State-of-the-art intra-procedural imaging for the mitral and tricuspid PASCAL Repair System

Rebecca T. Hahn * and Susheel K. Kodali

Columbia University Medical Center, New York Presbyterian Hospital, 177 Fort Washington Avenue, New York, NY 10032, USA

Received 19 December 2020; editorial decision 11 February 2021; accepted 22 February 2021

Advanced intra-procedural imaging techniques have been integral to technical and procedural success transcatheter devices. A novel leaflet approximation therapy, the PASCAL Transcatheter Valve Repair System (Edwards Lifesciences, Irvine, CA, USA) has demonstrated high procedural success, acceptable safety, and significant clinical improvement in patients with severe mitral and tricuspid regurgitation and has CE mark approval in Europe with pivotal trials underway in the USA. This review outlines the pre-procedural imaging views and advanced transoesophageal imaging protocols both mitral and tricuspid valve device implantation.

Keywords: mitral regurgitation • tricuspid regurgitation • transcatheter repair

Introduction

Despite the poor outcomes associated with untreated significant mitral (MR) and tricuspid regurgitation (TR), surgical interventions to treat these valvular conditions have been underutilized1,2 resulting in a large population of symptomatic patients with limited options. Recent trials have shown significant benefits with transcatheter edge-to-edge repair (TEER) device for primary3 and secondary4 MR. A novel leaflet approximation therapy, the PASCAL Transcatheter Mitral Valve Repair (TMVr) System (Edwards Lifesciences, Irvine, CA, USA) has demonstrated high procedural success, acceptable safety, and significant clinical improvement in compassionate use patients.5 The 1-year results of the PASCAL TrAnScatheter Mitral Valve RePair System (CLASP) early feasibility study (NCT03170349) showed low complication rates and high survival, sustained MR reduction, and significant improvements in functional status and quality of life.6

The compassionate use of the PASCAL Transcatheter Tricuspid Valve Repair (TTVr) device for TR reported a 30-day mortality of 7.1%, acceptable safety metrics7 with 85% achieving mild or moderate TR following device placement (P < 0.001). The single-arm, multicentre, prospective CLASP TR Early Feasibility Study (NCT03745313) recently reported its 30 days results showing a favourable safety profile with low major adverse events rate and no mortality at 30 days. The PASCAL TTVr device received CE mark in May 2020.

Although multiple prior imaging reviews have been published outlining the intra-procedural imaging for TEER guidance,8,9 there are differences in the procedural steps for the PASCAL device. Both the pivotal CLASP IID/IIF trial (NCT03706833) for degenerative and functional MR as well as the pivotal CLASP II TR trial (NCT04087145) for TR, are currently enrolling, and require pre-procedural transoesophageal echocardiography (TEE) for determination of valve morphology, severity of disease and adequacy of required intra-procedural imaging. This review will outline the standard TEE views for both pre-procedural and intra-procedural imaging and highlight the procedural differences with TEER. Patients whose images were used in this review were participants of the CLASP and CLASP TR studies. The studies were approved by the Columbia University Institutional Review Board.
**PASCAL repair system**

Features unique to the PASCAL repair system including a central spacer and adjacent paddles and clasps that attach the implant to the native leaflets to reduce regurgitation and is available in two sizes (Figure 1). The narrower width of the ACE device has been favoured for manoeuvring through dense chordal structures. The spacer and paddles are a single structure of interwoven nitinol wires acting as a

---

**Figure 1** The PASCAL Repair System. There are features unique to the PASCAL repair system including a central spacer and adjacent paddles and clasps that attach the implant to the native leaflets to reduce regurgitation. (Note: all dimensions are in millimeters).

**Figure 2** Primary imaging views for the mitral and tricuspid valve. The primary imaging views used for pre-procedural planning and intra-procedural guidance are shown in this figure.

| Mitral Valve View | Example | Tricuspid Valve View | Example |
|-------------------|---------|----------------------|---------|
| 4 Chamber MV View (ME) | ![Example Image] | 4 Chamber TV (ME) | ![Example Image] |
| Biplane: 4Ch/2CH | | RV Inflow/Outflow View ME (Sweep) | ![Example Image] |
| Commisural MV View (ME) | ![Example Image] | 4 Chamber TV (DE) | ![Example Image] |
| Biplane: Commisural/LAX | | Alternate Grasping Views (ME and DE) | ![Example Image] |
| 3 Chamber MV View (ME) | ![Example Image] | TG TV SAX | ![Example Image] |
| Transgastric MV SAX and LAX Views | ![Example Image] | DT RV view | ![Example Image] |
| 3D Volumes MV and IAS (ME) | ![Example Image] | 3D Volumes | ![Example Image] |

Abbreviations: 3D = three-dimensional, DE = distal esophageal, DT = deep transgastric, IAS = interatrial septum, LA = left atrium, LAX = long axis, LV = left ventricle, ME = mid-esophageal, MV = mitral valve, SAX = short axis, TG = transgastric, TV = tricuspid valve
Figure 3 Three-dimensional imaging of the mitral and tricuspid valves. Standardized imaging display for the en face view of the MV with both lateral and Z-plane rotation (A) and without Z-plane rotation (B); ruptured P2 chordae are seen (asterisk). A real-time 3D en-face view of the TV without Z-plane rotation, results in leaflet orientation similar to the transgastric view (C). Creating multi-beat colour Doppler 3D volumes of the systolic regurgitant jet, allows planimetry of the MR VCA post-device (D). MR, mitral regurgitation; MV, mitral valve; TV, tricuspid valve; VCA, vena contracta area.

Figure 4 Biplane imaging from the MV commissural view. Using simultaneous biplane imaging with the mid-oesophageal MV commissural view as the primary image, a sweep of the entire commissure can be performed. (A) The position of the orthogonal image (white arrow) at the lateral commissure (A1-P1 scallops). (B) The position of the orthogonal image at the midline (A2-P2 scallops) where a small flail posterior scallop is imaged (yellow arrow). (C) The position of the orthogonal image at the medial commissure (A3-P3 scallops). MV, mitral valve.
flexible frame to capture the leaflets and minimize leaflet stress.\textsuperscript{10,11} The nitinol clasps have a horizontal row of four retention elements near the top of the clasps intended to run parallel to the mitral leaflet collagen fibres, potentially reducing leaflet injury. The clasps can be actuated simultaneously or independently when grasping the leaflets allowing for optimization of leaflet insertion. An elongation mechanism allows positioning and repositioning with less risk of chordal entrapment.

---

**Figure 5** Four levels of imaging for the tricuspid valve. The path of the oesophagus allows for the generation of four imaging levels for the tricuspid valve: mid-oesophageal level, deep oesophageal level, transgastric and deep transgastric. A, anterior leaflet; Ao, aorta; LA, left atrium; LV, left ventricle; P, posterior leaflet; RA, right atrium; RV, right ventricle; S, septal leaflet.

**Figure 6** Biplane imaging from the TV commissural view. The mid-oesophageal right ventricular inflow-outflow view (at \( \sim \)50–80\(^\circ\)) is considered the TV ‘commissural’ view with the anterior (blue line) and posterior (green line) leaflets imaged and the septal leaflet (yellow line) behind the imaging plane. Moving the orthogonal biplane cursor towards the posterior wall (A) images the posterior and septal leaflets. Moving the orthogonal biplane cursor towards the aorta (B) images the anterior leaflet near the aorta and the septal leaflet. TV, tricuspid valve.
Shallow transgastric (TG), and deep transgastric (DT). For the MV imaging levels include: high oesophageal (HE), mid oesophageal (ME), and TV, the HE level is rarely used. A new distal oesophageal (DE) imaging level has been added for imaging the TV.

Because of anatomic variability not only of the cardiac structures themselves but also the relationship of the oesophagus to the heart structures, it is important to confirm complex valvular anatomy using 3D imaging. The ‘surgeon’s view’ imaging display for the en face view of the MV (Figure 3A) is advocated which requires varying degrees of Z-plane rotation depending on the acquisition image. The 3D en face MV view acquired from the 2D commissural view will image the posterior leaflet in the near field prior to Z-plane rotation (Figure 3B); some imagers/interventionalists prefer this view which minimizes image manipulation and mimics the 2D image by positioning the lateral commissure on the right and the medial commissure on the left side of the screen. Similarly the 3D en face TV view acquired from the 2D commissural view (and without Z-rotation), positions the interventricular septum on the right side of the screen, the aorta at 5 o’clock and the posterior leaflet in the near field (Figure 3C), an orientation similar to the TG SAX view. Creating multi-beat colour Doppler 3D volumes without splice artefacts for measurement of systolic regurgitant jet vena contracta area (VCA) is possible even with irregular rhythms (Figure 3D).

Mitral valve

Because of the relative positions of the oesophagus and left atrium, aligning the annulus perpendicular to the insonation beam may require right flexion in addition to retroflexion. Aligning the annulus perpendicular to the insonation beam has the following advantages: (i) both biplane images are typically perpendicular to leaflet coaptation (which allows simultaneous imaging of the clasp arms); (ii) orientation of the real-time multi-planar 3D image or 3D en face view is easier; and (iii) the trajectory of the system is more accurately assessed.

The ME MV commissural view at a transducer angle between 50° and 70°, is often seen as the ‘home’ view for the PASCAL system (Figures 2 and 4). Using biplane imaging, the orthogonal imaging plane can be positioned across the commissural line and thus sweep from the lateral commissure of A1/P1 (right sector, Figure 5A) to the midline (A2/P2, Figure 4B), and finally the medial commissure (A3-P3, Figure 4C), without and with colour flow Doppler. TG views may be useful not only for Doppler of the aortic valve (i.e. to calculate forward stroke volume) but also to evaluate the MV (Figure 2). Although short-axis views of the MV are rarely used given the use of ME 3D imaging, occasionally acoustic shadowing prevents an adequate assessment of the tissue bridge and the TG short-axis view can be helpful. In addition, commissural regurgitant jets may be aligned with the insonation beam only from the TG views (Figure 2).

Tricuspid valve

The TV is the largest and most apically positioned of the four cardiac valves with a normal orifice area between 7 and 9 cm² requiring a larger field of view with greater depth of imaging, both factors resulting in a loss of spatial and temporal resolution. In addition, given the position of the TV in relation to the oesophagus the annulus cannot be aligned perpendicular to the insonation angle in the ME and DE views and imaging the thin TV leaflets throughout the cardiac cycle using lateral resolution, is also more challenging. Finally, the TV leaflet morphology is highly variable creating a complex regurgitant orifice.

Transoesophageal echocardiography imaging protocols

The PASCAL repair system is implanted under TEE and fluoroscopic guidance. The imaging protocols will be divided into the following sections: (i) standard views for pre-procedural planning, (ii) pre-procedural assessment of valve morphology and function, and (iii) guidance of the procedure. Each step will be divided into mitral-specific and tricuspid-specific imaging protocols.

Standard views for pre-procedural planning

Appropriate 2D and 3D imaging with Doppler should be performed prior to and following device placement to quantify valve function. Figure 2 shows the primary imaging levels and views required for assessment of MV and TV morphology and function utilizing the probe manipulations described in prior guidelines. The standard four levels of imaging include: high oesophageal (HE), mid oesophageal (ME), shallow transgastric (TG), and deep transgastric (DT). For the MV

Figure 7 Post-device orifice area. Three-dimensional imaging is used to directly planimeter the MV orifice areas separately since the medial and lateral orifices are not typically in the same horizontal plane. Aligning the short-axis plane at the tips of leaflet in diastole (blue lines) allows the lateral orifice area (A) to be planimetered from the short-axis view (blue box). Realigning the short-axis plane for the medial orifice is shown in (B). MV, mitral valve.
Thus, all probe manipulations and four-probe levels are required for imaging the TV (Figure 2 and 5).\textsuperscript{12,16} Similar to MV imaging, the ‘home view’ for the TV is the ME RV inflow-outflow view (mechanical rotation of $\pm 60^\circ$) (Figure 6). From this view (either at the ME or DE level), the anterior leaflet is near the aorta and the posterior leaflet near the posterior free wall with the septal leaflet out-of-plane. Using this as the primary view, simultaneous biplane imaging can be used to image the entire coaptation line with the septal leaflet: from the aortic side (anterior-septal commissure) to the lateral side of the valve (posterior-septal commissure). The ME RV inflow-outflow view can thus be considered the TV ‘commissural’ view. Colour Doppler from the TV commissural view shows the long-axis of the typically elliptical or crescent-shaped jet along the length of the septal leaflet (Figure 2), and a sweep of the commissural line will thus identify the location of the regurgitation orifice. Importantly, the DE view typically images the TV through only right heart structures with no intervening left heart structures (i.e. prosthetic mitral devices) and may circumvent the acoustic shadowing from left heart structures. The TG level of imaging is essential for TV interventions. Right flexion with ante-flexion creates the TG RV inflow-outflow view and simultaneous biplane imaging at the TV leaflet tips results in a short-axis view of the TV. A single plane short-axis view can be obtained by using only anteflexion, at a mechanical rotation of between 25° and 60°.\textsuperscript{15} From the short-axis view, the coaptation gaps at the tips of the three leaflets, as well as the exact origin of the TR jet can be assessed. This view may be particularly useful for aligning the clasp arms, particularly when 3D imaging is limited. Further insertion of the probe towards the apex of the heart results in the DT views which aligns the Doppler insonation angle for more accurate measurement of transvalvular flow velocities (Figure 2).

### Assessment of valve morphology and function

Precise identification of atrioventricular valve morphology and function is required for pre-procedural planning in order to confirm: (i) severity of regurgitation, (ii) number and location of regurgitant jets, and (iii) suitability of anatomy for the PASCAL repair system. Although suitability for TEER has been delineated,\textsuperscript{17} defining morphologic suitability for the PASCAL repair system remains speculative at this time although investigators have shown that poor TEER patients may be candidates for this device.\textsuperscript{5}

## Mitral valve

*Mitral valve morphology:* both degenerative and functional MR may be appropriate targets for the PASCAL therapy with anatomic

---

### Table 1 Anatomic considerations for the PASCAL Repair System

|                          | Inclusion                          | Suggested anatomic exclusions                                                                 |
|--------------------------|------------------------------------|-----------------------------------------------------------------------------------------------|
| Mitral regurgitation     | • Primary severe, symptomatic MR    | Mitral valve anatomy precludes proper device deployment and function, including:               |
|                          | • Secondary severe, symptomatic MR  | • Evidence of moderate to severe calcification in the grasping area                             |
|                          |                                    | • Evidence of severe bi-leaflet/multi scallop prolapse involvement                            |
|                          |                                    | • Presence of significant cleft or perforation in grasping area                                |
|                          |                                    | • Leaflet mobility length $<8\text{mm}$                                                     |
|                          |                                    | • Presence of two or more independent significant jets                                       |
|                          |                                    | • Mitral valve orifice area $<4.0\text{cm}^2$                                                |
|                          |                                    | • Echocardiographic evidence of intracardiac mass, thrombus, or vegetation                   |
|                          |                                    | • Echocardiographic evidence of severe right ventricular dysfunction per core lab assessment |
| Tricuspid regurgitation  | • Primary severe, symptomatic TR    | Tricuspid valve anatomy precludes proper device deployment and function, including:           |
|                          | • Secondary severe, symptomatic TR  | • Evidence of severe calcification in the annulus or subvalvular apparatus                    |
|                          |                                    | • Evidence of moderate to severe calcification in grasping area                                |
|                          |                                    | • Excessive chordae structure in grasping area                                                |
|                          |                                    | • Presence of perforation in grasping area                                                    |
|                          |                                    | • Severe leaflet tethering or immobile leaflet                                               |
|                          |                                    | • Primary non-degenerative tricuspid disease (e.g. carcinoid, rheumatic, endocarditis, traumatic, pacemaker lead-induced, iatrogenic, tricuspid stenosis) |
|                          |                                    | • Previous tricuspid valve repair or replacement that would interfere with device placement |
|                          |                                    | • Presence of trans-tricuspid pacemaker or defibrillator leads which would prevent proper TR reduction due to interaction of the lead with the leaflets |

MR, mitral regurgitation; TR, tricuspid regurgitation.
Intra-procedural imaging for PASCAL MR, mitral regurgitation; TR, tricuspid regurgitation.

**Table 2** Procedural steps for implantation of the PASCAL Repair System

| Procedural steps | Mitral valve implantation of the PASCAL Repair System | Tricuspid valve implantation of the PASCAL Repair System |
|------------------|------------------------------------------------------|--------------------------------------------------------|
| I. Mitral valve | a. Transseptal puncture—mitral specific | a. Positioning in the right atrium |
| d. Clasp identification | b. Advancing the delivery system (2D and 3D guidance) | b. Catheter trajectory, implant position, and orientation above leaflets |
| e. Positioning and orientation below the leaflets | c. Catheter trajectory, implant position, and orientation above leaflets | c. Clasp identification |
| f. Clasping the leaflets: | d. Clasping the leaflets: | d. Elongation—when needed to reposition or to introduce a second device |
| i. Simultaneous | ii. Independent | i. Implant release |
| ii. Single leaflet optimization (for optimal result) | ii. Single leaflet optimization (for optimal result) | j. Post-delivery assessment |
| g. Pre-release assessment | h. Elongation—when needed to reposition or to introduce a second device | i. Tricuspid valve orifice area and gradient |
| i. MR severity (closed implant) | | i. Tricuspid valve orifice area and gradient |
| ii. Confirm leaflet insertion with open implant | | ii. Independent |
| iii. Mitral valve orifice area and gradient | | iii. Simultaneous |
| ii. Independent | | ii. Single leaflet optimization (for optimal result) |
| f. Clasping the leaflets: | h. Elongation—when needed to reposition | i. TR severity (closed implant) |
| i. Simultaneous | | ii. Confirm leaflet insertion with open implant |
| ii. Independent | | iii. Mitral valve orifice area and gradient |
| ii. Single leaflet optimization (for optimal result) | g. Pre-release assessment | j. Post-delivery assessment |
| i. TR severity (closed implant) | | i. TR severity (closed implant) |
| ii. Confirm leaflet insertion with open implant | | ii. Tricuspid valve orifice area and gradient |
| iii. Tricuspid valve orifice area and gradient | | g. Pre-release assessment |
| h. Elongation—when needed to reposition | | i. TR severity (closed implant) |
| i. Implant release | | ii. Tricuspid valve orifice area and gradient |
| j. Post-delivery assessment | | g. Pre-release assessment |
| i. TR severity (closed implant) | | i. TR severity (closed implant) |
| ii. Tricuspid valve orifice area and gradient | | ii. Tricuspid valve orifice area and gradient |

MR, mitral regurgitation; TR, tricuspid regurgitation.

Differences previously reviewed.17,18 MV anatomy which may preclude leaflet coaptation device implant or sufficient reduction in MR are shown in Table 1. Specific patient characteristics should always be considered when determining anatomic eligibility. For instance, a patient with a body surface area of 1.5 m² could have significant reduction in MR without an increase in MV gradient with a baseline MV area of <4.0 cm².

**Mitral valve function**: A comprehensive assessment of MV function both at baseline and following device placement includes:

1. Assessment of MV orifice area and diastolic transmitral gradient: peak and mean transmural gradients should be recorded along with heart rate.19 In the PASCAL compassionate use report, a single device resulted in a mean MV area reduction of ~47% and mean gradient = 3.0±1.0 mmHg.5 Because gradients are dependent on loading conditions and chamber compliance, planimetry of the MV orifice at baseline and post-device, should also be performed using 3D volumes (Figure 7). Two devices resulted in a mean MV area reduction of ~59% and mean gradient = 4.0±1.0 mmHg.

2. Location and Severity MR: using the ME commissural view, simultaneous biplane imaging with a ‘sweep’ of the MV coaptation zone (Figures 2 and 4) allows the imager to identify the location and approximate size of the regurgitant jet(s). Standard measures of MR severity should be performed as per society guidelines.20,21 However intra-procedurally, the most efficient method for assessing MR severity both at baseline and following device placement is planimetry of the 3D VCA (Figure 3D).22 Finally, following transcatheter leaflet repair, 3D VCA has been shown to accurately assess MR severity23 and predict outcomes.24

3. Pulmonary venous inflow: systolic reversal of pulmonary vein inflow is a specific sign for severe MR.20 Following leaflet repair, improvement of forward systolic flow in the pulmonary veins has become an important measure of device efficacy, and a predictor of improved outcomes.25,26

4. Other parameters: following device placement, recent American Society of Echocardiography guidelines suggest other indicators of improvement in MR severity including: appearance of spontaneous contrast in the left atrium, an increase in forward stroke volume and a reduction in ejection fraction.27

**Tricuspid valve**

**Tricuspid valve morphology**: Similar to MV morphology, TR can be divided in primary and secondary disease. Primary TR is relatively rare with one study showing cardiac implantable devices the most frequent cause.28 Secondary TR is far more common and can be morphologically characterized as atrial functional and ventricular functional TR.29

**Tricuspid valve function**: A comprehensive assessment of TV function both at baseline and following device placement includes:

1. Assessment of TV orifice area and diastolic transtricuspid gradient: planimetry of the TV orifice should be performed using 3D multiplanar reconstruction and peak and mean transtricuspid gradients should be recorded along with heart rate.

2. Location and Severity TR: using the 2D ME RV inflow-outflow view and 3D biplane sweep of the TV coaptation zone, location and approximate size of the regurgitant jet(s) can be determined. Standard measures of of TR severity should be performed as per society guidelines.20,21 However new methods of assessing severity of TR16 as well as an extended severity grading scheme30 is currently being used in early feasibility and pivotal trials of transcatheter TV

Downloaded from https://academic.oup.com/ehjci/advance-article/doi/10.1093/ehjci/jeab040/6301168 by guest on 18 June 2021
**Mitral Valve Imaging Recommendations**

**Procedural Step for PASCAL Repair System: Transseptal puncture and introduction of catheters**

- Locate the position and direction of transseptal catheter puncture ~4.5 cm above the annular plane in the mid-to-posterior fossa (adjacent to the mitral commissural line) with a posterior and superior direction of the catheter.
- 3 imaging views are used to confirm the position: bicaval view (superior/inferior position), SAX view (anterior/posterior position) and the 4Ch view (height above the annular plane).
- Mal-positioned transseptal puncture results in difficulty achieving the optimal trajectory of the implant.
- 3D Imaging of the interatrial septum helps identify the location of the medial MV commissure and transseptal puncture site (red asterisk).

**Procedural Step for PASCAL Repair System: Advancing the Delivery System**

- Follow the entrance of the elongated implant (green asterisk) into the left atrium, ensuring that the implant is clear of adjacent anatomy. (Note: Guide catheter tip noted by red arrow)
- Image implant closure (blue asterisk)
- Guide manipulation of the steering mechanisms to position the implant (blue asterisk) above the desired mitral valve scallops.
- Confirm the appropriate catheter trajectory, implant position.
- Avoid trauma to adjacent structures with guide or elongated implant.
- 3D imaging is optional.
- 3D imaging is essential and the primary imaging modality for guiding implant the valve and confirming appropriate catheter trajectory.
- Real-time 3D multi-planar reconstructions allows for live imaging of the 2 orthogonal long-axis view, short-axis view and 3D en face view.

**Examples of Imaging**

**Caveats of Imaging**

- Maintaining the guide across the interatrial septum is recommended but not absolutely required to steer the implant in the left atrium.

**Figure 8** Procedural steps for PASCAL mitral device implantation. (A) The imaging requires for transseptal puncture, advancing the delivery system (2D and 3D guidance) and implant orientation. (B) The next procedural steps of positioning and orientating the device below the leaflets, clasping the leaflets and pre-delivery assessment. (C) The imaging necessary for post-implant assessment of mitral valve function as well as haemodynamic benefit, and safe removal of the delivery catheter.
### Mitral Valve Imaging Recommendations

| Procedural Step for PASCAL Repair System: Orient Implant and Identify Anterior and Posterior Clasp |
| --- |
| ・ Using color Doppler as a guide, position the implant over the desired location relative to the regurgitant orifice |
| ・ Guide the orientation/rotation of the implant paddles orthogonal to the commissure line at the desired location of implantation |
| ・ Determine which slider controls which clasp |
| ・ Determine the correct imaging plane enables imaging of both clasps simultaneously |

| Examples of Imaging |
| --- |
| ![Scommisural View](image1.png) ![LAX View](image2.png) |
| ![Anterior View](image3.png) ![Mid-esophageal Long-and View](image4.png) |
| ![Simultaneous Comp Visualization](image5.png) |

| Caveats of Imaging |
| --- |
| ・ If the regurgitant orifice is not at the A2-P2 coaptation, ideal implant orientation may not necessarily be perpendicular to the line of coaptation |
| ・ Inappropriate orientation may result in failure to grasp adequate anterior and posterior tissue risking single leaflet device attachment |
| ・ 2D single plane, biplane or 3D imaging can be used |
| ・ Simultaneous fluoroscopic imaging is essential |

### Procedural Step for PASCAL Repair System: Confirming position and orientation below the leaflets

| ・ Confirm location of the implant relative to the regurgitant lesion |
| ・ Advance the delivery system beneath the leaflets using 2D (single or biplane) imaging. |
| ・ Note that stored frictional force in the catheters cause the implant to rotate upon advancement and retraction of the device and orientation confirmation should always be performed |

| ・ Although 2D imaging may be the first clue to implant rotation (both paddles no longer imaged in a single plane), 3D imaging should be used to confirm the location and orientation of the implant |
| ・ Reducing the gain of the 3D image allows clear visualization of the implant beneath the thin mitral valve leaflets without changing the level of imaging |

### Figure 8 Continued.
Following implant closure and prior to release of the implant assess: 1) Mitral valve orifice area and gradients, 2) Residual regurgitant severity 3) Hemodynamic benefit (improvement in systolic forward flow): a. Pulmonary venous inflow b. LV outflow tract stroke volume c. New onset “smoke” in the LAA

**Mitral Valve Imaging Recommendations**
- Continuously image as the implant is retracted
- Once leaflets are laying on inner paddles the clasps are dropped and imaging verifies leaflet insertion: visualization of clasp bounce should be seen however does not ensure adequate leaflet length capture
- Simultaneous capture of leaflets is most commonly performed, however independent grasping may be performed
- After capture of both leaflets, single leaflet optimization may be performed for optimal result

**Examples of Imaging**
- High frame rate (FR) and line density (LD) are required thus performing this step typically requires 2D single plane (highest FR, LD), or 2D biplane (lower FR, LD) imaging
- Real-time 3D (with or without multi-planar imaging) results in the lowest FR and LD however can be used if visualization of leaflet motion is adequate

**Caveats of Imaging**
- High frame rate (FR) and line density (LD) are required thus performing this step typically requires 2D single plane (highest FR, LD), or 2D biplane (lower FR, LD) imaging
- Real-time 3D (with or without multi-planar imaging) results in the lowest FR and LD however can be used if visualization of leaflet motion is adequate

**Procedural Step for PASCAL Repair System: Pre-release assessment**
- Confirm the following: 1) adequate tissue bridge and leaflet insertion between paddles and spacer, 2) appropriate location of the implant, 3) appropriate reduction in MR
- Use of biplane imaging with the commissural view as the primary view, permits imaging of long-axis views on either side of the implant to confirm capture of both leaflets
- On initial closure note reduction in MR (may see acute increase in BP, reduction in LA pressure)
- Measurement of leaflet lengths before and after closure ensures adequate grasped leaflet length. (NOTE: Independent clasp opening can be performed for these measurements)

- Following implant closure and prior to release of the implant assess: 1) Mitral valve orifice area and gradients, 2) Residual regurgitant severity 3) Hemodynamic benefit (improvement in systolic forward flow): a. Pulmonary venous inflow b. LV outflow tract stroke volume c. New onset “smoke” in the LAA

- 3D planimetry of both the mitral valve area and the color Doppler vena contracta area should be performed using multi-planar reconstruction (not imaged here)
### Mitral Valve Imaging Recommendations

- If the implant requires repositioning in the atrium, it is set in the elongated position and slowly retracted into the atrium

### Examples of Imaging

- ![Elongated Position](image1)
- ![Retract into Atrium](image2)

### Caveats of Imaging

- In the elongated position, entanglement in chordae is minimized

### Procedural Step for PASCAL Repair System: Post-release assessment

- Following release of the implant verify the same parameters as noted above:  
  1. Mitral valve orifice area and gradients, 
  2. Residual regurgitant severity 
  3. Hemodynamic benefit (improvement in systolic forward flow): 
     - a. Pulmonary venous inflow 
     - b. LV outflow tract stroke volume 
     - c. New onset “smoke” in the LAA

- Standard quantitative methods (i.e. PISA, quantitative Doppler) cannot be performed accurately following PASCAL
- Quantitation of MR relies on 3D color Doppler planimetry of the vena contracta area

### Procedural Step for PASCAL Repair System: Image the delivery catheter to assure safe withdrawal

- Image the removal of the delivery catheter
- Document the resulting interatrial atrial defect
- Document the absence of a pericardial effusion

- Desirable mean transmural gradient is < 5 mmHg
- Desirable valve area is > 2.0 cm²

- Closing the iatrogenic atrial septal defect can be considered depending on the presence of a significant shunt (either left-to-right or right-to-left).

### Abbreviations:

- 2D = two-dimensional, 3D = three-dimensional, A = anterior mitral valve leaflet, Ao = aorta, IAS = interatrial septum, IVC = inferior vena cava, LA = left atrium, LUPV = left upper pulmonary vein, LV = left ventricle, MR = mitral regurgitation, MVOA = mitral valve orifice area, P = posterior mitral valve leaflet, RA = right atrium, RUPV = right upper pulmonary vein, RV = right ventricle, SVC = superior vena cava

---

**Figure 8** Continued.
### Procedural Step for PASCAL Repair System: Pre-Procedural Assessment

- Interventionalist and imager should agree on the orientation and nomenclature to be used throughout the procedure.
- 2 standard orientations are acceptable: the surgeon’s view with the anterior leaflet on top, or the interventionalist’s view with the anterior leaflet on the bottom of the 3D image. The latter orientation is the same as a 2D transeptal view and thus may be preferred.

### Procedural Step for PASCAL Repair System: Advancing the Delivery System

- Position the PASCAL™ delivery system so that the tip (double-echodensity, red star) is 1–2 cm into the RA from the IVC/RA junction.
- Follow the entrance of the elongated implant (blue star) into the right atrium, ensuring that the implant is clear of adjacent anatomy.
- Image implant closure (blue asterisk).

### Caveats of Imaging

- Directional indicators show the septal-lateral plane (blue arrow) and the anterior-posterior plane (green arrow).
- Note: the tricuspid valve frequently is composed of either only 2 leaflets, or >3 leaflets. Deep folds in the leaflets may also result in the appearance of additional leaflets.

### Caveats of Imaging

- 3D narrow sector from the bicaval view allows imaging of the tricuspid TV in the elevational plane.
- Avoid trauma to adjacent structures with guide or elongated implant.
- 3D imaging is optional.

### Caveats of Imaging

- 3D imaging is essential and the primary imaging modality for guiding the implant to the valve and confirming appropriate catheter trajectory.
- Real-time 3D multi-planar reconstructions allows for live imaging of the 2 orthogonal long-axis views, short-axis view and 3D en face view.

**Figure 9** Procedural steps for PASCAL tricuspid device implantation. (A) The imaging requires for pre-device assessment, advancing the delivery system (2D and 3D guidance) and positioning and orientating the device below the leaflets. (B) The next steps of clasping the leaflets and pre-delivery assessment. (C) The imaging necessary for post-implant assessment of tricuspid valve function as well as haemodynamic benefit.
### Tricuspid Valve Imaging Recommendations

| Procedural Step for PASCAL Repair System: Orient Implant and Identify Anterior and Posterior Clasp |
|-------------------------------------------------|
| • Using color Doppler as a guide, position the implant over the desired location relative to the regurgitant orifice |
| ![Image 1](https://example.com/image1.png) ![Image 2](https://example.com/image2.png) |
| • Guide the orientation/rotation of the implant arms to along the commissure line at the desired location of implantation |
| ![Image 3](https://example.com/image3.png) ![Image 4](https://example.com/image4.png) |
| • Determine which slider controls the individual clasps |
| • Determine the correct imaging plane which enables imaging of both clasps simultaneously |
| ![Image 5](https://example.com/image5.png) ![Image 6](https://example.com/image6.png) |
| • Most TR regurgitant jets occur along the septal leaflet coaptation line |
| • 3D multiplanar or en face views are essential |
| • 2D transgastric short-axis view should be used to confirm |
| • 2D single plane, biplane or 3D imaging can be used. In this example the yellow arrow indicates the septal clasp and the blue arrow indicates the lateral clasp |

| Procedural Step for PASCAL Repair System: Confirming position and orientation below the leaflets |
|-------------------------------------------------|
| • Image the delivery system advance beneath the leaflets using 2D (single or biplane) imaging |
| ![Image 7](https://example.com/image7.png) ![Image 8](https://example.com/image8.png) |
| • Confirm location and orientation of the implant using 2D imaging from multiple imaging levels |
| ![Image 9](https://example.com/image9.png) ![Image 10](https://example.com/image10.png) |
| • Transgastric short-axis views should be used to confirm orientation |
| • 2D transgastric views can be used to visualize leaflets (or leaflet tips) between the paddles and the spacer however this view will not typically allow a measurement of the leaflet length within the paddles or clasps |

**Figure 9** Continued.
| Tricuspid Valve Imaging Recommendations | Examples of Imaging | Caveats of Imaging |
|----------------------------------------|--------------------|-------------------|
| • Confirm location and                 | ![3D en face View](image) | • If an adequate 3D en face rendering is obtained, reducing the gain of the 3D image allows clear visualization of the implant beneath the tricuspid valve leaflets |
| orientation of the implant using 3D  | ![Implant in RA](image) | |
| imaging from multiple imaging levels  | ![Implant in RV](image) | |
| Procedural Step for PASCAL Repair System: Clasping the leaflets | | |
| • Continuously image both paddles and leaflets as the implant is retracted | ![ME Commissural View 2D Biplane](image) | |
| • Once leaflets are laying on inner paddles the clasps are dropped and Imaging verifies leaflet insertion: clasp “bounce” may not be seen in the setting of lower systolic force | ![Live 3D Multiplanar TG View](image) | |
| • Simultaneous capture of leaflets or independent grasping can be performed. | | • Although 2D single plane (highest FR,LD), or 2D biplane (lower FR, LD) imaging are preferred, mid-esophageal 2D imaging of the anterior clasp is frequently shadowed by the spacer (blue box, blue arrow) |
| • After capture of both leaflets, single leaflet optimization may be performed for optimal result | | • 3D live multiplanar transgastric views can be used to visualize both leaflets in the paddles (blue box). |
| Procedural Step for PASCAL Repair System: Pre-release assessment | | • NOTE: transgastric biplane imaging (LAX view) is not typically able to image leaflet insertion |
Intra-procedural imaging for PASCAL

| Tricuspid Valve Imaging Recommendations | Examples of Imaging | Caveats of Imaging |
|----------------------------------------|--------------------|-------------------|
| • Confirm the following:               |                    |                   |
| 1) adequate tissue bridge and leaflet |                    |                   |
| insertion between paddles and spacer,  | Live 3D R ME View  | Measurement of    |
| 2) appropriate location of the         | Septal = 1.3 cm    | leaflet lengths   |
| implant,                               | Apical = 1.9 cm    | before and after  |
| 3) appropriate reduction in TR         |                    | closure ensures   |
| • Use of biplane imaging with the      | Live 3D TG View    | adequate grasped  |
| commissural view as the primary view,  | Septal = 1.2 cm    | leaflet length.   |
| permits imaging of long-axis views on   | Apical = 1.2 cm    |                   |
| either side of the implant to confirm  |                    |                   |
| capture of both leaflets               |                    |                   |
| • Always confirm leaflet grasp in the  |                    |                   |
| transgastric views                     |                    |                   |
|                                       |                    |                   |
| • Following implant closure and       |                    |                   |
| prior to release of the implant assess:|                    |                   |
| 1) Tricuspid valve orifice area and    | Transgastric Short-axis View | 3D real-time       |
| gradients,                             |                     | multiplanar imaging can also be used to |
| 2) Residual regurgitant severity       |                     | confirm leaflet |
| 3) Hemodynamic benefit                 |                     | insertion between |
| (hepatic venous inflow)                |                     | the paddles and   |
| • If the implant requires              |                     | spacer           |
| repositioning in the atrium, it is     |                     |                   |
| set in the elongated position and      |                     |                   |
| slowly retracted into the atrium       |                     |                   |
|                                       |                     |                   |
|                                       |                     |                   |
|                                       |                     |                   |

Figure 9 Continued.
devices. Recent studies have correlated the extended grading scheme with outcomes. Intra-procedural guidance

Intra-procedural guidance of leaflet coaptation devices rely heavily on maximizing the strengths of both 2D and 3D imaging. Because of these unique structural and mechanistic features of the PASCAL and ACE devices, imaging can differ from the TEER device. General procedural considerations include: imaging the number and location of chordae which may determine whether to use the PASCAL or the ACE device, and the frequent use of multiple imaging planes to circumvent the acoustic shadowing created by the spacer.

Differences between the imaging steps for the TEER and PASCAL system include the safe introduction of the elongated device followed by implant closure and shortening prior to redirecting to the atrio-ventricular annular plane. Manoeuvring the shortened device reduces the risk of injury (i.e. the lateral left atrial wall for the mitral and interatrial septum for the tricuspid device). In order to utilize independent leaflet grasping, the individual clasps must be identified. Finally, repositioning by retraction of the elongated device infrequently causes injury to the subvalvular or valvular structures, but nonetheless must be carefully monitored during repositioning of the device.

The procedural steps outlined in Table 2, are shown with the essential TEE imaging views for the mitral device (Figure 8A–C) and tricuspid device (Figure 9A–C).

**Discussion**

The PASCAL repair system to treat MR and TR is currently in pivotal trials with pre-procedural TEE required for inclusion, and intra-procedural imaging essential for technical success. The inherent advantages of 2D (greater resolution) and 3D (improved anatomic visualization) should always be considered during each procedural step. The imaging levels and views for the MV have been standardized for commercially available TEER however imaging of the TV remains a challenge given the relationship between the TV and oesophagus previously discussed. Implantation of the TV device typically requires greater probe manipulations and use of multiple imaging planes (ME, DE, TG, and DT) as well as multiple imaging modalities (2D and 3D) to optimize visualization of leaflets within the clasps and confirm adequate leaflet grasp. Extensive probe manipulation as well as longer procedures, increase the risk of complications from TEE imaging. Additional imaging modalities such as transthoracic and intracardiac echocardiography (2D and 3D) have been successfully used during these procedures when TEE imaging is limited. As 3D intracardiac phased array probes become commercially available this imaging modality has the potential to supercede TEE imaging for the TV.

**Conclusions**

The novel PASCAL transcatheter valve repair system (Edwards Lifesciences, Irvine, CA, USA), has received CE mark for treatment of both MR and TR of either primary or secondary aetiology. Both devices are currently in pivotal trials. Because this device relies heavily on TEE imaging the current imaging review may be useful in patient selection and technical success of the procedure.

**Conflict of interest:** R.T.H. is a speaker and consultant for Edwards Lifesciences and is the Chief Scientific Officer for the Echocardiography Core Laboratory at the Cardiovascular Research Foundation for multiple industry-sponsored trials, for which she
receives no direct industry compensation. S.K.K. reports no relation-

References
1. Jung B, Delgado V, Rosenhek R, Price S, Prendergast B, Wendler O, And the EORP VHD II Investigators et al. Contemporary presentation and management of valvular heart disease: the EURObservational Research Programme Valvular Heart Disease II Survey. Circulation 2019; 140:1156–69.
2. Benfari G, Antoine C, Miller WL, Thapa P, Topilsky Y, Rossi A et al. Excess mor-
tality associated with functional tricuspid regurgitation complicating heart failure with reduced ejection fraction. Circulation 2019; 140:196–206.
3. Feldman T, Foster E, Glower DD, Kar S, Rinaldi MJ, Fai P S et al. Percutaneous repair or surgery for mitral regurgitation. N Engl J Med 2011; 364:1395–406.
4. Stone GW, Lindenfeld J, Abraham WT, Lim DS, Mishell JM et al. Transcatheter mitral-valve repair in patients with heart failure. N Engl J Med 2018; 379:2307–18.
5. Praz F, Spargas K, Christoscheris M, Bullesfeld L, Nickenig G, Deuschl F et al. Compartment use of the PASCAL transcatheter mitral valve repair system for patients with severe mitral regurgitation: a multicentre, prospective, observation-
al, first-in-man study. Lancet 2017; 390:773–80.
6. Webb JG, Hensey M, Szerlip M, Schaffer U, Cohen GN, Kar S et al. 1-Year out-
comes for transcatheter repair in patients with mitral regurgitation from the CLASP Study. JACC Cardiovasc Interv 2020; 13:2344–57.
7. Hahn RT, Zamorano JL. The need for a new tricuspid regurgitation grading scheme. Eur Heart J Cardiovasc Imaging 2017; 18:1342–3.
8. Wunderlich NC, Siegel RJ. Peri-interventional echo assessment for the MitraClip procedure. Eur Heart J Cardiovasc Imaging 2013; 14:935–49.
9. Hahn RT, Nabauer M, Zuber M, Nazif TM, Hausleiter J, Taramasso M et al. Intra-procedural imaging of transcatheter tricuspid valve interventions. JACC Cardiovasc Imaging 2019; 12:532–53.
10. Zhang Y, Wang YY, Morgan AE, Kim J, Handschumacher MD, Moskowitz CS et al. Mechanical effects of MitraClip on leaflet stress and myocardial strain in func-
tional mitral regurgitation - a finite element modeling study. PLoS One 2019; 14:e0223472-e.
11. Caballero A, Mao W, McKay R, Hahn RT, Sun W. A comprehensive engineering analysis of left heart dynamics after MitraClip in a functional mitral regurgitation patient. JACC Cardiovasc Interv 2020; 13:431–32.
12. Hahn RT, Abraham T, Adams MS, Bruce CJ, Glas KE, Lang RM et al. Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. J Am Soc Echocardiogr 2013; 26:921–64.
13. Badano LP, Agnoli E, de Isla LP, Gianfagna P, Zamorano JL. Evaluation of the tri-
cuspid valve: anatomy and function by transesophageal real-time three-dimen-
sional echocardiography. Eur J Echocardiogr 2009; 10:477–84.
14. Lang RM, Badano LP, Tsang W, Adams DH, Agnoli E, Buck T et al. EAE/AESE recommendations for image acquisition and display using three-dimensional echocardiography. J Am Soc Echocardiogr 2012; 25:3–46.
15. Hausleiter J, Braun D, Orban M, Labi A, Lurz P, Boekstegers P et al. Patient se-
lection, echocardiographic screening and treatment strategies for interventional tricuspid repair using the edge-to-edge repair technique. EuroIntervention 2018; 14:645–53.
16. Hahn RT. State-of-the-art review of echocardiographic imaging in the evaluation and treatment of functional tricuspid regurgitation. Cir Cardiovasc Imaging 2016; 9:e005332. doi: 10.1161/CIRCMAGING.116.005332. PMID: 27974407.
17. Bonow RO, O’Gara PT, Adams DH, Badhwar V, Bavaria JE, Elmariah S et al. 2020 Focused update of the 2017 ACC Expert Consensus Decision Pathway on the Management of Mitral Regurgitation in patients with the American College of Cardiology Solusion Set Oversight Committee. J Am Coll Cardiol 2020; 75:2236–70.
18. Stone GW, Vahanian AS, Adams DH, Abraham WT, Borer JS, Bax JJ et al. Clinical trial design principles and endpoint definitions for transcatheter mitral valve repair and replacement: part 1: clinical trial design principles: a consensus document from the mitral valve academic research consortium. J Am Coll Cardiol 2015; 66:278–307.
19. Baumgartner H, Hung J, Bermejo J, Chambers JB, Evangelista A, Griffin BP et al. Echocardiographic assessment of valve stenosis: EAE/AESE recommendations for clinical practice. J Am Soc Echocardiogr 2009; 22:1–23. quiz 101–2.
20. Zoghbi WA, Adams D, Bonow RO, Enriquez-Sarano M, Foster E, Grayburn PA et al. Recommendations for noninvasive evaluation of native valvular regurgita-
tion: a report from the American Society of Echocardiography Developed in Collaboration with the Society for Cardiovascular Magnetic Resonance. J Am Soc Echocardiogr 2017; 30:303–71.
21. Lancellotti P, Moura L, Pierard LA, Agricola E, Popescu BA, Tribouilloy C. On be-
half of the European Association of Echocardiography et al. European Association of Echocardiography recommendations for the assessment of valvu-
lar regurgitation. Part 2: mitral and tricuspid regurgitation (native valve disease). Eur J Echocardiogr 2010; 11:307–32.
22. Goebel B, Heck R, Hamadanchi A, Otto S, Doenst T, Jung C et al. Vena con-
tracta area for severity grading in functional and degenerative mitral regurgita-
tion: a transoesophageal 3D colour Doppler analysis in 500 patients. Eur Heart J Cardiovasc Imaging 2018; 19:639–46.
23. Avenatti E, Mackensen GB, El-Tallawi KC, Reissman M, Gruye L, Barker CM et al. Diagnostic value of 3-dimensional vena contracta area for the quantification of residual mitral regurgitation after MitraClip procedure. JACC Cardiovasc Interv 2019; 12:582–91.
24. Dietl A, Prieschek C, Eckert F, Birner C, Luchner A, Maier LS et al. 3D vena contracta area after MitraClip procedure: precise quantification of residual mi-
tral regurgitation and identification of prognostic information. Cardiovasc Ultrasound 2019; 16:1.
25. Ikemga H, Yoshida J, Hayashi A, Nagaura T, Yamaguchi S, Rader F et al. Usefulness of intraprocedural pulmonary venous flow for predicting recurrent mitral regurgitation and clinical outcomes after percutaneous mitral valve repair with the MitraClip. JACC Cardiovasc Interv 2019; 12:140–50.
26. Corrigan FE, 3rd, Chen JH, Mani A, Lisko JC, Alvarez L, Kamioka N et al. Pulmonary venous waveforms predict rehospitalization and mortality after per-
cutaneous mitral valve repair. JACC Cardiovasc Imaging 2019; 12:1905–13.
27. Zoghbi WA, Asch FM, Bruce C, Gillam LD, Grayburn PA, Hahn RT et al. Guidelines for the evaluation of valvular regurgitation after percutaneous valve repair or replacement: a report from the American Society of Echocardiography Developed in Collaboration with the Society for Cardiovascular Angiography and Interventions, Japanese Society of Echocardiography, and Society for Cardiovascular Magnetic Resonance. J Am Soc Echocardiogr 2019; 32:431–75.
28. Vieseth JF, Montagueo JM, Mahia P, Perez L, Lopez T, Marco I et al. New insights of tricuspid regurgitation: a large-scale prospective cohort study. Eur Heart J Cardiovasc Imaging 2021; 22:196–202.
29. Muraru D, Gupta AC, Ochoa-Jimenez RI, Barker DT, Arora P, Mihala S et al. Functional regurgitation of atrioventricular valves and atrial fibrillation: an elusive pathophysiological link deserving further attention. J Am Soc Echocardiogr 2020; 33:42–53.
30. Hahn RT, Zamorano JL. The need for a new tricuspid regurgitation grading scheme. Eur Heart J Cardiovasc Imaging 2017; 18:1342–43.
31. Santoro C, Marco Del Castillo A, Gonzalez-Gomez A, Montagueo JM, Hinojor R, Lorente A et al. Mid-term outcome of severe tricuspid regurgitation: are there any differences according to mechanism and severity? Eur Heart J Cardiovasc Imaging 2019; 20:1035–42.
32. Peny I, Sadeh B, Sherer C, Hochstadt A, Birer S, Aviram G et al. Quantitative as-
essment of effective regurgitant orifice: impact on risk stratification, and cut-off for severe and torrential tricuspid regurgitation grade. Eur Heart J Cardiovasc Imaging 2020; 21:768–776.
33. Szafrza FF, Borrelli A, Pedrazzini G, Lea LA, Paocchi VL, Cauli G et al. 3D transeosophageal echocardiography: a new imaging tool for assessment of mitral regurgitation and for guiding percutaneous edge-to-edge mitral valve repair. Prog Cardiovasc Dis 2017; 60:305–21.
34. Freitas-Ferraz AB, Rodés-Cabau J, Junquera Vega L, Beaudoin J, O’Connor K, Turgeon FY et al. Transeosophageal echocardiography complications associated with interventional cardiology procedures. Am Heart J 2002; 143:19–28.
35. Farn NP, Samargandy S, Gandhi S, Eckstein J. Intracardiac echocardiography for guidance of transcatheter mitrrial-edge-to-edge repair. EuroIntervention 2018; 14:e1004–e5.