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Bilateral Branch Pulmonary Artery Valve Implantation in Repaired Tetralogy of Fallot

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ABSTRACT (Total 294 words)

Background: Transcatheter, bilateral branch pulmonary artery (PA) valve implantation is a novel treatment for patients with severe pulmonary insufficiency and oversized right ventricle (RV) outflow tract. There is scarce data on efficacy and safety of this approach.

Methods: This was a retrospective study of 8 patients with repaired Tetralogy of Fallot who underwent bilateral branch PA valve implantation. Demographics, echocardiography, cardiac catheterization, and axial imaging data were reviewed. Variables were compared by a paired sample t-test.

Results: All patients were adult sized (weight 43 – 99 kg) with oversized RV outflow tract not suitable for conventional transcatheter pulmonary valve implantation. Staged bare metal PA stenting followed by valve implantation (interval 3-5 months) was technically successful in 7 patients with one stent embolization. In another patient proximal stent migration prevented placement of bilateral pulmonary valve stents. There were a total of 14 valved branch PA stents placed (Melody valve n=9, Sapien XT n=2, Sapien 3 n=3). In the 7 patients undergoing successful branch pulmonary valve placement, at median follow up of 10 months (range 3 months to 6 years), 13 (93%) valves had none/trivial insufficiency on echocardiography. Pre- and post-valve implantation cardiac magnetic resonance imaging in five patients showed significant reduction of indexed RV end-diastolic volume (152 ± 27 to 105 ± 15 mL/m^2, $p<0.001$).

Conclusions: Transcatheter, bilateral branch PA valve implantation was technically feasible with satisfactory efficacy and safety in patients with repaired Tetralogy of Fallot, severe pulmonary insufficiency, and oversized RV outflow tracts. Elimination of pulmonary insufficiency with this method resulted in reduced RV end-diastolic volume.

This approach can be offered as an alternative to surgery, particularly in patients considered high risk for standard surgical placement and who are not candidates for the newer self-expanding valve prosthesis for placement in RV outflow tracts larger than 30 mm diameter.

INTRODUCTION

Tetralogy of Fallot (TOF) is the most common cyanotic congenital heart defect, occurring in approximately 1 in 2,518 births in the United States (1). Surgical repair of TOF most commonly includes performing a trans-annular patch, resulting in free pulmonary insufficiency, which is well tolerated in the pediatric population but often results in long-term complications including right ventricular (RV) dilation and dysfunction (2, 3), ventricular arrhythmias (4), exercise limitations (5, 6) and sudden cardiac death (7). Severe pulmonary insufficiency, together with arrhythmias, symptoms, and/or moderate to severe RV enlargement, are indicators for pulmonary valve replacement (PVR) (8). Transcathter pulmomary valve implantation has revolutionized the treatment of pulmonary insufficiency, primarily for surgically placed RV to pulmonary artery (PA) conduits (9, 10). There is growing experience with valve implantation in non-conduit or native right ventricle outflow tracts (RVOT), usually preceded by bare metal pre-stenting (11). However, RVOTs greater than 30 mm diameter are not suitable for valve implantation due to the limitations of currently available trans-catheter pulmonary valve sizes (largest diameter Sapien XT valve 29 mm, Edwards Lifesciences, Irvine, CA) (12). Therefore, there is a need for alternative trans-catheter treatment options in these patients.

Trans-catheter, bilateral branch PA valve implantation has been tested in an ovine model (13) and reported in two patients (14, 15). The efficacy and safety of this innovative approach in long-term follow-up has not been well described. At our institution, bare metal pre-stenting followed by bilateral branch PA valve implantation has been offered as

an alternative to surgical valve placement in selected patients with repaired TOF and dysfunctional, large RVOT since 2011. This is the first report of this technique with short- and mid-term results using cardiac magnetic resonance imaging (CMR) RV volume data.

METHODS

This was a retrospective analysis of 8 patients who underwent trans-catheter, bilateral branch PA valve implantation at the Children's Hospital of Michigan. In 4 patients, the procedure was performed due to other comorbid conditions, which were felt to increase the risk of surgical pulmonary valve replacement, though in 4 patients it was offered as a primary treatment alternative to surgical pulmonary valve placement **(Supplemental Table 1).**

Data collected on the patients were demographic details of the patients, including patient age, sex, race, clinical characteristics, underlying anatomy, medications, details of the surgical repair, the results of the CMR as well as the echocardiograms performed at our center. The patients were NYHA classified according to their clinical status at time of procedure and follow-up. The echocardiograms were acquired at our center using a standard institutional protocol. CMR was performed using 1.5 Tesla scanners (GE Medical Systems). 1.5 Cine images were obtained using breath-hold SSPE method and were analyzed offline to assess the RV and LV end-diastolic volumes and end-systolic volumes by manually tracing the cavities at multiple levels by cardiologists and radiologists with expertise training. The entire RV was included in the measurement,

including the RVOT and the area under the patch. Medis Mass software (version 6) was used for the tracings. The cine phase velocity pulse sequence was used to measure the PR fraction. The indication for re-establishment of pulmonary valve competence was significant RV enlargement (RV end-diastolic volume index ≥ 150 mL/m^2 and/or end systolic volume ≥ 80 mL/m^2) and/or symptoms of exercise intolerance due to pulmonary insufficiency. Appropriate candidates for bilateral branch PA valve implantation had RVOT diameter >27 mm and branch PA diameter <27 mm. Procedural catheterization data was also analyzed. Post-valve implantation, patients were followed clinically and with repeat echocardiographic, and axial imaging evaluation. All angiographic images were reviewed and measured by 2 authors (NB and DK) who were blinded to the clinical outcomes, including narrowest PA branch diameter, sizing balloon waist and bare metal stent diameters, and valve stent final diameter. All the pre and post MRIs were reviewed and re-measured by two individual readers (MJZ and AJ), blinded to the results, with expertise in reading cardiac MRIs. All measurements were made at best visualization (either antero-posterior or lateral view). The RVOT was measured at its narrowest diameter level and the PA was measured in systole at its narrowest diameter. The Wayne State University Institutional Research Board approved this study.

Bilateral Branch PA Valve Implantation

Cardiac catheterization was performed under general anesthesia. The baseline hemodynamic study was followed by angiography in the RVOT, PA, and coronary arteries. Patients were not thought to be candidates for primary native RVOT pre-stenting with valve implantation, due to significantly dilated RVOT >30 mm in 6 patients and

instability of a 30 mm diameter balloon inflated in the RVOT in 2 patients (RVOT

diameter 28.6 mm). Balloon sizing of the branch PAs were performed using either Z-

Med II or Tyshak II balloon catheters (NuMed, Inc., Hopkinton, NY). Balloon catheters

that measured 3-4 mm in diameter greater than the largest diameter of the PA during

systole were used. Balloon stability was achieved and balloon waist was measured.

Branch PA bare metal stent placement was performed prior to valve implantation in

14/15 PA. Palmaz-XL stents (Cordis Endovascular, Warren, NJ) were delivered with

NuCLEUS balloon catheters (NuMed Corp, Hopkington, NY), with the intention to

achieve a "dog-bone" shape in the bare metal stent (**Fig. 1**). Branch PA valve

implantation was then performed. In circumstances where there was no discernable waist

in the bare metal stent, a staged approach was taken to allow for bare metal

endothelialization to avoid inadvertent stent embolization/malposition during stent valve

implantation. Patients who underwent a staged approach had branch PA valve

implantation at a separate catheterization 3-5 months later. Melody valves (Medtronic,

Minneapolis, MN) were used when narrowest stented diameter was $\leq$ 24 mm, whereas

Sapien (XT or 3) valves were used for stented PA's > 24 mm. Post-valve implantation,

distal PA angiography was performed to show valve function (**Fig. 2**). If angiography

raised a concern for valve dysfunction, intracardiac echocardiography was performed. All

patients were observed overnight and started on aspirin prior to discharge.

Statistical Analysis

The data were expressed as median (range), mean ± standard deviation, or frequency (%) based on the type and distribution of data. The data before and after valve implantation were compared using a paired sample t-test. A $p < 0.05$ was considered as statistically significant. The intra-class correlation coefficient (ICC) for inter-rater reliability for our two independent MRI readers was calculated. Statistical analysis was performed using SPSS version 24 (IBM, Armonk, NY). Cost analysis was performed with the matched controls of surgical PVR cases and the direct costs (including equipment, personnel, admission charges, medication charges etc) as well as indirect costs were reported. The average cost reported per case includes only the successful cases. The costs incurred due to the unsuccessful cases were not included in the cost assessment.

RESULTS

Baseline Data

A total of 8 patients underwent attempted bilateral branch PA valve implantation and 7 had successful implantation of the valves. (**Table 1**). 16 PAs were intended for treatment in 8 patients with 14 valves successfully implanted in 7 patients. All patients had the diagnosis of TOF, 6 patients with trans-annular patch augmentation of the RVOT and 2 with a limited trans-annular patch with homograft placement. All patients were adult size with median weight of 76 kg (range 43 – 99 kg). Baseline transthoracic echocardiography showed free pulmonary insufficiency and a dilated right ventricle without RVOT obstruction. Pre-procedural axial imaging was cardiac MRI in 7 patients and cardiac computed tomography angiography due to the presence of a pacemaker in 1 patient. In all patients, the RVOT measured at least 27 mm at it's narrowest on cardiac imaging.

Cardiac Catheterization (Table 2)

Angiography showed a significantly dilated RVOT with a median diameter of 30.6 mm (range 28.6 – 34.9 mm), not suitable for trans-catheter pulmonary valve implantation in the RVOT. The branch PA had a wide variety of sizes and pulsatility, during balloon compliance testing. A smaller / stenotic branch PA (diameter <16 mm by angiography) was noted in 6 branch PAs (40%), each with a systolic pressure gradient ≥15 mmHg. Larger, dynamic branch PA (diameter >20 mm) was noted in 9 (60%). The waist present in the sizing balloon was larger than the narrowest angiographic measurement by 2.9±1.6 mm.

Pre-stenting was performed in all branch PAs except in one patient (one PA), where the left pulmonary artery (LPA) was heavily calcified and non-pulsatile and was thought to provide a satisfactory landing zone for the Melody valve. For pre-stenting, primarily Palmaz-XL stents were delivered on NuCLEUS balloons. A Genesis-XD stent was used in one patient. To ensure that the stents were adequately latched onto contractile branch PA, the stent-delivery balloon diameter was chosen significantly larger than the waist of sizing balloon by 4.0±1.7 mm. For the branch PA valve implantation, Melody valve was used in 9 branch PAs and Sapien valve was used in 5 (Sapien XT n=2, Sapein 3 n=3) branch PAs. A Sapien valve was chosen when the narrowest stent diameter was greater than 25 mm.

Hemodynamic data (**Table 3A**) showed the immediate positive effect of bilateral branch PA valve implantation. RV and distal PA systolic pressures were unchanged. Distal PA diastolic and mean pressures significantly increased, due to elimination of pulmonary insufficiency. When branch PA stenosis was present, the systolic pressure gradient from RV to distal PA was significantly decreased due to relief of PA stenosis by stent placement. The final stent diameter was larger than the baseline angiographic branch PA diameter by 5.3±2.9 mm. Post-valve placement, distal PA angiography showed effective valve function in all except 1 valve, where there was moderate valve insufficiency of a Sapien XT valve placed in the LPA.

Bilateral branch PA stenting and valve implantation was technically successful in 7 out of 8 patients. There was a serious adverse event of stent embolization in one patient while retrieving the wire and catheter into the MPA. The embolized stent was successfully repositioned in the contralateral branch PA. A second stent was placed in the ipsilateral PA by oversizing it further. In another patient, the initial bare metal stent was placed in the LPA, though proximal migration was noted, requiring a second stent to be placed overlapping the distal 1/2 of the initial stent, latching it on to the LPA. Due to jailing off of the RPA from the proximal bare metal stent, attempts to access the RPA were unsuccessful in this patient. This patient did not have bilateral PA valves placed and went for surgical placement of the pulmonary valve. There were no other complications. All patients were successfully discharged the following day.

Follow-up (Table 3B)

Of the seven patients who underwent successful bilateral PA valve stent placement, the median clinical follow up was 10 months (range 3 months to 6 years). Symptomatically, four patients improved from NYHA class III to II and 3 remained with class II symptoms. There have been no instances of endocarditis and no surgical or trans-catheter re-interventions required. Follow up transthoracic echocardiography showed none or trivial valve insufficiency in all but 1 patient having moderate insufficiency of a Sapien XT valve in the LPA. Follow-up CMR was performed in 5 patients at median follow up of 2 years (range 3 months to 6 years). Two patients refused follow-up CMR imaging. RV systolic and diastolic volumes were significantly decreased in all 5 patients and RV ejection fraction improved in 3 patients (**Fig. 3**). One patient with severe RV dilation (RV end diastolic volume index 195 mL/m2) had a lower ejection fraction despite reduction in RV volume. No valve stent fractures were present on follow up chest radiography or fluoroscopy in all patients. The intra-class correlation coefficient (ICC) for inter-rater reliability for our two independent MRI readers was 0.9 for the RV volumes and 0.8 for the RVEF.

Cost Analysis

We performed cost analysis of this procedure, using 4 adult patients who underwent standard uncomplicated surgical valve placement in the RVOT position. Supplemental table 2 lists the demographic characteristics of the surgical cohort group, all of which were considered low risk. We combined the costs of both the BMS placement procedure and bilateral valve stent placement in our bilateral PA valve stent group. The average direct costs in the bilateral valve PA stent group ($61,063/patient) were significantly

higher than their surgical counterparts ($34,729/patient). As expected, the indirect costs were significantly higher in the surgical group ($16,342/patient) versus their trans catheter counterparts ($8,799/patient). The overall costs for surgical valve placement was $51,071/patient and for the bilateral valved PA stent $69,862/patient, with a differential cost just under $19,000 favoring surgical pulmonary valve placement.

DISCUSSION

This report describes the technical feasibility, safety and efficacy of a staged, trans-catheter bilateral branch PA valve implantation for treatment of pulmonary insufficiency in patients, whose RVOT measurements were too large to accommodate the current valve-stent maximal dimensions. This is the largest case series of this approach with intermediate follow up data. Implanted valves were fully functional in 13/14 (93%) branch PAs. Furthermore, follow-up cardiac MRI showed reduction of the RV volume in five patients following valve placement.

Bilateral branch PA valve implantation was first described in an ovine model (13) and then in a human by Gillespie *et al.* in 2011 (14). Technical feasibility was shown, but no follow up data was described. The second case was published by Maschietto *et al.* in 2013; an 18-year-old male with dilated RVOT and right PA stenosis (15). Short-term (3 month) follow up data was available, with improved clinical symptoms (NYHA class III to II) and RV volume reduction on cardiac MRI.

We report a series of 7 patients undergoing successful bilateral valve stent placement in the PAs, with a maximum follow up of 6 years, including 5 of the seven patients who underwent follow-up cardiac MRI. All implanted valves have remained functional without need for re-intervention, except one case of moderate valve insufficiency of the Sapien XT valve in the LPA, which is being followed conservatively. This valve was implanted on a smaller, pre-stented LPA (narrowest diameter 19 mm) using 26 mm Sapien valve. The final diameter of valve measured 22.6 mm, with moderate insufficiency noted by ICE imaging. We speculate that the valve insufficiency was secondary to not achieving full expansion of the Sapien valve, thereby not allowing full coaptation of the valve leaflets. Due to this experience, our practice has changed towards implanting a Melody valve when possible, which is more likely to be functional, even if not fully expanded.

This is a relatively new and experimental approach, which may be as effective in improving RV volume and hemodynamics as conventional RVOT valve implantation in patients with severe pulmonary insufficiency. Although our cohort had only 5 patients with follow up cardiac MRI, our data suggests that bilateral branch PA valve implantation had a favorable effect on RV volume and function. It is not uncommon in the repaired TOF population to have mild LV dysfunction, as a consequence of inter-ventricular interactions from a dilated RV. However, the LV ejection fraction did not change in our cohort post valve implantation. In our cohort, one patient (patient #5) had lower RV ejection fraction post-valve implantation. We speculate that this RV failed to

remodel due to pre-procedural excessive RV volume overload (RV end diastolic volume index 195 mL/m^2).

In patients with larger PAs (> 22 mm), no PA stenosis, and absence of a balloon waist during sizing, we advocate a staged approach of bare metal PA stenting followed by valve implantation to create the solid landing zone for the valve stent. Our patients were brought back for valve implantation 3-5 months following initial bare metal PA stenting. Though there is no direct evidence when stents endothelialize, we believe this interval allows for endothelialization of the stent to the vascular wall, as suggested by animal studies on coronary stents which endothelialize in 2-3 weeks (16), preventing inadvertent stent embolization during subsequent valve stent implantation. Pre-stenting was performed in all branch PAs except in our first patient (one PA). In contrast to a homograft, the PA's have significantly less mobility, torque, and compressive forces resulting in fewer fractures. This is supported by the fact that RV to PA conduit stent fractures are significantly more common than PA stent fractures (17, 18).

In our opinion, balloon sizing is essential, as angiography underestimates the size and compliance of the pulsatile branch PAs. Our choice of stent delivery balloon for large branch PAs is the NuCLEUS balloon catheter (Numed Corp, Hopkington, NY), with a unique design incorporating a waist in the mid portion of the balloon. At a specified pressure, the central waist is designed to expand to 90% of the rated balloon diameter. When positioning the stent for delivery, the middle of NuCLEUS balloon catheter is positioned at the narrowest portion of branch PA (**Fig. 1**). Using this technique, the stent

can be shaped as a dog-bone, flaring both the proximal and distal ends. This can minimize the risk of stent embolization and provide a better landing zone for the subsequently placed valve stent. A recently available alternative is the larger Balloon in Balloon (BIB) catheters, which also allow for precise positioning of larger stents.

There was one unsuccessful patient in whom the decision to implant bilateral stented valves was aborted. This was a 37-year-old female with TOF status post trans annular patch repair who has NYHA class III heart failure symptoms. Her cardiac MRI showed dilated RV with iRVEDV of 130 ml/m2. She was brought to the lab with the possibility of stents to be placed in her branch PA as her RVOT measured 34 mm at its narrowest segment. Since the Tyshak II 25X4 latched well in the proximal LPA segment a stent was mounted on the Nucleus 25x5 balloon catheter and advanced to the proximal LPA. Even though the initial appearance of the stent was satisfactory and there was no contrast observed around the stent on post-stent angiography, proximal displacement of the stent occurred during balloon withdrawal. Another Palmaz XL4010 stent was mounted on a Zmed II 26 x 4 cm Balloon catheter and advanced to the proximal LPA to overlap the distal part of the previously placed stent. Unfortunately, due to jailing off of the proximal RPA, further attempts to access the RPA were unsuccessful and the procedure aborted. She was referred to surgical PVR.

In a cost analysis study from the U.S. markets, between trans-catheter pulmonary valve implantation and surgical PVR, although the cost for the Melody device and Ensemble (Medtronic, Minneapolis, Minnesota) delivery catheters were higher than the cost of the

homograft/surgical valve, the hospital costs and physician fees were lower, which resulted in almost equivalent total costs (19). Vergales et al. noted a 5-year societal cost attributed to percutaneous PVR of $106,276 and that for the traditional surgical conduit replacement at 5 years being higher at $141,273 (20).

In our experience, this advantage favoring standard Melody valve placement in the RVOT position is eliminated in patients undergoing bilateral pulmonary valve stent placement. Surgical placement of pulmonary valves had lower overall costs than bilateral pulmonary valve stent placement. Though the surgical cohort were considered all low risk patients, with the bilateral pulmonary valve cohort having 4 moderate to high surgical risk, certainly the costs favor surgical valve placement in the low risk group. We also recognize that the endocarditis risk may be doubled, given the presence of two valve substrates. At this time, the physiologic implications of the RVOT dead space following bilateral branch PA valve implantation are unclear. It also remains unknown how the RV volume and function would be affected long-term with this procedure, though the early results are encouraging.

Soon, larger stents will be available for use in patients with transannular patch augmentation of the RVOT with dimensions > 30 mm in diameter. The Medtronic Harmony transcatheter pulmonary valve (Medtronic, Minneapolis, MN) is designed to treat larger native RVOT, with encouraging results shown in an early feasibility study (21), with a pivotal investigational device exemption study currently underway (22).

Even with the development of oversized self-expanding stents, bilateral valve stent placement in the PA's may still play a role in a select group of patients. A recent paper by Lindsay et al, noted 9% of their patients showing aortic root compression in patients with stents being placed in the RVOT, especially oversized stents, such as the Sapien valve stent (23). Thus, we feel this technique described in our paper may still have relevance even after introduction of the larger stent size valve series.

Limitations

This was a retrospective study with an inherent limitation. Our cohort was small, although this is the largest series describing this technique. Follow-up CMR was not obtained in 2 patients, due to loss to follow-up. We do not believe this affects the reporting of our post-valve CMR data. However, the possibility of a selection bias cannot be excluded.

CONCLUSION

Trans-catheter, bilateral branch PA valve implantation was technically feasible with satisfactory hemodynamic benefit and safety for the treatment of severe pulmonary insufficiency in patients with repaired TOF and oversized RVOT. Competency of the valves placed in the branch PAs resulted in RV volume reduction by CMR. However, the in-hospital costs were significantly higher in the bilateral pulmonary valve group. This technique could be offered to patients as an alternative to surgery, though we would recommend this procedure, after consultation with the surgeons, only to patients

considered moderate to high risk for standard surgical placement of a pulmonary valve in the RVOT position.

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FIGURE LEGEND

Figure 1. Pre-stenting and Melody valve placement, proximal right pulmonary artery (RPA). (A) Baseline angiography shows a pulsatile proximal RPA. In systole, there is mild narrowing (b: 20.2 mm) compared to distal (a: 27.2 mm) and proximal (c: 27.3 mm) segment of RPA. (B) Balloon sizing of RPA shows a minimal balloon waist of 23.2 mm. (C) Pre-stenting using a Palmaz-XL 4010 stent mounted on a 25 mm x 4 cm NuCLEUS balloon catheter through a 12-Fr Flexor sheath. The stent is implanted so that a dog-bone shape is achieved to avoid embolization. (D) Post-stent angiography shows mild stent waist (b: 21.7 mm), compared to the distal (a: 24.9 mm) and proximal (24.9 mm) ends of stent. (E) Melody valve placement in RPA. Melody TPV 22 (PB1018) is implanted on 24 mm x 4 cm NuMed BIB catheter. (F) Post-Melody in RPA. There is no insufficiency of Melody valve.

Figure 2. Pre- and post-bilateral branch pulmonary artery (PA) valve implantation. (A) Baseline PA angiography. Right ventricular outflow tract is dilated. Proximal LPA is heavily calcified with no stenosis or pulsatility. There is a stent in proximal RPA. (B) Post-valve implantation. Simultaneous bilateral distal PA angiography shows no valve insufficiency. In this case, pre-stenting was not performed in the LPA due to a satisfactory landing zone.

Figure 3. Comparison of cardiac magnetic resonance imaging before and after bilateral branch pulmonary artery valve implantation in five patients.
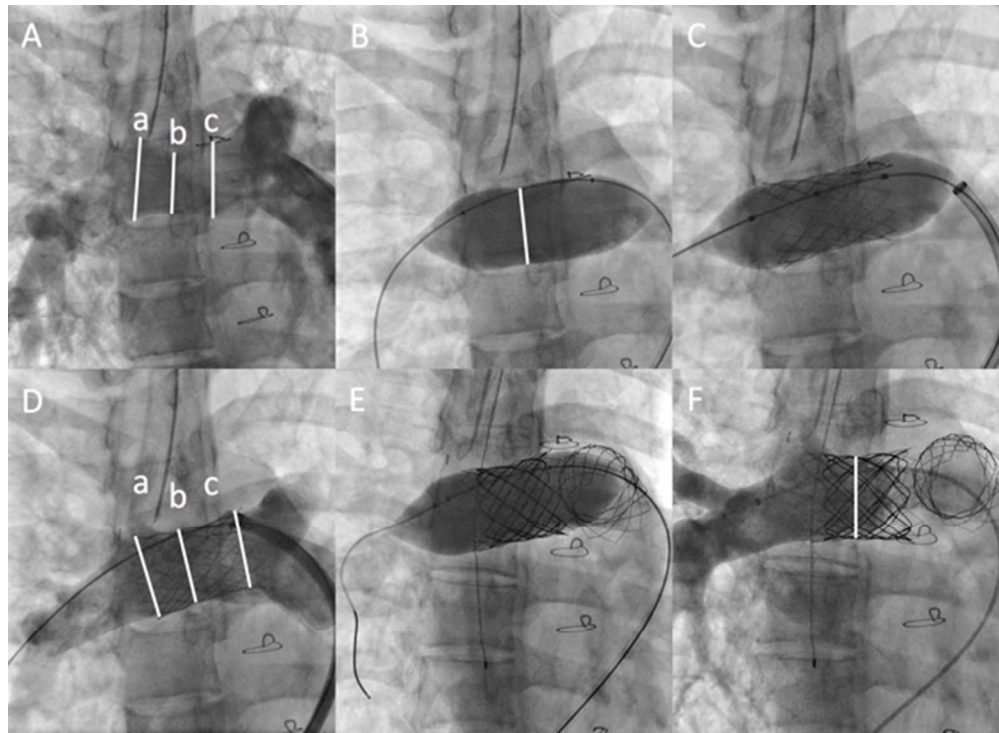
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54x39mm (300 x 300 DPI)
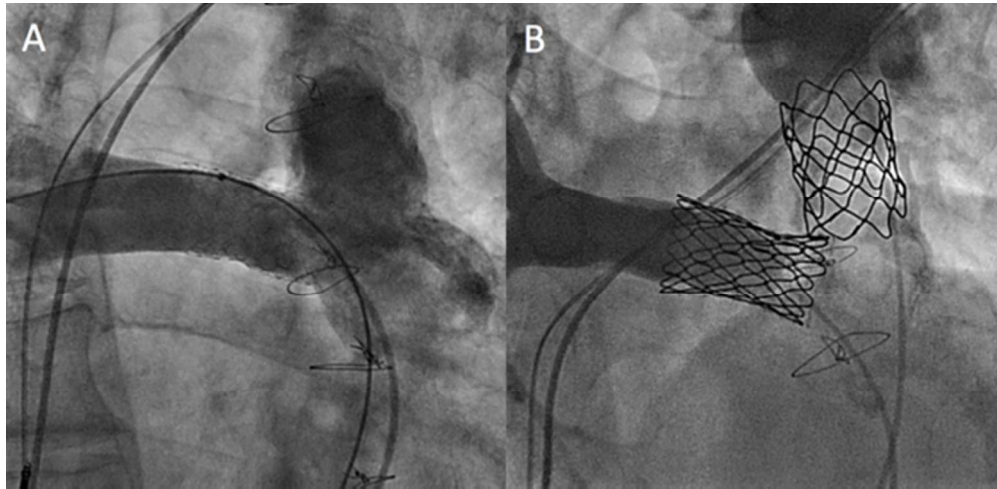
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54x26mm (300 x 300 DPI)

Figure 3. Comparison of cardiac magnetic resonance imaging before and after bilateral branch pulmonary artery valve implantation in five patients.

254x190mm (72 x 72 DPI)

Table 1. Baseline demographic and cardiac magnetic resonance (CMR) data.

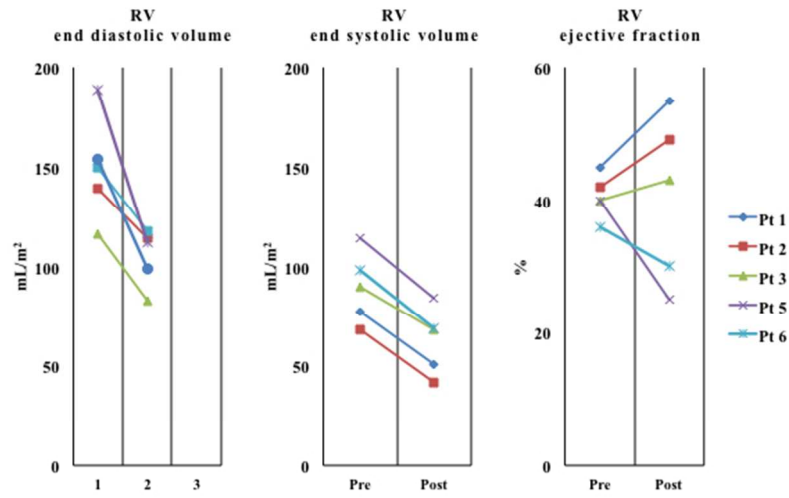| Pt	Age (year)	Gender	Weight (kg)	NYHA class	Cardiac MR						
					RVEDV index (mL/m2)	RVESV index (mL/m2)	RV ejection fraction	Pulmonary regurgitation fraction	RVOT (mm)	RPA (mm)	LPA (mm)
1	57	M	76.6	III	139	77	45%	35%	27.3	10	15.6
2	36	M	82	III	122	74	40%	35%	27.9	18.9	8.6
3	26	F	43.7	II	146	87	40%	69%	31.2	22.2	14.2
4	20	F	61.1	II	162	85	47%	46%	31.8	21.3	19.8
5	49	F	89.3	III	195	115	41%	61%	29.5	19.8	16.4
6	16	M	55.9	II	149	94	37%	39%	31.5	22.8	10.7
7	67	M	99.8	III	NA*				30.9	20.8	25.4

Abbreviations: RVEDV, right ventricle end diastolic volume; RVESV, right ventricle end systolic volume; RVOT, right ventricle outflow tract; RPA, right pulmonary artery; LPA, left pulmonary artery
*Cardiac CT angiography was used as a pre-procedural assessment, because of presence of pacemaker.

Table 2. Catheterization data on bilateral branch pulmonary artery stenting and valve implantation

Pt	Branch PA	Baseline		Pulmonary artery stenting			Interval Time (months)	Bilateral branch pulmonary valve implantation			
		Angio (mm)	Balloon Sizing Waist (mm)	Stent	Balloon	Waist of stent (mm)		Type of valve	Valve deployment balloon size (mm)	Angiographic valve insufficiency	Final valve stent diameter (mm)
1	RPA	10.9	NA	Genesis PG 3910	Z-Med II 16mm x 2 cm	15	5	Melody	18	None	14.3
	LPA	15.2	16.4	No pre-stenting done due to heavily calcified LPA				Melody	18	None	18.5
2	RPA	18.3	21.0	Palmaz XL P4010	NuCLEUS 25 mm x 4 cm	21.3	4	Melody	22	None	22.9
	LPA	12.3	13.5	Palmaz XL P4010	Z-Med II 20 mm x 2 cm	18.0		Melody	20	None	20.2
3	RPA	21.0	21.3	Palmaz XL P4010	NuCLEUS 25 mm x 4 cm	22.3	5	Melody	24	None	22.6
	LPA	9.3	15.9	Palmaz XL P3110	BIB 22 mm x 4 cm	22.3		Melody	24	None	21.7
4	RPA	20.2	23.2	Palmaz XL P4010	NuCLEUS 25 mm x 4 cm	21.7	4	Melody	24	None	23.4
	LPA	18.0	22.0	Palmaz XL P4010	NuCLEUS 25 mm x 4 cm	19.2		Melody	24	None	23.6
5	RPA	22.0	24.9	Palmaz XL P5010	NuCLEUS 28 mm x 4 cm	24.8	3	Sapien XT	29	None	26.0
	LPA	15.2	17.9	Palmaz XL P4010	NuCLEUS 25 mm x 4 cm	19.0		Sapien XT	26	Moderate	22.6
6	RPA	22.3	25.8	Palmaz XL P4010	NuCLEUS 28 mm x 4 cm	25.1	3	Sapien 3	29	None	26.5
	LPA*	10.9	15.3	Palmaz XL P3110	BIB 18 mm x 4 cm	15.2		Melody	20	None	17.4
7	RPA	23.3	26.2	Palmaz XL P4010	NuCLEUS 30 mm x 4 cm	25.7	4	Sapien 3	29	None	28
	LPA	21.5	23.6	Palmaz XL P4010	NuCLEUS 28 mm x 3 cm	25.0		Sapien 3	29	None	28

*LPA stent embolization: Initially, LPA was stented by 29 mm length Genesis XD mounted on 16 mm x 3 cm Z-Med II balloon. This stent embolized into the main pulmonary artery and re-positioned in the proximal stented RPA, followed by further dilation using a 24 mm x 4 cm ATLAS Gold balloon.

Table 3. Improvement of clinical variables before and after bilateral branch pulmonary artery valve implantation

(A) Immediate hemodynamic effect in cardiac catheterization

Variables		Baseline	Post-valve implantation
RV pressure	Systolic (mmHg)	40±14	35±5
	% systemic	42±12	38±8
Distal PA pressure	Systolic (mmHg)	28±12	29±4
	Diastolic (mmHg)	7±4	12±3
	Mean (mmHg)	15±5	19±3
	Systolic pressure gradient (mmHg)	13±9	6±7
Angiography	Narrowest diameter of branch PA (mm)	16.3±4.7	21.7±3.5
	Valve insufficiency — None/trivial	0	13/14 (93%)
	Valve insufficiency — Mild	0	0
	Valve insufficiency — Moderate	0	1/14 (7%)
	Valve insufficiency — Severe	7/7 (100%)	0

(B)   Follow up data

Variables			Baseline	Post-valve implantation	*p* value
Symptoms	NYHA	Class II	3/7 (43%)	7/7 (100%)	NA
		Class III	4/7 (57%)	0	
Cardiac MRI (4 patients)	RV end diastolic volume index (mL/m2)		150±27	105±15	**<0.001**
	RV end systolic volume index (mL/m2)		90±18	63±17	**<0.001**
	RV ejection fraction (%)		40±3	40±13	0.43
	LV ejection fraction (%)		60±3	59±5	NA
Echocardiography	Valve insufficiency	None/trivial	0	13/14 (93%)	NA
		Mild	0	0	
		Moderate	0	1/14 (7%)	
		Severe	7/7 (100%)	0	

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Supplemental Table 1: Reasons for bilateral branch PA valve implantation

Patient #	Reason for bilateral branch PA valve implantation
1	Ventricular tachycardia induced relatively poor cardiac function s/p ICD implantation
2	Tachyarrhythmia induced relatively poor cardiac function
3	Patient preference
4	Tachyarrhythmia induced relatively poor cardiac function
5	Patient preference
6	Patient preference
7	Relatively Poor Cardiac function
8	Patient preference

Supplemental Table 2: Surgical PVR comparative group

Pt	Age (year)	Gender	Weight (kg)	Length of Stay
1	16	M	115	4
2	32	M	71	4
3	16	F	76	4
4	19	M	91	6
5	20	F	67	3