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REVIEW

Transgastric imaging—The key to successful periprocedural TEE guiding for edge-to-edge repair of the tricuspid valve

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Abstract

Intraprocedural transesophageal echocardiography (TEE) guidance plays an essential role in transcatheter repair therapy of the tricuspid valve (TV). So far, several different imaging concepts are in use. We propose an imaging protocol that fully addresses the morphological complexity of the TV and further offers efficacious workarounds for the frequently occurring restrictions of TV imaging in edge-to-edge repair of the TV. As a tertiary referral center with a large experience of more than 250 cases of transcatheter edge-to-edge repair (TEER) of the TV performed at the Heart Valve Center in Mainz/Germany, we have constantly adapted our peri-interventional echocardiographic approach to accomplish both. As a key measure for success, we intensely rely on the transgastric acoustic windows that not only deliver high-resolution information on the morphology of the TV and all relevant procedural steps but also help to avoid the frequent shadowing artifacts experienced in transesophageal imaging.

KEYWORDS
echocardiography, edge-to-edge, interventional imaging, transcatheter, transesophageal, tricuspid valve

1 | INTRODUCTION

Intraprocedural transesophageal echocardiography (TEE) guidance plays an essential role in transcatheter edge-to-edge repair (TEER) of the tricuspid valve (TV). However, adequate imaging can be demanding for several reasons. First, visualization of the TV is potentially restricted due to its unfavorable anterior position, that is, prone to shadowing artifacts by structures closer to the TEE probe. Second, TV morphology itself is highly variable and sometimes difficult to recognize as is the identification of different pathomechanisms causing tricuspid regurgitation (TR). Finally, for successful intervention, leaflet and device interaction needs to be precisely visualized and very closely evaluated.

So far, several different imaging concepts are in use.[1–7] As a tertiary referral center with a high annual caseload close to 100 transcatheter tricuspid valve (TV) interventions, we have developed a guiding protocol that has constantly been further adapted over the last years to better address the morphological complexity of the TV. Key part of our protocol is the use of transgastric acoustic windows. They deliver a maximum of morphological and functional information for all relevant intra-procedural steps, that is, evaluation of morphology, development of a repair strategy, and visualization of leaflet/device interaction. Furthermore, the frequent shadowing artifacts experienced in transesophageal imaging are avoided using the transgastric windows. As it has not been proposed in a similar fashion, we refer to the use of transgastric imaging to guide leaflet grasping as the "Mainz-Approach".

FIGURE 1 Set-up in hybrid OR. Set-up in the hybrid OR with the echocardiographer's position at the head of the cath-lab table. Two mobile protective shields (yellow arrows) with a transparent leaded screen guarantee for sufficient radiation protection. Note the C-arm position lateral to the table providing enough space for echo machine, table, and seating

The central idea of a rigorous focus on morphology is woven into a structured protocol involving the following steps: an optimal TEE set-up in the cath-lab (1), a comprehensive verification of acoustic windows (2), a careful evaluation of TV morphology (3), development of an adequate interventional strategy (4), procedural guidance (5) and evaluation of interventional success (6). Our protocol applies to both CE-marked TEER devices in use, the TriClip system (Abbott, Chicago, IL, USA)[8,9] and the PASCAL repair system (Edwards Lifesciences, Irvine, CA, USA).[10–12]

2 | Guiding Protocol

2.1 | Step 1: Set-up in the cath-lab

A safe and proper set-up for the echocardiographer in the cath-lab needs to maximally reduce radiation exposure and to provide an ergonomic working environment. We highly recommend the echocardiographer's position to be at the head of the table with the C-arm in a left-lateral position to accomplish these requirements best. Only now two mobile leaded acrylic shields can be placed directly in between C-arm and echocardiographer and enough space is provided for ultrasound system, seating, and a table for probe suspension (Figure 1).

2.2 | Step 2: Verification of acoustic windows and their respective views

As imaging of the TV can be restricted by its unfavorable anterior position, verification of all relevant acoustic windows is paramount. Our protocol relies on two transesophageal (i.e., a mid- and a deep-esophageal) and one transgastric window. Each acoustic window is used for specific views/imaging planes.

2.2.1 | Mid-esophageal RV inflow-outflow view

Transesophageal imaging aims to generate unrestricted inflow-outflow views of the right ventricle (RV) that can be used as the primary imaging plane for biplane imaging and 3D rendering. Firstly, we identify the mid-esophageal (ME) acoustic window from which a correct inflow-outflow view of the RV can be achieved (search angle of TEE transducer typically is 60–80 degrees; Figure 2A and B). It cuts the TV parallel to the line of coaptation of anterior and posterior leaflets with the septal leaflet. If the imaging plane is correct the perpendicular plane (generated by activation of biplane imaging) shows a mirrored 4-chamber view of the TV. As a marker of imaging quality, the septal leaflet should be fully visualized without shadowing artifacts, especially at the anterior commissure.

2.2.2 | Deep-esophageal RV inflow-outflow view

Often an unrestricted inflow-outflow view of the TV can be more successfully obtained from a deep-esophageal window (Figure 2D and E). This view is acquired by advancing the TEE probe into the distal esophagus directly behind the posterior wall of the right atrium (Figure 2F). From this transducer position an unobstructed visualization of

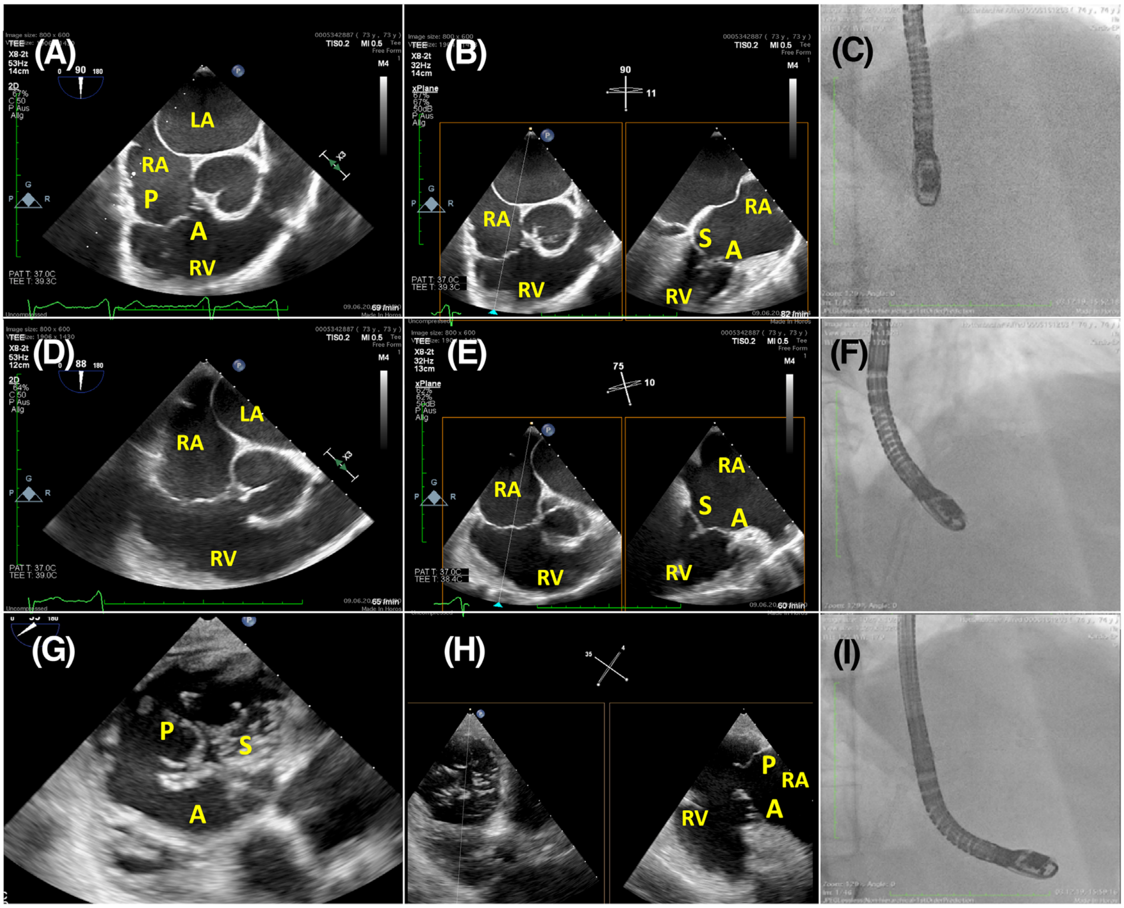


FIGURE 2 Essential acoustic windows for edge-to-edge repair of the TV, Essential acoustic windows for edge-to-edge repair with simultaneous biplane views and corresponding fluoroscopic images of TEE probe position; (A-C): mid-esophageal RV inflow-outflow view; (D-F): deep-esophageal RV inflow-outflow view; (G-I): transgastric short-axis view of the TV

the TV is more likely as left atrium, aortic valve, and inter-atrial septum are bypassed and shadowing artifacts are avoided. If present, it is the ideal window for performing a biplane evaluation of TV function and for acquiring high frame rate 3D volumes of the TV.[1,13,14] The correct search angle of TEE transducer is typically slightly higher than for the inflow-outflow view from the ME window (80–100 degrees).

2.2.3 | Transgastric short-axis view

An essential view for TV leaflet evaluation is the transgastric short axis (SAX) or en face view generated from a transgastric window (Figure 2G and H). It is the only 2-dimensional view providing visualization of all leaflets at the same time.[1] The aim is to generate a transversal imaging plane of the TV, showing all leaflets in one plane. Optimal orientation of the primary imaging plane can be controlled by simultaneous biplane imaging showing the TV annulus in a strict vertical orientation on the secondary imaging plane (Figure 2H). The TEE probe is advanced into the stomach and anteflexed with an additional turning of the probe toward the patient's right (clockwise) (Figure 2I). Search angle rotation usually ranges between 20 and 60 degree, higher angles may be required in cases with very severe RV enlargement and cardiac axis deviation. Small adjustments of probe position and angulation can help to optimize the imaging plane.[15] Examples of views from all three different acoustic windows are given in Figure 2. It also displays the corresponding TEE probe positions that can be easily controlled by fluoroscopy throughout the procedure.

2.2.4 | Use of 3D imaging

From all acoustic windows 3D data sets of the TV can be obtained.[16] As the quality of 3D data sets fully depends on the quality of 2D images care must be taken to generate 3D data from windows with an unrestricted view of the TV.[17]

Periprocedural 3D imaging can offer several advantages, especially in patients in whom transgastric imaging is restricted. Next to the three-dimensional display of the complete valvular morphology, specific tools like multiplanar reconstruction (MPR) can help to measure valvular dimensions, coaptation gap size or to guide device/leaflet interaction.

For a proper 3D MPR evaluation of the TV morphology all three imaging planes need to be correctly aligned. A transversal plane must be brought in parallel to the TV annulus. Orientation of the two other planes should create a RV inflow-outflow view and a 4-chamber view. Slight translation of the transversal plane can improve identification

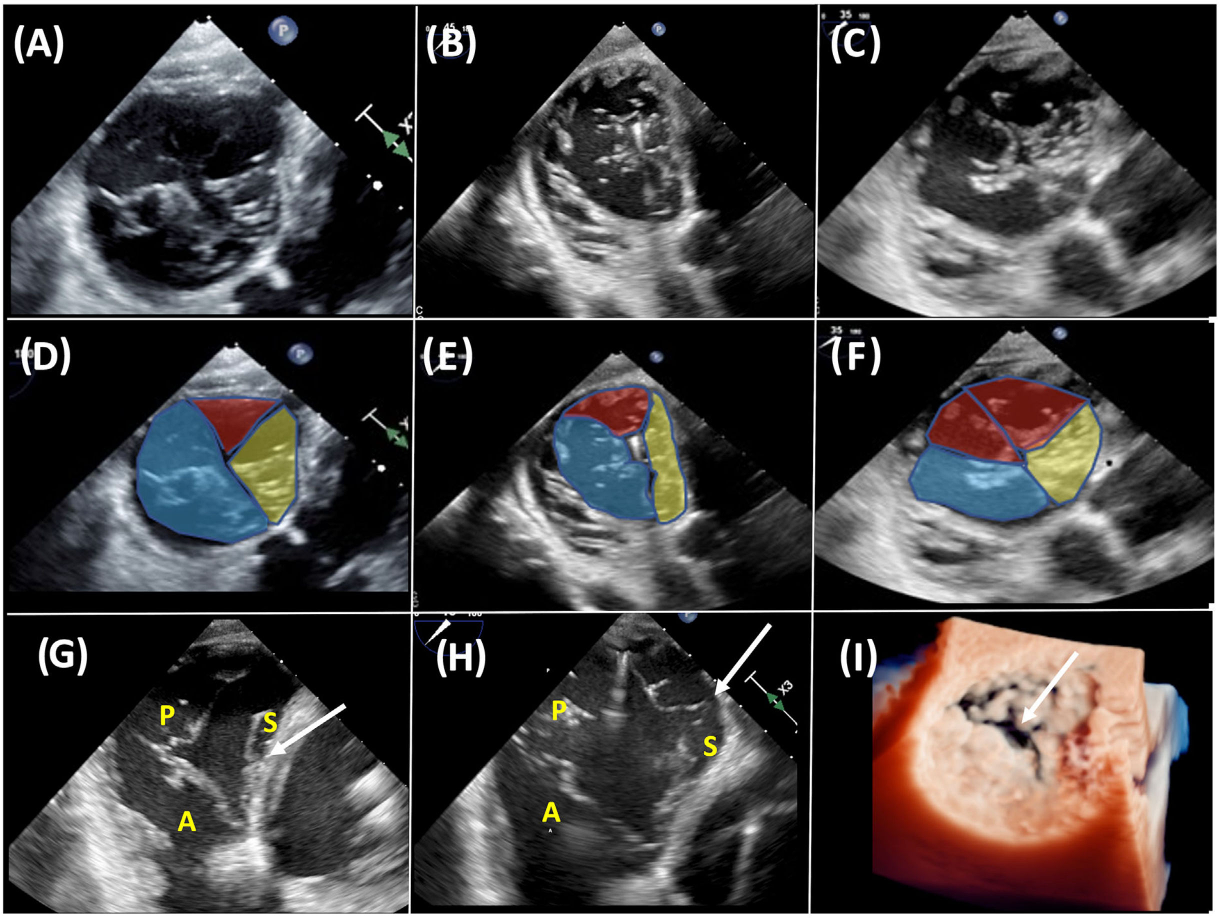


FIGURE 3 TV morphology with varying size and number of leaflets, commissures, and indentations. Transgastric SAX views of the TV showing anatomical variability of tricuspid valve leaflets (A-C) with PTL in red, STL in yellow and ATL in blue (D-F). Depending on depth and size a smaller septal leaflet indentation (G) can be differentiated from a more pronounced septal leaflet commissure separating two septal leaflets (H; white arrows). Finally, (I) shows a "true view" rendered 3D zoom volume that gives a meaningful overview of TV morphology including the size of the central coaptation gap

of the leaflet edges and thus coaptation gap size. Rotation of the 4-chamber like imaging plane into a position perpendicular to the line of coaptation will depict leaflet lengths, annular diameter and gap size at any chosen target zone (Figure 4F–G).

2.3 | Step 3: Evaluation of TV morphology

The TV is the most complex and anatomically variable valve of the heart. Despite its name, the TV is truly tricuspid in only about half of the investigated subjects. In the other half, it is frequently quadricuspid with an additional leaflet, most commonly presenting as a second posterior leaflet.[18,19] (Figure 3A–F).

Hence, a thorough assessment of TV morphology and identification of the underlying pathology causing TR is key to developing a suitable interventional strategy.[20]

Pulling the free mural wall (anterior and/or posterior leaflet) towards the septal leaflet (STL) is the principle of TEER as the STL works as an anchor leaflet for any of the devices. Thus, a sufficient STL leaflet length and mobility is crucial to guarantee successful TEER and it should be carefully evaluated before the procedure. STL radial length at the target zone, and presence of tethering are paramount to recognize, as they directly influence treatment success.[21,22] Further, indentations of the septal leaflet, typically seen in the anterior part, need to be well appreciated to prevent insufficient grasping (Figure 3).

2.3.1 | Coaptation gap size

A key anatomical feature present in most patients with progressive secondary TR that will limit the success of edge-to-edge repair is the coaptation gap size (CGS).[23] Annular dilation or spherical remodeling of the RV causing leaflet tethering can lead to the generation of a coaptation gap, most typically between the anterior (ATL) or posterior (PTL) tricuspid leaflet and the STL. Irrespective of tethering pattern or annular dimensions, the CGS defines the limits of TEER therapy. Data suggests a CGS of > 7 mm as a predictor for technical failure in patients treated with 2nd generation MitraClip.[2,21,24] With the newer generation devices incorporating longer device arms, TV with greater gaps

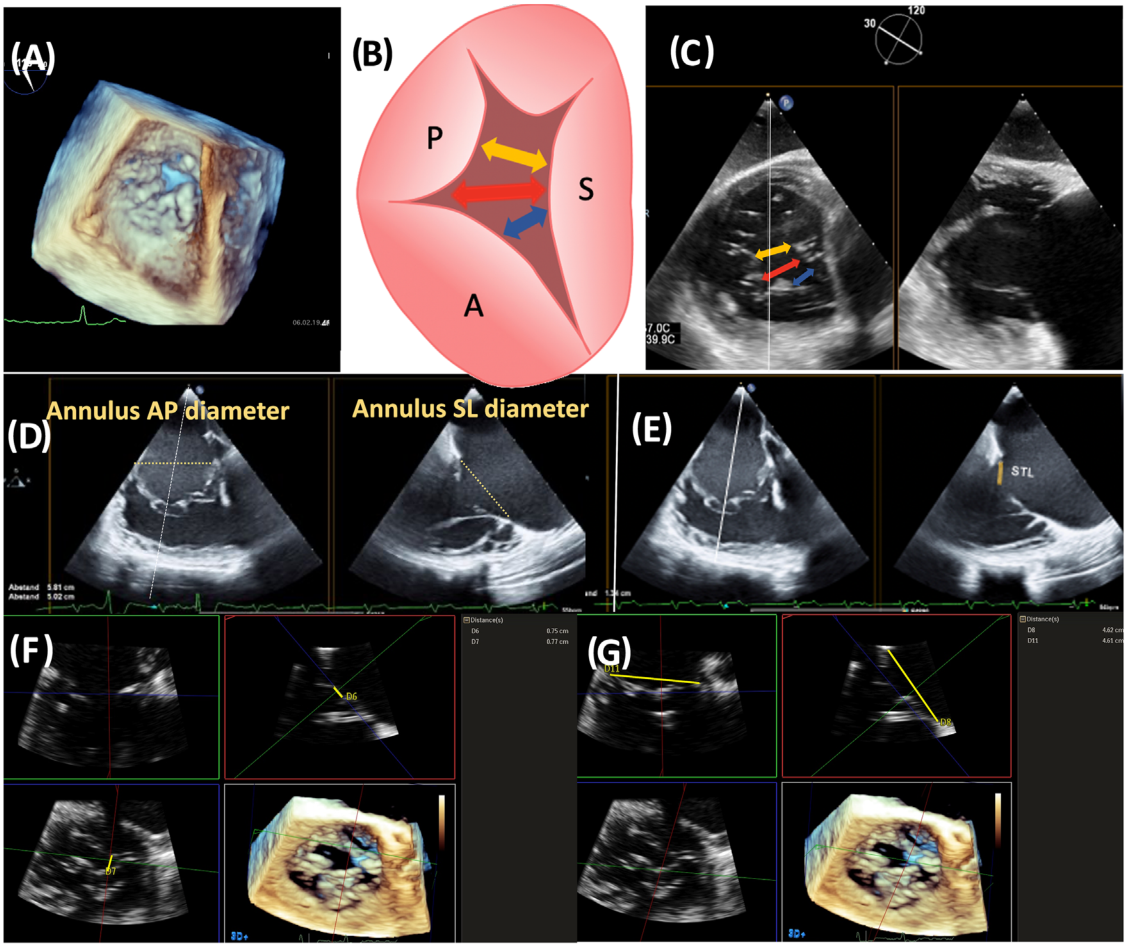


FIGURE 4 Key measures of TV morphology before TEER. 3D-TEE of the TV showing a large central coaptation gap (A). Schematic view of TV in the same orientation of transgastric SAX view, depicting gap size measurements of maximal gap diameter in s/l dimension (CGS, red arrow) and at two different target zones: one between anterior and septal leaflet (blue arrow) and one between posterior and septal leaflet (yellow arrow) (B). Biplane SAX view of the TV with the before mentioned gap measurements (C). Biplane commissural view with anteroposterior and septal-lateral annulus diameters (D); septal leaflet length measured at the target zone (E). Multiplanar reconstruction of 3D TEE image of the TV after the cropping lines of the two orthogonal views are adapted to the annular plane showing: central coaptation gap (top right and bottom left) (F), and annulus measurement of both anteroposterior and septal-lateral diameters (top right and left) (G)

(≤10 mm) can still be reasonably treated with TEER.[25] Large coaptation gaps, especially in a non-central or non-anteroseptal position have shown to yield the worst post-procedural outcomes, while treatment of isolated septoanterior coaptation defects are associated with much more favorable results.[21,26] Gap size at the target zone of device implantation needs to be differentiated from a maximal gap size in the center of the valve (as reported in the above-mentioned studies). While a gap size at the target zone defines the probability to successfully implant a device, a central gap size is associated with the probability of device success (i.e., TR reduction to ≤2+).

Biplane imaging from the RV inflow-outflow view can give a fair idea of the gap size in the corresponding 4-chamber view. However, for 2D-echocardiography only a transgastric short-axis view can display the full extent and the exact location of the coaptation gap. Here, it is important to correctly align the imaging planes and to image the true leaflet edges as otherwise the gap can be overestimated. When a transgastric window cannot be acquired, 3D MPR has proven a good alternative to measure the coaptation gap size and locate the target zone for device implantation (see page 7 and Figure 4F–G).[27] 3D volumes can be acquired from all acoustic windows but in general temporal and spatial resolution is superior in volumes generated from esophageal windows.

2.4 | Step 4: Device strategy

A differentiated device strategy is key for successful TEER of the TV. The strategic considerations on where to start the intervention and by what pattern the devices should be implanted need to be clarified upfront after the meticulous valve analysis described.

In general, interventional strategy is similar to that in TEER of the mitral valve. Device implantation is aimed at the site of the least coaptation (or maximum of color doppler information). In TEER of the TV though this site often cannot be addressed directly (due to excessive coaptation gap sizes) and a multiple device strategy is needed. The

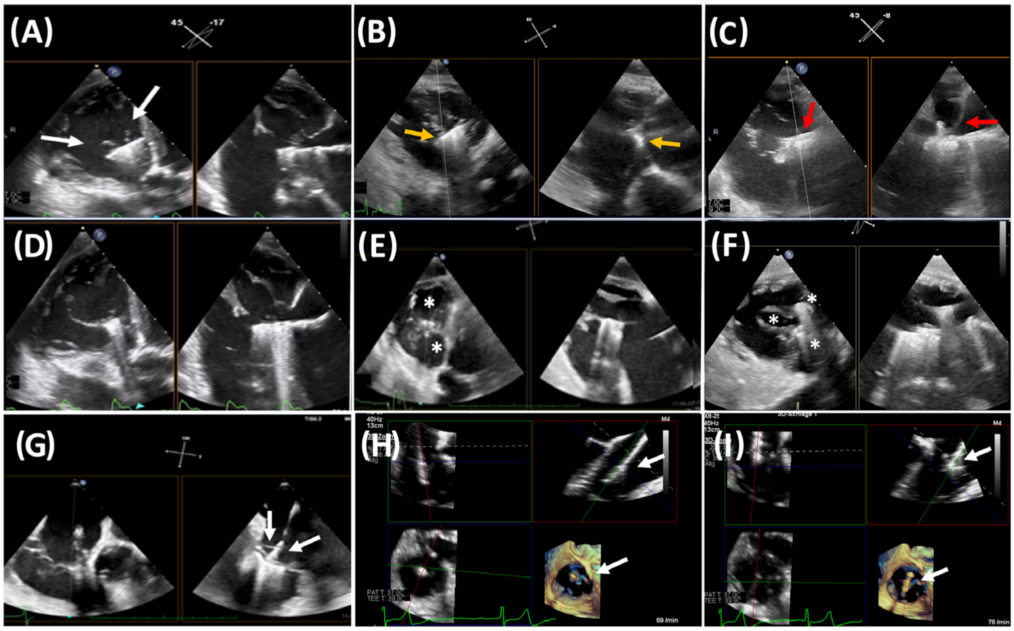


FIGURE 5 Transgastric SAX views of the TV with biplane imaging. (A-F): (A) shows a TEER device still opened with both leaflets already resting on its arms (white arrows – note the bright edge of leaflets); (B) and (C) document a "sweep" across the device confirming engagement of ATL on anterior device arm (yellow arrows) and of the STL on septal device arm (red arrows); (D): tissue bridge of ATL and STL just after device closure (note how bright leaflet edges run directly to the center of the device); (E) shows a typical double orifice (asterisks) after implantation of one device in anteroseptal commissure, whereas the TV in (F) has a triple orifice (asterisks) after implantation of one device in the anteroseptal and one device in the posteroseptal commissure. Alternative views for patients without a transgastric window: DE RV inflow-outflow view with biplane imaging showing leaflet capture at the device (arrows showing both leaflets resting at opened device arms) (G); Live 3D Multiplanar Reconstruction of the TV showing device alignment with the annular plane and TV leaflets (H), and rotation of the device in anteroseptal orientation (I) (white arrows showing device)

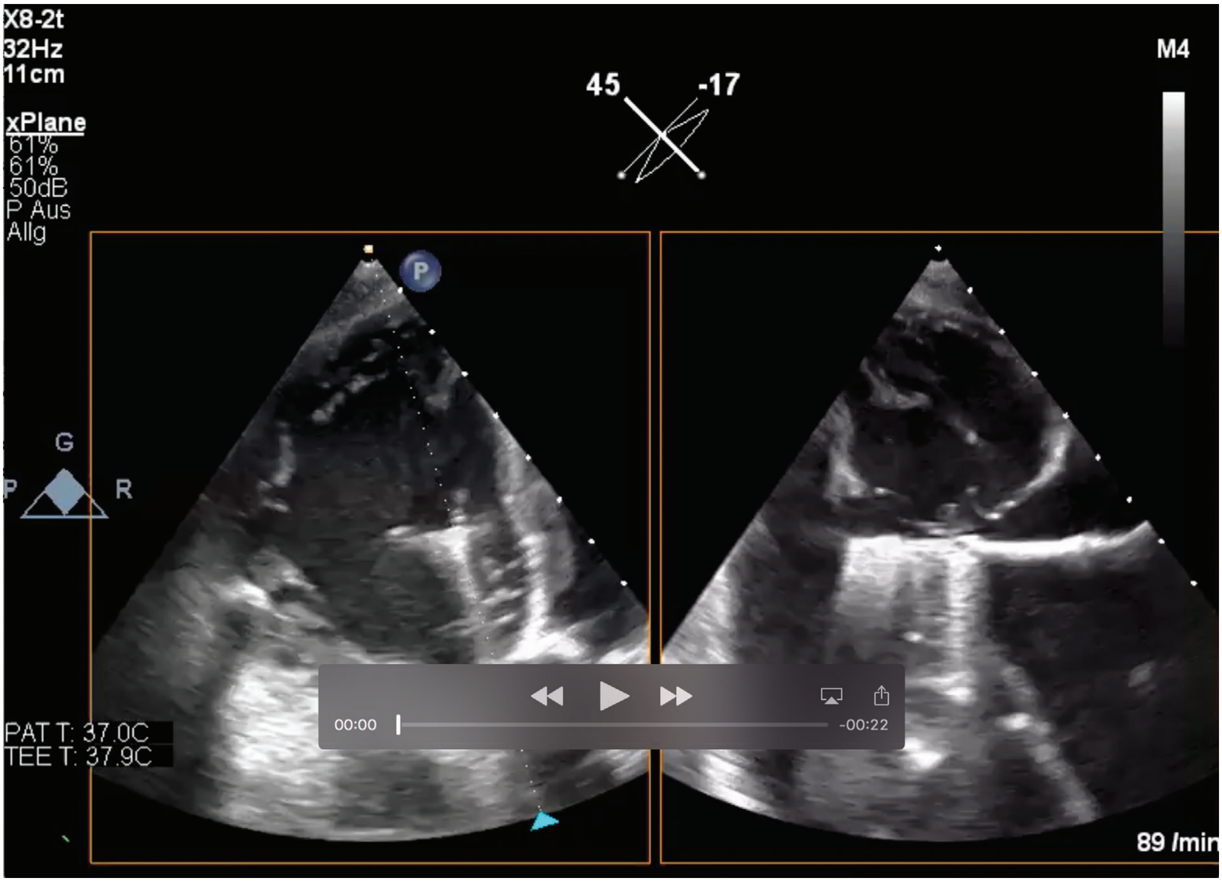
target zone for the first device is then adjacent to the maximal gap size. Typically, a target zone offering a smaller gap size for the first device is found closer to the commissures. Predominantly this will be at the anterior commissure as in most patients the coaptation gap extends anteriorly.[8] Beyond creating coaptation the first device will enable implantation of a following device as it now holds the leaflets in a more central position. This technique facilitates the treatment of large coaptation gaps. Depending on the extension of the coaptation gap into the anterior versus the posterior commissure two patterns of device placements can be differentiated. The treatment of only the anteroseptal commissure has been coined "bicuspidization"; also following the surgical blueprint, the treatment of both commissures is referred to as the "clover strategy" (Figure 5E–F).[28–30] For both techniques, starting anteriorly is strongly advised as a more posteriorly placed device may lead to strong shadowing artifacts in the transgastric view that possibly prohibit additional device placement. In very specific indications, for example, a prolapsing posterior leaflet, dedicated device strategies come into place that directly address the pathology without taking into account optimized imaging measures.

2.5 | Step 5: Procedural guidance–leaflet grasping

Procedural guidance steps include imaging of device steering, visualization of leaflet device interaction and evaluation of interventional success. As previously described by other groups device introduction and steering in the RA can be visualized by biplane imaging firstly from a bicaval view and then from a RV inflow-outflow view.[6] Especially in patients with multiple pacemaker leads though 3D imaging can help to guide valve approximation as it provides better depth perception and spatial orientation than biplane echocardiography or fluoroscopic imaging.

Unlike in other suggested guiding protocols, we have developed using the transgastric views as the primary imaging planes to visualize device introduction into the RV and, more importantly, to visualize leaflet grasping (Figure 5). Firstly, the amount of morphological information of the TV is much higher than from transesophageal views which facilitates recognition of commissures or indentations in between leaflets/scallops that need to be avoided when grasping. Secondly, the device itself, and especially the leaflet engagement and insertion of the leaflets into the device, can be imaged more precisely in the transgastric view. This precision is due to the plethora of information provided by a transversal imaging plane but also due to less shadowing artifacts usually found in transesophageal views. The latter sometimes even disqualify transesophageal views to an extend that they cannot be used for guiding the grasping process at all. In these cases, a familiar use of transgastric views will decide over treatment success vs procedural abortion.

In detail, we use transgastric SAX to guide device orientation at the target zone and with biplane imaging we visualize translation of



VIDEO 1 The “Mainz-Approach”: TEE Transgastric SAX view of the TV showing a grasping sequence with the correct position of the leaflets on device arms, device closure and, immediate appreciation of a new double orifice (bicuspidization technique)

the device in the secondary imaging plane (Figure 5A). For successful guiding of leaflet grasping in the transgastric SAX explicit care needs to be taken to image the bright (echo-rich) edge of the corresponding leaflets. Only then immobilization of the leaflets, when caught by the device arms, can be immediately appreciated. Proper leaflet engagement on the device arms can also be controlled from transesophageal windows (Figure 5G). We have learnt though that the display of the complete leaflet edge (and its behavior after being loaded on the device arm) in the transgastric SAX often yields better proof of correct leaflet position as the visualization of the (frequently shadowed) sagittal leaflet sections shown in transesophageal imaging planes (Figure 5A). Further, proof of leaflet engagement can be backed-up by biplane transgastric imaging through a “sweep” across both device arms (Figure 5B and C). This is helpful despite the constraint that the device arms usually cannot be displayed in full length in the secondary imaging plane (unless device orientation is parallel to ultrasound beam) (Figure 5B). In the great majority of cases, we stay with transgastric imaging also to guide device arm closure. Again, the visualization of the complete leaflet and how it is pulled into the device offers an advantage over transesophageal imaging.

In general, the imaging sector should be narrowed in order to optimize spatial and temporal resolution. This is especially relevant when

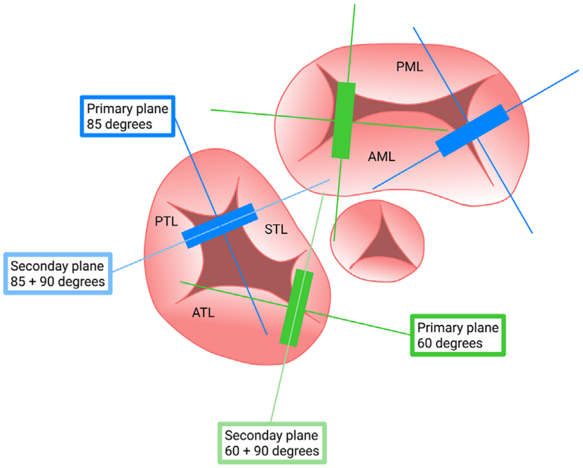


FIGURE 6 Search angle adjustment for biplane imaging after device implantation in TEER of the TV. As in TEER for the mitral valve, biplane imaging to control for leaflet insertion in the TV space also relies on a correct search angle of the primary imaging plane (perpendicular to the opening angle of the device). As depicted in the picture, the correct search angle for the primary plane will increase from an anteroseptal to a posteroseptal device position just as it does in the mitral space with a more lateral position

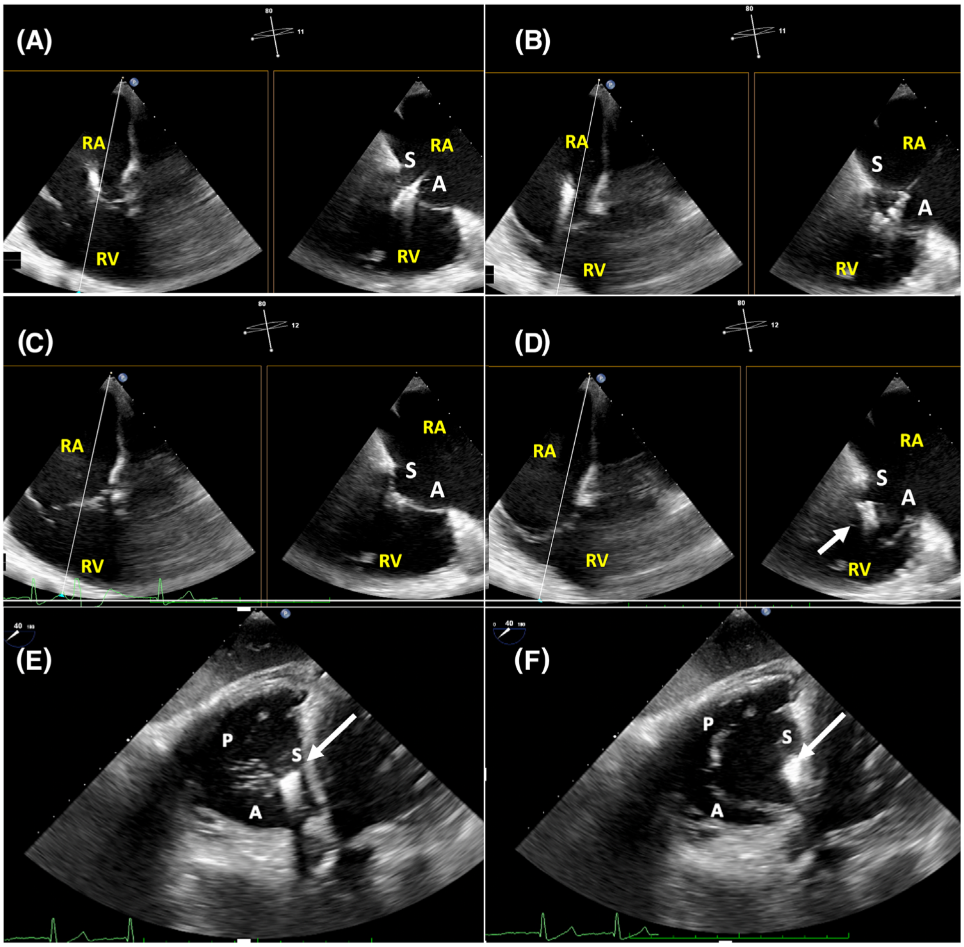


FIGURE 7 Single leaflet detachment (SLD) with disconnection of ATL after insufficient grasping. Serial biplane images showing a device deployment complicated by an early disconnection of the ATL with the device. Device before (A), during (B), and just after deployment (C). Initially both leaflets seem to insert correctly (C) whereas only a few minutes later, loss of ATL insertion was noted (D). SAX view of the TV with biplane imaging showing device an intact appearing tissue bridge before deployment (E) and the detached ATL after deployment (F)

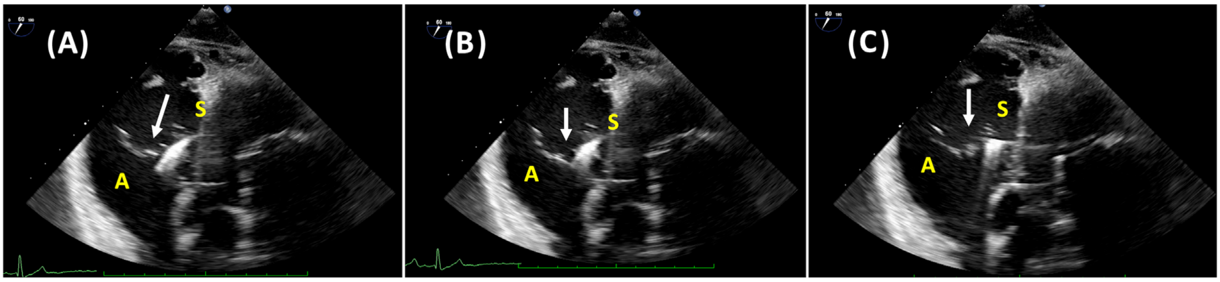
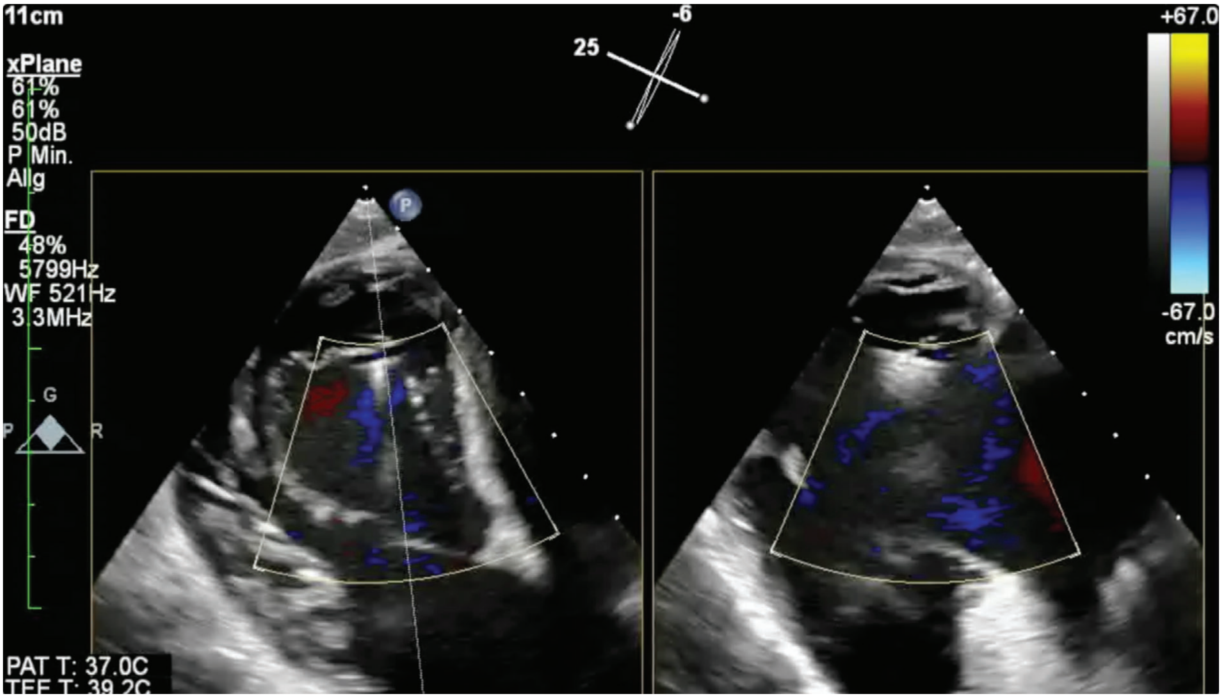


FIGURE 8 Transgastric SAX view of the TV showing a grasping sequence with insufficient anterior leaflet grasping leading to an early SLD. Successful leaflet capture (ATL and STL) by the device (A); ATL partially slips off the anterior device arm (arrow) during device closure (B); partial leaflet grasp (C), note leaflet edge not running into the very center of the device

the grippers/clasps are lowered, and device arms are closed – a procedural step that requires full attention and should be comprehensively recorded by a long loop. Doing this will allow for retrospective review of leaflet grasping and give confidence in final evaluation of leaflet insertion (Figure 5D, Movie 1). An additional advantage of grasping in the transgastric view is the opportunity to immediately visualize the double (bicuspidization technique) or triple orifice (clover technique) created by leaflet approximation, which is a crucial imaging information to ensure a successful grasping (Figures 5E and F, Figure 8).[28]

In the few patients without a transgastric imaging window the success of the intervention relies on transesophageal imaging only. If unrestricted views are present leaflet grasping can be well visualized by



VIDEO 2 TEE Transgastric SAX view of the TV with color flow Doppler showing central tricuspid regurgitation and a pacemaker lead at the posteroseptal commissure

single or biplane imaging (Figure 5G). A work-around to control device orientation is the use of live 3D MPR (Figure 5H and I). Orientation of the imaging planes is similar to offline 3D MPR analysis (see step 2). If spatial and temporal resolution allow for using live 3D MPR to guide leaflet grasping the 4-chamber like imaging plane needs to be exactly at the device-carrying catheter to control leaflet-device interaction.

2.6 | Step 6: Procedural guidance–success evaluation

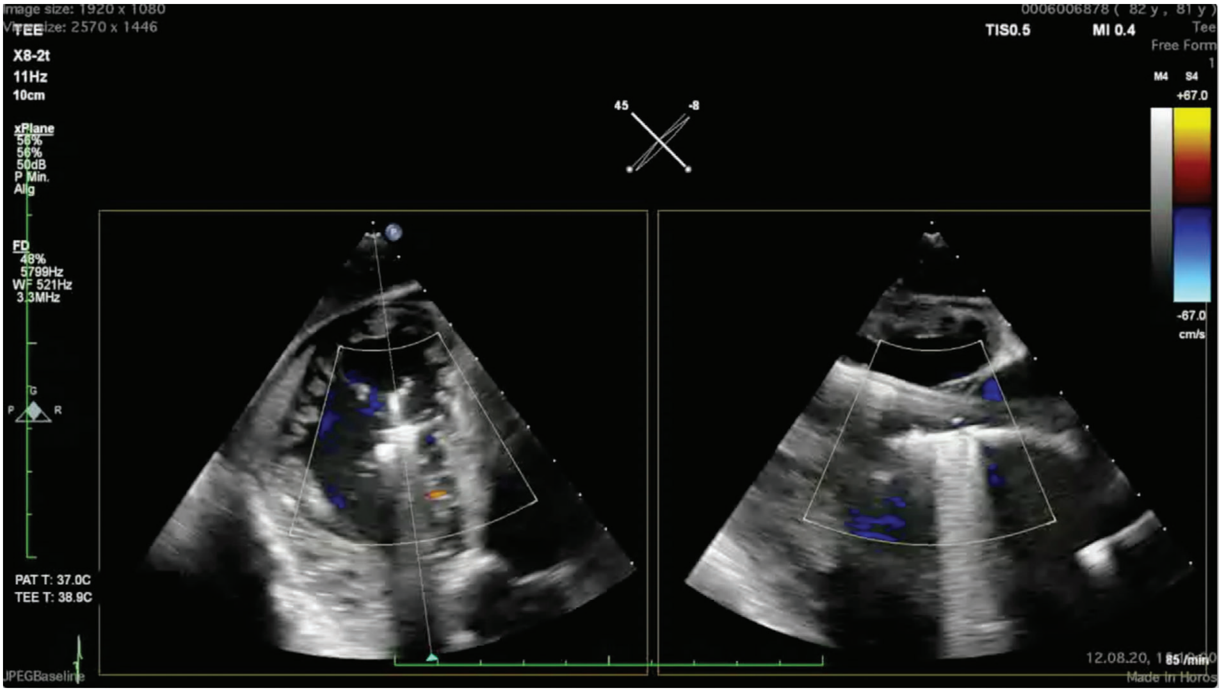
Before device deployment, adequate leaflet grasping needs to be confirmed to prevent single leaflet detachment (SLD) (Figures 7 and 8) or device embolization. We highly recommend to do this firstly in the transgastric SAX view of the TV as this is from where grasping was visualized and leaflet insertion can be very exactly detected (Figure 5D, Figure 8).

Additionally, we visualize the tissue bridge using biplane imaging from a transesophageal window. Depending on the position and rotation of the device the search angle of the primary plane needs to be adjusted. This adjustment is analogous to biplane visualization of TEER result in the mitral space (Figure 6). If adequate insertion of both leaflets can also be ensured in this view, the device is deployed. Adequate insertion is present if both leaflets reach to the center of the device. High mobility of one leaflet may be a sign of insufficient insertion and may lead to leaflet detachment after device deployment.

Sometimes the difficult imaging conditions of transesophageal windows lead to undecisive information about leaflet insertion. In these cases, we highly recommend basing the decision on whether a device should be deployed on the information gained by transgastric imaging.

Assuring adequate leaflet insertion before device deployment is paramount as uneven or insufficient grasping may lead to SLD. An example on how sensitive transgastric imaging is to detect insufficient leaflet grasping is presented in Figure 8. A case with an early ATL detachment review of the transgastric visualization of the grasping process revealed an ATL slip leading to a suboptimal grasping length that after deployment translated into an early leaflet disconnection (Figure 7). Transgastric imaging also has a learning curve, but the amount and detail of information derived make it a powerful tool to deliver high-quality TEER of the TV.

In addition, color flow Doppler (CFD) assessment before deployment is performed to evaluate adequate reduction of TR which is also a sign of adequate leaflet grasping. TV inflow gradient must be checked before device release, especially when placing multiple devices to ensure an acceptable transvalvular gradient excluding relevant stenosis. After deployment CFD and transvalvular gradients are key to evaluate the acute effect of TEER on TR and influence the decision to implant a second or third device[31] (Movies 2 and 3). Exact grading of residual TR is challenging due to the presence of multiple jets. Sizes of residual PISA zones, density of CW Doppler signal and hepatic vein systolic flow are indirect signs of residual TR severity. 3D CFD planimetry of vena contracta area can be performed for a more accurate quantification of residual regurgitation.[31,6]



VIDEO 3 TEE Transgastric SAX view of the TV with color flow Doppler showing an optimal result after the placement of one device anteroseptal in a central position. Minimal residual regurgitation around pacemaker lead

3 | CONCLUSION

Imaging requirements in TEER of the TV are demanding compared to other interventional procedures and play a major role for the safety and effectiveness of the procedure. Therefore, a standardized approach of periprocedural guiding is essential to assure optimal results.

We recommend a systematic approach that highly relies on transgastric imaging. Only with the plentitude of morphological information gained by scanning from transgastric windows can all relevant procedural steps adequately be guided. As long as TEE is the primary imaging modality to guide TEER for the TV, an experienced use of the transgastric windows will significantly impact success rates and should be a dedicated part of the imaging protocol in practice.

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CONFLICT OF INTEREST

All other authors have no conflicts of interest to declare.

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