

ORIGINAL ARTICLE

Intentional Fracture of Bioprosthetic Valve Frames in Patients Undergoing Valve-in-Valve Transcatheter Pulmonary Valve Replacement

See Editorial by Chhatriwalla and Sorajja

BACKGROUND: Percutaneous transcatheter pulmonary valve replacement (TPVR) has good clinical and hemodynamic outcomes in treating dysfunctional bioprosthetic valves (BPV) in the pulmonary position. Valve-in-valve therapy can further decrease the inner diameter (ID), potentially resulting in patient-prosthesis mismatch in patients with smaller BPVs.

METHODS AND RESULTS: To evaluate feasibility and outcomes of intentional BPV fracture to enlarge the pulmonary valve orifice with TPVR, 37 patients from 13 centers who underwent TPVR with intended BPV fracture were evaluated. A control cohort (n=70) who underwent valve-in-valve TPVR without attempted fracture was evaluated. BPV was successfully fractured in 28 patients and stretched in 5 while fracture was unsuccessful in 4. A Melody valve was implanted in 25 patients with fractured/stretched frame and a Sapien (XT 3) valve in 8. Among patients whose BPV was fractured/stretched, the final ID was a median of 2 mm larger (0–6.5 mm) than the valve's true ID. The narrowest diameter after TPVR in controls was a median of 2 mm smaller ($P<0.001$) than true ID. Right ventricular outflow tract gradient decreased from median 40 to 8 mm Hg in the fracture group. Cases with fracture/stretching were matched 1:1 (weight, true ID) to controls. Post-TPVR peak gradient was lower but not significant (8.3 ± 5.2 versus 11.8 ± 9.2 mm Hg; $P=0.070$). There were no fracture-related adverse events.

CONCLUSIONS: Preliminary experience shows intentional fracture of BPV frame can be useful for achieving larger ID and better hemodynamics after valve-in-valve TPVR.

Shabana Shahanavaz, MBBS
Jeremy D. Asnes, MD
Jochen Grohmann, MD
Athar M. Qureshi, MD
Jonathan J. Rome, MD
Daniel Tanase, MD
Matthew A. Crystal, MD
Larry A. Latson, MD
Brian H. Morray, MD
William Hellenbrand, MD
David T. Balzer, MD
Marc Gewillig, MD
Jon C. Love, MD
Farhouch Berdjis, MD
Matthew J. Gillespie, MD
Doff B. McElhinney, MD

Key Words: hemodynamics
■ prostheses and implants ■ pulmonary valve ■ stents ■ tetralogy of Fallot

© 2018 American Heart Association, Inc.

<https://www.ahajournals.org/journal/circinterventions>

WHAT IS KNOWN

- Although percutaneous transcatheter pulmonary valve replacement has yielded good clinical and hemodynamic outcomes in treating dysfunctional bioprosthetic valves, valve-in-valve therapy can further decrease the internal diameter of the bioprosthetic valve, especially in smaller bioprosthetic valves, thus leading to functional stenosis.

WHAT THE STUDY ADDS

- Intentional fracture of the bioprosthetic valve in the pulmonary position can be a useful technique to achieve larger internal diameter and better hemodynamic result in valve-in-valve therapy.

Surgical pulmonary valve replacement (PVR) with a bioprosthetic valve (BPV) is a common method of treating postoperative right ventricular outflow tract (RVOT) dysfunction in patients with repaired congenital heart disease.¹⁻³ Many types of BPV have been used off-label for PVR, most of which are indicated for aortic valve replacement and comprise a valve mounted within a rigid frame. Inevitably, BPVs implanted in the pulmonary position develop structural deterioration that can result in stenosis or regurgitation, with pathological changes that can include calcification, thickening, pannus, thrombus, tears, and inflammation associated with endocarditis.⁴⁻⁶ Various risk factors for BPV dysfunction have been reported.⁷⁻¹³ Surgical replacement has been the standard for managing pulmonary BPV failure but entails an important risk of morbidity and mortality, particularly with increasing number of prior open heart procedures.¹⁴

With the introduction of transcatheter valve technology, percutaneous valve-in-valve (VIV) replacement within a dysfunctional BPV has emerged as an attractive alternative to surgery, and early results have been encouraging.¹⁵⁻¹⁷ However, although homograft and xenograft conduits can often be expanded beyond their nominal diameter, even if contracted and calcified,¹⁸ transcatheter VIV placement is limited by the internal diameter of the rigid-frame BPV. In general, a BPV is composed of 4 components: a tissue valve, a single or multipart supporting framework composed of metal or plastic that is typically preformed into a complex 3-dimensional shape, a sewing ring, and a polymer cloth covering. The labeled nominal size of a BPV device typically refers to the outer diameter of the stent/supporting framework, whereas the true inner diameter (ID) is generally 2 to 5 mm smaller, depending on the manufacturer and make.¹⁹ Placement of a percutaneous valve within the BPV further narrows the lumen of these valves and limits the ultimate effective orifice size and potential gradient reduction, which can be a limiting factor in patients with

a relatively small BPV or who have undergone prior VIV transcatheter PVR (TPVR).¹⁵⁻¹⁸

Historically, surgical PVR was the only reasonable treatment option if the internal diameter of the VIV was too small. However, intentional fracture of the surgical BPV frame using ultrahigh-pressure balloons has been reported as a means of facilitating further expansion of the valve in the aortic, pulmonary, and tricuspid positions.²⁰⁻²³ To date, there have been few systematic studies of this practice, and none focused on intentional frame fracture to optimize hemodynamic outcomes of VIV in right-sided BPVs. Therefore, we undertook this multicenter study in an effort to identify patient-related, valve-related, or technical factors associated with outcomes of attempted frame fracture in patients undergoing VIV within a BPV in the pulmonary position.

METHODS

The data, analytic methods, and study materials will not be made available to other researchers for purposes of reproducing the results or replicating the procedure.

Patients

All patients who underwent percutaneous catheterization for intended TPVR within a previously placed surgical BPV in the pulmonary position at 13 participating institutions were reviewed. Those in whom frame fracture was attempted were analyzed for this study. Patients who underwent TPVR after dilation of a BPV using an ultrahigh-pressure balloon (Atlas, Atlas Gold, Vida, or True, Bard Peripheral Vascular, Inc, Tempe, AZ) without the express intent to fracture the valve frame were not included, and there were no reported cases of unintended fracture. Written informed consent was obtained for clinical catheterization and TPVR. Institutional review board approval for retrospective data collection and analysis was obtained at each of the participating centers.

Precatheterization data included demographic, diagnostic, and historical information. BPV type was abstracted from the medical record, and the sizes (nominal, stent ID, and true ID) were recorded from published manufacturer data. BPV types included Perimount, Perimount 2700, Magna, and Carpentier-Edwards Standard (Edwards Lifesciences, Irvine, CA), Mosaic (Medtronic Inc, Minneapolis, MN), Epic Supra and Trifecta (St. Jude Medical, Minneapolis, MN), and MitroFlow (Sorin Group, Plymouth, MN). In the sizes studied, the stent ID of these valves is 0 to 4 mm smaller than the nominal diameter and the reported true ID ranges from 2 to 4.5 mm smaller than the nominal diameter. Acute postimplantation hemodynamic data and final valve diameter were recorded. Peak and mean Doppler RVOT gradient were collected immediately post-procedure and at most recent follow-up, and any follow-up chest radiograms or computed tomography studies were reviewed.

TPVR Procedure

TPVR was performed after general techniques that have been well described.⁶⁻⁸ Specific technical measures, including

selection of balloon type, size, and inflation pressure, were at the discretion of the implanting physician. Procedural details were abstracted from the cardiac catheterization report and images, including type, size (diameter and length), and maximum inflated pressure of the balloon used to attempt frame fracture, placement of a pre-stent before VIV, attempted frame fracture before or after VIV, and narrowest valve diameter at baseline and after intervention. Minimum inner valve diameter at baseline was measured as the diameter of the first balloon waist, and postintervention diameter was measured as the ID of the TPV stent (inner edge to inner edge) at the narrowest point. Differences between diameters (balloon, pre- and postimplant measured, and published stent ID and true ID) were calculated. To standardize assessment across BPV types and sizes, and to allow comparison according to diagnostic and technical factors (eg, valve types, pre-stenting or post-dilation performed versus not performed, etc), the difference between final diameter and reported true ID was compared between groups. The location of the frame fracture was assessed relative to curvature of the RVOT, the commissural posts of the BPV, and the lap weld in cases with a radio-opaque metallic frame.

Control Cohort

We also collected limited demographic, procedural, and valve-related data for patients who underwent VIV TPVR without frame fracture at 4 of the participating centers, including various types of BPV with labeled sizes ranging from 19 to 29 mm. The purpose of this control cohort was both to document internal diameters typically achieved after VIV TPVR, which have not been reported previously, and to provide a descriptive and statistical comparison group for patients in whom VIV TPVR was performed with intentional BPV ring fracture. Controls were also matched 1:1 on weight and BPV true ID for comparison of final post-TPVR diameter and gradients.

Data Analysis

Categorical data were presented as frequency (%), and continuous data were presented as median (minimum-maximum). Paired *t* test analysis was used to compare continuous data before and after intervention within patients, and the Wilcoxon signed-rank test and Fisher exact test were used to compare continuous and categorical variables between groups. Statistical significance was defined as $P < 0.05$.

RESULTS

Patients and Outcomes

A total of 37 patients with a dysfunctional pulmonary valve BPV who underwent percutaneous VIV implant had attempted frame fracture, as summarized in Table 1. The underlying diagnosis was a variant of tetralogy of Fallot in 25 patients, valvar pulmonary stenosis in 4, and other in 8. The frame was successfully fractured in 28 of these patients (Figures 1–4; Movies I and II in the [Data Supplement](#)) and was successfully stretched but not fractured in 5 others (Figure 5) while attempted frame fracture was unsuccessful in 4. The 5 patients in

whom the ring was stretched had either a Perimount 2700 ($n=4$) or Carpentier-Edwards Standard ($n=1$) BPV, which have rigid metal frames comprising commissural posts and a base but not a full circumferential ring (Figure 5). In 2 of the patients with a Perimount 2700 that was stretched, there was an existing in situ fracture of the frame that was enlarged (Figures I and II in the [Data Supplement](#)). The control cohort comprised 70 patients who underwent VIV TPVR without intended frame fracture, with a nominal BPV diameter ≤ 23 mm in 42, 25 to 27 mm in 24, and 29 mm in 5.

In the 33 patients who underwent frame fracture or stretching, VIV TPVR was performed with a Melody valve (Medtronic Inc, Minneapolis, MN) in 24 and a Sapien XT or Sapien 3 valve (Edwards Lifesciences, Irvine, CA) in 8. One of the 28 patients who underwent successful frame fracture did not receive a transcatheter valve (discussed below). Seventeen of the patients in whom the frame was fractured or stretched had a bare metal pre-stent placed, 6 before and 11 after the frame was fractured.

The diameter of the balloon used to fracture the frame was at least 1 mm larger than the stent ID in all of the patients who underwent successful frame fracture, and in all but 3, it was at least 2 mm larger (median 2 mm). In contrast, of the 56 control patients in whom an ultrahigh-pressure balloon was used for pre- or post-dilation, the balloon was ≥ 1 mm larger than the stent ID in only 4 and ≥ 2 mm in 2, and in most cases was smaller (median -0.5 mm; $P < 0.001$ versus fracture patients). Among patients who underwent successful frame fracture, the median balloon inflation pressure at the time of fracture was 18 atm (12–26) and was >14 atm in 25 (89%) but varied among BPV types (Table 2). In 3 of the 4 control patients with a balloon size ≥ 1 mm larger than the stent ID, the maximum inflation pressure was ≤ 14 atm and in 1 was not reported but appeared to be relatively low on the stored fluoroscopy image. In the single case where fracture occurred at an inflation pressure of 12 atm, the balloon was 4 mm larger than the stent ID.

In all patients who underwent successful frame fracture or stretching, the postintervention minimum valve diameter was larger than ($n=30$) or the same size as ($n=3$) the manufacturer reported true ID, by a median of 2 mm (0–6.5 mm; Table 1; Figure 6). This differed significantly from control patients with an unfractured BPV ($n=70$), in whom the narrowest ID after TPVR was a median of 2 mm smaller ($P < 0.001$) than the reported true ID (1.4 mm smaller in the 42 control patients with labeled BPV size ≤ 23 mm; $P < 0.001$), with some variation depending on the type of valve (Figure 6). Among fractured or stretched valves, the final diameter–true ID difference did not seem to differ between TPV or BPV valve types or according to technical factors such as performance of pre-stenting or post-dilation. The median

Table 1. Summary of Patient-Related, Valve-Related, and Procedural Variables in Patients Undergoing TPVR With Attempted BPV Frame Fracture

Variable	Successful Frame Fracture n=28	Frame Stretched But Not Fractured n=5	Attempted Frame Fracture Unsuccessful n=4
Patient age, y*	15.5 (8 to 66)	25.7 (15 to 37)	21.5 (11 to 42)
Duration from BPV implant to VIV, y*	6 (3 to 16)	10.2 (4.7 to 16)	6.5 (3 to 11.5)
BPV type			
Perimount	15	...	1
Perimount 2700	...	4	...
Carpentier-Edwards Standard	1	1	...
Magna or Magna Ease	4	...	...
Mosaic	2	...	1
Trifecta	...	...	2
Epic or Epic Supra	5	...	...
MitroFlow	1	...	...
BPV diameter (nominal), mm			
19	5	...	1
21	5	2	...
23	17	3	2
25	...	...	1
27	1	...	...
Balloon type			
Atlas Gold	19	2	4
Atlas	4	...	...
Vida	5	3	...
Balloon diameter, mm			
20	6	...	...
22	5	2	3
24	16	1	...
26	1	2	1
Balloon length, cm			
2	15	3	1
4	14	2	3
Minimum inner BPV diameter at baseline, mm*	17 (13 to 22)	17 (16.2 to 21)	17.9 (16 to 18.6)
Difference of true ID–preintervention minimum diameter, mm*	1.0 (–1 to 10)	2.6 (0 to 3.8)	2.2 (0 to 3.3)
Difference of balloon diameter–true ID, mm*	3 (1 to 5.5)	6 (1 to 7)	3.5 (1 to 6)
Difference of balloon diameter–stent ID, mm*	2 (1 to 4)	3 (0 to 6)	2.3 (0 to 5)
Pre-stent implanted			
No	13	3	4
Before attempted fracture	8	...	...
After attempted fracture	7	2	...
Valve implanted before attempted fracture	7	...	1
Minimum diameter after TPVR, mm*	22 (18.0 to 24.7)	22 (19 to 25.5)	20 (19 to 23)
Difference of post-TPVR diameter–true ID, mm*	2 (0 to 5)	2 (0 to 6.5)	–0.1 (–1.5 to 0)*
RVOT gradient, mm Hg			
Preintervention peak gradient*	40 (18 to 105)	41 (15 to 69)	25 (15 to 30)
Final postintervention peak gradient*	8 (0 to 24)	3 (0 to 13)	14 (2 to 20)
Discharge Doppler maximum gradient*	20 (0 to 42)	29 (15 to 44)	29 (15 to 50)

BPV indicates bioprosthetic valve; ID, internal diameter; RVOT, right ventricular outflow tract; TPVR, transcatheter pulmonary valve replacement; and VIV, valve-in-valve.

*For continuous variables, data are presented as median (min, max).

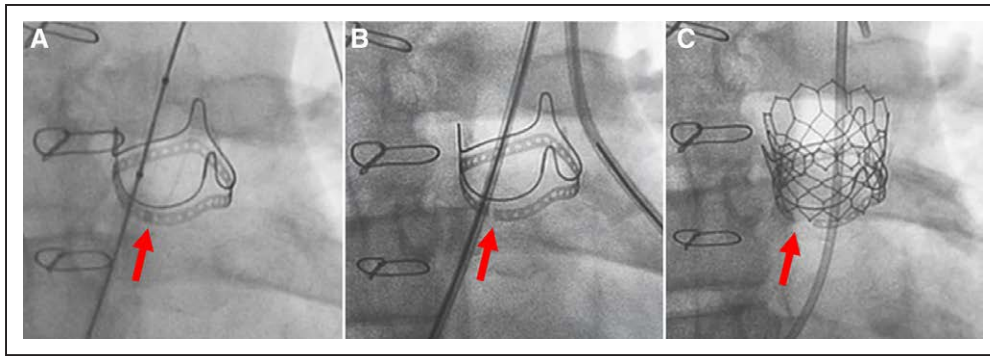


Figure 1. These images are of a 23-mm Edwards Magna valve, which has a similar radiographic appearance to the Perimount bioprosthetic valve. A 23-mm Edwards Magna valve (A) before ultrahigh-pressure dilation, (B) after dilation with a 24-mm Vida balloon to 16 atm and fracture of the frame, and (C) after implantation of a 26-mm Sapien 3 valve. Note that the separation at the point of fracture in the frame, which occurred at the site of the lap weld (as seen in A) is larger after implantation of the valve (C, red arrow) than after fracture and balloon deflation (B, red arrow).

peak gradient after TPVR was 8 mm Hg (0–24) in fracture patients and 3 mm Hg (0–13) in those whose frame was stretched (Table 1). When cases with successful fracture or stretching were matched 1:1 by weight and true ID to controls, the post-TPVR peak gradient was lower

but did not reach significance (8.3 ± 5.2 versus 11.8 ± 9.2 mm Hg; $P=0.070$) despite a higher preintervention gradient (43.0 ± 17.9 versus 34.2 ± 20.1 mm Hg; $P=0.072$).

Of the 25 successfully fractured BPVs that had a radio-opaque metallic frame with a visible lap weld

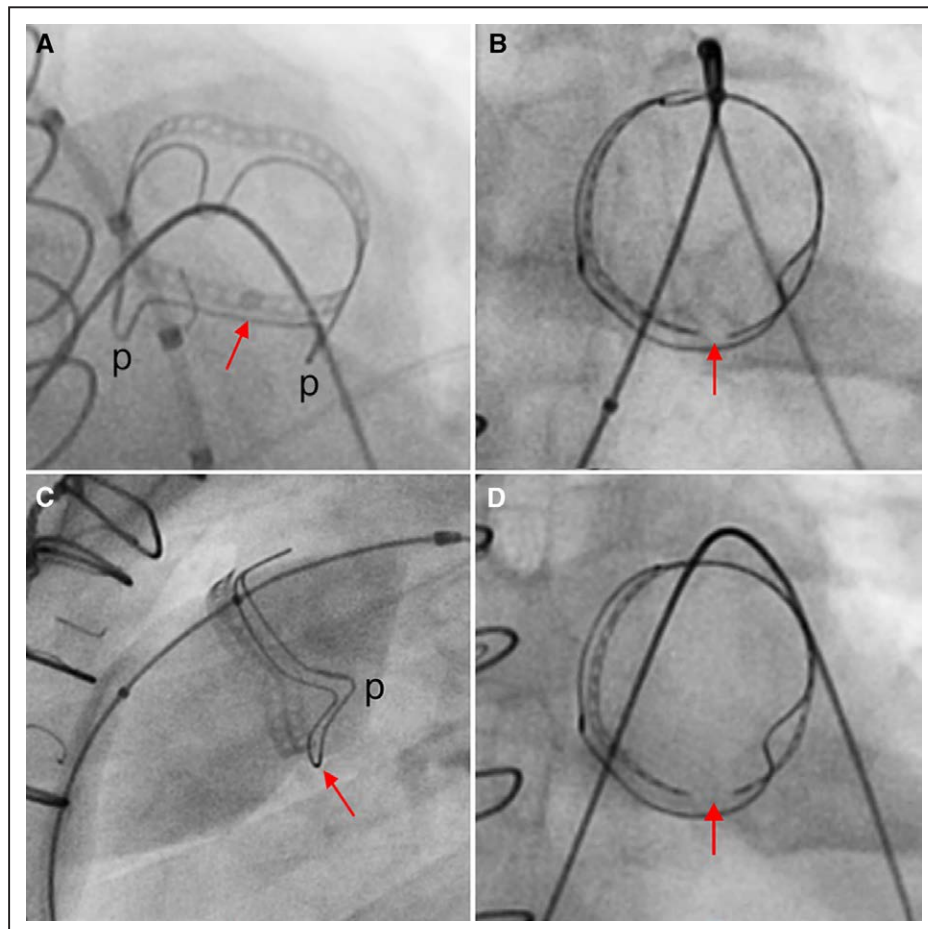


Figure 2. These fluoroscopic images are from a patient who underwent fracture of a 23-mm Magna bioprosthetic valve, followed by valve-in-valve transcatheter pulmonary valve replacement with a Sapien 3 valve.

A, This preintervention image shows the radio-opaque Elgiloy alloy frame/band, with the lap weld indicated by the arrow. B, After fracture of the ring using a 24 mm x 4 cm Vida balloon inflated to 15 atm, there is a clear separation in the Elgiloy band at the site of the lap weld (arrow). C, The valve was further dilated with a 26 mm x 2 cm balloon, (D) after which the separation of the fractured frame edges was wider (arrow). C, Note that the posterior wire band stretched beyond the fractured frame (arrow), and the posterior commissural posts (p) on either side of the fracture were substantially splayed and shortened (compare to A).

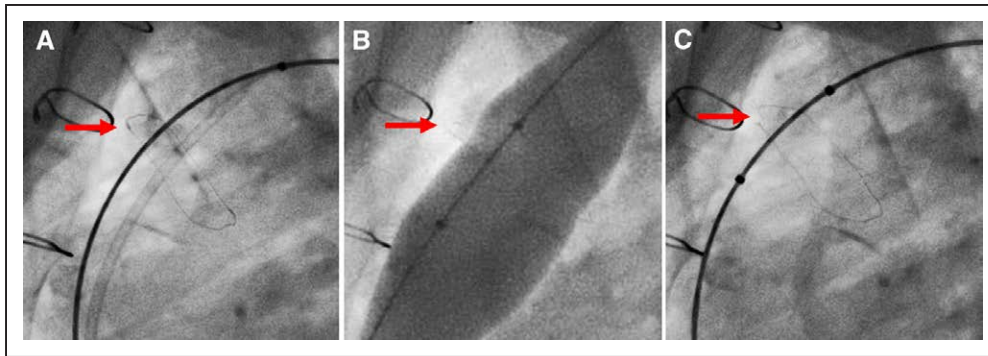


Figure 3. These fluoroscopic images from the lateral projection show the faintly visible ring of a 21-mm Epic Supra valve, which fractured with inflation of a 22-mm diameter 2-cm long Atlas balloon to 14 atm of pressure.

The anteriorly located lap weld (arrow in **A**) is the location of the fracture, as indicated by the arrows in **(B)** and **(C)**. The degree of separation of the fractured edges seems similar after balloon deflation as with the balloon inflated.

(valves other than Mosaic or MitroFlow), the fracture appeared as separation at the site of the lap weld in 16 while in the other 9 cases the location was either at another site in the frame or not characterized (Figures 1–3). The fracture was reportedly along the inner (lesser) curvature of the RVOT in 14 cases, the outer curvature in 5, and the side in 2 (3 not visible). The length of the separation between fractured edges and recoil (narrowing of the separation) after deflation of the balloon was not measured systematically, but some variability was seen, as depicted and described in Figures 1 to 3. In the patient with a MitroFlow valve, which has a radio-lucent plastic frame and a radio-opaque tungsten-impregnated silicone sewing ring, the radio-lucent frame clearly fractured during balloon inflation (Movie II in the [Data Supplement](#); Figure 4). In all 5 of the stretched valves, conformational changes of the basal-commissural frame were visualized (Figure 5; Figures I and II in the [Data Supplement](#)).

Unsuccessful Frame Fracture

Attempted fracture was unsuccessful, and not associated with stretching, in 4 patients, all of whom underwent TPVR with a Melody valve before ($n=1$) or after ($n=3$) attempted frame fracture. Reasons identified or postulated as potential contributors to unsuccessful fracture included resistant valve type (Trifecta) in 2 patients, relatively small balloon size (22 mm balloon in 23 mm valve, balloon diameter equal to stent ID) in 1, and inability to stabilize a large and short balloon across the frame in 1 (26 mm \times 2 cm Atlas Gold balloon use to dilate a 25 mm Mosaic valve in an angled RVOT, with attempted fracture after distal malposition of a Melody valve and residual stenosis).

Adverse Events

In 1 patient who underwent successful fracture of a 23 mm Perimount BPV frame with a 24 mm Atlas Gold balloon, a pre-stent was implanted on a 22 mm balloon,

and during advancement of the Melody valve delivery system, the stent was dislodged and embolized into the main pulmonary artery, so the decision was made to

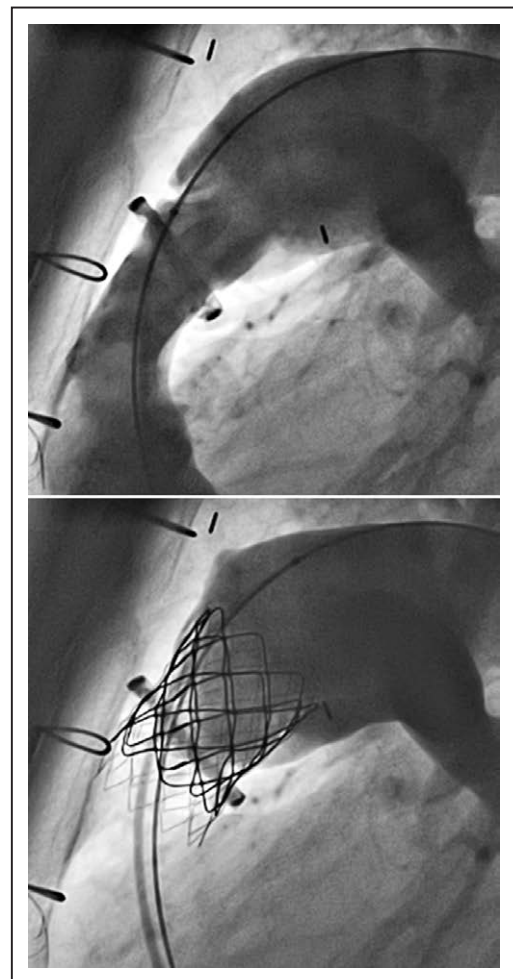


Figure 4. Fracturing a Mitroflow valve.

These pulmonary artery angiograms demonstrate enlargement of the bioprosthetic valve frame of a 22-mm MitroFlow valve (**top**) before intervention and (**bottom**) after fracture of the radio-lucent frame with a 22-mm Vida balloon inflated to 15 atm. This is the same valve shown in Movie II in the [Data Supplement](#). The fracture of the radio-lucent plastic frame is not visible, and there is no clear fracture of the elastic radio-opaque tungsten-impregnated silicone sewing ring, as it is in some other valves.

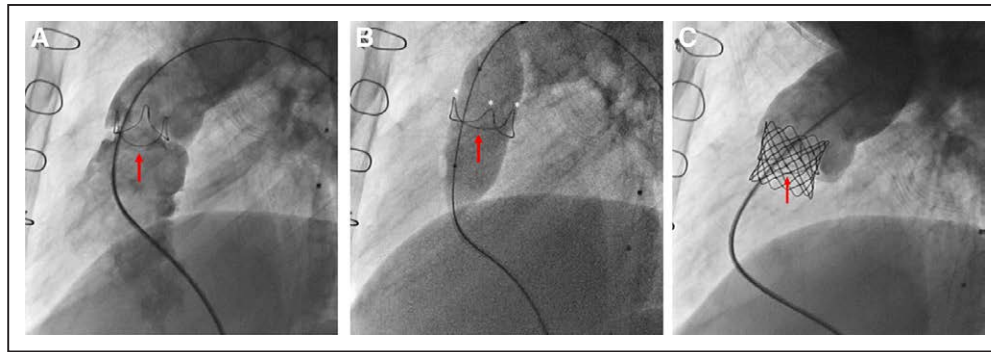


Figure 5. This sequence of fluoroscopy and angiographic images depicts stretching of the basal-commissural frame of a 23-mm Perimount 2700 bioprosthetic valve (BPV) with a 24-mm Atlas Gold balloon.

A. At baseline, the intercommissural portion of the valve frame has an upward concave curve (red arrow), **(B)** which flattens markedly with inflation of the ultrahigh-pressure balloon, which effectively results in stretching and elongation of the BPV circumference. Similar to the wire frame in Figure 1, the commissural posts are also splayed outward and widened (*). **C.** The persistently flattened frame can be seen through the Melody valve stent (arrow).

refer the patient for surgical removal of the stent and valve replacement. A primary contributing factor to the dislodgment was that the pre-stent was implanted distally within the BPV with extension to but not completely across the frame/sewing ring proximally.

There were no other valve- or intervention-related procedural or early adverse events. One patient developed a retroperitoneal hematoma requiring hospitalization and blood transfusion, with no evidence of active bleeding from TPVR vascular access sites identified, and 1 patient had a postcatheterization brachial plexus injury.

Follow-Up

Patients who underwent successful frame fracture or stretching were followed for a median of 3 months (0.1–53 months) after TPVR. During that time, there were no reinterventions on the pulmonary valve and no reported valve-related complications. Ten patients had postdischarge chest radiography or fluoroscopy, which

did not reveal any stent fracture or change in TPV configuration/location. No patients underwent follow-up chest computed tomography.

DISCUSSION

Intentional Frame Fracture in Patients Undergoing Pulmonary VIV for BPV Dysfunction

In this multicenter series, BPV frame fracture was successfully achieved in 27 of 36 patients in whom it was attempted in conjunction with VIV TPVR, and the frame was successfully stretched in 5 of the other 9 patients. Among patients in whom the valve frame was successfully fractured or stretched, the final ID was a median of 2 mm larger (0–6.5 mm) than the reported true ID for the valve in question, which stood in clear contrast to control patients with an unfractured BPV, in whom the final diameter was a median of 2 mm smaller than the true ID. These findings indicate a substantial

Table 2. Details of 28 Successful Frame Fracture Cases Stratified by Valve Type and Size

Valve Type	Valve Size, mm Labeled/Stent ID/True ID	No. of Patients	Patient Weight,* kg	Fracturing Balloon Diameter,* mm	Balloon Pressure at Frame Fracture,* atm	Initial Balloon Waist,* mm	Final Inner Diameter,* mm
Perimount/Magna†	19/18/17	5	23.5–69	20	20–22	15–18	19–22
	21/20/19	3	29–75	22–24	15–18	17–20	21.2–22
	23/22/21	11	58–140	24–26	12–23	16–22	20–24.7
CE Standard	27/25/23	1	87	24	26	13	24
Mosaic	23/20.5/18.5	2	55–59	24	15–20	18–19.2	19.9–22
MitroFlow	23/19/19	1	96	22	14	13	21
Epic	21/19/16.5	1	49	20	20	14	18
	23/21/18.5	2	50–77	22	16	16–17	20.5–22
Epic Supra	21/21/18.5	1	25	22	14	14.5	20
	23/23/20.5	1	79	22	15	14.8	20.5

ID indicates internal diameter.

*Data presented as minimum-maximum.

†Includes Magna Ease.

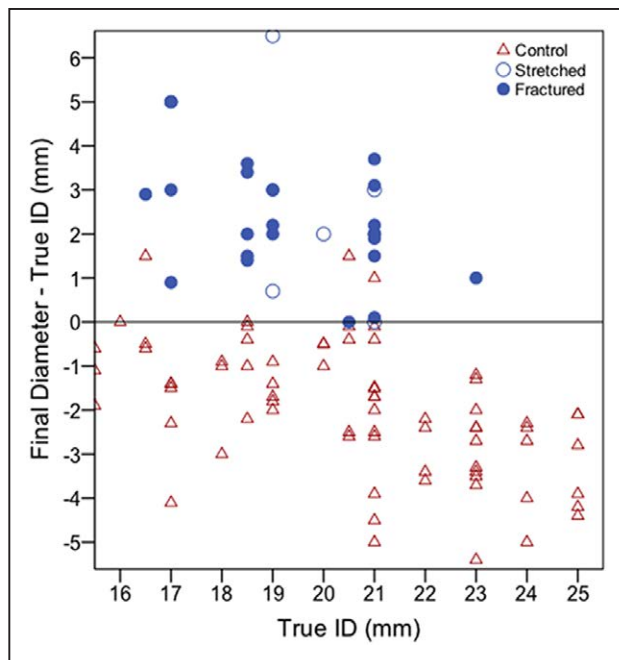


Figure 6. This scatterplot demonstrates the relationship between reported true internal diameter (ID) and the difference between final post-transcatheter pulmonary valve replacement diameter and true ID (positive indicated final diameter >true ID; negative indicates final diameter <true ID) for 70 unfractured control valves and valves with a successfully fractured or stretched frame.

benefit from frame fracture, similar to what has been achieved in the aortic position^{21,22} or with intentional fracture of balloon expandable stents in the pulmonary circulation.^{24,25} In most cases, the valve frame was fractured before TPVR and expanded to the maximum recommended diameter of the transcatheter valve, so the magnitude of gradient reduction resulting from the fracture was not observed directly. The absolute increase in BPV diameter varied from case to case, and it is unclear whether this was primarily a function of the maximum balloon size chosen or whether there are intrinsic or environmental factors that limited the extent of expansion to different degrees in different cases.

In several older BPV types that had wire a frame comprising commissural posts and a base but without a rigid circumferential ring (ie, Perimount 2700, Carpentier-Edwards Standard), the effective orifice of the valve was enlarged not by fracture per se but by stretching the framework with ultrahigh-pressure balloon dilation. Two of those valves had developed a spontaneous fatigue fracture of the wire frame in situ, which facilitated stretching similar to the valves treated with intentional overload fracture. These cases were included in this report because the intent was to fracture/expand the BPV beyond its implanted diameter and that therapeutic objective was achieved, and because we felt it was important to document that those specific BPV types may be expanded even if not fractured. In contrast to frame fracture, there was no threshold

inflation pressure at which expansion occurred (ie, yield point) as the stretch gradually expanded with progressively higher inflation pressure. Deformation/stretching of the wire frame forming the commissural posts was also observed in patients who underwent successful fracture of the Elgiloy band of a Perimount or Magna valve (Figure 2). The degree of expansion achieved in the stretched valves was similar to those in which the frame was fractured.

Deliberate fracture of a Perimount valve with an ultrahigh-pressure balloon was first described by Tanase et al,²⁰ who performed preprocedure bench testing and demonstrated loss of integrity of the Elgiloy band/frame without destruction of the surrounding Dacron sewing ring. With deflation, the elastic properties of Elgiloy resulted in some recoil but with maintenance of the circular geometry. In 2 recent in vitro studies, investigators attempted to fracture the frame of various new (ie, not explanted) aortic BPVs, characterizing inflation pressures required to reach the yield point and visual changes in the BPV frames.^{26,27} They were able to fracture all of the BPV types tested except the Trifecta and Hancock II valves using ultrahigh-pressure balloons with a diameter 1 mm larger than the labeled valve size, and the sewing cuff was never disrupted. Inflation pressures at the point of fracture ranged from 8 to 24 atmospheres depending on the surgical valve, and the fracture was followed by an immediate drop in balloon pressure and often an audible crack. Their finding that Mosaic valves tended to fracture at lower pressures than other BPV types was consistent with our observations in this study and the clinical series described by Nielsen-Kudsk et al.²³ The same groups reported clinical series of 20 and 10 patients who underwent intentional frame fracture during VIV transcatheter aortic valve replacement within small BPVs, either before or after valve implant, which largely reflected the in vitro findings. In all cases, frame fracture led to further expansion of the transcatheter valve and reduction in the gradient.^{22,23}

Technical Considerations

Four of the attempted frame fractures in this series were unsuccessful. Two of these were in Trifecta valves, which Allen et al²⁶ were also unable to fracture in their in vitro study. Of the other 2 unsuccessful fracture attempts, 1 was a complicated situation in which a 26 mm×2 cm balloon, which could not be stabilized across the frame because of the large diameter-length ratio of the balloon and the angled BPV implant location. The other unsuccessful attempt used a balloon with a diameter equal to the stent ID, which is smaller than in any of the successful fracture cases. There were too few unsuccessful cases to allow comparison of technical factors, other than valve type, that may have differed from the successful fracture cohort.

The technical requirements for successful frame fracture are likely to vary according to BPV type and size, and possibly to other factors as well, including tissue remodeling within and around the valve, and the geometry of the implant location. As in prior *in vitro* and *in vivo* studies,^{22,23,26,27} the balloon size used to fracture the frame was usually 1 mm larger than the nominal valve size and ≈ 3 to 5 mm larger than the true ID. In this series and the Chhatiwalla experience,²² slightly smaller or larger balloons were also used successfully in several cases, but the balloon was always at least 1 mm larger than the stent ID. In contrast, in the subset of our control cohort who underwent pre-dilation of the BPV or post-dilation after TPVR with an ultrahigh-pressure balloon, the balloon was typically smaller than the stent ID. The inflation pressure required for frame fracture varied somewhat according to valve type, with most cases in the 16 to 20 atm range, but was as low as 12 atm in 1 patient with a Perimount valve in whom a balloon 4 mm larger than the stent ID was used, and as high as 26 atm in the single patient who underwent fracture of a CE Standard valve. Even in the same type of BPV with similar balloon sizing, the inflation pressure at which fracture was achieved was not consistent. This could be because of imprecise recording of the fracture pressure, variability in the strength of the lap weld from valve to valve, or other factors related to BPV-tissue interactions or geometry. In any event, there are certain valve types that seem amenable to fracture, and operators intending to fracture the frame of such valves should recognize that both inflation pressure and balloon size must be sufficient and can be adjusted to achieve a successful result. As demonstrated in a computational study by Capelli et al,²⁸ balloon diameter relative to the stenosis (ie, the frame in this situation) is a critical factor in applying force to the stenosis, and larger balloon diameter allows application of the same force with lower inflation pressure, as in the patient mentioned above whose BPV was fractured with 12 atm inflation pressure.

Based on the observation that both 2 and 4 cm long balloons were used to achieve fracture, balloon length is not a critical factor for valves in the 19 to 23 mm labeled size range and should be selected based on other factors, such as anatomic considerations or technical advantages or disadvantages in a particular situation. With larger BPV size and balloon diameter, a shorter balloon may be less stable, as was the case in one of the unsuccessful attempts in this series. However, that case was also complicated by angled RVOT geometry, a factor that can interfere with balloon stability in its own right. Although shorter balloons may be harder to stabilize in some cases, they can be inflated more rapidly and with less volume, which may be beneficial, and they may be less prone to cause trauma to adjacent structures. Thus, it may be prudent to consider shorter

length ultrahigh-pressure balloons as the first option for intentional frame fracture, with addition of rapid pacing or transition to a longer balloon if necessary to achieve a stable balloon position.

As discussed previously, there remain several technical and therapeutic considerations that have not been resolved, either in our experience or prior *in vitro* studies or clinical series of patients who underwent transcatheter VIV replacement within an aortic BPV.^{22,23,26,27} For example, the maximum expansion of a BPV that can be achieved after frame fracture is unclear as are valve related and environmental factors that may mitigate enlargement of a fractured valve. Another issue that is more pertinent when the frame is fractured before valve implant than after is whether a pre-stent is necessary to resist intrinsic or *in situ* recoil of the fractured frame. In some cases in this series, there was substantial separation between the fractured frame edges after balloon deflation and additional sustained expansion after expansion with a larger balloon (Figure 2) while in others, the separation was initially more modest (Figure 2). We were not able to measure this separation in all cases because of inconsistent imaging, but the variety observed suggests that there are differential forces contributing to valve frame recoil after fracture. This was also observed in the cases in which a spontaneously broken frame was expanded (Figure 5). Accordingly, the importance of implanting a pre-stent or a TPV with high radial strength likely varies as well. Because a pre-stent occupies space within the BPV, potentially infringing on the achievable orifice area, if it is worthwhile to avoid pre-stenting it does not provide any additional benefit, but if placing a stent allows sufficient additional resistance against recoil to enlarge the valve more than the thickness of the stent, the trade-off will be favorable. A majority of patients who underwent TPVR with a Melody valve in this series had a pre-stent implanted, either before or after frame fracture, but we were unable to assess systematically whether the presence or absence of a pre-stent affected the magnitude of ultimate frame enlargement or whether there was important recoil after implanting the valve. Given the limited data and the observations noted above, it seems reasonable to recommend implanting a pre-stent or high radial strength TPV if there is visible recoil of the frame after fracture or if the separation of the fractured edges is minimal or even smaller than at the point of maximal balloon expansion, in an effort to optimize the effective orifice area after TPVR.

As discussed in prior studies, when performing VIV TPVR,¹⁵ or VIV implant in any position for that matter,²⁹ it is essential to deploy the valve and any pre-stents across the basal valve frame/sewing ring. This is highlighted by 2 of the cases in this series: in 1 case, the Melody valve was implanted distal to the basal ring, after which an unsuccessful attempt was made

to fracture the BPV frame, and in another case, a pre-stent implanted after frame fracture did not span the frame/sewing ring and embolized during advancement of the TPV delivery system. As demonstrated in Figure III in the [Data Supplement](#), the commissural posts of a BPV can splay outward and are not a sufficient framework to hold a VIV implant stably without extending the valve/stent across the basal BPV frame. This is true regardless for VIV TPVR both with and without frame fracture. Although the complications mentioned above were not related to the fractured frame, it is worth emphasizing that a pre-stent or valve implanted after frame fracture should be delivered on a sufficiently large balloon to account for expansion of the fractured frame.

Potential Caveats and Concerns

A natural concern about intentional frame fracture is vascular injury or potential disruption of the interface between the valve and tissue. A recent *in vitro* study did not reveal any protruding frame edges after intentional overload fracture of various BPV devices,²⁷ but even if the fractured edges did protrude, the intact sewing frame should protect against vascular damage. As discussed in a recent editorial, potential mitigation of this process because of valve-tissue interaction has not been elucidated but may be an important consideration.³⁰ As far as disruption of the sewing ring-tissue interface, we did not observe any cases of suspected rupture of paravalvular leak, and none of the previous reports of frame fracture described such a complication. That is not to say that such complications cannot occur, but it is reassuring that no instances have been reported.

One of the most significant concerns with the Melody valve implanted into expandable RVOT conduits has been stent fracture, but that complication has been observed only rarely after TPVR into a BPV.^{15,16} The low incidence of stent fracture after VIV TPVR suggests that the structural framework present in most BPVs protects the Melody valve from forces associated with cardiac contraction and interaction with adjacent structure, such as the aorta and chest wall.³¹ Fracturing the BPV frame could potentially expose the TPV to some of the external forces against which the rigid frame provided protection. Although there were no stent fractures during short-term follow-up in this study, longer-term evaluation will be necessary to assess whether this is a legitimate concern.

In patients undergoing catheterization for intended TPVR, 5% of patients do not receive a Melody valve because of risk of coronary artery compression.³² In general, transcatheter valve implant into a BPV with an intact sewing ring is less likely to result in that complication because of the fact that the size and profile of the BPV does not change after TPVR. However, the

potential for coronary compression should be considered and evaluated before TPVR with adjunctive frame fracture, as expanding the BPV may introduce the possibility of displacing surrounding tissues and compromising coronary flow.

We attempted to standardize valve size-related outcomes across groups by calculating the difference between final TPV ID and reported true ID. Although we recognize that this metric was still subject to potential variability and confounding, and was not a perfect method of indexing, we think it should have reduced some of the intrinsic uncertainty in attempting to compare outcomes across BPV types and sizes.

CONCLUSIONS

Intentional fracture of certain rigid-frame BPV devices in the pulmonary position is feasible, allows greater enlargement of the TPV compared with implant into an unfractured BPV, and in this preliminary experience was not associated with any direct complications. Although additional data will be necessary to understand the applications and limitations of this adjunctive technique, it is reasonable to consider intentional frame fracture as a means of further expanding the diameter of transcatheter valves implanted within a dysfunctional BPV. The impetus for fracturing the valve frame in most of the patients in this series was related to the fact that the BPV was smaller than ideal for an adult, and placement of a TPV within the relatively small BPV would result in further loss of orifice area. Placement of a relatively small pulmonary BPV may be inevitable when the valve is implanted at a young age, but with the advent of transcatheter valve therapy and VIV replacement, the question of what size surgical valve to implant has assumed greater importance. For most types of BPV, a minimum nominal size of 25 or 27 mm is necessary to ensure a good hemodynamic result after VIV TPVR, and an even larger BPV may be appropriate if the fit is acceptable. For pulmonary BPV devices that are 25 mm or larger at implant, frame fracture may not be necessary at the time of the initial VIV TPVR, but if the transcatheter valve fails over time and repeat VIV is an option, the largest starting point would be ideal. Accordingly, BPV frame fracture may be a useful adjunct not only for patients with a small BPV but also in circumstances where patient-prosthesis mismatch occurs after VIV implant, and it is necessary to enlarge the original BPV to allow a second VIV TPVR.

ARTICLE INFORMATION

Received January 25, 2018; accepted May 30, 2018.

Guest Editor for this article was Lee N. Benson, MD.

The Data Supplement is available at <https://www.ahajournals.org/doi/suppl/10.1161/CIRCINTERVENTIONS.118.006453>.

Correspondence

Shabana Shahanavaz, MBBS, Washington University School of Medicine, One Children's Place, Campus Box 8116- NWT, St Louis, MO 63110. Email Shahanavaz_s@Wustl.edu

Affiliations

Division of Cardiology, Department of Pediatrics, Washington University in St. Louis School of Medicine, MO (S.S., D.T.B.). Yale University, New Haven, CT (J.D.A., W.H.). Department of Congenital Heart Defects and Pediatric Cardiology, Heart Center, University of Freiburg, Germany (J.G.). The Lillie Frank Abercrombie Section of Cardiology, Texas Children's Hospital, Baylor College of Medicine, Houston (A.M.Q.). The Children's Hospital of Philadelphia, PA (J.J.R., M.J.G.). Department of Paediatric Cardiology and Congenital Heart Defects, German Heart Centre, Munich (D.T.). Division of Pediatric Cardiology, Morgan Stanley Children's Hospital, Columbia University Medical Center, New York, NY (M.A.C.). Department of Cardiology, Joe DiMaggio Children's Hospital, Hollywood, FL (L.A.L.). Division of Pediatric Cardiology, Seattle Children's Hospital, University of Washington School of Medicine (B.H.M.). Department of Pediatric Cardiology, University Hospitals Leuven, Belgium (M.G.). Division of Pediatric Cardiology, University of New Mexico, Albuquerque (J.C.L.). Children's Hospital of Orange County, CA (F.B.). Departments of Pediatrics and Cardiothoracic Surgery, Lucile Packard Children's Hospital Heart Center, Stanford University School of Medicine, Palo Alto, CA (D.B.M.).

Disclosures

Drs Balzer, Gewillig, Gillespie, Hellenbrand, McElhinney, and Morray were consultants for Medtronic Inc (Minneapolis, MI). Drs Asnes and Gewillig were Proctor for Edwards Lifesciences (Irvine, CA). The other authors report no conflicts.

REFERENCES

- Lee C, Park CS, Lee CH, Kwak JG, Kim SJ, Shim WS, Song JY, Choi EY, Lee SY. Durability of bioprosthetic valves in the pulmonary position: long-term follow-up of 181 implants in patients with congenital heart disease. *J Thorac Cardiovasc Surg*. 2011;142:351–358. doi: 10.1016/j.jtcvs.2010.12.020
- Jang W, Kim YJ, Choi K, Lim HG, Kim WH, Lee JR. Mid-term results of bioprosthetic pulmonary valve replacement in pulmonary regurgitation after tetralogy of Fallot repair. *Eur J Cardiothorac Surg*. 2012;42:e1–e8. doi: 10.1093/ejcts/ezs219
- Nomoto R, Sleeper LA, Borisuk MJ, Bergerson L, Pigula FA, Emani S, Fynn-Thompson F, Mayer JE, Del Nido PJ, Baird CW. Outcome and performance of bioprosthetic pulmonary valve replacement in patients with congenital heart disease. *J Thorac Cardiovasc Surg*. 2016;152:1333.e3–1342.e3. doi: 10.1016/j.jtcvs.2016.06.064
- Saleeb SF, Newburger JW, Geva T, Baird CW, Gauvreau K, Padera RF, Del Nido PJ, Borisuk MJ, Sanders SP, Mayer JE. Accelerated degeneration of a bovine pericardial bioprosthetic aortic valve in children and young adults. *Circulation*. 2014;130:51–60. doi: 10.1161/CIRCULATIONAHA.114.009835
- Soor GS, Leong SW, Butany J, Shaper JL, Williams WG. Pulmonary site bioprostheses: morphologic findings in 40 cases. *Arch Pathol Lab Med*. 2009;133:797–802. doi: 10.1043/1543-2165-133.5.797
- Butany J, Nair V, Leong SW, Soor GS, Feindel C. Carpentier-Edwards Perimount valves—morphologic findings in surgical explants. *J Card Surg*. 2007;22:7–12. doi: 10.1111/j.1540-8191.2007.00336.x
- Butany J, Feng T, Luk A, Law K, Suri R, Nair V. Modes of failure in explanted mitroflow pericardial valves. *Ann Thorac Surg*. 2011;92:1621–1627. doi: 10.1016/j.athoracsur.2011.06.092
- Flameng W, Rega F, Vercaalsteren M, Herijgers P, Meuris B. Antimineralization treatment and patient-prosthesis mismatch are major determinants of the onset and incidence of structural valve degeneration in bioprosthetic heart valves. *J Thorac Cardiovasc Surg*. 2014;147:1219–1224. doi: 10.1016/j.jtcvs.2013.03.025
- Zubairi R, Malik S, Jaquiss RD, Imamura M, Gossett J, Morrow WR. Risk factors for prosthesis failure in pulmonary valve replacement. *Ann Thorac Surg*. 2011;91:561–565. doi: 10.1016/j.athoracsur.2010.07.111
- Carpentier A. Hemodynamic factors affecting the fate of valvular bioprostheses. *Circulation*. 2010;121:2083–2084. doi: 10.1161/CIRCULATIONAHA.110.954123
- Flameng W, Herregods MC, Vercaalsteren M, Herijgers P, Bogaerts K, Meuris B. Prosthesis-patient mismatch predicts structural valve degeneration in bioprosthetic heart valves. *Circulation*. 2010;121:2123–2129. doi: 10.1161/CIRCULATIONAHA.109.901272
- Waller BF, McKay C, Van Tassel J, Allen M. Catheter balloon valvuloplasty of stenotic porcine bioprosthetic valves: part I: anatomic considerations. *Clin Cardiol*. 1991;14:686–691.
- Sénage T, Le Tourneau T, Foucher Y, Pattier S, Cuffe C, Michel M, Serfaty JM, Mugnot A, Périgaud C, Carton HF, Al Habash O, Baron O, Roussel JC. Early structural valve deterioration of Mitroflow aortic bioprostheses: mode, incidence, and impact on outcome in a large cohort of patients. *Circulation*. 2014;130:2012–2020. doi: 10.1161/CIRCULATIONAHA.114.010400
- Khanna AD, Hill KD, Pasquali SK, Wallace AS, Masoudi FA, Jacobs ML, Jacobs JP, Karamlou T. Benchmark outcomes for pulmonary valve replacement using the Society of Thoracic Surgeons Databases. *Ann Thorac Surg*. 2015;100:138–145; discussion 145. doi: 10.1016/j.athoracsur.2015.03.025
- Gillespie MJ, Rome JJ, Levi DS, Williams RJ, Rhodes JF, Cheatham JP, Hellenbrand WE, Jones TK, Vincent JA, Zahn EM, McElhinney DB. Melody valve implant within failed bioprosthetic valves in the pulmonary position: a multicenter experience. *Circ Cardiovasc Interv*. 2012;5:862–870. doi: 10.1161/CIRCINTERVENTIONS.112.972216
- Cabalka AK, Asnes JD, Balzer DT, Cheatham JP, Gillespie MJ, Jones TK, Justino H, Kim DW, Lung TH, Turner DR, McElhinney DB. Transcatheter pulmonary valve replacement using the melody valve for treatment of dysfunctional surgical bioprostheses: a multicenter study. *J Thorac Cardiovasc Surg*. 2018;155:1712.e1–1724.e1. doi: 10.1016/j.jtcvs.2017.10.143
- Finch W, Levi DS, Salem M, Hageman A, Aboulhosn J. Transcatheter melody valve placement in large diameter bioprostheses and conduits: what is the optimal “Landing zone”? *Catheter Cardiovasc Interv*. 2015;86:E217–E223. doi: 10.1002/ccd.25922
- Cabalka AK, Hellenbrand WE, Eicken A, Kreutzer J, Gray RG, Bergersen L, Berger F, Armstrong AK, Cheatham JP, Zahn EM, McElhinney DB. Relationships among conduit type, pre-stenting, and outcomes in patients undergoing transcatheter pulmonary valve replacement in the prospective North American and European Melody Valve Trials. *JACC Cardiovasc Interv*. 2017;10:1746–1759. doi: 10.1016/j.jcin.2017.05.022
- Bapat V, Mydin I, Chadalavada S, Tehrani H, Attia R, Thomas M. A guide to fluoroscopic identification and design of bioprosthetic valves: a reference for valve-in-valve procedure. *Catheter Cardiovasc Interv*. 2013;81:853–861. doi: 10.1002/ccd.24419
- Tanase D, Grohmann J, Schubert S, Uhlemann F, Eicken A, Ewert P. Cracking the ring of Edwards Perimount bioprosthesis with ultrahigh pressure balloons prior to transcatheter valve in valve implantation. *Int J Cardiol*. 2014;176:1048–1049. doi: 10.1016/j.ijcard.2014.07.175
- Brown SC, Cools B, Gewillig M. Cracking a tricuspid perimount bioprosthesis to optimize a second transcatheter sapien valve-in-valve placement. *Catheter Cardiovasc Interv*. 2016;88:456–459. doi: 10.1002/ccd.26507
- Chhatrivala AK, Allen KB, Saxon JT, Cohen DJ, Aggarwal S, Hart AJ, Baron SJ, Dvir D, Borkon AM. Bioprosthetic valve fracture improves the hemodynamic results of valve-in-valve transcatheter aortic valve replacement. *Circ Cardiovasc Interv*. 2017;10:e005216. doi: 10.1161/CIRCINTERVENTIONS.117.005216
- Nielsen-Kudsk JE, Andersen A, Therkelsen CJ, Christensen EH, Jensen KT, Krusell LR, Tang M, Terp KA, Klaaborg KE, Greisen JR, Nørgaard BL, Andersen HR. High-pressure balloon fracturing of small dysfunctional Mitroflow bioprostheses facilitates transcatheter aortic valve-in-valve implantation. *EuroIntervention*. 2017;13:e1020–e1025. doi: 10.4244/EIJ-D-17-00244
- McElhinney DB, Marshall AC, Schievano S. Fracture of cardiovascular stents in patients with congenital heart disease: theoretical and empirical considerations. *Circ Cardiovasc Interv*. 2013;6:575–585. doi: 10.1161/CIRCINTERVENTIONS.113.000148
- Morray BH, McElhinney DB, Marshall AC, Porras D. Intentional fracture of maximally dilated balloon-expandable pulmonary artery stents using ultra-high-pressure balloon angioplasty: a preliminary analysis. *Circ Cardiovasc Interv*. 2016;9:e003281. doi: 10.1161/CIRCINTERVENTIONS.115.003281
- Allen KB, Chhatrivala AK, Cohen DJ, Saxon JT, Aggarwal S, Hart A, Baron S, Davis JR, Pak AF, Dvir D, Borkon AM. Bioprosthetic valve fracture to facilitate transcatheter valve-in-valve implantation. *Ann Thorac Surg*. 2017;104:1501–1508. doi: 10.1016/j.athoracsur.2017.04.007
- Johansen P, Engholt H, Tang M, Nybo RF, Rasmussen PD, Nielsen-Kudsk JE. Fracturing mechanics before valve-in-valve therapy of small aortic bioprosthetic heart valves. *EuroIntervention*. 2017;13:e1026–e1031. doi: 10.4244/EIJ-D-17-00245

28. Capelli C, Nordmeyer J, Schievano S, Lurz P, Khambadkone S, Lattanzio S, Taylor AM, Petrini L, Migliavacca F, Bonhoeffer P. How do angioplasty balloons work: a computational study on balloon expansion forces. *EuroIntervention*. 2010;6:638–642. doi: 10.4244/EIJV6I5A106
29. Webb JG, Wood DA, Ye J, Gurvitch R, Masson JB, Rodés-Cabau J, Osten M, Horlick E, Wendler O, Dumont E, Carere RG, Wijesinghe N, Nietlisbach F, Johnson M, Thompson CR, Moss R, Leipsic J, Munt B, Lichtenstein SV, Cheung A. Transcatheter valve-in-valve implantation for failed bioprosthetic heart valves. *Circulation*. 2010;121:1848–1857. doi: 10.1161/CIRCULATIONAHA.109.924613
30. McElhinney DB. When device failure translates to therapeutic efficacy: intentional fracture of bioprosthetic valve rings as an adjunctive technique in transcatheter valve-in-valve replacement. *Circ Cardiovasc Interv*. 2017;10:e005662. doi: 10.1161/CIRCINTERVENTIONS.117.005662
31. McElhinney DB, Cheatham JP, Jones TK, Lock JE, Vincent JA, Zahn EM, Hellenbrand WE. Stent fracture, valve dysfunction, and right ventricular outflow tract reintervention after transcatheter pulmonary valve implantation: patient-related and procedural risk factors in the US Melody Valve Trial. *Circ Cardiovasc Interv*. 2011;4:602–614. doi: 10.1161/CIRCINTERVENTIONS.111.965616
32. Morray BH, McElhinney DB, Cheatham JP, Zahn EM, Berman DP, Sullivan PM, Lock JE, Jones TK. Risk of coronary artery compression among patients referred for transcatheter pulmonary valve implantation: a multicenter experience. *Circ Cardiovasc Interv*. 2013;6:535–542. doi: 10.1161/CIRCINTERVENTIONS.113.000202