size is too small to compare PDI with other established risk predictors and risk scores, so it is unclear whether PDI offers incremental usefulness over existing methods. While this was an "all-comers" study, patients who were deemed to have at high risk for RVF did not undergo LVAD implantation and that constitutes an unavoidable "selection bias". As aforementioned, this bias may also explain why a low PDI failed to predict RVF, contrary to our initial expectations. Finally, as this analysis is retrospective, not all confounders might have been accounted for.

6. Conclusions

Pressure-dimension index is a novel index that reflects both structural alterations and functional changes in the RV. Patients with a high preoperative PDI are at risk for postoperative short-term mortality and lower survival free of RVF after an LVAD implantation, and this increased mortality is presumed to be due to RVF. However, a high PDI was not suggestive of a poor long-term survival in LVAD patients. While PDI was found as an independent predictor of short-term survival or short-term survival free of RVF, it is uncertain whether it offers incremental usefulness over existing parameters for clinical decision-making and therefore further studies are needed to determine the role of PDI for identifying patients at-risk for post-LVAD RVF.

7. References

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Parameter	1^{st} Tertile (n=16)	2^{nd} Tertile (n=17)	3^{rd} Tertile (n=16)	P value
Demographic and Clinical Variables	Demographic and Clinical Variables	Demographic and Clinical Variables	Demographic and Clinical Variables	Demographic and Clinical Variables
Age (y)	48.4 ± 8.6	49.8 ± 8.0	52.6 ± 6.6	0.30
Gender (%Male)	81.3%	88.2%	75.0%	0.62
Body Surface Area (m^2)	1.96 ± 0.18	1.91 ± 0.21	1.82 ± 0.18	0.21
Heart Rate (bpm)	92.25 ± 12.73	87.53 ± 15.40	90.94 ± 13.23	0.60
Systolic BP (mmHg)	111.77 ± 26.55	110.19 ± 14.45	110.64 ± 23.17	0.94
Diastolic BP (mmHg)	69.95 (28.75)	73.50 (10.50)	74.95 (11.75)	0.88
Type of Cardiomyopathy Ischemic Nonischemic	37.5% 62.5%	76.5% 37.5%	37.5% 62.5%	**0.03**
NYHA Class Advanced Class III Class IV	75.0% 25.0%	64.7% 35.3%	68.8% 31.3%	0.81
Rhythm on ECG Sinus Rhythm Atrial Fibrillation	56.3% 43.8%	82.4% 17.6%	75.0% 25.0%	0.24

Parameter	1st Tertile (n=16)	2nd Tertile (n=17)	3rd Tertile (n=16)	P value
Echocardiographic Parameters	Echocardiographic Parameters	Echocardiographic Parameters	Echocardiographic Parameters	Echocardiographic Parameters
Left Ventricular EDD (mm)	70.00 ± 7.65	67.82 ± 7.89	72.05 ± 8.86	0.34
Left Ventricular ESD (mm)	55.60 (10.21)	52.56 (8.13)	55.20 (6.00)	0.35
Left Ventricular EF (%)	20.00 (5.00)	20.00 (5.00)	20.00 (10.00)	0.58
Right Ventricular EDD (mm)	46.26 ± 5.54	$40.26 \pm 4.58^{*}$	$34.50 \pm 5.76^{+++}$	**<0.001**
TAPSE (mm)	18.56 ± 3.44	18.71 ± 2.85	16.56 ± 3.69	0.14
TRV (m/s)	2.83 ± 0.47	3.14 ± 0.42	$3.26 \pm 0.47^{+}$	**0.03**
Systolic Pulmonary Pressure (mmHg)	41.94 ± 11.29	51.00 ± 13.57	$54.13 \pm 14.49^{+}$	**0.03**
Pressure/Dimension Index ($mmHg/cm^2$)	1.94 ± 0.36	$3.09 \pm 0.34^{*}$	$4.67 \pm 1.39^{+++}$	**<0.001**
Severity of TR Mild-Moderate Severe	81.3% 18.8%	94.1% 5.9%	87.5% 12.5%	0.52
Right Ventricular Failure by Visual Assessment (%)	31.3%	29.4%	43.8%	0.65
Laboratory Variables	Laboratory Variables	Laboratory Variables	Laboratory Variables	Laboratory Variables
Blood Urea Nitrogen (mg/dl)	23.28 ± 7.74	24.88 ± 4.82	24.11 ± 7.93	0.91
Creatinine (mg/dl)	0.94 ± 0.16	1.04 ± 0.31	0.86 ± 0.15	0.24
ALT (IU/L)	17.00 (34.00)	17.50 (31.50)	13.00 (20.50)	0.67
AST (IU/L)	19.00 (21.00)	17.50 (18.50)	16.00 (12.00)	0.91
Albumin (mg/dl)	3.90 ± 0.26	3.84 ± 0.54	3.88 ± 0.51	0.96

Table 1. Demographic, anthropometric, clinical, echocardiographic and laboratory data for pressure-dimension index tertiles. P values that were lower than 0.05 were given in bold. BP, blood pressure; NYHA, New York Heart Association; EDD, end-diastolic diameter; ESD, end-systolic diameter; EF, ejection fraction; TAPSE, tricuspid annular plane excursion; TRV, tricuspid regurgitation velocity; TR, tricuspid regurgitation; ALT, alanine transaminase; AST, aspartate transaminase.

* $p<0.05$ for pairwise comparisons between 1st and 2nd tertiles.

+ $p<0.05$ for pairwise comparisons between 1st and 3rd tertiles.

++ $p<0.05$ for pairwise comparisons between 2nd and 3rd tertiles.

Table 2. Short and long-term outcome data for study groups. P values that were lower than 0.05 were given in bold. RVF, right ventricular failure. PCWP, pulmonary capillary wedge pressure; SWI, stroke work index; RVF, right ventricular failure.

Parameter	1st Tertile (n=16)	2nd Tertile (n=17)
Right Heart Catheterization Findings	Right Heart Catheterization Findings	Right Heart Catheterization
PCWP (mmHg)	30.00 (8.50)	28.00 (12.50)
Mean Pulmonary Artery Pressure (mmHg)	36.00 (14.50)	34.50 (17.00)
Right Atrial Pressure (mmHg)	15.00 ± 4.12	11.75 ± 4.91
Right Atrial Pressure / PCWP	0.55 ± 0.15	0.46 ± 0.16
Cardiac Index (L/min/m^2)	1.84 ± 0.31	1.90 ± 0.36
Pulmonary Vascular Resistance (Woods Unit)	2.53 ± 0.87	2.90 ± 1.53
Right Ventricular SWI (mmHg.ml/m^2)	425.77 ± 185.27	505.31 ± 147.64
Outcomes	Outcomes	Outcomes
Probable RVF at Postoperative Day 7	26.7%	37.5%
Definitive RVF at Postoperative Day 14	7.1%	6.3%
Mortality at Postoperative Day 15	12.5%	5.9%
Mortality or Definitive RVF at Postoperative Day 15	18.8%	11.8%
Total Mortality	50.0%	29.4%

$^{+}$ $p<0.05$ as compared to 1st tertile

$^{++}$ $p<0.05$ as compared to 2nd tertile

¶ Standardized residuals were higher than +1.96.

Table 3. Univariate and multivariate determinants of short-term mortality and short term combined end-point for study groups. P values that were lower than 0.05 were given in bold. For short-term all-cause mortality, age was not a univariate determinant but found as a significant determinant of short-term mortality in multivariate analysis. TAPSE, tricuspid annular systolic excursion; NYHA, New York Heart Association; RV, right ventricle; TR, tricuspid regurgitation.

Parameter	Univariate Analysis	Multivariate Analysis	Multivariate Analysis	Multivariate Analysis
	P Value	**OR**	**95% CI**	**P Value**
Short-Term All-Cause Mortality	Short-Term All-Cause Mortality	Short-Term All-Cause Mortality	Short-Term All-Cause Mortality	Short-Term All-Cause Mortality
Gender (Female)	**0.045**			
NYHA Class (Class IV)	**0.024**			
TAPSE (mm)	**0.053**			
NYHA Class (Class IV)	**0.024**			
Echocardiographic RVF (%)	**0.047**			
Severity of TR (severe)	**0.032**	4.79	1.15 – 19.88	**0.031**
RV Pressure Dimension Index 1st Tertile (Reference) 2nd Tertile 3rd Tertile	**0.081 0.004**	5.27	1.05 – 26.49	**0.044**

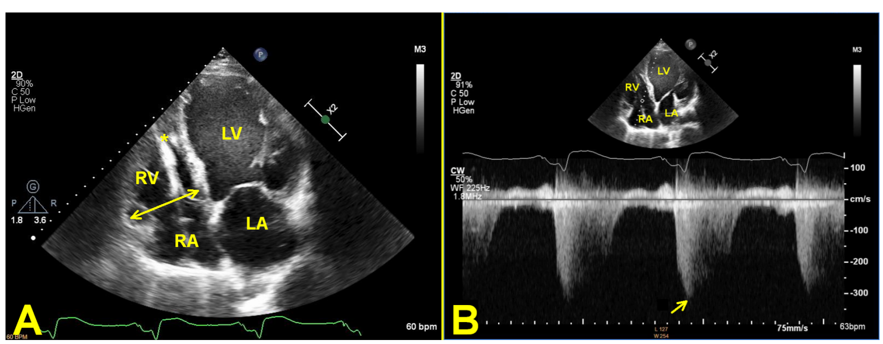
Parameter	Univariate Analysis	Multivariate Analysis	Multivariate Analysis	Multivariate Analysis
Short-Term Mortality or Definitive Right Ventricular Failure	Short-Term Mortality or Definitive Right Ventricular Failure	Short-Term Mortality or Definitive Right Ventricular Failure	Short-Term Mortality or Definitive Right Ventricular Failure	Short-Term Mortality or Definitive Right Ventricular Failure
Age (per year)	**0.046**	0.89	0.83 – 0.96	**0.003**
NYHA Class (Class IV)	**0.047**			
TAPSE (mm)	**0.013**	0.84	0.73 – 0.98	**0.027**
Echocardiographic RVF (%)	**0.017**			
RV Pressure Dimension Index 1st Tertile (Reference) 2nd Tertile 3rd Tertile	0.105 **0.008**	7.26	1.37 – 38.87	**0.027**

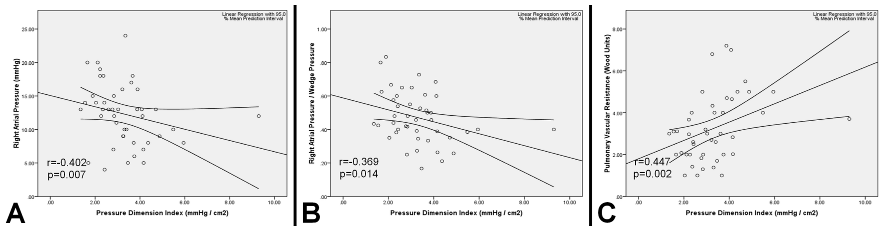
Figure Legends

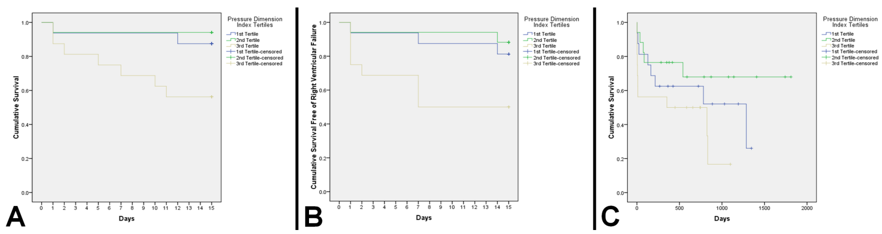
Figure 1. Echocardiographic still images showing the calculation of right ventricular pressure dimension index. Right ventricular minor diameter is measured immediately above the tricuspid valve in end diastole (Panel A, arrows). Pulmonary artery systolic pressure was calculated using tricuspid regurgitation velocity (Panel B, arrow) and right atrial pressure estimated using inferior vena cava diameter (not shown here). Asterisk shows an implantable cardioverter-defibrillator lead within the right ventricle. LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

Figure 2. Correlations between pressure-dimension index right atrial pressure (A), right atrial to wedge pressure ratio (B) and pulmonary vascular resistance (C). Pressure-dimension index was calculated with 2-dimensional echocardiography, while all others were measured with right heart catheterization.

Figure 3. Kaplan-Meier curves for short-term survival to postoperative day 15 (A), short-term survival free of definitive right ventricular failure to postoperative day 15 (B) and long-term survival (C) for pressure-dimension index tertiles.




Right Atrial Pressure (mmHg)
r=-0.402
p=0.007
Pressure Dimension Index (mmHg / cm2)
A
Right Atrial Pressure / Wedge Pressure
r=-0.369
p=0.014
Pressure Dimension Index (mmHg / cm2)
B
Pulmonary Vascular Resistance (Wood Units)
r=0.447
p=0.002
Pressure Dimension Index (mmHg / cm2)
C


Cumulative Survival
Days
Pressure Dimension Index Tertiles
A
Cumulative Survival Free of Right Ventricular Failure
Days
Pressure Dimension Index Tertiles
B
Cumulative Survival
Days
Pressure Dimension Index Tertiles
C