State-of-the-Art Review of Echocardiographic Imaging in the Evaluation and Treatment of Functional Tricuspid Regurgitation

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Abstract—Functional or secondary tricuspid regurgitation (TR) is the most common cause of severe TR in the Western world. The presence of functional TR, either isolated or in combination with left heart disease, is associated with unfavorable natural history. Surgical mortality for isolated tricuspid valve interventions remains higher than for any other single valve surgery, and surgical options for repair do not have consistent long-term durability. In addition, as more patients undergo transcatheter left valve interventions, developing transcatheter solutions for functional TR has gained greater momentum. Numerous transcatheter devices are currently in early clinical trials. All patients require an assessment of valve morphology and function, and transcatheter devices typically require intraprocedural guidance by echocardiography. The following review will describe tricuspid anatomy, define echocardiographic views for evaluating tricuspid valve morphology and function, and discuss imaging requirements for the current transcatheter devices under development for the treatment of functional TR. **(*Circ Cardiovasc Imaging*.2016;9:e005332. DOI: 10.1161/CIRCIMAGING.11.005332.)**

Key Words: echocardiography ■ three-dimensional echocardiography ■ transcatheter ■ transesophageal echocardiography ■ transthoracic echocardiography ■ tricuspid valve ■ tricuspid valve insufficiency

Functional or secondary tricuspid regurgitation (TR) is the most common cause of severe TR in the Western world.[1] Interest in the tricuspid valve (TV) has increased in recent years,[2,3] with recognition of the progressive nature of the disease[4,5] and the impact of secondary TR on outcomes.[6–9] The prevalence of secondary TR with mitral valve disease is >30%,[2,10] with some studies suggesting that >1.6 million patients in the United States may currently be experiencing this disease.[11] The presence of functional TR, either isolated or in combination with left heart disease, is associated with unfavorable natural history.[6–9,12] Although functional TR responds to medical therapy, once annular dilatation occurs, tricuspid repair and replacement may be needed to prevent progression of the disease and improve outcomes.[12–15] Often patients are referred to surgery late when right ventricular (RV) dilatation and failure are advanced and isolated tricuspid surgery in this context is associated with high morbidity and mortality. Trend analysis of the Society of Thoracic Surgeons database between 2000 and 2010 confirms that patients undergoing surgery for TR in the United States had increasing age, a higher comorbidity burden, and a higher proportion of emergency presentation.[16] Surgical mortality for isolated TV interventions remains higher than for any other single valve surgery.[16,17] This evidence has supported early prophylactic interventions (combined tricuspid repair for less than severe TR at the time of the left-sided disease treatment).[18–20] However, as more left-sided valve disease is treated with transcatheter therapies,[21–24] the negative impact of TR on survival of these patients[25–27] has underscored the importance of developing transcatheter solutions for this disease.

Numerous transcatheter devices are currently in early clinical trials. All of these devices require knowledge of anatomy and imaging. A comprehensive understanding of transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) imaging using both 2-dimensional and 3D modalities is essential to allow early and accurate detection, timing and effectiveness of treatment, guidance during interventions, and assessment of residual disease. The following review will describe tricuspid anatomy, define echocardiographic views for evaluating TV morphology and function, and discuss imaging requirements for the current transcatheter devices under development for the treatment of functional TR.

TV Anatomy

Normal Anatomy

The TV is the largest and most apically positioned valve, and its functional anatomy, similar to the mitral valve, can be divided into 4 components: the fibrous annulus (with attached atrium and ventricle), the 3 leaflets, the papillary muscles, and the chordal attachments.[3,10,28–31] The tricuspid annular plane is

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nearly vertical and ≈45° from the sagittal plane. The annulus is complex and dynamic, allowing it to change with varying loading conditions. Unlike the mitral valve, there is no fibrous continuity with the corresponding semilunar valve. Three-dimensional echocardiography has been integral in our understanding of TV anatomy.[30–33] A normal annulus is triangular or ovoid and saddle shaped, superiorly (atrially) displaced in the anteroseptal portion near the RV outflow tract and aortic valve and the posterolateral portion and inferiorly (apically) displaced in the posteroseptal portion near the inflow of the coronary sinus and the anterolateral segment.[2,31] Normal tricuspid annular circumference and area in healthy subjects are 12±1 cm and 11±2 cm^2, respectively.[31,34] During atrial systole and again in late systole/early diastole, there is a significant increase in annular area (29.6±5.5%) and circumference.

The 3 TV leaflets vary in both circumferential (annular) and radial size. The relative circumferential or annular ratios of the anterior:septal:posterior leaflets in normal patients are 1:1:0.75.[3,29] The anterior leaflet is the longest radial leaflet with the largest area and the greatest motion. The septal leaflet is the shortest in the radial direction and the least mobile. This short septal leaflet is attached to the tricuspid annulus directly above the interventricular septum with many third-order chordae attached directly to the septum; it is inserted into the septum ≤10 mm apical to the septal insertion of the anterior mitral leaflet (ie, apically displaced). The posterior (or mural) leaflet may have multiple scallops and is the shortest circumferentially; however, it may not be clearly separated from the anterior leaflet in ≈10% of patients. Anatomic landmarks for each leaflet vary significantly depending on the size and shape of the annulus; however, the commissure between the septal and posterior leaflets (which are always clearly separated) is usually located near the entrance of the coronary sinus to the right atrium (RA). A normal TV area is between 7 and 9 cm^2 and is thus the largest of the four cardiac valves. Because of its large size and the low pressure differences between the RA and RV, peak transtricuspid diastolic velocities are typically lower than 1 m/s with mean gradients of <2 mm Hg.

The TV apparatus includes 2 distinct papillary muscles (anterior and posterior) and the third variable papillary muscle. The largest is typically the anterior papillary muscle with chordae supporting the anterior and posterior leaflets. The moderator band may join this papillary muscle. The posterior papillary muscle, which is often bifid or trifid, lends chordal support to the posterior and septal leaflets. The septal papillary muscle is variable: absent in up to 20% of normal patients or small and multiple. Unlike the mitral valve, chordae may arise directly from the septum to the anterior and septal leaflets. Accessory chordae may attach to the RV free wall and the moderator band.

Tricuspid Anatomy With Functional TR

The causes of functional or secondary TR have typically included RV dilatation, RV or pulmonary hypertension, and RV failure (regional or global).[3] A more recently recognized cause of functional TR is isolated annular dilatation[35,36] or isolated/idiopathic TR.[37] In the latter entity, there are no associated comorbidities, structural valve disease, significant pulmonary artery hypertension, or overt cardiac disease although some investigators have postulated effects from aging or atrial fibrillation.[36,38] For patients with chronic atrial fibrillation, RA and RV volumes are important determinants in the development of severe functional TR.[4]

When functional dilatation occurs, the septal portion of the annulus is typically spared, and so the annulus primarily dilates along the anterior and posterior leaflet attachments, causing the annulus to become more circular and planar.[32] Greater degrees of TR are associated with larger annular areas, larger RA and left atrial volumes, a more circular annular shape, and RV dilatation.[39] Bench-top modeling[40] suggests that as little as 40% annular dilatation may result in significant TR (compared with 75% dilatation for mitral regurgitation). This translates to a corresponding annular area of 8.8±0.2 cm^2 and a septal-lateral diameter of 2.3±0.05 cm, significantly less than suggested by the current guidelines.[41] Animal models of TR have suggested that greater degrees of TR are associated with greater stretch of the posterior leaflet (as compared with the anterior or septal leaflets), with greater annular dilatation or RV dilatation and with displacement of the papillary muscles, with little effect from the loss of the annulus' saddle shape.[42] Recent studies, however, have also shown that significant anatomic differences in RV, valve, and annular anatomy may occur based on the cause of functional TR.[38] With idiopathic TR, there was marked basal RV dilatation with relatively normal RV length (RV conical deformation), as well as marked annular dilatation but with normal tenting height. With functional TR associated with pulmonary hypertension, there was significant lengthening of the RV with less basal dilatation (and low basal:mid ventricular diameter ratios) consistent with elliptical/spherical RV deformation, as well as some annular dilation (less than idiopathic patients) and significantly greater tenting height than the idiopathic patients.[38] Numerous authors have also explored the relationship between tenting of the leaflets and severity of TR with tenting areas and volumes correlating with TR severity and with outcomes after surgical repair.[43–46] Our understanding of when to intervene on these patients continues to evolve with our understanding of the complex relationship among the RV, valve, and annulus.

Imaging of the TV

Visualization of the TV should be performed from multiple TTE and TEE windows. Recent American Society of Echocardiography (ASE) guidelines outline the recommended TTE views for performing a comprehensive evaluation of the valve[47] and measurement of the right heart chamber.[48] For performing a comprehensive TEE, New ASE guidelines also emphasize imaging of the TV.[49] The approach to 3D imaging of the TV has been addressed in both guidelines[50] and reviews.[51]

Transthoracic Echocardiography

Because of the complex nature of the TV, and the difficulty in visualizing all 3 leaflets in a single 2D plane, a comprehensive assessment of the TV should be performed from multiple transthoracic windows. Recent ASE guidelines outline the recommended views for performing a comprehensive evaluation of the RV and TV[47]; however, identification of the tricuspid

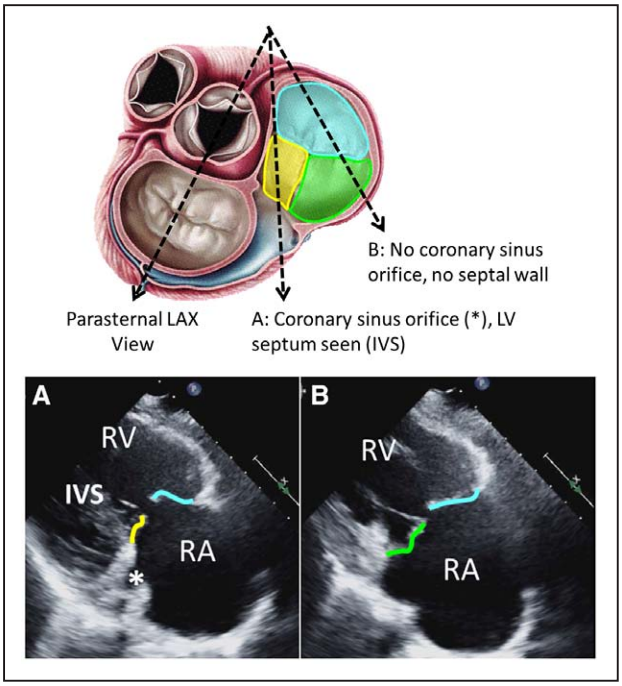

Figure 1. Parasternal inflow views. From the parasternal long-axis (LAX) view, the transducer is angled inferiorly and to the right (toward the right hip) to produce the parasternal inflow view. If the coronary sinus ostium (*) or the muscular interventricular ventricular septum (IVS; **A**), then the leaflets imaged are the anterior (blue) and septal (yellow). With the transducer angled more acutely inferiorly and to the right (**B**) with no IVS seen, the anterior (blue) and posterior (green) leaflets are imaged (with no septal leaflet). RA indicates right atrial; and RV, right ventricle.

leaflets from the standard transthoracic views remains controversial, in part, because of the variability of imaging planes that can be acquired from varying degrees of transducer angulation (Figures 1 through 3) as well as the anatomic variability of the TV.[33,52] Understanding the anatomy of the TV and adjacent structures should clarify the imaging planes and allow for an accurate identification of the tricuspid leaflets. From the parasternal inflow views (Figure 1), the far-field leaflet may be the septal leaflet (if septum/left ventricle are in view) or the posterior leaflet (with more extreme rightward and inferior tilt).[53] From the parasternal short-axis views (Figure 2), an extreme anterior angulation may result in imaging of a single large anterior leaflet or the anterior and posterior leaflet. From the apical 4-chamber views (Figure 3), the posterior leaflet may be imaged if a posterior angulation is used and the anterior leaflet when anterior angulation is used.[33,52,54]

Imaging of the right heart is similarly nuanced because of the unusual shape of the RV, discontinuity of the AV valve and outflow tract, and position in chest.[55] The recent ASE Chamber Quantification Guideline[48] recommends 3 apical 4-chamber views for imaging the RV: apical 4-chamber, RV-focused apical 4-chamber, and modified apical 4-chamber views. Although the RV has typically been measured from the standard apical 4-chamber view, the new guidelines suggest measuring the RV from the dedicated view focused on the RV because the entire RV free wall is imaged. Representative measurements for RV and TV measurements are shown in Figure 4. Other measurements of RV size and function are extensively reviewed in the ASE guidelines.[48] RV wall thickness is measured from subcostal views that may also allow Doppler alignments of the TR jet. In addition, an assessment of RA filling pressure should be made from evaluation of size and respirophasic variability of the inferior vena cava (IVC).

Transesophageal Echocardiography

The current ASE guidelines for performing a comprehensive TEE examination[49] includes additional images, many of which are intended to improve imaging of the TV. In addition, the TEE examination of the TV should include imaging from several depths and multiplane angles. Given the position of the heart in relation to the esophagus and stomach,

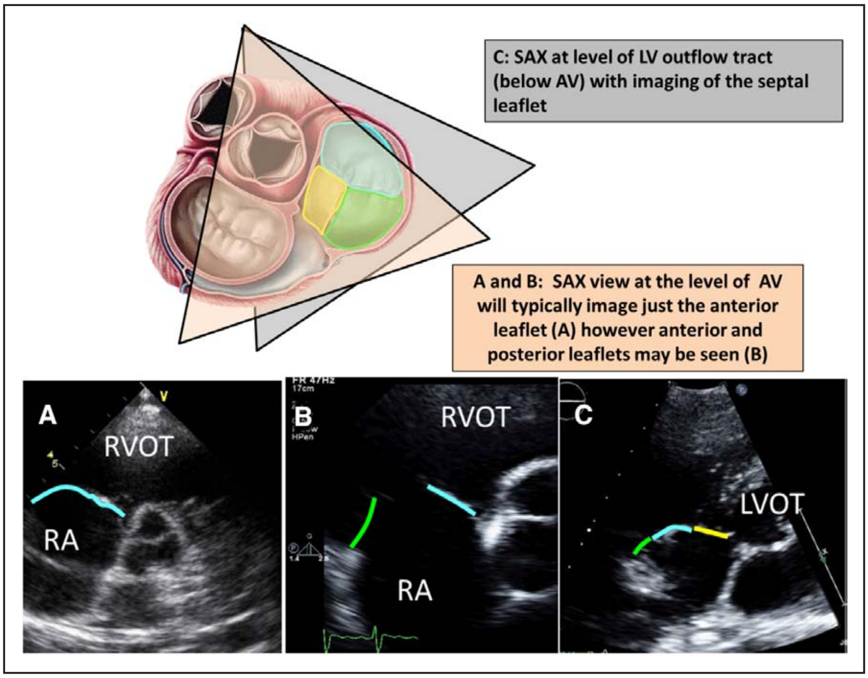

Figure 2. Parasternal short-axis (SAX) views. From the short-axis view at the level of the aortic valve (AV), a single anterior leaflet is typically imaged (**A**). This in part is because of the lower (apical) position of the septal leaflet. As the lateral portion of the annulus dilates and loses its saddle shape, the anterior and posterior leaflets may be imaged (**B**). As the transducer is angled toward the left ventricular outflow tract (LVOT), the septal leaflet may be seen (**C**). RA indicates right atrial; and RVOT, right ventricular outflow tract

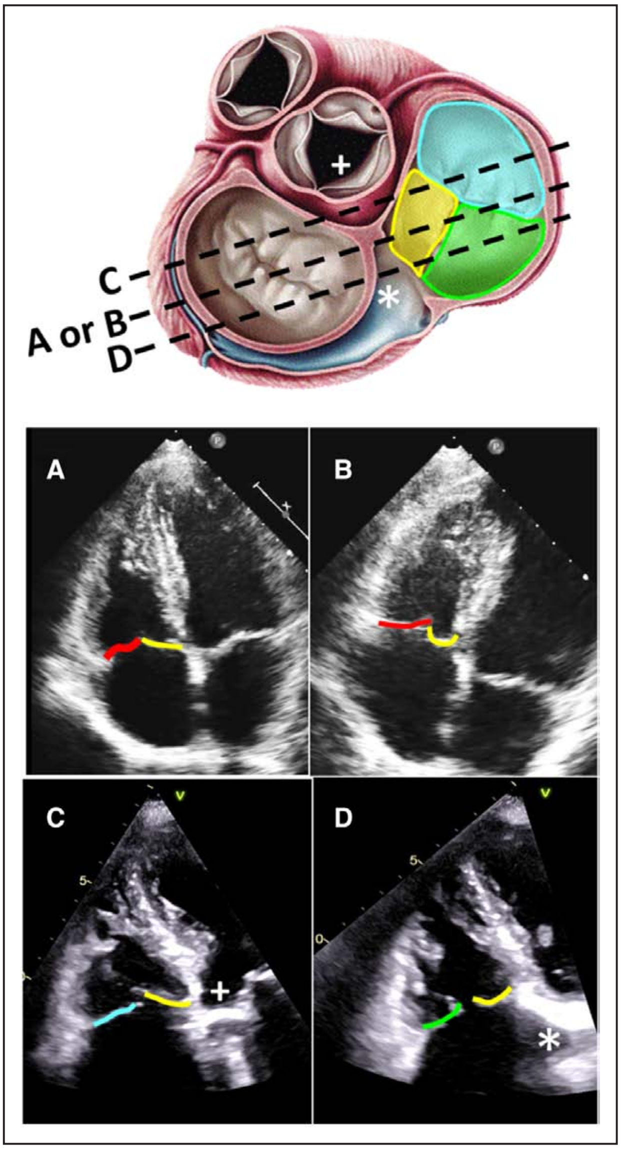

Figure 3. Apical 4-chamber views. From the 4-chamber views of the right ventricle (**A** and **B**), the septal leaflet can be clearly identified; however, the opposing leaflet can be the anterior or the posterior leaflet (red line). Angling the transducer anteriorly, so that a portion of the aorta (+) is imaged (**C**), will image the septal and anterior leaflets. Angling the transducer posterior so that a portion of the coronary sinus (*) is imaged (**D**) will image the septal and posterior leaflets.

midesophageal, distal esophageal, shallow transgastric, and deep transgastric views may bring the probe close to the TV for both 2D and 3D imaging (Figure 5).

Multilevel imaging begins at the midesophageal depth. The 4-chamber view permits the visualization of the septal and typically the anterior leaflet; simultaneous biplane imaging may help clarify which leaflet is imaged because the anterior leaflet is typically seen adjacent to the aorta (Figure 5A). Because the lower right heart border is close to the diaphragm, slow insertion brings the TEE probe to the distal esophagus, just proximal to the gastroesophageal junction; from this imaging plane, there is no left atrium in view, only the RA and coronary sinus (Figure 5B). Because this view of the TV is unobstructed by left heart structures, it is ideal for performing a comprehensive evaluation of TV function and for acquiring 3D volumes of the TV. Advancing the TEE probe into the stomach results in transgastric views (Figure 5C). Simultaneous multiplane imaging (or rotating the probe 60°–90°) results in the only 2D view that provides simultaneous visualization of all 3 TV leaflets. Advancing the TEE probe further into the stomach along with rightward anterior flexion produces a deep transgastric view of the TV (Figure 5D), which also permits optimal color flow and spectral Doppler evaluation of TR jets.

It is important at each level to rotate through multiple planes to comprehensively evaluate the TV and to use the simultaneous multiplane modality to help with identifying leaflets and appreciating adjacent anatomy.

Three-Dimensional Echocardiography

Three-dimensional echocardiography has significantly improved the accuracy of imaging and identification of the tricuspid leaflets and associated anatomic components of the TV complex and obviates the need for mental reconstruction of multiple 2D planes.[51] Lang et al[50] have suggested standardized imaging display for the en face view of the TV with the interatrial septum placed inferiorly (at the 6 o'clock position) regardless of the atrial or ventricular orientation. Because of the anterior position of the right heart, 3D TTE images may be equal or sometimes better in quality when compared with 3D TEE images. The current 3D systems have different resolutions for each of the 3 dimensions with axial resolution (≈0.5 mm) better than lateral (≈2.5 mm) and elevational resolution (≈3 mm).[51] Similar to 2D imaging, however, images in the far-field may be subject to beam widening and attenuation. When creating 3D images, keeping these current equipment limitations in mind will help determine the best plane for imaging a specific abnormality. The best imaging plane for the TV leaflets in systole (closed leaflets) should be the apical views and in diastole (open leaflets) the parasternal views, thus optimal imaging of the TV may require an imaging plane between these standard windows, a low parasternal view or medially positioned apical view. Obtaining multiple volumes from different views may still be necessary to fully characterize the valve and annulus. Finally, because of the complex nature of the valve, the volume acquired may need to have adjacent structures to help identify leaflet anatomy, the aortic valve/aorta to identify the anterior leaflet, and the interatrial septum/mitral valve to identify the septal leaflet.

Having adjacent structures to orient the 3D image may be even more important during TEE acquisitions. The interatrial septum (and adjacent mitral valve) should be positioned at 6 o'clock (Figure 6). Using TTE, the 3D volume is rotated to image the TV leaflets from the RV (Figure 6A; Movie I in the Data Supplement) with the aorta (and thus the anterior leaflet) to the right of the screen and the interatrial septum (and the septal leaflet) in the far field. Using TEE, the 3D volume is rotated to image the tricuspid leaflets from the atrial side (Figure 6B; Movie II in the Data Supplement) with the aortic valve (and anterior leaflet) to the left on the screen and the interatrial septum (and septal leaflet) in the far field. The coronary sinus enters the RA close to the commissure between the septal and posterior leaflets.

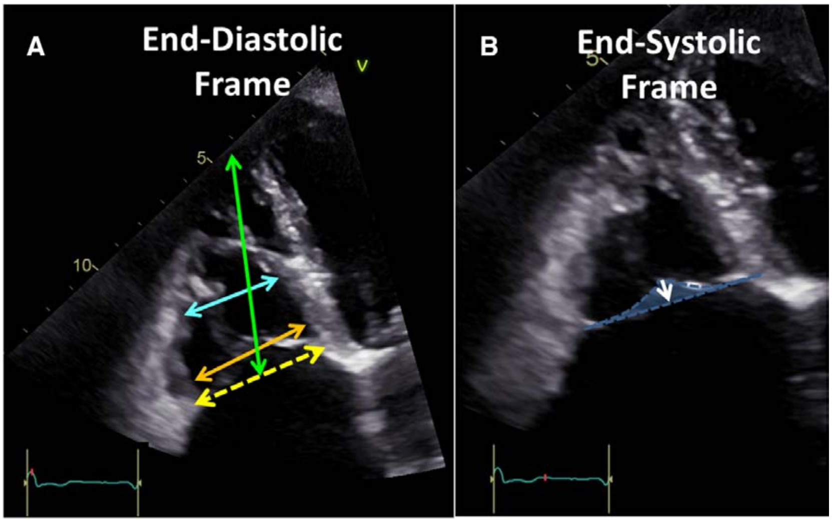

Figure 4. Representative measurements for right ventricular (RV) and tricuspid valve measurements are shown. Measurement of the septolateral tricuspid annular dimension should be performed in end-diastole (**A**, yellow dashed arrow) from the apical 4-chamber transthoracic view. RV measurements (basal RV, orange arrow; mid RV, blue arrow; long-axis RV, green arrow). **B**, Measurements for the tricuspid tenting height (white arrow) and tenting area (blue shaded area) are performed in end systole.

Grading Severity of TR

Grading of the severity of the TR has been well described by the ASE guidelines[56] and the European Association of Echocardiography guidelines.[57] Figure 7 summarizes the parameters most commonly used for this assessment. Not in the guidelines, but previously validated by both thermodilution techniques[58] and open surgical techniques,[59] is the jet area:RA area ratio (in %). Importantly, many of the studies validating the use of these parameters have significant limitations with a lack of the "gold standard" for comparison or support from outcomes data. Future studies are needed to determine the validity and prognostic utility of these parameters.

A recent study evaluated the utility of an algorithm for assessing the severity of TR.[60] Severe TR was present in the presence of a suggestive color Doppler jet and if any one or more of the following combinations of criteria were present: (1) IVC diameter >2.5 cm and RA area >18 cm^2 (in the absence of ASD or pulmonic valvular disease); (2) jet area >10 cm^2 and vena contracta width >7 mm; (3) systolic

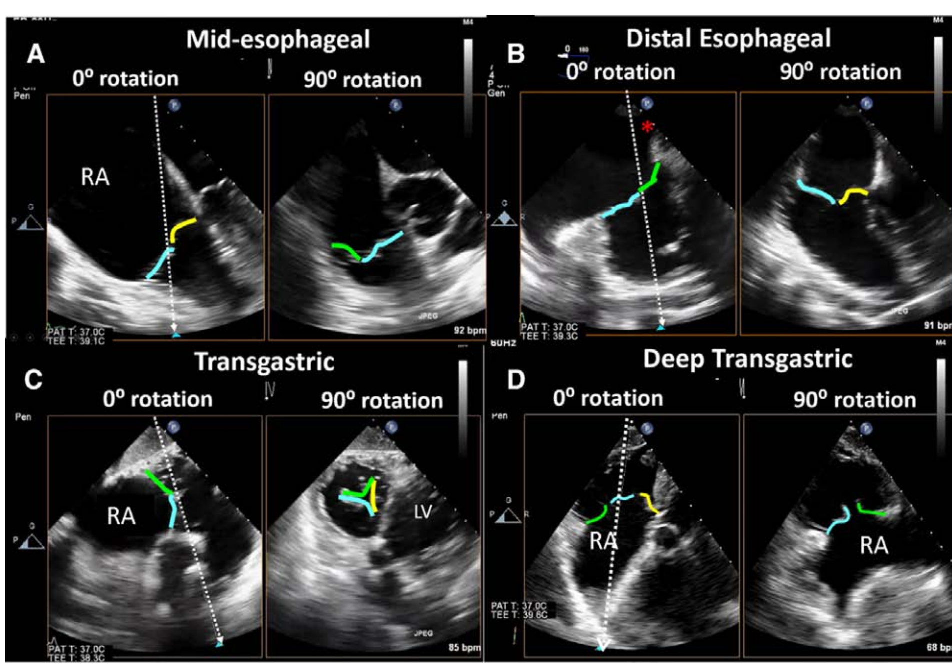

Figure 5. Multilevel imaging of the tricuspid valve (TV). **A**, Example of simultaneous multiplane imaging at the midesophageal depth. The 4-chamber view permits the visualization of the septal and typically the anterior leaflet; simultaneous biplane imaging may help clarify which leaflet is imaged because the anterior leaflet is typically seen adjacent to the aorta. Low esophageal views (**B**) at the level of the coronary sinus (*) typically image the posterior and anterior leaflets. Advancing the transesophageal echocardiography (TEE) probe into the stomach and rotating approximately 20°–60° produces the transgastric basal short-axis view (**C**), which is the only 2-dimensional view that usually provides simultaneous visualization of all 3 TV leaflets. Using the simultaneous multiplane imaging mode, all the leaflet coaptation points can be imaged. Advancing the TEE probe along with rightward anterior flexion and returning the mutiplane angle to 0°–20° produces a deep transgastric view of the TV (**D**).

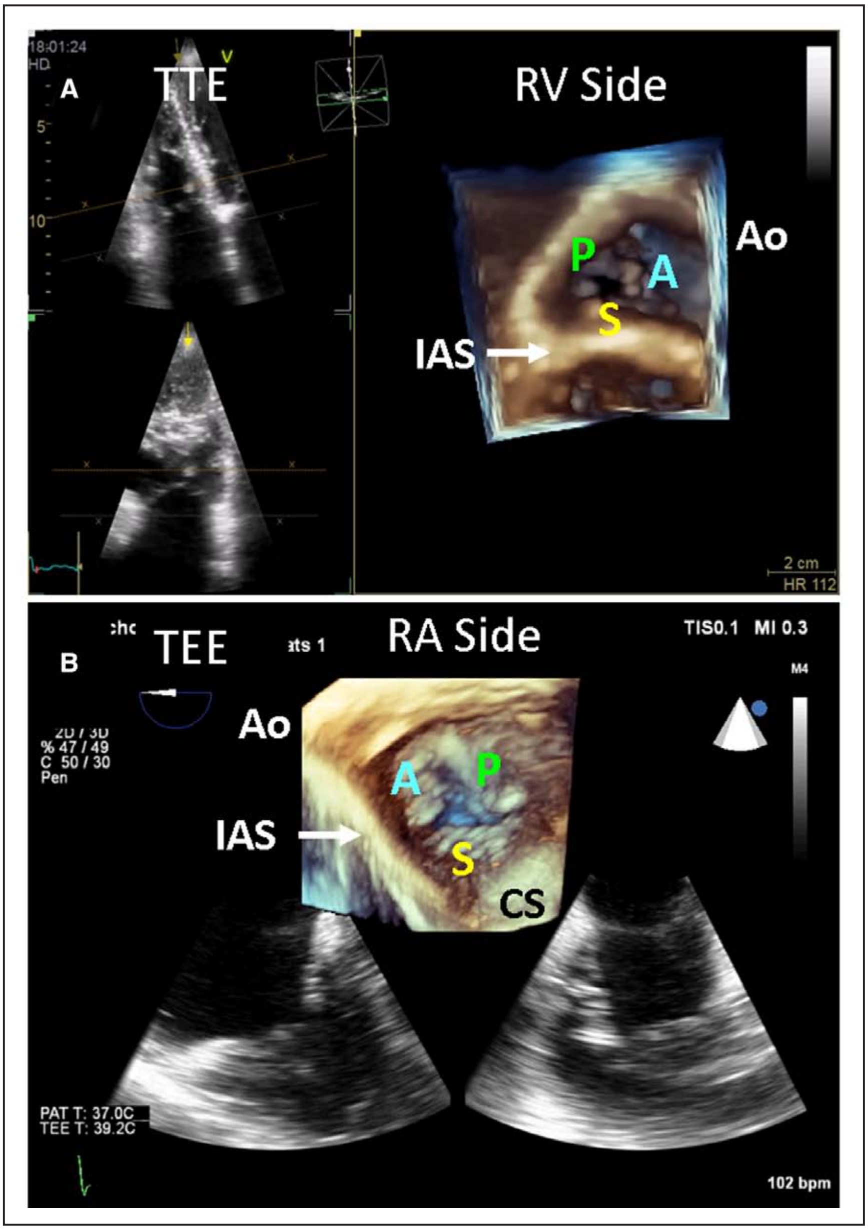

Figure 6. Examples of 3-dimensional (3D) imaging from transthoracic (A) and transesophageal (B) windows. **A**, Narrow-volume, single-beat acquisition from the TTE apical window with orthogonal 2-dimensional images to the left and the recommended 3D orientation (from the right ventricular [RV] view) on the right (Movie I in the Data Supplement). The anterior leaflet (A) is thus to the right, posterior leaflet (P) is to the left and the septal leaflet (S) is in the far field. **B**, User-defined single-beat volume of just the tricuspid valve from a distal esophageal level in a patient with severe tricuspid regurgitation (systole frame images; Movie II in the Data Supplement). The anterior leaflet (A) is thus to the left, posterior leaflet (P) is to the right and the septal leaflet (S) is in the far field. Ao indicates the aorta; CS, coronary sinus; IAS, interatrial septum; and RA, right atrial.

flow reversal in the hepatic veins in the absence of AV dissociation, ventricular pacing, or atrial arrhythmia; (4) triangular continuous wave Doppler signal with density equal to or greater than that of tricuspid inflow. These parameters (Figure 8) correlated best with expert-reads and magnetic resonance imaging determined regurgitant volume and fraction (using >48% to define severe) and improved interobserver agreement.

Quantitation of the severity TR can be performed by many methods (Figure 9). Although the proximal isovelocity surface area (PISA) method is simple and easy to perform,[61] the shape of the tricuspid regurgitant orifice is often elliptical[62] or stellate, which may result in significant underestimation of the ROA by this method. In addition, both the large ROA size and the low flow rates across the tricuspid annulus further contribute to the underestimation of ROA by the PISA method which could be as much as 20%.[63] More recently, 3D PISA has been used to quantify TR.[64] This method uses a vendor-specific software package to analyze the largest convergence zone, and a specific software that measures the 3D PISA. Regurgitant orifice area is then calculated as 3D PISA×$V_{aliasing}$)/peak TR velocity, where $V_{aliasing}$ is the aliasing velocity. In this study, 3D PISA-derived ROA correlated well with 3D planimetered vena contracta (r=0.97).

Few studies have used quantitation of TR by relative stroke volumes.[61,65,66] In these studies, a single plane tricuspid annular diameter was measured from the 4-chamber view and the tricuspid annular area calculated using a circular formula to calculate the tricuspid annular area. The sample volume for measuring the velocity–time integral was placed at the tips of the leaflets, unlike the recommended position of the sample volume for mitral quantitation, which is at the level of annulus. Despite these limitations, there was a high correlation with catheterization-derived data. This method has not been validated in patients with pathological TR, which may be associated with asymmetrical dilatation of the annulus.

Parameters	Mild	Moderate	Severe
Qualitative			
TV morphology	Mildly abnormal leaflets (e.g. mild rheumatic thickening, limited prolapse)	Moderately abnormal leaflets (e.g. moderate thickening or prolapse)	**Severe valve lesions (e.g. Flail leaflet, ruptured papillary muscle, severe retraction, large perforation or vegetation)**
Interventricular septal motion	Normal	Typically normal	Paradoxical/ volume overload pattern
Color flow TR jet [Note: not recommended for sole grading of severity]	**Small RA penetration or not holosystolic**	Moderate RA penetration or large penetration and late systolic	Deep RA penetration and holosystolic jet
Flow convergence zone	**Not visible, transient or small**	Intermediate in size and duration	**Large throughout systole**
CW signal TR jet	Faint/parabolic or partial contour	Dense, variable contour	Dense, triangular with early peaking contour (peak <2 m/s in very severe TR)
IVC diameter	Normal	2.1 -2.5 cm	>2.5 cm
Semi-quantitative			
Color flow jet area (cm^2) [Central Jet][a]	<5	5-10	> 10
Color jet area:RA area (%)	10-20	10-33	>33
Vena contracta (cm)	<0.3	<0.6	**≥ 0.7**
PISA Radius (cm)[b]	≤0.5	0.6-0.9	> 0. 9
Hepatic vein flow	Systolic dominance	Systolic blunting[c]	**Systolic flow reversal**
Tricuspid inflow	E-wave < 1 m/sec or A-wave dominant	Variable	E-wave ≥1.0 m/sec
Quantitative			
EROA (mm^2) [by PISA]	<20	20-39[d]	≥40
EROA (mm^2) [by 3D]	Unknown	Unknown	>75
Regurgitant volume(mL) [by PISA]	<30	30-45[d]	≥45
RV and RA size	Usually normal	Usually normal or mild dilatation	Usually dilated[e]

CW = continuous wave; EROA = effective regurgitant orifice area; RA = right atrium; RV = right ventricular; TR = tricuspid regurgitation; TV = tricuspid valve valve

Bolded qualitative and semi-quantitative signs are considered specific of their TR grade

^ There may be uncertainty between mild and moderate or between moderate and severe; consider further evaluation (eg cardiac magnetic resonance imaging, exercise echocardiography, right and left heart cath) to clarify, if clinically indicated or needed for clinical trial classification.

aWith Nyquist limit >50-60 cm/s

b With Baseline Nyquist limit shift of 28 cm/s.

c Signs are non-specific and are influenced by many other factors (RV diastolic function, atrial fibrillation, RA pressure). A cutoff of 18

d-There is little data to support further separation of these values.

e RV and RA can be within the "normal" range for patients with acute severe TR or with chronic severe TR associated with restrictive cardiomyopathy

Figure 7. Parameters used to grade severity of tricuspid regurgitation (note: after Zoghbi et al[56] and Lancellotti et al[57]). CW indicates continuous wave; EROA, effective regurgitant orifice area; IVC, inferior vena cava; PISA, proximal isovelocity surface area; RA, right atrial; RV, right ventricle; TR, tricuspid regurgitation; and TV, tricuspid valve.

Three-dimensional methods may help improve the accuracy of quantitative Doppler methods. Using either 3D planimetered diastolic annular area or 2 orthogonal diastolic annular diameters and a pulsed sample volume at the annulus to measure the velocity–time integral, a diastolic stroke volume can be measured. Subtracting the forward stroke volume (from the either left ventricular outflow tract or RV outflow tract) results in the regurgitant volume. These methods require validation.

Many studies have shown the utility of 3D color Doppler to quantify TR.[62,64,67,68] Velayudhan et al[67] was one of the first to correlate standard Doppler methods of quantifying TR with planimetry of the 3D vena contracta area (VCA). Using the validated measure of regurgitant jet area/RA area >34%[59] and regurgitant jet area >10 cm^2 to define severe TR,[69] a 3D TTE planimetered VCA of >0.75 cm^2 was the most sensitive cutoff (sensitivity, 85.2%; specificity, 82.1%). This higher cutoff has also been shown by Chen et al,[68] with severe TR by 2D criteria associated with a 3D VCA of >0.6±0.4 cm^2 and nonsevere TR by 2D methods with a 3D VCA of ≤0.3±0.1 cm^2. However, receiver-operator curve demonstrated that a 3D VCA of 0.36 cm2 was the best cutoff value for severe TR, with sensitivity of 89% and specificity of 84% in predicting severe TR defined by 2D echocardiographic integrative criteria.

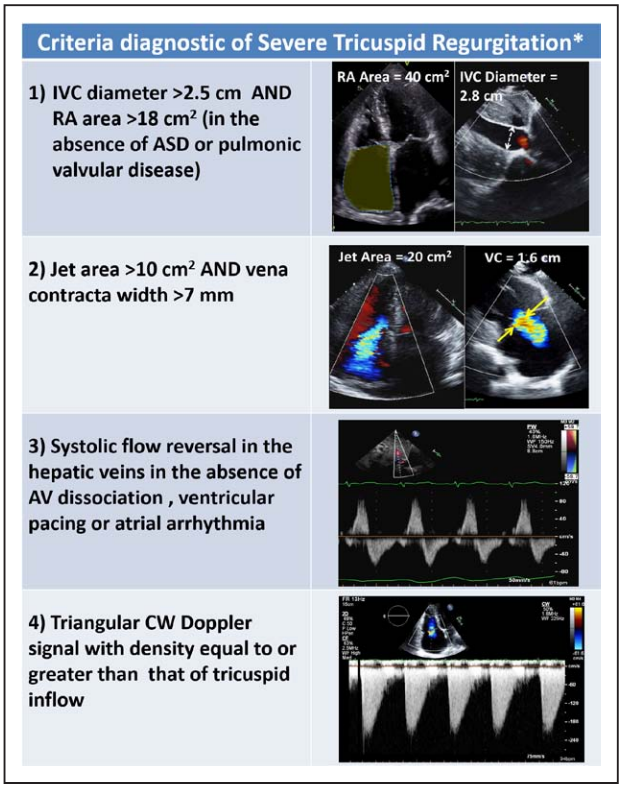

Figure 8. Combination of diagnostic criteria used to assess the severity of tricuspid regurgitation (TR). This figure lists the 4 proposed combination criteria described by Grant et al.[60] In this algorithm, severe TR was present in the presence of a suggestive color Doppler jet and if any ≥1 of the combinations shown were present. ASD indicates atrial septal defect; CW, continuous wave; IVC, inferior vena cava; and RA, right atrial.

Outcomes Based on Echocardiographic Measurements

Significant tricuspid annular dilatation measured by TTE may be a better predictor of severe late TR after MV surgery.[14,70,71] Because of the linear relationship between annular diameter and tricuspid regurgitant volume, annular diameter criterion has been used as a surrogate for regurgitation volume. Significant annular dilatation is defined by a diastolic diameter of ≥40 mm or >21 mm/m^2 in the 4-chamber transthoracic view (Figure 4A)[71] and is the main imaging criteria used to indicate severe TR in the current the American Heart Association/American College of Cardiology guidelines.[72] Severe TR (stages C and D) is associated with poor prognosis independent of age, left ventricular and RV function, and RV size.[6,12] With the use of more sophisticated imaging techniques such as 3DE. Dreyfus et al[73] suggest that the cutoff for severe TR should be >42 mm or 23 mm/m^2, which is supported by other studies.[74]

In addition to annular dimensions, other echocardiographic predictors of postoperative recurrent TR (Figure 4B) include TTE measurements of TV tethering distance of >0.76 cm[44] or tethering area of >1.63 cm[75] predicted recurrent TR after surgery. RV end-systolic area of ≥20.0 cm^2 predicted worse event-free survival.[76] Measures of RV function remain unclear determinants of outcome with some studies suggesting no significant impact of reduced function on outcomes.[76,77] Dreyfus et al[71] studied intraoperative predictors of worsening TR and found that 48% of patients with a tricuspid annular dimension of >70 mm (septolateral dimension) had worsening of their TR over time if not repaired at the time of surgery (compared with only 2% with a concomitant repair). Recent studies, however, have called into question the appropriateness of this measurement.[73]

Transcatheter Approaches to TR

In the setting of high surgical risk of reoperation and the growing number of patients with transcatheter left heart devices, transcatheter solutions for functional TR are being aggressively investigated. Several challenges specific to transcatheter approaches must, however, be considered.[78] These challenges include severe dilatation and noncircular shape of the annulus, thin, or nonuniform annular tissue (particularly for the septal leaflet), angle of catheter approach (SVC or IVC), noncompacted/small RV chamber with papillary muscles and moderator band, thin RV free wall, and right coronary artery proximity to the annulus.

Echocardiographic imaging of the TV plays an essential role in quantifying regurgitation and chamber size and function, as well as guiding the procedures. Because the TV is close to the chest wall, TTE imaging may in some patients result in better anatomic characterization of the TV than TEE imaging. Nonetheless, the multiple windows afforded by the proximity of the TV to the esophagus and gastric fundus provides the imager with many options to image the entire tricuspid apparatus using both 2D and 3D modalities. Whereas transcatheter interventions on the TV could be performed using TTE, there are many advantages to using TEE to guide these procedures. First is the ability to continuously image without interrupting the procedure to confirm catheter or wire position. Second, and equally important, is the reduction in exposure of the imager to radiation. Standardization of the image display and the development of software to automate image orientation will further enable intraprocedural imaging of the TV. The current spectrum of devices for transcatheter repair of the native TV has recently been reviewed,[78,79] but a few procedures deserve special mention with procedural and imaging considerations summarized in the Table.

Numerous authors have recently reported successful treatment of TR with the MitraClip (Abbott Vascular, Abbott Park, IL).[80,81] In the series of 3 patients reported by Hammerstingl et al,[80] the transjugular MitraClip procedure was successfully guided by TEE from the superior vena caval approach with no evidence for tricuspid stenosis, and clinical benefit was seen in all patients. In patients with large central coaptation defects, a modified zipping technique was performed with the first clip placed as close as possible to the defect to facilitate the second clip placement. An acceptable mean tricuspid gradient after the clip placement was defined as <3 mm Hg. Imaging for the clip requires aligning the plane of the annulus as perpendicular to the insonation beam as possible; the low esophageal views are typically the best for assessing the regurgitant jet and imaging leaflet grasp, as well as documenting transtricuspid gradients. Transgastric views

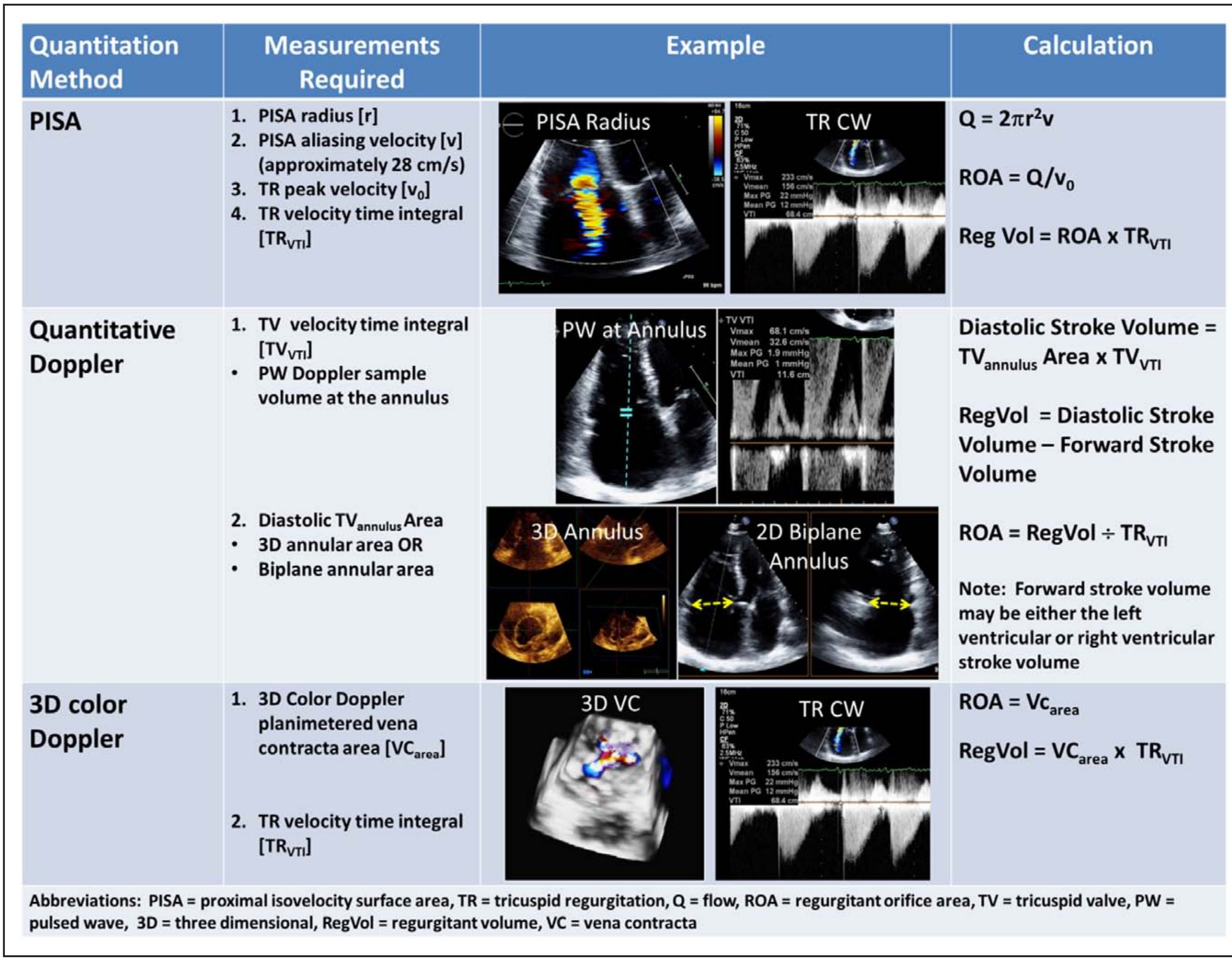

Figure 9. Methods for quantifying tricuspid regurgitation. In this figure, the 3 methods for quantifying tricuspid regurgitation are listed with the required measurements and calculations. 3D indicates 3-dimensional; PISA, proximal isovelocity surface area; PW, pulsed wave; Q, flow; RegVol, regurgitant volume; ROA, regurgitant orifice area; TR, tricuspid regurgitation; TV, tricuspid valve; and VC, vena contracta.

can be used to confirm the position of the clips with Doppler performed from deep transgastric views. More recent reports suggest that a transfemoral venous approach may result in similar outcomes.[82] A small series of 18 patients who underwent MitraClip of the TV was recently presented. The mean age was 80 years, with logistic EuroSCORE II (European System for Cardiac Operative Risk Evaluation) of 10, and New York Heart Association class III (67%) or class IV (33%) and most had grade 3 or 4 TR (with 4 denoting massive or torrent TR with a vena contracta of >1.5 cm and loss of valve function). All patients experienced a reduction of TR of at least 1 grade, with 70% in grade 1 or 2 at 30 days and >70% were also in New York Heart Association class II (Jörg Hausleiter, MD, unpublished data, 2016.). Similar to MitraClip, complications may include device entanglement in the chordae, clip detachment, or significant tricuspid stenosis. Recently, Vismara et al[83] developed an ex vivo porcine model of functional TR and showed that if a single clip is used, grasping the medial segment (near the tips) of the septal and anterior leaflets resulted in the greatest increase in forward flow, with grasping of the septal and posterior leaflet tips also effective. If a 2-clip procedure is anticipated, then grasping the commissure and medial segments of the septal and anterior leaflets allowed for the best postprocedural outcome, ensuring a complete re-establishment of physiological-like hemodynamics.

The Forma Spacer (Edwards Lifesciences, Irvine, CA) device is implanted from a left subclavian vein approach, introducing an anchor, attached to a foam-filled spacer device that then forms a surface against which the leaflet tips coapt. Since the early report of 7 successful implants in high-risk patients with severe TR with no procedural complications,[84] the United States early feasibility trial was begun (ClinicalTrials.gov Identifier: NCT02471807) and is currently enrolling patients. Three sizes of the spacer device are currently available, 12-, 15-and 18-mm diameter, with device choice determined by the largest echocardiographic vena contracta width. Preprocedural planning is essential, utilizing computed tomography to determine the complex anatomy of the RV (ie, location of trabeculations, moderator band, and papillary muscle; Figure 10A). Intraprocedural imaging relies heavily on both intraprocedural fluoroscopic (Figure 10B, 10C, and 10E) and 2D (Figure 10D) and 3D (Figure 10F) TEE guidance. Initial preimplantation TEE imaging focuses on

Table. Important Imaging Considerations for Transcatheter Tricuspid Repair Devices

	Questions for Imaging Before Procedure	Procedural Considerations	Important Imaging Views
Leaflet clipping	Which leaflets are involved? Is the coaptation gap approachable directly or should adjacent regions be targeted? Is the leaflet length adequate for grasping?	Greatest increase in cardiac output may be obtained with septal-anterior and septal-posterior leaflet tip clips If a multiclip approach is used, closing the septal-anterior coaptation may yield the best result	Midesophageal and deep-esophageal/GE junction views typically yield the best imaging for leaflet grasp as well as 3D reconstruction for positioning the clip Avoid views with acoustic shadowing of the leaflet tips (ie, typically transgastric) 3D color Doppler to assess residual TR
Forma	What is the tricuspid EROA and which device would optimally reduce TR? What is the EOA at baseline and would a device cause significant obstruction? What is the ideal path for the anchor within the RV and are there important anatomic considerations (ie, large papillary muscles, moderator band or trabeculations)?	Thickened, nonpliable leaflets isolated commissural jets may not allow complete leaflet closure around the device Pacemakers may interfere with optimal leaflet coaptation around the device	Transgastric views with 3D for reconstruction of the RV anchor path and landing zone Midesophageal simultaneous biplane views centered on the regurgitant jet to optimize device position for TR reduction 3D color Doppler to assess TR before and after device placement
Trialign	Is the TR purely functional? Will bicuspidization of the valve result in adequate reduction of TR? Is there adequate annular shelf (at least 2–4 mm)? Will >1 pair of pledgeted sutures be needed? Where is the right coronary artery in relation to the annulus?	Degenerative TR may not benefit from annular reduction Pacemakers causing tethering of the leaflet tips may not benefit from annular reduction	Mid- and deep-esophageal 2D views of the wire depth of annular crossing (with use of transgastric views in some instances) 3D reconstruction for measurement of annulus, EOA and EROA before and after device placement
Caval devices	Are the symptoms primarily congestive hepatopathy? Is the IVC size appropriate for stent and transcatheter valve Is there adequate distance between the RA and hepatic veins to fit a transcatheter valve?	Largest IVC stent currently available=30 mm Obstruction of the hepatic vein must be avoided	Mid- and deep-esophageal 2D views of the IVC–RA junction Shallow-transgastric views of the IVC and hepatic vein

The table lists 4 of the devices currently implanted in the most number of patients, with suggested intraprocedural echocardiographic imaging considerations. 3D indicates 3-dimensional; EOA, effective orifice area; EROA, effective regurgitant orifice area; GE, gastroesophageal; IVC, inferior vena cava; RA, right atrium; RV, right ventricular; and TR, tricuspid regurgitation.

(1) identification of the ideal landing zone of the RV anchor (corresponding to the position on computed tomography), (2) imaging of the path of the anchor within the RV to assess for possible impediments to positioning (ie, papillary muscles, trabeculations, or moderator band); (3) location and severity of TR using the methods described above to aid in optimal positioning of the device. During implantation, TEE is ideal for (1) guiding the balloon-tip catheter to the ideal location for anchor position, (2) confirming the unimpeded path of the device catheter sweep from posterior to anterior annulus, (3) anchor deployment into the RV myocardium with tug test to ensure stable device implantation and absence of pericardial effusion, (4) positioning of the device to optimize reduction in TR. After device placement, 2D/3D TTE imaging can be performed to assess the final position and 3D VCA of the residual jets.

The Trialign™ system (Mitralign Inc., Tewksbury, MA) attempts to replicate the results of a modified Kay bicuspidization procedure,[85] which has shown good midterm[86] and long-term[87] results. The procedure is nearly entirely guided by echocardiography (Figure 11). To accomplish bicuspidization, the system places pledgeted sutures within the TV annulus spanning the length of the posterior leaflet and using a dedicated plication lock device and brings the 2 pledgeted sutures together. Since the first-in-human implantation of the Trialign™ system,[88] numerous other investigators have reported the successful use of this device for TR.[89,90] PTVAS SCOUT trial (The Early Feasibility of the Mitralign Percutaneous TV Annuloplasty System; ClinicalTrials.gov Identifier: NCT02574650) has completed enrollment in the United States, and the Conformité Européene (CE) mark trial in Europe (SCOUT II) has begun enrolling. The Trialign™ system uses a deflectable catheter via the transjugular approach to deliver the device. The guide catheter and then wire delivery catheter (Figure 11A through 11C) are positioned by echocardiographic guidance retrograde beneath the annulus, between the posterior and septal tricuspid leaflet commissures. An insulated radiofrequency wire is used to cross the annulus with TEE imaging used to ensure adequate annular depth, away from the base of the leaflet and away from the right coronary artery. To image the wire crossing, multiple views can, and typically should, be used, including midesophageal views (typically at 60°–90° rotation) or transgastric views where the posterior annulus is in the near field. Implantation of sutured pledget is performed using the wire as a catheter rail (Figure 11D and 11E). After placement of the first pledget, the second wire/pledget is ideally positioned ≈2.5 cm from the first catheter near the commissure between the posterior and anterior TV leaflets. Measurement of this distance can be performed along the curve of the annulus on 3D TEE images (either directly on the surgical view or on multiplanar reconstruction; Figure 11F). Greater distances, particularly with a curved posterior annulus, may increase the stress on the annular tissue during plication and risks a pull-through (typically of a single pledget). A dedicated plication lock device is used to bring the 2 sutures together, plicating the annulus and effectively bicuspidizing the TV (Figure 11G through 11J).

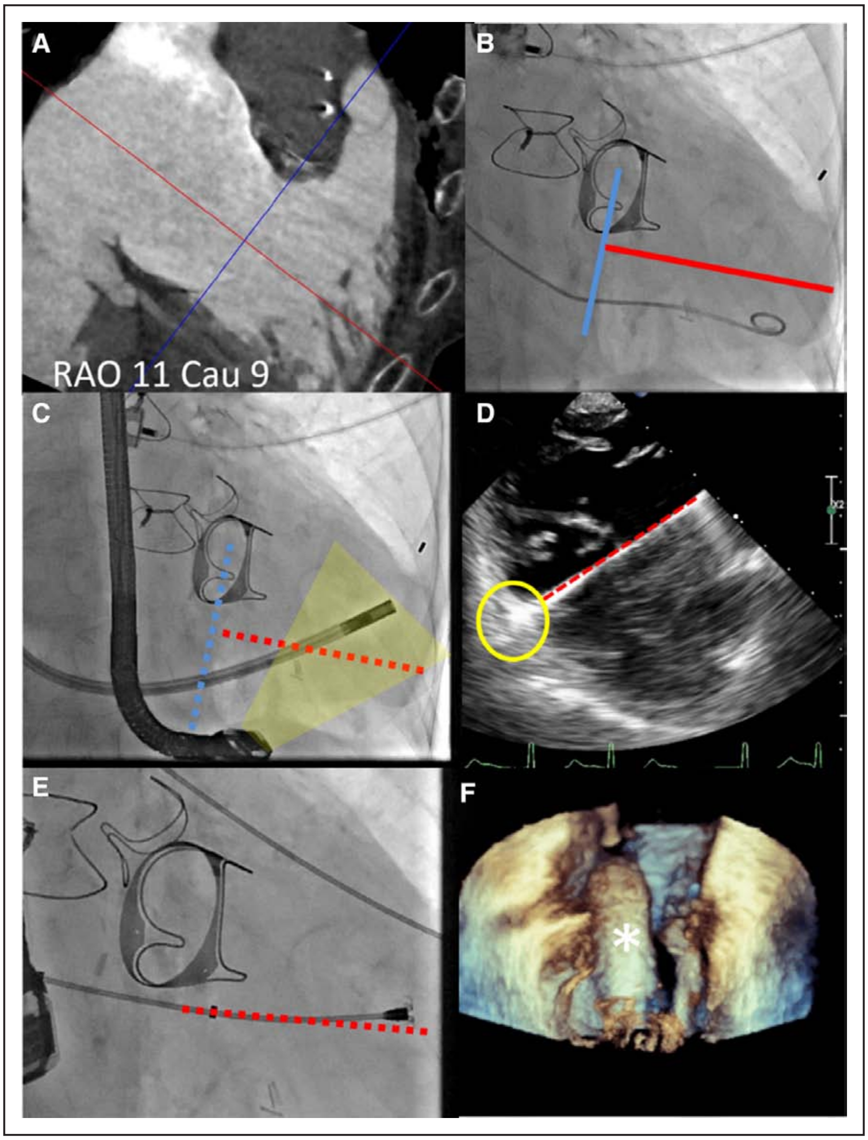

Figure 10. Imaging for the Forma device. **A**, The preprocedural computed tomography performed to not only assess optimal position of the anchor but also determine the optimal fluoroscopic angle of coplanarity. **B**, The intraprocedural right ventriculogram performed in the optimal collimator position with the plane of the annulus marked by the blue line and the proposed position of the anchor marked by the red line. **C**, Fluoroscopic image of the guide catheter positioning which is too anterior (ideal position marked by the red dotted line) and was repositioned before anchor deployment shown by transesophageal echocardiography in **D**, the red line is the anchor lead, the yellow circle shows the implanted anchor. Note that the imaging plane for **D** is denoted in yellow in **C**. After anchor deployment in the correct position (**E**), the spacer (**F**, white *) is positioned across the tricuspid annulus using 3-dimensional imaging and color Doppler. Cau indicates caudal; and RAO, right anterior oblique.

Adaptation of the transcatheter aortic valve technology has been used to treat the upstream effect of severe TR by placing a transcatheter valve into the IVC alone[91,92] or in addition to a valve in the superior vena cava.[93,94] In an animal model of severe TR, the caval valve implantation technique was shown to be effective in decreasing the mean IVC pressure.[95] This group then performed the first-in-human bicaval caval valve implantation procedure confirming continued improvement in mean caval pressures >12 months of follow-up, improvement in symptoms, and normalization of liver function.[93] The single-center HOVER trial (Heterotopic Implantation of the Edwards-Sapien XT Transcatheter Valve in the Inferior Vena Cava for the Treatment of Severe Tricuspid Regurgitation; ClinicalTrials.gov Identifier: NCT02339974)[91] is currently enrolling patients. This study is testing the short-term safety (<30 days) and mid- and long-term efficacy (6 months and >1 year) of the heterotopic implantation of the Edwards-Sapien XT valve in the IVC for the treatment of severe TR in patients who are inoperable or at a high surgical risk for TV replacement. Important preprocedural imaging includes CT to assess the IVC diameters both at the junction of the RA/IVC and inferior to the hepatic veins, the distance from the RA/IVC to the superior most hepatic vein and the optimal angle to visualize the takeoff of the hepatic vein from the IVC. To secure the balloon-expandable valve, the IVC needs to be downsized by placement of ≥1 vascular stents placed from the femoral vein approach. The balloon-expandable valve is then deployed from a right transjugular approach with the bottom edge of the valve is placed just superior to the most superior hepatic vein.

Because the tricuspid annulus dilates in the septo-to-lateral direction in functional TR, investigators of The TriCinch System (4TECH Cardio, Galway, Ireland) have developed a tethering device that cinches the anteroposterior dimension of the annulus to improve coaptation. The delivery system allows transfemoral fixation of a stainless-steel corkscrew into the anteroposterior TV annulus, connected through a Dacron band to a self-expanding nitinol stent, and placed in the hepatic region of the IVC. PREVENT trial (The Percutaneous Treatment of Tricuspid Valve Regurgitation With the TriCinch System; ClinicalTrials.gov Identifier: NCT02098200) is currently enrolling patients in centers in France, Italy, and Switzerland.

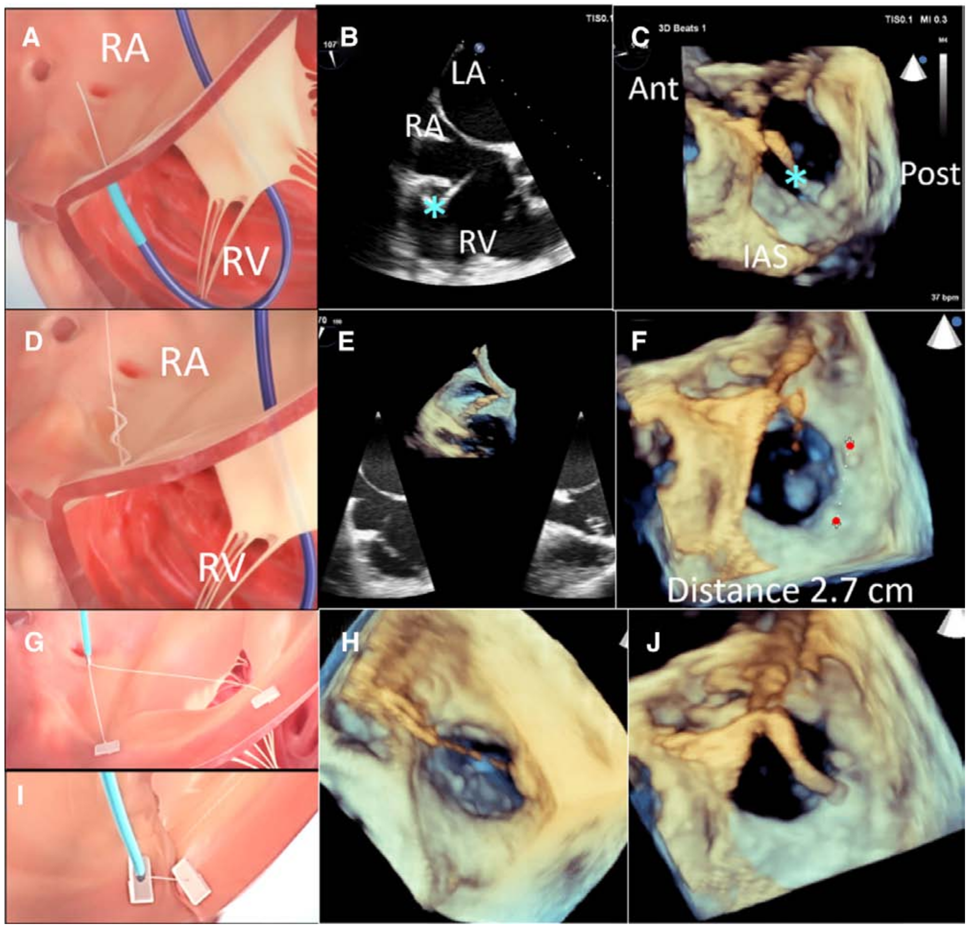

Figure 11. Imaging for the Trialign device. Deployment of the Trialign device relies on 2-dimensional (2D) and 3D echocardiographic imaging. **A**, The positioning of the wire delivery catheter (*) beneath the annulus with 2D (**B**) and 3D (**C**) imaging confirming the location and the depth within the annular plane. **D**, The delivery of the pledget suture, which is continuously monitored by both 2D and 3D imaging (**E**). After placement of the second pledget suture at the desired distance from the first (**F**), the sutures are plicated (**G** and **H**) until maximal reduction in annular dimensions is achieved (**I** and **J**). Ant indicates anterior; IAS, interatrial septum; LA, left atrium; Post, posterior; RA, right atrium; and RV, right ventricle.

Other devices, such as the transatrial intrapericardial tricuspid annuloplasty device, are currently under investigation.[96] This delivery device is formed from a nitinol wire, preshaped into a self-expanding loop to encircle the heart from within the pericardial space. Pericardial access is performed by introducing the device into the RA via a transfemoral vein approach, and the guidewire is used to puncture the RA appendage. The nitinol loop is then opened and positioned to encircle the heart in the AV groove. In the initial animal study, the suture was tightened to the desired tension using real-time 1.5-T magnetic resonance imaging. The RA appendage puncture was closed with an atrial septal occluder. Initial trials in humans are expected soon. The Cardioband (Valtech Cardio, Ltd, Or Yehuda, Israel) is a transcatheter annuloplasty device that mimics an incomplete surgical ring, through a transfemoral, transseptal delivery system. Specially designed anchors are positioned using echocardiographic and fluoroscopic guidance, connecting the implant to the mitral annulus. The Cardioband mitral repair system received CE mark in 9/2015 and the first-in-human implants of the Cardioband Tricuspid (TR) system were reported in 9/2016. A CE study is currently underway for this device.

Conclusion

Interest in the TV has increased in the setting of evidence that functional TR impacts morbidity and mortality. The complex anatomy and function of this valve can be imaged using multiple echocardiographic modalities. In addition, intraprocedural imaging for transcatheter solutions for functional TR relies on echocardiography.

Disclosures

Dr Hahn is the Principle Investigator SCOUT trial (The Early Feasibility of the Mitralign Percutaneous Tricuspid Valve Annuloplasty System) for which she receives no compensation. She is a speaker for Abbott Vascular, GE Medical, and St. Jude Medical.

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