

Children's Mercy Kansas City

SHARE @ Children's Mercy

Manuscripts, Articles, Book Chapters and Other Papers

3-1-2015

Changes in speckle tracking echocardiography measures of ventricular function after percutaneous implantation of the Edwards SAPIEN transcatheter heart valve in the pulmonary position.

Shahryar M. Chowdhury

Ziyad M. Hijazi

John F. Rhodes

Saibal Kar

Raj Makkar

~~See next page for additional authors~~

Let us know how access to this publication benefits you

Follow this and additional works at: <https://scholarlyexchange.childrensmercy.org/papers>



Part of the [Cardiology Commons](#), [Cardiovascular Diseases Commons](#), and the [Congenital, Hereditary, and Neonatal Diseases and Abnormalities Commons](#)

Recommended Citation

Chowdhury, S. M., Hijazi, Z. M., Rhodes, J. F., Kar, S., Makkar, R., Mullen, M., Cao, Q., Mandinov, L., Buckley, J., Pietris, N. P., Shirali, G. S. Changes in speckle tracking echocardiography measures of ventricular function after percutaneous implantation of the Edwards SAPIEN transcatheter heart valve in the pulmonary position. *Echocardiography (Mount Kisco, N.Y.)* 32, 461-469 (2015).

This Article is brought to you for free and open access by SHARE @ Children's Mercy. It has been accepted for inclusion in Manuscripts, Articles, Book Chapters and Other Papers by an authorized administrator of SHARE @ Children's Mercy. For more information, please contact hlsteel@cmh.edu.

Creator(s)

Shahryar M. Chowdhury, Ziyad M. Hijazi, John F. Rhodes, Saibal Kar, Raj Makkar, Michael Mullen, Qi-Ling Cao, Lazar Mandinov, Jason Buckley, Nicholas P. Pietris, and Girish S. Shirali



Published in final edited form as:

Echocardiography. 2015 March ; 32(3): 461–469. doi:10.1111/echo.12700.

Changes in Speckle Tracking Echocardiography Measures of Ventricular Function after Percutaneous Implantation of the Edwards SAPIEN Transcatheter Heart Valve in the Pulmonary Position

Shahryar M. Chowdhury, M.D.^{*}, Ziyad M. Hijazi, M.D.[†], John F. Rhodes, M.D.[‡], Saibal Kar, M.D.[§], Raj Makkar, M.D.[§], Michael Mullen, M.D.[¶], Qi-Ling Cao, M.D.[†], Lazar Mandinov, M.D., Ph.D.^{**}, Jason Buckley, M.D.^{*}, Nicholas P. Pietris, M.D.^{*}, and Girish S. Shirali, M.B.B.S., F.A.C.C., F.A.S.E.^{††}

^{*}Department of Pediatrics, Medical University of South Carolina, Charleston, South Carolina

[†]Rush Center for Congenital & Structural Heart Disease, Rush University Medical Center, Chicago, Illinois

[‡]Department of Pediatrics, Duke University Medical Center, Durham, North Carolina

[§]Department of Medicine, Cedar Sinai Medical Center, Los Angeles, California

[¶]Department of Medicine, The Heart Hospital, London, United Kingdom

^{**}Edwards Lifesciences, Irvine, California

^{††}The Ward Family Heart Center, Children's Mercy Hospital, Kansas City, Missouri

Abstract

Background—Patients with free pulmonary regurgitation or mixed pulmonary stenosis and regurgitation and severely dilated right ventricles (RV) show little improvement in ventricular function after pulmonary valve replacement when assessed by traditional echocardiographic markers. We evaluated changes in right and left ventricular (LV) function using speckle tracking echocardiography in patients after SAPIEN transcatheter pulmonary valve (TPV) placement.

Methods—Echocardiograms were evaluated at baseline, discharge, 1 and 6 months after TPV placement in 24 patients from 4 centers. Speckle tracking measures of function included peak longitudinal strain, strain rate, and early diastolic strain rate. RV fractional area change, tricuspid annular plane systolic excursion, and left ventricular LV ejection fraction were assessed. Routine Doppler and tissue Doppler velocities were measured.

Results—At baseline, all patients demonstrated moderate to severe pulmonary regurgitation; this improved following TPV placement. No significant changes were detected in conventional measures of RV or LV function at 6 months. RV longitudinal strain (−16.9% vs. −19.6%, $P < 0.01$), strain rate (-0.87 s^{-1} vs. -1.16 s^{-1} , $P = 0.01$), and LV longitudinal strain (−16.2% vs.

–18.2%, $P = 0.01$) improved between baseline and 6 month follow-up. RV early diastolic strain rate, LV longitudinal strain rate and early diastolic strain rate showed no change.

Conclusion—Improvements in RV longitudinal strain, strain rate, and LV longitudinal strain are seen at 6 months post-TPV. Diastolic function does not appear to change at 6 months. Speckle tracking echocardiography may be more sensitive than traditional measures in detecting changes in systolic function after TPV implantation. (*Echocardiography* 2015;32:461–469)

Keywords

cardiac imaging; congenital heart disease; strain-strain rate; pulmonary valve; right ventricular function

Patients with congenital heart disease requiring right ventricular (RV) to pulmonary artery (PA) conduits frequently develop free pulmonary regurgitation, severely dilated RVs, and decreased ventricular function over time.¹ Even after pulmonary valve replacement, these patients show little improvement in ventricular function when assessed by traditional echocardiographic markers.^{2–10}

Transcatheter pulmonary valve (TPV) implantation is a new option to replace dysfunctional pulmonary valves in RV-PA conduits. The COngenital Multicenter trial of Pulmonic vAlve regurgitation Studying the SAPIEN interventIOnal transcatheter heart valve (COMPASSION) is a prospective, nonrandomized, multicenter study to assess the safety and efficacy of the SAPIEN transcatheter heart valve for the treatment of dysfunctional RV-PA conduits. Though still enrolling patients, early phase 1 results have shown good feasibility, effectiveness, and safety.¹¹

The objective of this study was to evaluate changes in right and left ventricular function using speckle tracking echocardiography (STE) after SAPIEN TPV placement. We hypothesized that after percutaneous pulmonary valve placement, traditional echocardiographic measurements of RV function would remain unchanged while speckle tracking echocardiographic measures of RV function would improve.

Methods

Patients were enrolled prospectively from 4 participating centers. Inclusion criteria included: (1) weight equal to or exceeding 35 kilograms; (2) in situ conduit size between 16 mm and 24 mm in diameter; (3) moderate or severe pulmonary regurgitation defined as 3+ pulmonary regurgitation by transthoracic echocardiogram (TTE), or RV-PA conduit obstruction with a mean gradient of >35 mmHg by TTE; and (4) symptoms as evidenced by cardiopulmonary exercise testing. Informed consent was obtained from all potential subjects and/or their legal guardians. The Institutional Review Board at each participating institution approved the trial.

Procedure

The protocol for valve implantation has been reported previously and is summarized here for convenience.¹¹ Procedures were performed under general anesthesia with biplane

fluoroscopic guidance. The minimum diameter of the conduit was assessed by angiography. Risk for coronary compression was assessed with aortic root angiography or selective coronary angiography with simultaneous inflation of a noncompliant balloon in the conduit. Pretesting of the conduit with a bare metal stent was performed. A 23 or 26 mm SAPIEN transcatheter heart valve was then implanted over a stiff guidewire and expanded via balloon inflation.

Echocardiographic Protocol

A secondary analysis of echocardiograms submitted to the COMPASSION core laboratory was performed. Echocardiograms were acquired by experienced sonographers at each center following a protocol which included a complete set of standardized views to evaluate ventricular function. The image acquisition protocol was developed by the echocardiography core laboratory. On-site or web-based training to the local SAPIEN TPV implantation sites was provided. TTEs were performed at baseline prior to TPV implantation, prior to discharge after TPV implantation, 30-day follow-up, and 6-month follow-up. All studies were performed under baseline physiologic conditions, not under the influence of anesthesia. Echocardiograms were in DICOM format, compressed, with frames rates limited to the lesser of either acquisition frame rate or 30 frames per second. All measurements were made off line by a single reviewer and averaged over 3 beats. Pulmonary regurgitation was graded from 0 to 4 using the criteria in Figure 1. We graded pulmonary regurgitation based on jet length and jet entrance into the RV body—easily reproducible measures to compare over time.^{12,13}

Two-Dimensional, Doppler, and Tissue Doppler Measures of Myocardial Function

To assess systolic function, left ventricular (LV) ejection fraction (EF) derived using single plane Simpson's method because all patients had adequate images for reliable measurement. From a standard apical four-chamber window, RV fractional area change (FAC) was defined as $([\text{end-diastolic area} - \text{end-systolic area}]/\text{end-diastolic area}) \times 100$. Tricuspid annular plane systolic excursion (TAPSE) was obtained, and RV longitudinal shortening was calculated as $([\text{RV end-diastolic length} - \text{RV end-systolic length}]/\text{RV end-diastolic length})$. Pulsed tissue Doppler imaging (TDI) S' velocities at the tricuspid valve annulus, interventricular septum, and the lateral mitral valve annulus were obtained from the apical four-chamber view.

To evaluate diastolic function, Doppler velocities of transtricuspid and transmitral flow (E and A) were obtained from an apical four-chamber window. Tissue Doppler velocities of the tricuspid annulus, interventricular septum, and the lateral mitral valve annulus (E⁰ and A') were obtained. Derived ratios (E:A, E:E') were calculated.

Speckle Tracking Echocardiography Measures of Myocardial Function

Speckle tracking was performed as a secondary analysis of echocardiograms submitted to COMPASSION core laboratory. A single, blinded observer performed offline analysis of DICOM images using vendor-independent software (2D Cardiac Performance Analysis,

TomTec Imaging Systems, Inc, Munich, Germany). Myocardial motion was tracked through the cardiac cycle, calculating myocardial deformation from echo-genic speckles in the B-mode image. Endocardium was manually traced in the LV from the lateral to the septal component of the mitral annulus. The RV was traced from the lateral tricuspid annulus to the septal component of the tricuspid annulus. Speckle tracking measures of deformation from the apical four-chamber view included peak longitudinal strain, strain rate, and early diastolic strain rate for both ventricles. These measurements were calculated as an average of 6 segments for each ventricle. Tracking was visually assessed, and deformation curves were not accepted if greater than one segment demonstrated inadequate tracking. Inter-observer and intra-observer variability were assessed 4 weeks after the initial measurements in 24 (25%) studies—one from each patient and 6 from each timepoint.

Statistical Analysis

To determine the trend from time 0 to time 3, repeated measures ANOVA with a Greenhouse–Geisser correction was conducted on all individuals with measurements for each of the 4 time points. Post hoc comparisons using the Bonferroni correction were then performed in those variables which showed a statistically significant repeated measure ANOVA. Missing data was not imputed as numbers were sufficient to conduct appropriate analyses. The mean \pm SD was calculated for each variable. Intra- and inter-observer variability was assessed by percent error of the mean (the difference between the 2 measurements was divided by the mean of those 2 measurements) and by intra-class correlation coefficient (ICC) using a random effects model measuring absolute agreement. An ICC of 0.75 was deemed acceptable intra- or inter-observer variability. A P-value <0.05 was considered significant. Statistics were analyzed using SPSS v. 20 (IBM, New York, NY, USA).

Results

Patient Population

Between April 2008 and May 2010, 33 patients from 4 centers had successful SAPIEN TPV implantation. A total of 132 echocardiograms were performed. Of these, 17 echocardiograms were excluded for inability to perform STE due to inadequate RV free wall and/or apical segment capture in the echocardiographic window, or, for inadequate apical four-chamber windows. These 17 echocardiograms came from a total of 9 patients. Therefore, 24 patients had echocardiograms suitable for speckle tracking analysis (2 segments were excluded from the RV analysis) at each of the 4 time points so that repeated measures ANOVA could be performed. Demographic data from these patients are presented in Table I. Age ranged from 11 to 57 years old. At baseline, all but 2 patients demonstrated severe pulmonary regurgitation. The majority of patients displayed mixed conduit dysfunction with both significant stenosis and regurgitation; the others had significant regurgitation only. No patients had isolated conduit stenosis without regurgitation. The baseline average indexed RV end-diastolic volume was 130.9 ± 62.6 mL/m² and the baseline pulmonary regurgitant fraction was $28.6 \pm 18.0\%$ as previously reported.¹¹ However, greater than 50% of patients had uninterpretable MRIs due to previous history of stainless steel stents placed in the outflow tract. Studies using other TPVs have shown

comparable problems with MRI data.¹⁴ Changes in conduit stenosis, RV size, and tricuspid valve regurgitant gradient are found in Table II. Changes in pulmonary insufficiency are shown in Figure 1.

Two-Dimensional, Doppler, and Tissue Doppler Measures of Myocardial Function

No significant changes were detected in the two-dimensional measures of RV or LV systolic function, including RV FAC, TAPSE, and LV EF. Tissue Doppler S velocities of the tricuspid and lateral mitral annulus improved immediately after TPV implantation, but returned to baseline by 30-day follow-up (Table III).

Inflow Doppler velocities and the E:A ratios of the RV and LV showed no significant changes after 6 months. Tricuspid TDI E⁰ velocity increased immediately after TPV implantation, but returned to baseline by 30-day follow-up. The lateral mitral annulus E:E' increased between baseline and discharge after TPV placement, but no changes from baseline were detected at 6 month follow-up (Table IV).

Speckle Tracking Echocardiography Measures of Myocardial Function

Changes in STE measures of ventricular function are depicted graphically in Figure 2. No changes were detected in RV or LV strain or strain rate between baseline and discharge. However, both RV longitudinal strain and strain rate improved from baseline to 6 month follow-up. LV longitudinal strain also improved from baseline to 6 month follow-up. Early diastolic strain rate showed no changes in the RV or LV throughout the follow-up period. Intra- and inter-observer variability were adequate for all measures (Table V).

Discussion

TPV implantation allows the opportunity to study the effects of pulmonary valve replacement on ventricular function without the confounding effects of cardiopulmonary bypass. To our knowledge, this is the first study to report improvement in measures of RV deformation at 6 months post-TPV implantation in this population.

Patients with pulmonary regurgitation only or mixed disease (pulmonary stenosis and regurgitation) have been shown to have no change in RV ejection fraction by MRI after TPV.^{3,4,10} Studies assessing changes in traditional echocardiographic measures of RV systolic function have reported similar results.^{3,15} Also, patients under going surgical pulmonary valve replacement for severe pulmonary regurgitation respond similarly.⁵⁻⁹ Our results are in line with these studies as previously reported.² It has been hypothesized that patients with chronic RV volume overload suffer from irreversible RV remodeling and/or damage to myocardium and that the arrest of worsening RV dilation and dysfunction is the best one can hope for after pulmonary valve replacement.³ Others have suggested that effective stroke volume (stroke volume minus pulmonary regurgitant volume) improves after TPV, thereby not requiring an increase in EF in this population.¹⁰

However, due to the acute and long-term loading changes after TPV implantation, MRI EF and previously studied echocardiographic markers are difficult to interpret and may not best represent changes in RV function in this population. Speckle tracking echocardiography has

been shown to have many advantages over traditional measures of myocardial function. STE-derived strain and strain rate are relatively geometry independent, angle independent, and less load dependent than traditional markers of myocardial function.¹⁶ STE measures of deformation have been shown to detect changes in systolic function prior to a change in EF in many disease processes and are useful in diseases that affect the right heart, such as tetralogy of Fallot.^{17–21} The current study follows the pattern of these previous studies, that is, changes in speckle tracking measures of cardiovascular function were identified while other echocardiographic measures of function remained unchanged, suggesting again that STE measures of myocardial deformation may be more sensitive markers of systolic function than traditional echocardiographic measures.

Reports of the use of STE to assess changes in RV function after TPV have been sparse. A study of 10 patients found an increase in STE-derived RV strain between baseline and discharge, results dissimilar to the current study.²² The use of only basal segments in the analysis of that study make the comparison of results difficult as the potential incremental increase in longitudinal strain values from base to apex in both ventricles is not accounted for.^{23,24} Also, no follow-up postdischarge were performed, making medium-term comparisons impossible. Another study of 10 patients receiving Melody valve implantation did include follow-up to 6 months.²⁵ This group found an immediate decrease in RV strain values and no change in RV longitudinal strain or strain rate at 6 months follow-up, again results dissimilar to the current study. Despite having similar patterns of right ventricle-pulmonary artery conduit dysfunction to our cohort, the differences in findings may be explained by a few important factors. The RV volumes between the 2 studies were disparate. As previously reported, patients in this study had an average indexed RV end-diastolic volume of 130.9 mL/m² while the previous study reported an RV end-diastolic volume of 85.3 mL/m².^{11,25} This relatively low degree of RV dilation may have not been enough to provoke significant remodeling or improvement in function following TPV placement. Also, the smaller sample size used in the previous study may have precluded detection of significant changes. Of note, RV and LV strain improved after TPV when assessed by MRI feature tracking in patients with pulmonary stenosis.²⁶

Changes in RV size were seen at 30 days, earlier than changes in RV strain and strain rate. The degree of RV remodeling needed to improve systolic function may take a considerable amount of time, 6 months in the current study. Longer follow-up will be needed to assess for further improvements in myocardial deformation. The present cohort has also been noted to have improved exercise capacity at 6 months.¹¹ Though the relationship between myocardial deformation parameters and exercise capacity was not assessed, it is feasible that the improvements seen in exercise are contributed to by the change in systolic function as seen by STE. Future studies may utilize stress echocardiography to further understand the relationship between STE and functional outcomes in this population.

Interestingly, improvements in TDI measures of systolic function were noted between baseline and discharge. They then trended back to baseline at the 1-month visit. In contrast, STE derived strain and strain rate showed no changes in the same period. This may be explained by the load-dependency of TDI measures of systolic function in left ventricles and volume-loaded right ventricles.^{27–29} While STE measures are influenced by loading

conditions to a degree, it is possible that they are influenced less by loading conditions than are TDI measures.³⁰ Alternatively, autoregulatory mechanisms that accompany loading changes may account for the lack of change seen in strain and strain rate.³¹

Our results are also different from those of Knirsch et al. who assessed STE measures of function after surgical pulmonary valve replacement and found an initial decrease in RV strain at 1 month with interval improvement at 6 months without a return to preoperative levels.³² The differences between this study and the current study may be secondary to the effects of cardio-pulmonary bypass on the RV—namely the potential for irreversible myocardial damage. The populations between the studies were also different. For example, the sample in Knirsch et al.'s study all had severe pulmonary regurgitation and only 2 had significant pulmonary stenosis. Also, RV dilation in the previous study was significantly greater than in the current study, possibly limiting the potential for improvement in RV function after pulmonary valve replacement due to irreversible remodeling after chronic volume overload.

Left ventricular strain improved at 6 months after TPV implantation. This change in function may be secondary to improved ventricular–ventricular interaction.³³ Alternatively, these changes may be due to improved LV preload secondary to an increase in effective RV ejection after the elimination of pulmonary regurgitation. This is supported by the fact that LV strain rate did not change as it is known that strain is more load dependent than strain rate.^{34,35}

Changes in RV diastolic function following pulmonary valve replacement are sparsely reported. We found no changes in early diastolic strain rate after TPV. This is similar to what has been reported when assessing TDI measures of diastolic function by Coats et al.³ In contrast, we did find acute changes in TDI measures that were not sustained by 6 month follow-up. Similarly, Frigiola et al. found an increase in TDI tricuspid E' after surgical pulmonary valve replacement.³⁶ These changes in the E' velocity may again be secondary to acute loading changes. Though, consistently, there appears to be no change in echocardiographic measures of diastolic function 6 months post-TPV. It is possible that changes in diastolic function appear later post-TPV after RV mass has decreased.³⁷

There are limitations to this study. Echocardiograms were compressed and stored at 30 frames per second when read by the core lab. While strain measures are accurate at this frame rate, strain rate can be underestimated, which may confound our interpretation of changes in STE measures of diastolic function over time.³⁸ Speckle tracking echocardiographic measures of RV function were not the primary outcomes of this study. Thus, the echocardiographic protocol was not designed with STE in mind and 9 patients were excluded. Most patients were excluded for RV free wall and apical segments being inadequately captured in the echocardiographic window. Future protocols using STE post-TPV implantation should stress the importance of optimal image acquisition including all RV segments. The percentage of success in obtaining adequate images for speckle tracking analysis of the RV should then be assessed. Myocardial deformation parameters were only measured in the longitudinal direction. It is possible that circumferential and radial fibers were also affected by TPV, though the dominant orientation of muscle fibers in the RV is

longitudinal. STE measures have high intra-observer and inter-observer variability, especially in the right ventricle.^{35,39} This study found acceptable variability in the LV measures of myocardial deformation, though RV systolic strain and strain rate measures showed borderline acceptable inter-observer variability ICC. However, observer percent error of the mean was comparable to other 2D and Doppler indices of function measured in this study as reported in the pediatric Ventricular Volume Variability study, of which our center was a participant.⁴⁰ Future directions in software development may consider including RV-specific STE algorithms that incorporate models for RV shape and increased automation to decrease measurement variability. This study used vendor-independent STE software, essential for performing studies in a core lab environment. The use of vendor-specific software would decrease the feasibility of performing this analysis in the core lab and increase measurement variability as vendors do not share STE algorithms. The response of RV function to TPV implantation may differ in patients with mixed disease versus pure pulmonic insufficiency. It may also differ in patients of different ages and in patients who experienced different timing of TPV implantation after onset of conduit dysfunction. However, while this is the largest study to assess STE measures of deformation after TPV, the sample size is insufficient to provide meaningful subgroup analysis. Of course, as with all measures based on deformation or the velocity of deformation, intrinsic myocardial contractility cannot be isolated. Changes in deformation are inherently influenced by loading conditions/ventricular size and may contribute to the changes in strain seen in this study. We measured LV EF by single plane Simpson's method to measure EF in all of our patients as a significant proportion of echocardiograms did not have the necessary images to measure EF by the biplane Simpson's method; this may limit the accuracy of our measurement of EF and is a limitation to the study. Unfortunately, there are no well-accepted objective echocardiographic measures of pulmonary insufficiency. We used pulmonary regurgitant jet length to stratify grades of pulmonary insufficiency. This measure does have many limitations; however, we used it in the criteria as it is a simple measurement with low variability. This way we could accurately detect changes in pulmonary regurgitation over time. We decided to create an objective measure of pulmonary regurgitation for this study. We felt an objective method would be superior to the routinely used subjective measures. We based our severity categories on prior work showing a PR jet length of <1.0 cm was, the prevailing thought that jet length of >2.0 cm was pathologic, and the thought that PR could also be stratified based on the PR jet entrance into the RV body.^{12,13,41,42}

Conclusion

Improvements in speckle tracking–derived RV longitudinal strain and strain rate and LV longitudinal strain are seen at 6 months post-TPV in patients with pulmonary regurgitation only or mixed pulmonary stenosis and regurgitation. Diastolic function does not appear to change at 6 month follow-up. Speckle tracking echocardiography may be more sensitive than traditional measures in detecting changes in systolic function after TPV implantation.

Acknowledgments

Funding Sources: This study was funded by Edwards Lifesciences, LLC.

References

1. Caldarone CA, McCrindle BW, Van Arsdell GS, et al. Independent factors associated with longevity of prosthetic pulmonary valves and valved conduits. *J Thorac Cardiovasc Surg.* 2000; 120:1022–1031. [PubMed: 11088021]
2. Chowdhury SM, Hijazi Z, Rhodes J, et al. Early echocardiographic changes after percutaneous implantation of the Edwards SAPIEN transcatheter heart valve in the pulmonary position. *Echocardiography.* 2013; 30:786–793. [PubMed: 23432507]
3. Coats L, Khambadkone S, Derrick G, et al. Physiological consequences of percutaneous pulmonary valve implantation: The different behaviour of volume- and pressure overloaded ventricles. *Eur Heart J.* 2007; 28:1886–1893. [PubMed: 17595193]
4. Coats L, Khambadkone S, Derrick G, et al. Physiological and clinical consequences of relief of right ventricular outflow tract obstruction late after repair of congenital heart defects. *Circulation.* 2006; 113:2037–2044. [PubMed: 16636174]
5. Ghez O, Tsang VT, Frigiola A, et al. Right ventricular out-flow tract reconstruction for pulmonary regurgitation after repair of tetralogy of Fallot: Preliminary results. *Eur J Cardiothorac Surg.* 2007; 31:654–658. [PubMed: 17267236]
6. Dave HH, Buechel ER, Dodge-Khatami A, et al. Early insertion of a pulmonary valve for chronic regurgitation helps restoration of ventricular dimensions. *Ann Thorac Surg.* 2005; 80:1615–1620. [PubMed: 16242426]
7. Gengsakul A, Harris L, Bradley TJ, et al. The impact of pulmonary valve replacement after tetralogy of Fallot repair: A matched comparison. *Eur J Cardiothorac Surg.* 2007; 32:462–468. [PubMed: 17627832]
8. Vliegen HW, van Straten A, de Roos A, et al. Magnetic resonance imaging to assess the haemodynamic effects of pulmonary valve replacement in adults late after repair of tetralogy of Fallot. *Circulation.* 2002; 106:1703–1707. [PubMed: 12270866]
9. Oosterhof T, van Straten A, Vliegen HW, et al. Preoperative thresholds for pulmonary valve replacement in patients with corrected tetralogy of Fallot using cardiovascular magnetic resonance. *Circulation.* 2007; 116:545–551. [PubMed: 17620511]
10. Vezmar M, Chaturvedi R, Lee KJ, et al. Percutaneous pulmonary valve implantation in the young: 2-year followup. *JACC Cardiovasc Interv.* 2010; 3:439–448. [PubMed: 20398873]
11. Kenny D, Hijazi ZM, Kar S, et al. Percutaneous implantation of the Edwards SAPIEN transcatheter heart valve for conduit failure in the pulmonary position: Early phase 1 results from an international multicenter clinical trial. *J Am Coll Cardiol.* 2011; 58:2248–2256. [PubMed: 22078433]
12. Takao S, Miyatake K, Izumi S, et al. Clinical implications of pulmonary regurgitation in healthy individuals: Detection by cross sectional pulsed Doppler echocardiography. *Br Heart J.* 1988; 59:542–550. [PubMed: 3382565]
13. Feigenbaum, H.; Armstrong, WF.; Ryan, T. *Echocardiography.* 6th ed.. Lippincott Williams & Wilkins; Philadelphia: 2005.
14. McElhinney DB, Hellenbrand WE, Zahn EM, et al. Short and medium-term outcomes after transcatheter pulmonary valve placement in the expanded multicenter US melody valve trial. *Circulation.* 2010; 122:507–516. [PubMed: 20644013]
15. Kjaergaard J, Iversen KK, Vejstrup NG, et al. Effects of chronic severe pulmonary regurgitation and percutaneous valve repair on right ventricular geometry and contractility assessed by tissue Doppler echocardiography. *Echocardiography.* 2010; 27:854–863. [PubMed: 20546000]
16. Friedberg MK, Mertens L. Tissue velocities, strain, and strain rate for echocardiographic assessment of ventricular function in congenital heart disease. *Eur J Echocardiogr.* 2009; 10:585–593. [PubMed: 19401299]
17. D'Andrea A, Stisi S, Caso P, et al. Associations between left ventricular myocardial involvement and endothelial dysfunction in systemic sclerosis: Noninvasive assessment in asymptomatic patients. *Echocardiography.* 2007; 24:587–597. [PubMed: 17584198]
18. Galderisi M, de Simone G, Inzetti P, et al. Impaired inotropic response in type 2 diabetes mellitus: A strain rate imaging study. *Am J Hypertens.* 2007; 20:548–555. [PubMed: 17485020]

19. Bellavia D, Abraham TP, Pellikka PA, et al. Detection of left ventricular systolic dysfunction in cardiac amyloidosis with strain rate echocardiography. *J Am Soc Echocardiogr.* 2007; 20:1194–1202. [PubMed: 17596912]
20. Mori K, Hayabuchi Y, Inoue M, et al. Myocardial strain imaging for early detection of cardiac involvement in patients with Duchenne's progressive muscular dystrophy. *Echocardiography.* 2007; 24:598–608. [PubMed: 17584199]
21. Li Y, Xie M, Wang X, et al. Evaluation of right ventricular global longitudinal function in patients with tetralogy of fallot by two-dimensional ultrasound speckle tracking imaging. *J Huazhong Univ Sci Technol Med Sci.* 2010; 30:126–131. [PubMed: 20155469]
22. Moiduddin N, Asoh K, Slorach C, et al. Effect of transcatheter pulmonary valve implantation on short-term right ventricular function as determined by two-dimensional speckle tracking strain and strain rate imaging. *Am J Cardiol.* 2009; 15:862–867. [PubMed: 19733725]
23. Biswas M, Sudhakar S, Nanda NC, et al. Two- and three-dimensional speckle tracking echocardiography: clinical applications and future directions. *Echocardiography.* 2013; 30:88–105. [PubMed: 23297852]
24. Mertens LL, Friedberg MK. Imaging the right ventricle—current state of the art. *Nat Rev Cardiol.* 2010; 7:551–563. [PubMed: 20697412]
25. Moiduddin N, Texter KM, Cheatham JP, et al. Strain echocardiographic assessment of ventricular function after percutaneous pulmonary valve implantation. *Congenit Heart Dis.* 2012; 7:361–371. [PubMed: 22672111]
26. Harrild DM, Marcus E, Hasan B, et al. Impact of transcatheter pulmonary valve replacement on biventricular strain and synchrony assessed by cardiac magnetic resonance feature tracking. *Circ Cardiovasc Interv.* 2013; 6:680–687. [PubMed: 24300136]
27. Pascotto M, Caso P, Santoro G, et al. Analysis of right ventricular Doppler tissue imaging and load dependence in patients undergoing percutaneous closure of atrial septal defect. *Am J Cardiol.* 2004; 94:1202–1205. [PubMed: 15518625]
28. Firstenberg MS, Greenberg NL, Main ML, et al. Determinants of diastolic myocardial tissue Doppler velocities: Influences of relaxation and preload. *J Appl Physiol.* 2001; 90:299–307. [PubMed: 11133922]
29. Dincer I, Kumbasar D, Nergisoglu G, et al. Assessment of left ventricular diastolic function with Doppler tissue imaging: Effects of preload and place of measurements. *Int J Cardiovasc Imaging.* 2002; 18:155–160. [PubMed: 12123306]
30. Jategaonkar SR, Scholtz W, Butz T, et al. Two-dimensional strain and strain rate imaging of the right ventricle in adult patients before and after percutaneous closure of atrial septal defects. *Eur J Echocardiogr.* 2009; 10:499–502. [PubMed: 19155264]
31. La Gerche A, Jurcut R, Voigt JU. Right ventricular function by strain echocardiography. *Curr Opin Cardiol.* 2010; 25:430–436. [PubMed: 20592586]
32. Knirsch W, Dodge-Khatami A, Kadner A, et al. Assessment of myocardial function in pediatric patients with operated tetralogy of Fallot: Preliminary results with 2D strain echocardiography. *Pediatr Cardiol.* 2008; 29:718–725. [PubMed: 18506501]
33. Davlouros PA, Kilner PJ, Hornung TS, et al. Right ventricular function in adults with repaired tetralogy of Fallot assessed with cardiovascular magnetic resonance imaging: Detrimental role of right ventricular outflow aneurysms or akinesia and adverse right-to-left ventricular interaction. *J Am Coll Cardiol.* 2002; 40:2044–2052. [PubMed: 12475468]
34. Pascotto M, Santoro G, Caso P, et al. Global and regional left ventricular function in patients undergoing transcatheter closure of secundum atrial septal defect. *Am J Cardiol.* 2005; 96:439–442. [PubMed: 16054478]
35. Eyskens B, Ganame J, Claus P, et al. Ultrasonic strain rate and strain imaging of the right ventricle in children before and after percutaneous closure of an atrial septal defect. *J Am Soc Echocardiogr.* 2006; 19:994–1000. [PubMed: 16880094]
36. Frigiola A, Tsang V, Bull C, et al. Biventricular response after pulmonary valve replacement for right ventricular outflow tract dysfunction: Is age a predictor of outcome? *Circulation.* 2008; 118:S182–S190. [PubMed: 18824753]

37. Romeih S, Kroft LJ, Bokenkamp R, et al. Delayed improvement of right ventricular diastolic function and regression of right ventricular mass after percutaneous pulmonary valve implantation in patients with congenital heart disease. *Am Heart J.* 2009; 158:40–46. [PubMed: 19540390]
38. Risum N, Ali S, Olsen NT, et al. Variability of global left ventricular deformation analysis using vendor dependent and independent two-dimensional speckle-tracking software in adults. *J Am Soc Echocardiogr.* 2012; 25:1195–1203. [PubMed: 22981228]
39. Weidemann F, Eyskens B, Jamal F, et al. Quantification of regional left and right ventricular radial and longitudinal function in healthy children using ultrasound-based strain rate and strain imaging. *J Am Soc Echocardiogr.* 2002; 15:20–28. [PubMed: 11781550]
40. Colan SD, Shirali G, Margossian R, et al. The ventricular volume variability study of the Pediatric Heart Network: Study design and impact of beat averaging and variable type on the reproducibility of echocardiographic measurements in children with chronic dilated cardiomyopathy. *J Am Soc Echocardiogr.* 2012; 25:842–854. [PubMed: 22677278]
41. Nanda, N.; Domanski, M. *Atlas of Transesophageal Echocardiography.* 2nd ed.. Lippincott Williams & Wilkens; Philadelphia: 2007.
42. Zoghbi WA, Enriquez-Sarano M, Foster E, et al. Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional and Doppler echocardiography. *J Am Soc Echocardiogr.* 2003; 16:777–802. [PubMed: 12835667]

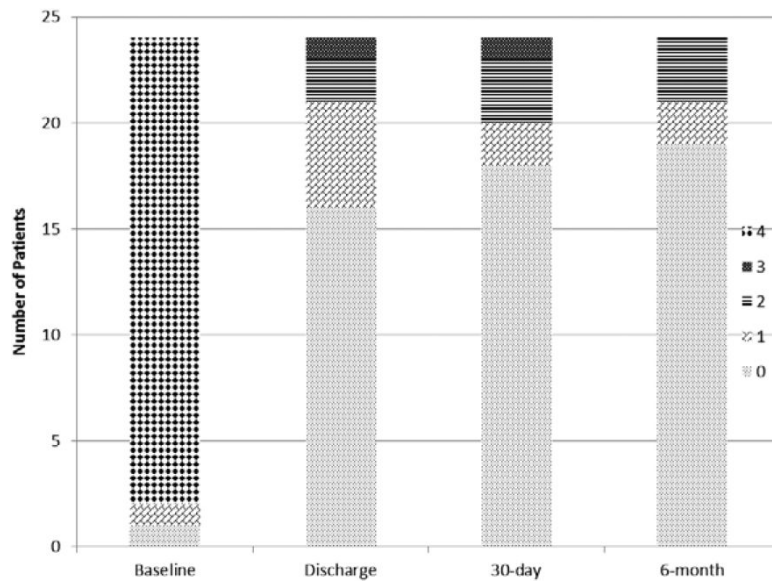


Figure 1.

Change in pulmonary insufficiency after TPV implantation. Changes in pulmonary regurgitation over the follow-up period. Pulmonary regurgitation was graded from 0 to 4 based on regurgitant jet length and extension into the RV: 0 = none; 1 = trivial (<1 cm); 2 = mild (1–2 cm); 3 = moderate (>2 cm, does not extend into RV body); or 4 = severe (>2 cm, extends into RV body).

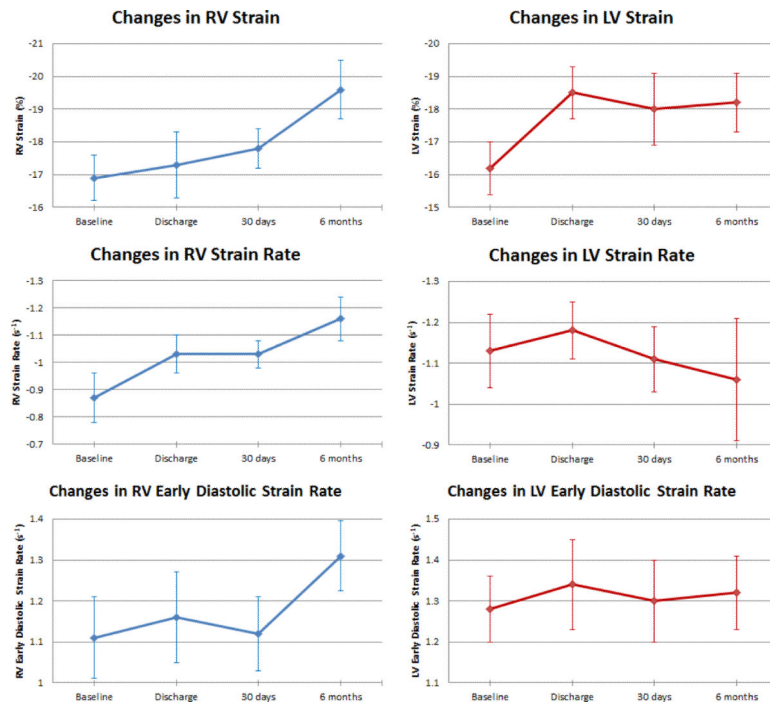


Figure 2.

Measures of speckle tracking echocardiographic myocardial deformation after TPV implantation. Changes in right and left ventricular measures of myocardial deformation by speckle tracking echocardiography over time after transcatheter pulmonary valve implantation. **Statistically significant change from baseline. LV = left ventricle, RV = right ventricle, TPV = transcatheter pulmonary valve.

TABLE I**Patient Demographics**

Age, years	32.3 ± 17.0
Weight, kg	73.5 ± 24.1
Male/female	17/7
Diagnosis	
Tetralogy of Fallot	12
Ross procedure	7
Other	5
Conduit dysfunction	
Regurgitation only	7
Mixed	17
Pulmonary stenosis grade	
None (<16 mmHg)	4
Mild (16-30 mmHg)	3
Moderate (31-45 mmHg)	8
Severe (>45 mmHg)	9
Pulmonary regurgitation grade	
None	0
Trivial (<1 cm)	0
Mild (1-2 cm)	1
Moderate (>2 cm, does not extend into RV body)	1
Severe (>2 cm, extends into RV body)	22

Pulmonary stenosis was graded based on net peak gradient: Pulmonary regurgitation was graded based on regurgitant jet length and extension into the right ventricle.

TABLE II

Pulmonary Valve Function and Right Ventricular Size after TPV Implantation

Measure	Baseline (Time 0)	Discharge (Time 1)	30-Day Follow-Up (Time 2)	6-Month Follow-Up (Time3)	Repeated Measures ANOVA (P-Value)	Multiple Comparison With Bonferroni Correction (P < 0.05)
Conduit stenosis peak gradient (mmHg)	42.4 ± 5.5	22.1 ± 2.1	22.3 ± 3.1	20.7 ± 2.6	<0.01	Time 0 vs. 1, 2, 3
Conduit stenosis mean gradient (mmHg)	24.1 ± 3.2	13.2 ± 1.3	13.1 ± 1.8	12.3 ± 1.7	<0.01	Time 0 vs. 1, 2, 3
RV end-diastolic area (cm ²)	41.4 ± 1.9	42.3 ± 2.3	37.6 ± 2.0	37.1 ± 1.6	<0.01	Time 0 vs. 2, 3 Time 1 vs. 2, 3
RV end-systolic area (cm ²)	29.3 ± 1.3	29.7 ± 2.0	26.1 ± 1.6	25.4 ± 1.0	<0.01	Time 0 vs. 3 Time 1 vs. 2, 3
Indexed RV end-diastolic area (cm ² /m ²)	23.3 ± 5.6	23.5 ± 4.9	21.4 ± 4.9	21.0 ± 5.2	<0.01	Time 0 vs. 2, 3 Time 1 vs. 2, 3
TR peak gradient(mmHg)	56.2 ± 5.1	47.1 ± 3.2	40.2 ± 2.6	40.9 ± 2.6	<0.01	Time 0 vs. 2, 3 Time 1 versus 2

Values are mean ± SD. RV = right ventricle.

TABLE III

Changes in Conventional Measures of Systolic Function After TPV Implantation

Measure	Baseline (Time 0)	Discharge (Time 1)	30-Day Follow-Up (Time 2)	6-Month Follow-Up (Time 3)	Repeated Measures ANOVA (P-Value)	Multiple Comparison With Bonferroni Correction (P < 0.05)
RV FAC (%)	29.0 ± 1.9	30.1 ± 1.7	29.2 ± 2.0	31.4 ± 1.1	0.72	n/a
RV LS (%)	0.14 ± 0.01	0.15 ± 0.01	0.15 ± 0.01	0.16 ± 0.01	0.48	n/a
TDI: Tricuspid S (cm/sec)	7.7 ± 0.5	9.1 ± 0.4	8.0 ± 0.4	8.2 ± 0.4	<0.01	Time 0 vs. 1 Time 1 vs. 2
LV EF (%)	52.2 ± 2.4	55.8 ± 2.1	53.9 ± 2.2	54.1 ± 1.4	0.47	n/a
TDI: Lateral S (cm/sec)	8.2 ± 0.3	10.1 ± 0.6	8.4 ± 0.3	8.9 ± 0.4	<0.01	Time 0 vs. 1 Time 1 vs. 2
TDI: Septal S (cm/sec)	6.3 ± 0.4	7.3 ± 0.5	5.8 ± 0.3	6.0 ± 0.2	<0.01	Time 1 vs. 2

Results are reported in mean ± SD. EF = ejection fraction, FAC = fractional area change, LS = longitudinal shortening, LV = left ventricle, RV = right ventricle, TDI = tissue Doppler imaging.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

TABLE IV

Changes in Conventional Measures of Diastolic Function after TPV Implantation

Measure	Baseline (Time 0)	Discharge (Time 1)	30-Day Follow-Up (Time 2)	6-Month Follow-Up (Time 3)	Repeated Measures ANOVA (P-Value)	Multiple Comparison With Bonferroni Correction (P < 0.05)
RV Doppler E (cm/sec)	72.6 ± 5.5	77.9 ± 5.1	76.6 ± 5.7	70.3 ± 3.7	0.31	n/a
RV Doppler A (cm/sec)	44.9 ± 4.0	59.1 ± 5.5	51.1 ± 4.4	49.2 ± 4.9	0.02	n/a
RV Doppler E:A	1.8 ± 0.2	1.5 ± 0.2	1.6 ± 0.2	1.7 ± 0.2	0.37	n/a
TDI: tricuspid E' (cm/sec)	7.9 ± 2.1	8.9 ± 2.1	7.8 ± 1.7	7.9 ± 1.7	<0.01	Time 0 vs. 1 Time 1 vs. 2
TDI: tricuspid E:E'	7.4 ± 0.9	8.4 ± 0.7	9.3 ± 1.2	8.3 ± 0.8	0.29	n/a
LV Doppler E (cm/sec)	96.3 ± 5.3	111.6 ± 7.9	91.7 ± 6.4	94.8 ± 4.8	0.01	Time 1 vs. 2
LV Doppler A (cm/sec)	54.2 ± 4.0	64.5 ± 4.5	58.3 ± 3.9	57.3 ± 4.1	0.05	n/a
LV Doppler E:A	2.0 ± 0.2	1.9 ± 0.2	1.8 ± 0.1	2.0 ± 0.2	0.56	n/a
TDI: lateral E' (cm/sec)	14.6 ± 0.8	14.5 ± 0.9	13.4 ± 0.9	14.3 ± 1.0	0.32	n/a
TDI: lateral E:E'	6.8 ± 0.5	8.7 ± 0.8	7.3 ± 0.6	7.5 ± 0.5	0.04	Time 0 vs. 1

Results are reported in mean ± SD. LV = left ventricle, RV = right ventricle, TDI = tissue Doppler imaging.

TABLE V

Intra-Observer and Inter-Observer Variability of Speckle Tracking Measures of Ventricular Function

	Intra-Observer % Error of the Mean (%)	Intra-Observer ICC (r Value)	Inter-Observer % Error of the Mean (%)	Inter-Observer ICC (r Value)
LV longitudinal strain	0.9 (-4.2 to 4.6)	0.9	2.9 (-2.5 to 12.3)	0.86
LV longitudinal strain rate	-1.3 (-14.6 to 16)	0.84	2.4 (-9.1 to 16)	0.81
LV longitudinal early diastolic strain rate	3.0 (-8.2 to 15)	0.82	7.7 (-1.6 to 16)	0.84
RV longitudinal strain	0.1 (-5.2 to 2.9)	0.93	3.1 (-10.5 to 3.6)	0.75
RV longitudinal strain rate	0.4 (-9.1 to 10.3)	0.88	-3.3 (-13.4 to -0.2)	0.77
RV longitudinal early diastolic strain rate	-3.7 (-10.6 to 5.2)	0.94	5.1 (-6.2 to 15.5)	0.87

Values reported as median (interquartile range) or correlation r-values. All P-values were <0.01. ICC = intra-class correlation coefficient, LV = left ventricle, RV = right ventricle.