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Acute and short-term haemodynamic impact of transcatheter pulmonary valve implantation on left ventricular systolic and diastolic function

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Abstract

Objectives: Assess the acute and short-term haemodynamic impact of transcatheter pulmonary valve implantation on left ventricular systolic and diastolic function stratified by pre-transcatheter pulmonary valve implantation physiology. *Background:* Transcatheter pulmonary valve implantation is a widely available option to treat residual or recurrent pulmonary stenosis and pulmonary insufficiency. Transcatheter pulmonary valve implantation acutely increases pulmonary artery size and diastolic pressure in patients with pulmonary insufficiency and acute pulmonary edema has been reported after transcatheter pulmonary valve implantation, possibly related to acute left ventricular volume loading. However, the impact of transcatheter pulmonary valve implantation on left ventricular diastolic function has not been established. *Methods:* Patients who underwent transcatheter pulmonary valve implantation from 2010 to 2017 at our centre were grouped by indication for transcatheter pulmonary valve implantation as pulmonary stenosis, pulmonary insufficiency, or mixed disease. Separate analysis was performed on those who underwent transcatheter pulmonary valve implantation for pulmonary stenosis versus pulmonary insufficiency or mixed disease. Intracardiac haemodynamics immediately before and after transcatheter pulmonary valve implantation and echocardiographic assessment of left ventricular systolic and diastolic function at baseline, 1-day post transcatheter pulmonary valve implantation, and 1-year post transcatheter pulmonary valve implantation were compared between groups. *Results:* In 102 patients who underwent transcatheter pulmonary valve implantation, the indication was pulmonary stenosis in 29 (28%), pulmonary insufficiency in 28 (29%), and mixed disease in 44 (43%). There were no significant differences in left ventricular systolic or diastolic function between groups at baseline, immediately after transcatheter pulmonary valve implantation, or 1-year post implantation. The mean pulmonary artery wedge pressure increased equally across groups. *Conclusions:* While patients with pulmonary insufficiency likely have acute left ventricular volume loading following transcatheter pulmonary valve implantation, this does not appear to be haemodynamically significant as transcatheter pulmonary valve implantation was not associated with measurable changes in left ventricular systolic or diastolic function acutely or 1-year post implantation.

Transcatheter pulmonary valve implantation is a now widely available non-surgical option to treat both right ventricular outflow tract obstruction and insufficiency. Pulmonary valve replacement for pulmonary insufficiency, whether performed surgically or via a transcatheter approach, has been shown to decrease right ventricular end-diastolic and end-systolic volumes.[1–4] Pulmonary valve replacement has also been shown to increase early left ventricular diastolic filling and left ventricular end diastolic volumes, and may improve left ventricular systolic function.[1,3,5–13] Additionally, transcatheter pulmonary valve implantation has been shown to decrease symptoms with exercise, lead to restoration of reserve in right ventricular ejection fraction during exercise stress testing in patients with right ventricular outflow tract obstruction, improve exercise capacity, and lead to improvements in exercise recovery.[14–16]

Previous studies have demonstrated an acute increase in pulmonary artery dimensions and diastolic pressure following transcatheter pulmonary valve implantation in patients with pulmonary insufficiency.[17] There are also case reports detailing acute pulmonary edema shortly after transcatheter pulmonary valve implantation hypothesising acute left ventricular volume loading as the aetiology.[18] However, the acute haemodynamic effects of relief of right ventricular outflow tract obstruction and placement of a competent pulmonary valve on left ventricular diastolic function remain unknown.

Therefore, the objective of this study was to assess the acute and subacute changes in left ventricular systolic and diastolic function using both invasive haemodynamics and

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echocardiographic assessments to determine if transcatheter pulmonary valve implantation is associated with changes in left ventricular function and if these changes are impacted by the underlying disease state (right ventricular outflow tract obstruction versus pulmonary insufficiency) or other patient factors.

Materials and methods

This study was approved by the University of Michigan Institutional Review Board with waiver of informed consent.

Study population

A retrospective review was performed of all patients who underwent successful transcatheter pulmonary valve implantation at the University of Michigan Congenital Heart Centre from January 2010 to December 2017. Only patients who underwent valve implantation in the pulmonary position were included. Patients who had conduit rehabilitation and transcatheter pulmonary valve implantation performed during separate procedures were excluded as their physiology, and response to transcatheter pulmonary valve implantation, could have changed significantly following conduit rehabilitation but prior to transcatheter pulmonary valve implantation. One patient with severe left ventricular dysfunction at baseline was excluded as it would be difficult to accurately assess changes in left ventricular systolic and diastolic function.

Patients were defined as undergoing transcatheter pulmonary valve implantation for pulmonary stenosis if there was a peak to peak right ventricular outflow tract gradient of at least 35 mmHg during the cardiac catheterisation and for pulmonary insufficiency if they had moderate or greater insufficiency by echocardiography or cardiac magnetic resonance imaging pulmonary regurgitant fraction of 20% or more on pre-procedural studies. Mixed disease was defined as meeting the criteria for both pulmonary stenosis and pulmonary insufficiency.

Data collection

Demographic data, complete cardiac surgical history, and other clinical information were obtained via review of internal medical records. Echocardiography and cardiac magnetic resonance imaging reports were reviewed to obtain baseline data. Catheterisation procedural data, including procedural length, contrast total, and haemodynamic assessments before and after transcatheter pulmonary valve implantation was obtained from procedural reports. Of note, left ventricular end diastolic pressure was only measured prior to transcatheter pulmonary valve implantation and pulmonary artery wedge pressure was used as a surrogate of left ventricle end diastolic pressure after transcatheter pulmonary valve implantation. Follow-up echocardiography data was collected from echocardiograms performed the day after transcatheter pulmonary valve implantation (routine practice at our institution) and as close to 1 year from the procedure as was available. Only echocardiograms performed and interpreted at our institution were included in this study. Left ventricular ejection fraction and left ventricular and right ventricular subjective systolic function using standard American Society of Echocardiography classification was collected. Left ventricular diastolic function data collected included mitral valve peak E velocity, peak A velocity, E:A ratio, septal annulus e' velocity, septal E/e', lateral annulus e' velocity, and lateral E/e'.

Outcomes

The primary outcome measure was change in left ventricular systolic and diastolic function by echocardiogram from baseline to immediately after and 1-year after transcatheter pulmonary valve implantation. Secondary outcome measures included the changes in left ventricle end diastolic pressure/pulmonary artery wedge pressure measured during the catheterisation before and immediately after transcatheter pulmonary valve implantation.

Statistical analysis

Data are presented as frequency (percent) for categorical variables and mean ± standard deviation or median with interquartile range for continuous variables. Group comparisons in all analyses were made in three ways; pulmonary stenosis versus pulmonary insufficiency versus mixed, pulmonary stenosis versus pulmonary insufficiency, and pulmonary stenosis versus pulmonary insufficiency/mixed. Patient, pre-procedural, procedural, and post-procedural characteristics between groups were compared using Chi-square test or Fisher's exact test for categorical variables and analysis of variance, Kruskal–Wallis test, two-sample t-test or Wilcoxon rank sum test for continuous variables, as appropriate. Changes in left ventricular systolic and diastolic function (including pulmonary artery wedge pressure) by echocardiogram from baseline to immediately after and 1 year after transcatheter pulmonary valve implantation were examined using one-sample t-test and compared between groups of disease types using analysis of variance or two-sample t-test. Lastly, Chi-square test or Fisher's exact test for categorical variables and two-sample t-test or Wilcoxon rank sum test for continuous variables were used to identify patient factors associated with acute increase in left ventricular loading, defined as an increase in the post-transcatheter pulmonary valve implantation pulmonary artery wedge pressure by more than 1 standard deviation of the mean change of pulmonary artery wedge pressure from baseline to post-transcatheter pulmonary valve implantation. This was performed as we felt this patient population may have findings indicative of a higher post-procedural risk of diastolic dysfunction. All statistical analyses were performed using SAS Version 9.4 (SAS Institute Inc., Cary, NC), with statistical significance set at $p\text{-value} < 0.05$ using a two-sided test.

Results

A total of 102 patients met inclusion criteria for the study. Of these patients, 29 (28%) underwent transcatheter pulmonary valve implantation for pulmonary stenosis, 29 (28%) for pulmonary insufficiency, and 44 (43%) for mixed disease. The majority of patients underwent Melody® Transcatheter Pulmonary Valve implantation (88 patients, 86%; Medtronic Inc., Minneapolic MN, United States of America), while an Edwards Sapien XT™ and Edwards Sapien S3™ Transcatheter Heart Valve (Edwards Lifesciences LLC, Irving CA, United States of America) was implanted in 6 (6%) and 8 (8%), respectively. The only differences in demographics and pre-procedural characteristics between groups were that patients with pulmonary stenosis were more males and patients with pulmonary insufficiency were older at the time of transcatheter pulmonary valve implantation (Table 1).

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Table 1. Patient and pre-procedural characteristics by type of disease

Characteristics	Type of disease				p-Value		
	PS (n = 29)	PI (n = 29)	Mixed (n = 44)	PI + Mixed (n = 73)	PS versus PI versus Mixed†	PS versus PI + Mixed‡	PS versus PI¥
Male, sex	24 (82.8)	12 (41.4)	26 (59.1)	38 (52.1)	0.005*	0.004*	0.001*
Weight at TPVi, kg	67.2 ± 26.1	61.2 ± 21.3	63.7 ± 22.9	62.7 ± 22.2	0.62	0.38	0.34
BSA at TPVi, m^2	1.70 ± 0.37	1.61 ± 0.35	1.67 ± 0.37	1.65 ± 0.36	0.59	0.46	0.31
Age at TPVi, years	17.9 (14.6–28.2)	28.5 (21.4–42.5)	16.9 (15.2–26.5)	21.7 (15.6–29.9)	0.04*	0.75	0.12
Caucasian race	23 (79.3)	27 (93.1)	38 (86.4)	65 (89)	N/A	0.10	0.10
TOF variants	10 (34.5)	18 (62.1)	17 (38.6)	35 (47.9)	0.07	0.22	0.04*
More than one previous cardiac surgeries	28 (96.6)	23 (79.3)	38 (86.4)	61 (83.6)	N/A	0.10	0.10
Previous surgical PVR	7 (24.1)	7 (24.1)	7 (15.9)	14 (19.2)	0.60	0.58	1.00
Previous RV to PA conduit/Homograft	23 (79.3)	20 (69.0)	36 (82.8)	56 (76.7)	0.42	0.78	0.37
RV end diastolic volume by cMRI, ml/m^2 (n = 70)	123 ± 41.0	148 ± 51.0	137 ± 33.5	141 ± 40.1	0.19	0.12	0.12
RVEF by cMRI, % (n = 70)	43.6 ± 8.3	46.2 ± 10.4	46.3 ± 9.4	46.3 ± 9.6	0.60	0.31	0.43
LVEF by cMRI, % (n = 70)	54.5 ± 6.2	52.0 ± 6.6	53.4 ± 5.7	52.9 ± 6	0.48	0.37	0.26

PS, pulmonary stenosis; PI, pulmonary insufficiency; BSA, body surface area; TPVi, transcatheter pulmonary valve implantation; TOF, tetralogy of Fallot; PVR, pulmonary valve replacement; RV, right ventricle, cMRI, cardiac magnetic resonance imaging; PA, pulmonary artery; RVEF, right ventricle ejection fraction; LVEF, left ventricle ejection fraction; N/A, not applicable.
Data are presented as n (%) for categorical variables and Mean ± Standard deviation or Median (interquartile range) for continuous variables.
†p-Value from Chi-square test for categorical variable and analysis of variance or Kruskal–Wallis test for continuous variables for three group comparison of PS versus PI versus Mixed.
‡p-Value from Chi-square test or Fisher's exact test for categorical variable and two-sample t-test or Wilcoxon rank sum test for comparison of PS versus PI + Mixed.
¥p-Value from Chi-square test or Fisher's exact test for categorical variable and two-sample t-test or Wilcoxon rank sum test for comparison of PS versus PI.
*$p < 0.05$.

Catheterisation results

There was no group difference in baseline right ventricle end diastolic pressure, left ventricle end diastolic pressure, or pulmonary artery wedge pressure (Table 2). While the mean pulmonary artery wedge pressure following transcatheter pulmonary valve implantation increased by a mean of 3 mmHg ± standard deviation 3.2 mmHg from baseline in all patients ($p < 0.0001$), this change was consistent across all groups (Figs 1 and 2). Patients in the pulmonary stenosis group had longer procedure times ($p = 0.07$) and received an average of 42 ml of additional contrast compared to the pulmonary insufficiency + mixed group ($p = 0.01$). However, this additional contrast calculates to less than 1 ml/kg.

Echocardiography results

Baseline, immediate post procedure, and 1-year follow-up echocardiographic findings based on disease type are presented in Table 3. There was no change in left ventricular systolic function either by EF (Fig 3) or subjective classification. Immediately following transcatheter pulmonary valve implantation, there were no significant differences in changes of echocardiographic indices of diastolic function between groups. After 1 year, the only difference observed was in the mitral valve peak E velocity, which minimally increased in those with pulmonary stenosis or mixed disease but slightly decreased in those with pulmonary insufficiency ($p = 0.02$). When comparing changes in diastolic function in patients with pulmonary stenosis to those with either pulmonary insufficiency or mixed disease, there was a slight increase in the mitral valve E:A ratio in those with pulmonary stenosis and a slight decrease in those with pulmonary insufficiency or mixed disease immediately after transcatheter pulmonary valve implantation that was not observed at the 1-year post transcatheter pulmonary valve implantation echocardiogram.

For patients with an acute change in left ventricular diastolic function [change in pulmonary artery wedge pressure > 1 standard deviation (3.2 mmHg)], there was no association of the change with any patient characteristics or any of the pre-transcatheter pulmonary valve implantation echocardiographic or magnetic resonance imaging measures, with the exception of a lower septal annulus e' velocity ($p = 0.01$) (Table 4).

Discussion

Our study showed that while there is a mild acute increase in the pulmonary artery wedge pressure following transcatheter pulmonary valve implantation, this change was consistently seen across all patients, was not associated with any patient factors, and did not correlate with any echocardiographic measures of diastolic function. While this increase in pulmonary artery wedge pressure might represent true acute left ventricular volume loading, the mechanism is not clear. If due primarily to placement of a competent pulmonary valve, we might have expected this acute increase to be more pronounced in patients primarily with pulmonary insufficiency but that is not what was observed. It is also possible that the mild acute increase in pulmonary artery wedge pressure is due to volume and contrast administration during the cardiac catheterisation procedure. Although not unexpected, patients with pulmonary stenosis received more contrast than those with primarily pulmonary insufficiency or mixed disease. In theory, this additional contrast load and increase in pulmonary artery wedge pressure could bias the results and mask a real difference in acute left ventricular loading in those with pulmonary

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Table 2. Cardiac catheterisation data

	PS	PI	Mixed	PI + Mixed	p-Value: PS versus PI versus Mixed†	PS versus PI + Mixed‡	PS versus PI¥
Baseline haemodynamics							
RVEDP (mmHg)	11.9 ± 4.3	11.6 ± 4.7	11.0 ± 3.9	11.2 ± 4.2	0.66	0.48	0.79
LVEDP (mmHg)	10.6 ± 4.6	10.9 ± 4.3	9.7 ± 3.8	10.2 ± 4.0	0.52	0.68	0.82
Right PAWP (mean, mmHg)	10.6 ± 4.9	10.3 ± 4.2	9.6 ± 3.5	9.9 ± 3.8	0.59	0.42	0.78
Left PAWP (mean, mmHg)	11.4 ± 4.9	10.9 ± 4.7	9.9 ± 3.7	10.3 ± 4.1	0.43	0.32	0.73
Post TPVi haemodynamics							
RVEDP (mmHg)	10.1 ± 4.6	10.7 ± 4.4	9.3 ± 3.1	9.8 ± 3.7	0.31	0.73	0.64
Change in RVEDP (mmHg)	−1.8 ± 3.0	−0.9 ± 2.4	1.7 ± 2.9	−1.4 ± 2.8	0.40	0.56	0.23
PAWP (mean, mmHg)	13.5 ± 6.3	14.5 ± 4.2	14.2 ± 5.1	14.3 ± 4.7	0.86	0.60	0.60
Change in mean PAWP (mmHg)	2.9 ± 3.1	2.5 ± 3.1	3.4 ± 3.5	3.1 ± 3.3	0.70	0.87	0.71
Procedural details							
Duration of procedure (hours)	4.5 (3.4–5.5)	3.9 (3.0–5.0)	4.0 (3.1–4.6)	3.9 (3.0–4.7)	0.18	0.07	0.10
Contrast total (ml)	275 ± 88	213 ± 62.8	246 ± 76.1	233 ± 72.5	0.01*	0.01*	0.004*

PS, pulmonary stenosis; PI, pulmonary insufficiency; RVEDP, right ventricle end diastolic pressure; LVEDP, left ventricle end diastolic pressure; PAWP, pulmonary artery wedge pressure; TPVi, transcatheter pulmonary valve implantation.
Data are presented as Mean ± Standard deviation or Median (interquartile range).
†p-Value from analysis of variance or Kruskal–Wallis test for three group comparison of pulmonary stenosis versus pulmonary insufficiency versus Mixed.
‡p-Value from two-sample t-test or Wilcoxon rank sum test for comparison of pulmonary stenosis versus pulmonary insufficiency + Mixed.
¥p-Value from two-sample t-test or Wilcoxon rank sum test for comparison of pulmonary stenosis versus pulmonary insufficiency.
*p < 0.05.

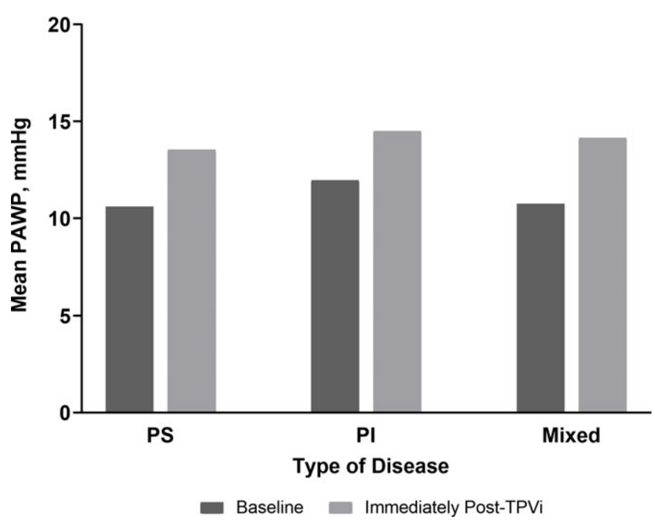

Figure 1. Change in PAWP based on type of disease.

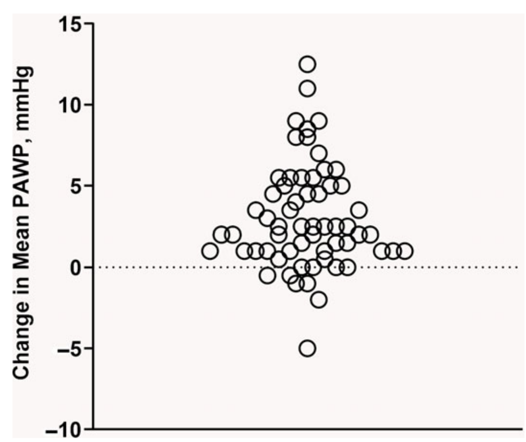

Figure 2. Change in PAWP scatter plot.

insufficiency (type II error). However, the additional contrast dose was on average less than 1 ml/kg so this is unlikely to have biased our results. Also, the duration of the procedure was similar between pulmonary stenosis versus pulmonary insufficiency or mixed disease groups making it unlikely that there was a significant difference in the amount of IV fluids patients received during the procedure.

Overall, we found no meaningful differences in left ventricular systolic or diastolic function after transcatheter pulmonary valve implantation, either in the short term or at 1-year follow-up. There was minimal change in left ventricle ejection fraction (−0.2 to −1.3 across groups) across the entire cohort, with no significant difference between groups. The statistically significant changes in echocardiographic indices of diastolic function (lower baseline mitral valve E:A ratio in patients with pulmonary insufficiency, slight increase in the mitral valve peak E velocity in patients with pulmonary stenosis and mixed disease, increase in mitral valve E:A ratio in those with pulmonary stenosis versus decrease in those with pulmonary insufficiency or mixed disease) are unlikely to be clinically significant. However, echocardiographic assessments of diastolic function may not fully capture true diastolic dysfunction in patients with complex congenital heart disease. A recent study in patients over 13 years of age with tetralogy of Fallot showed that typical echocardiographic measures of

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Table 3. Baseline, immediate post TPVI, and 1-year post TPVi echocardiography measurements by type of disease

	n	PS (n = 29)	PI (n = 29)	Mixed (n = 44)	PI+mixed (n = 73)	p-Value PS versus PI versus Mixed†	PS versus PI + Mixed‡	PS versus PI¥
Baseline								
LVEF, %	52	59.6 ± 7.1	59.4 ± 6.3	63.0 ± 6.1	61.7 ± 6.4	0.17	0.31	0.92
MV peak E velocity, m/second	100	1.00 ± 0.33	1.08 ± 0.30	1.06 ± 0.25	1.07 ± 0.27	0.53	0.27	0.33
MV peak A velocity, m/second	100	0.62 ± 0.25	0.61 ± 0.24	0.56 ± 0.27	0.58 ± 0.25	0.57	0.44	0.80
MV E:A ratio	100	1.66 ± 0.52	1.87 ± 0.61	2.19 ± 1.06	2.06 ± 0.92	0.03*	0.01*	0.18
Septal annulus e′ velocity	55	0.08 ± 0.02	0.09 ± 0.04	0.09 ± 0.03	0.09 ± 0.03	0.52	0.26	0.43
Septal E/e′	55	11.8 ± 3.3	14.8 ± 8.2	13.3 ± 5.7	13.8 ± 6.6	0.42	0.15	0.23
Lateral annulus e′ velocity	55	0.12 ± 0.04	0.14 ± 0.05	0.13 ± 0.03	0.13 ± 0.04	0.56	0.36	0.34
Lateral E/e′	55	8.0 ± 2.6	8.8 ± 4.6	8.7 ± 2.9	8.7 ± 3.5	0.74	0.44	0.55
Change from pre-TPVi to immediately after TPVi								
LVEF, %	30	−1.0 ± 8.8	−0.2 ± 4.9	−1.3 ± 6.4	−1.1 ± 6.0	0.95	0.99	0.85
MV peak E velocity, m/second	96	0.15 ± 0.22	0.02 ± 0.27	0.09 ± 0.23	0.06 ± 0.24	0.17	0.12	0.07
MV peak A velocity, m/second	93	0.03 ± 0.17	0.02 ± 0.29	0.09 ± 0.19	0.06 ± 0.24	0.36	0.54	0.84
MV E:A ratio	93	0.21 ± 0.50	−0.01 ± 0.79	−0.24 ± 0.95	−0.15 ± 0.89	0.08	0.02*	0.24
Septal annulus e′ velocity	30	0.02 ± 0.04	0.003 ± 0.03	0.001 ± 0.04	0.001 ± 0.03	0.30	0.12	0.27
Septal E/e′	30	−0.67 ± 5.1	0.44 ± 5.4	0.09 ± 6.7	0.20 ± 6.2	0.93	0.71	0.68
Lateral annulus e′ velocity	30	0.004 ± 0.02	0.003 ± 0.05	0.00 ± 0.03	0.001 ± 0.04	0.96	0.81	0.94
Lateral E/e′	30	1.4 ± 2.0	0.24 ± 2.8	0.64 ± 2.6	0.50 ± 2.6	0.63	0.37	0.35
Change from pre-TPVi to 1-year post- TPVi								
LVEF, %	30	−0.80 ± 8.2	2.9 ± 7.9	−4.5 ± 6.0	−1.9 ± 7.4	0.11	0.71	0.37
MV peak E velocity, m/second	82	0.06 ± 0.18	−0.11 ± 0.22	0.02 ± 0.21	−0.03 ± 0.22	0.02*	0.09	0.01*
MV peak A velocity, m/second	80	0.02 ± 0.17	−0.10 ± 0.27	0.03 ± 0.18	−0.01 ± 0.22	0.054	0.45	0.09
MV E:A ratio	80	0.07 ± 0.60	0.09 ± 0.74	−0.22 ± 0.95	−0.11 ± 0.89	0.26	0.30	0.92
Septal annulus e′ velocity	28	0.005 ± 0.03	−0.003 ± 0.05	−0.01 ± 0.03	−0.01 ± 0.04	0.61	0.37	0.66
Septal E/e′	28	−0.81 ± 3.5	0.25 ± 3.6	−0.11 ± 5.0	0.03 ± 4.4	0.87	0.61	0.55
Lateral annulus e′ velocity	30	0.01 ± 0.04	−0.03 ± 0.05	0.01 ± 0.03	−0.01 ± 0.05	0.06	0.21	0.053
Lateral E/e′	30	−1.4 ± 2.6	1.3 ± 2.2	−1.3 ± 3.2	−0.3 ± 3.1	0.10	0.35	0.04*

TPVi, transcatheter pulmonary valve implantation; PS, pulmonary stenosis; PI, pulmonary insufficiency; LVEF, left ventricle ejection fraction; MV, mitral valve.
Data are presented as Mean ± Standard deviation.
†p-Value from analysis of variance for three group comparison of pulmonary stenosis versus pulmonary insufficiency versus Mixed.
‡p-Value from two-sample t-test for comparison of pulmonary stenosis versus pulmonary insufficiency + Mixed.
¥p-Value from two-sample t-test for comparison of pulmonary stenosis versus pulmonary insufficiency.
*$p < 0.05$.

left ventricular diastolic function are not able to differentiate between patients with an elevated left ventricle end diastolic pressure by cardiac catheterisation (defined as greater than 12 mmHg) versus those with a normal left ventricle end diastolic pressure.[19] The authors concluded that the typical measures of diastolic function may not be reliable in this patient population. Patients with tetralogy of Fallot represented 44% of our cohort and therefore it is possible that we may underestimate the impact of transcatheter pulmonary valve implantation on diastolic function as measured by echocardiographic indices in these patients.

Previous studies showing increased left ventricular diastolic volumes,[2,3,5–13] and a case report detailing acute pulmonary edema following transcatheter pulmonary valve implantation[18] indicate that questions remain on the impact of pulmonary valve replacement (transcatheter and surgical) on left ventricular diastolic function. While we expected patients with pulmonary insufficiency or mixed disease to have more acute left ventricular volume loading following transcatheter pulmonary valve implantation than those with isolated pulmonary stenosis based on these previous studies, our catheterisation and echocardiographic data from this study did not show significant differences in the left ventricular diastolic function between groups. The above-mentioned study describing difficulty in reliably measuring diastolic function by echo in patients with tetralogy of Fallot,[19] however, highlights some of the challenges that remain in addressing these questions. Further prospective studies could better define the effect of

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Table 4. Patient and pre-procedural characteristics by change in PAWP

	Change in mean PAWP		
	>1 SD (> 3.2 mmHg)	<1 SD (< 3.2 mmHg)	
Characteristics	n = 24	n = 37	p-Value†
Male sex	18 (75.0)	20 (57.1)	0.1
Age at TPVi, years	17.0 (15.7–39.6)	21.0 (14.4–32.3)	1
Caucasian race	21 (87.5)	30 (81.1)	0.73
TOF variants	11 (45.8)	15 (40.5)	0.68
More than one previous cardiac surgeries	21 (87.5)	34 (91.9)	0.67
Previous surgical PVR	8 (33.3)	9 (24.3)	0.44
Previous RV to PA conduit/Homograft	15 (62.5)	27 (73.0)	0.39
Reason for TPVi			0.92
PS	7 (29.2)	12 (32.4)	
PI	6 (25.0)	10 (27.0)	
Mixed	11 (45.8)	15 (40.5)	
Pre-procedure Echo			
RVOT PIPG, mmHg	59.5 ± 24.8	56.9 ± 22.7	0.68
≥ Moderate Pulmonary insufficiency	17 (70.8)	25 (67.6)	0.79
≥ Moderate RV function	5 (20.8)	8 (21.6)	0.94
≥ Moderate LV Function (qualitative)	0 (0.0)	0 (0.0)	N/A
LVEF, % (n = 32)	61.3 ± 5.5	59.4 ± 6.6	0.42
MV peak E velocity, m/second	1.03 ± 0.30	1.07 ± 0.32	0.56
MV peak A velocity, m/second (n = 59)	0.60 ± 0.27	0.64 ± 0.32	0.58
MV E:A ratio (n = 59)	1.9 ± 0.8	1.8 ± 0.7	0.80
Septal annulus e′ velocity (n = 31)	0.07 ± 0.01	0.10 ± 0.03	0.01*
Septal E/e′ (n = 31)	14.9 ± 3.3	12.4 ± 7.0	0.18
Lateral annulus e′ velocity (n = 31)	0.13 ± 0.02	0.14 ± 0.05	0.37
Lateral E/e′ (n = 31)	8.4 ± 2.1	8.5 ± 3.8	0.96
Pre-procedure MRI			
RVEDV (n = 37)	137 ± 41.3	136 ± 39.6	0.93
Pulmonary regurgitant fraction (n = 36)	28.5 ± 9.5	22.9 ± 12.4	0.16
RVEF, % (n = 37)	46.1 ± 10.3	44.9 ± 7.0	0.67
LVEF, % (n = 37)	54.5 ± 5.8	53.3 ± 5.6	0.54

PAWP, pulmonary artery wedge pressure; SD, standard deviation; TPVi, transcatheter pulmonary valve implantation; TOF, tetralogy of Fallot; PVR, pulmonary valve replacement; RV, right ventricle; PA, pulmonary artery; PS, pulmonary stenosis; PI, pulmonary insufficiency; RVOT right ventricular outflow tract; PIPG, peak instantaneous pressure gradient; LV, left ventricle; LVEF, left ventricle ejection fraction; MV, mitral valve; N/A, not applicable.
Data are presented as n (%) for categorical variables and Mean ± Standard deviation or Median (interquartile range) for continuous variables.
†p-Value from Chi-square test or Fisher's exact test for categorical variable and two-sample t-test or Wilcoxon rank sum test for continuous variables.
*$p < 0.05$.

pulmonary valve replacement on left ventricular diastolic function. These should include more consistent haemodynamic assessment of left heart haemodynamics (including pulmonary artery wedge pressure and left ventricle end diastolic pressure) following transcatheter pulmonary valve implantation and inclusion of current typical and novel methods of measuring left ventricular diastolic function by echocardiography (potentially including left atrial size, left ventricular tissue tracking, left atrial systolic strain, and left ventricular diastolic strain) as these may prove important in better evaluating post procedural haemodynamic changes in this population.

Limitations

There are several limitations in this study, including the retrospective nature of data collection. Additionally, many of the patients who undergo transcatheter pulmonary valve implantation at our center primarily follow with outside cardiologists and therefore follow-up echocardiographic data was not available for all patients. To help standardise the assessments of left ventricular systolic and diastolic function, however, we felt that only including internally performed and interpreted echocardiograms was the best methodology despite the limitation it imposed. The study is also not adequately powered to assess for the potential differences baseline anatomy plays in left

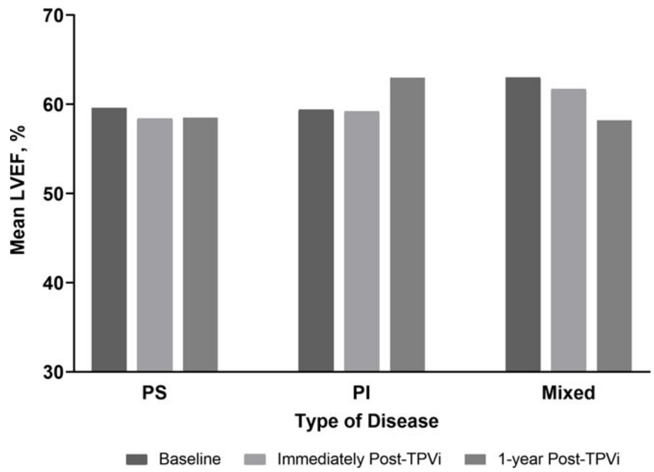

Figure 3. Change in LVEF based on type of disease.

ventricular function (e.g., tetralogy of Fallot variants versus aortic valve disease with subsequent Ross procedure).

In conclusion, while acute left ventricular loading related to a newly competent pulmonary valve after transcatheter pulmonary valve implantation remains a plausible mechanism for several of the physiologic changes reported after surgical or transcatheter pulmonary valve replacement, this is not likely to be haemodynamically significant as no changes in left ventricular systolic or diastolic function were observed either acutely or at 1-year after transcatheter pulmonary valve implantation in our series. Though pulmonary artery wedge pressures increased after transcatheter pulmonary valve implantation, indicating increased left ventricular end diastolic pressures, this was observed in all patients regardless of disease type and was not associated with other measures of diastolic dysfunction and may be due to volume and contrast administered during the cardiac catheterisation. Given the shortcomings of typical echocardiographic measures of diastolic function in patients with complex congenital heart disease, a future prospective study, including use of novel measures of left ventricular diastolic function,[19] could potentially help shed light on risk factors for acute diastolic dysfunction after transcatheter pulmonary valve implantation.

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Conflicts of interest. No relevant conflicts of interest.

Ethical standards. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national guidelines on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008, and has been approved by the institutional committees (University of Michigan Institutional Review Board).

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