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Review Article

Developing Insights Regarding Tricuspid Valve Regurgitation: Morphology, Assessment of Severity, and the Need for a Novel Grading Scheme

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ABSTRACT

Current understanding that progressive tricuspid regurgitation (TR) is associated with worse outcomes has highlighted the clinical need for a more accurate assessment of TR morphology and severity. This need has been further emphasized owing to the development of a myriad of percutaneous right-sided interventions, which may offer successful treatment of TR in selected patients. Understanding the etiology and quantification of the severity of TR has important implications in the selection of novel therapeutic strategies, i.e., medical vs. percutaneous vs. surgical approaches. Newer grading schemas that better reflect the TR lesion severity have been recently proposed and may facilitate monitoring of the evolution of TR following percutaneous and/or surgical treatment. In this review, we summarize contemporary concepts regarding tricuspid valve morphology, TR etiology, and associated mechanisms and echocardiographic approaches to grade TR severity.

ABBREVIATIONS

AFTR, Atrial functional tricuspid regurgitation; ASE, American Society of Echocardiography; CIED, Cardiac implantable electronic devices; CMRI, Cardiovascular magnetic resonance image; CW, Continuous wave; EDV, End-diastolic volume; EROA, Effective regurgitant orifice area; FAC, Fractional area change; LS, Longitudinal strain; MR, Mitral regurgitation; PA, Pulmonary artery; PASP, Pulmonary artery systolic pressure; PISA, Proximal isovelocity surface area; PH, Pulmonary hypertension; PM, Papillary muscle; RA, Right atrial; RV, Right ventricle; Rvol, Regurgitant volume; S′, Peak systolic velocity; TA, Tricuspid annulus; TAPSE, Tricuspid annular plane systolic excursion; TEE, Transesophageal echocardiography; TTE, Transthoracic echocardiography; TR, Tricuspid regurgitation; TV, Tricuspid valve; VC, Vena contracta; VFTR, Ventricular functional tricuspid regurgitation.

Introduction

The need for accurate assessment of tricuspid regurgitation (TR) severity has long held importance in clinical practice owing to the attendant mortality risk for patients with moderate-to-severe TR.[1–6] However, there is now an even greater emphasis on the detection of significant TR owing to the advent of percutaneous right-sided interventions, which may offer successful treatment of TR in selected patients.[7–9] Recent studies regarding the outcomes of tricuspid valve (TV) percutaneous interventions[7–10] have advocated for the need to alter the current clinical grading schema,[11,12] with the greatest emphasis on further stratification of severe TR, owing to the variable impact on mortality. Additionally, greater understanding of the underlying mechanisms of TR itself using a comprehensive echocardiographic approach is integral to selecting the optimal treatment for TR on an individual patient basis. Accordingly, it is important for all cardiologists in current practice

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to understand the TV apparatus, as well as the causes, mechanisms, and repercussions of TR.

Normal Tricuspid Valve Anatomy

The TV is the largest of all 4 cardiac valves with a physiologically normal orifice area of 7-9 cm^2.[13–16] While it has classically been described as being comprised of 3 distinct leaflets, recent studies have highlighted that accessory leaflets are not uncommon, varying anywhere in number from 2 to 6 in total.[17–21] The anterior TV leaflet is extremely mobile, has the largest area, and lies immediately adjacent to the aortic valve. The septal leaflet is typically the smallest, associated with less mobility and chordal attachments which are positioned directly above the interventricular septum. The posterior leaflet is juxtaposed with the right ventricular free wall and is typically the one exhibiting accessory leaflets, when anatomic variation is present. Conventionally, the TV has 3 papillary muscles (PMs). The anterior papillary is usually the largest owing to the need for its chordae to support both the anterior and posterior leaflets. The posterior PM typically provides chordal support to the posterior and septal leaflet, while the septal PM, usually the smallest, supports the septal leaflet alone when present, but may be overall absent at times.[11,12,16,20,22,23] The TV apparatus is supported by the tricuspid annulus (TA) (Figure 1). Akin to the geometry of the mitral annulus, the TA has an elliptical saddle shape in healthy individuals.[13] Owing to the relatively fixed septal element of the TA, dilatation of the TA occurs predominantly in the direction of the right ventricular free wall.[23–25]

Approach to Tricuspid Regurgitation Assessment

Classification of TR is based upon the underlying mechanism and broadly divided into 2 categories: primary or intrinsic (7%-10%) and secondary or functional (up to 90%).[11,12,26] It is essential to identify the causative TR mechanism because the optimal approach to treatment may be different.[27–29] In the case of primary TR etiologies, the abnormality occurs within the valve apparatus itself[11,30] and can be either acquired or congenital. Overall, 3-dimensional (3D) echocardiography is the method of choice for morphologic and anatomical assessment of primary TR as depicted in Figure 2.

Myxomatous degeneration is one of the most common causes of primary TR, often occurring concurrently in both the mitral valve and TV[11] (Figure 2a). TV prolapse is relatively common and is characterized by systolic displacement of redundant and elongated TV leaflets into the right atrium (Figure 2a). This entity does not have specific diagnostic criteria.[11,12] TR caused by the leads of cardiac implantable electronic devices is increasingly frequent owing to the growing number of device-lead implants used in clinical practice and can lead to a spectrum of complications including leaflet impingement (Figure 2b), adherence, entanglement, and/or perforation.[26,31,32] Device leads can also serve as a nidus for nascent thrombus and/or endocarditis.[33] In fact, endocarditis (Figure 2c) is an important cause of TR, classically associated with intravenous drug use, infected catheters, and immune deficiency.[33] An additional acquired etiology is tricuspid leaflet or chordae rupture (Figure 2d), most frequently associated with chest trauma or right heart biopsy.[11] Of the congenital cardiac entities, Ebstein anomaly is the most common cause of TR and is characterized by "atrialization" of the right ventricle (RV) due to apical displacement of the septal leaflet.[30,34,35] Pentacuspid, quadricuspid (Figure 2e), and bicuspid TVs (Figure 2f) have been rarely reported and may cause variable degrees of TR, at times.[36]

In secondary TR, the critical difference lies in the presence of remodeling of the RV as the primary driver for TR (Table 1). Recent publications have helped expand the knowledge of the mechanism of secondary TR beyond RV remodeling and have shown that right atrial (RA) remodeling constitutes a different mechanism of secondary TR, distinct from RV dilatation. This has resulted in the recent proposition that functional TR entails 2 distinct categories, (1) ventricular functional TR (VFTR) and (2) atrial functional TR (AFTR).

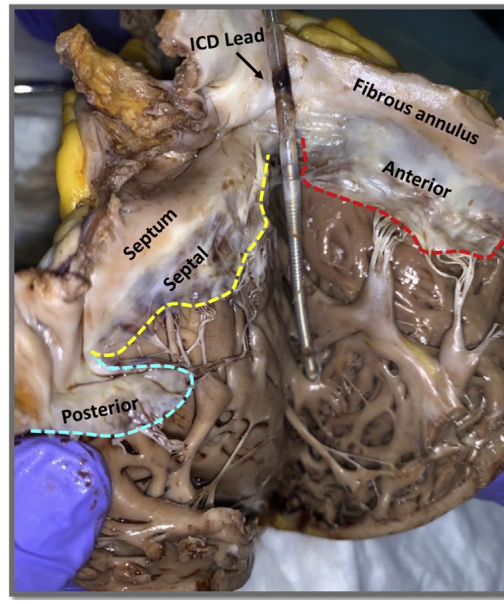

Figure 1. Autopsy heart. The figure illustrates the tricuspid apparatus and the right ventricle. The tricuspid valve is classically described as having a trileaflet morphology. The septal leaflet, outlined by the color yellow, is adjacent to the interventricular septum and is attached directly through the RV wall or through its papillary muscle by multiple chordae tendineae in a parachute-like fashion. The red dotted line outlines the anterior leaflet contour which is supported by the anterior papillary muscle. The posterior leaflet is outlined by the color blue and is adjacent to the right ventricle wall. The posterior papillary muscle is often bifid or trifid and provides chordal support to the posterior and septal leaflets. This patient has an ICD lead.
Abbreviations: ICD, implantable cardioverter defibrillator (arrow); RV, right ventricle.

In VFTR, right ventricular dilatation, with or without dysfunction, results in direct TA dilatation, which coupled with leaflet tethering secondary to apical PM displacement, and may result in TV leaflet malcoaptation with varying degrees of TR.[12,16,30,39] While TA dilatation and PM displacement often coexist, either one individually may also prompt the onset of TR.[40] Left-sided heart disease, frequently caused by mitral and aortic valve diseases, is the most common cause of secondary ventricular TR[1,24,30] (Figure 2g). In patients with heart failure and reduced ejection fraction, TR is frequently observed, particularly in the advanced stages of left ventricle dysfunction.[30,41] Pulmonary hypertension (PH), when present, may also exacerbate TV dysfunction.[1,28] Interestingly, in patients with PH, the characteristic pattern of RV remodeling is an elliptical dilatation and deformation involving the mid RV disproportionately, associated with only mild TA dilatation.[16,37,42,43] Even more interesting is the finding that in patients with PH, the tricuspid leaflet area-to-closure area, a surrogate of TV leaflet remodeling, may serve as a key determinant of the onset of significant functional TR.[44] Phenotypically, centrally directed TR jets appear to have the highest prevalence in severe VFTR.[45]

Conversely, a dilated TA with posteriorly directed TR jets and/or minimal leaflet tethering are seen in the context of patients with chronic atrial fibrillation, where RA enlargement occurs independent of the presence of left heart disease or PH.[27,30,37,43] In this scenario, designated AFTR, the TA area correlates more closely with RA size than with RV dimensions.[4,27,46–48] When RV dilation does occur, it is usually confined to the basal inflow region and results in a more conical RV remodeling. In AFTR, significant RV dilatation is mostly a delayed occurrence with progression of moderate-to-severe TR.[48] Understanding the mechanistic subtypes of functional TR has important clinical implications, particularly regarding the treatment approach. It has been suggested that in a select group of patients with AF, restoration of sinus rhythm is associated with RA and TA reverse remodeling and

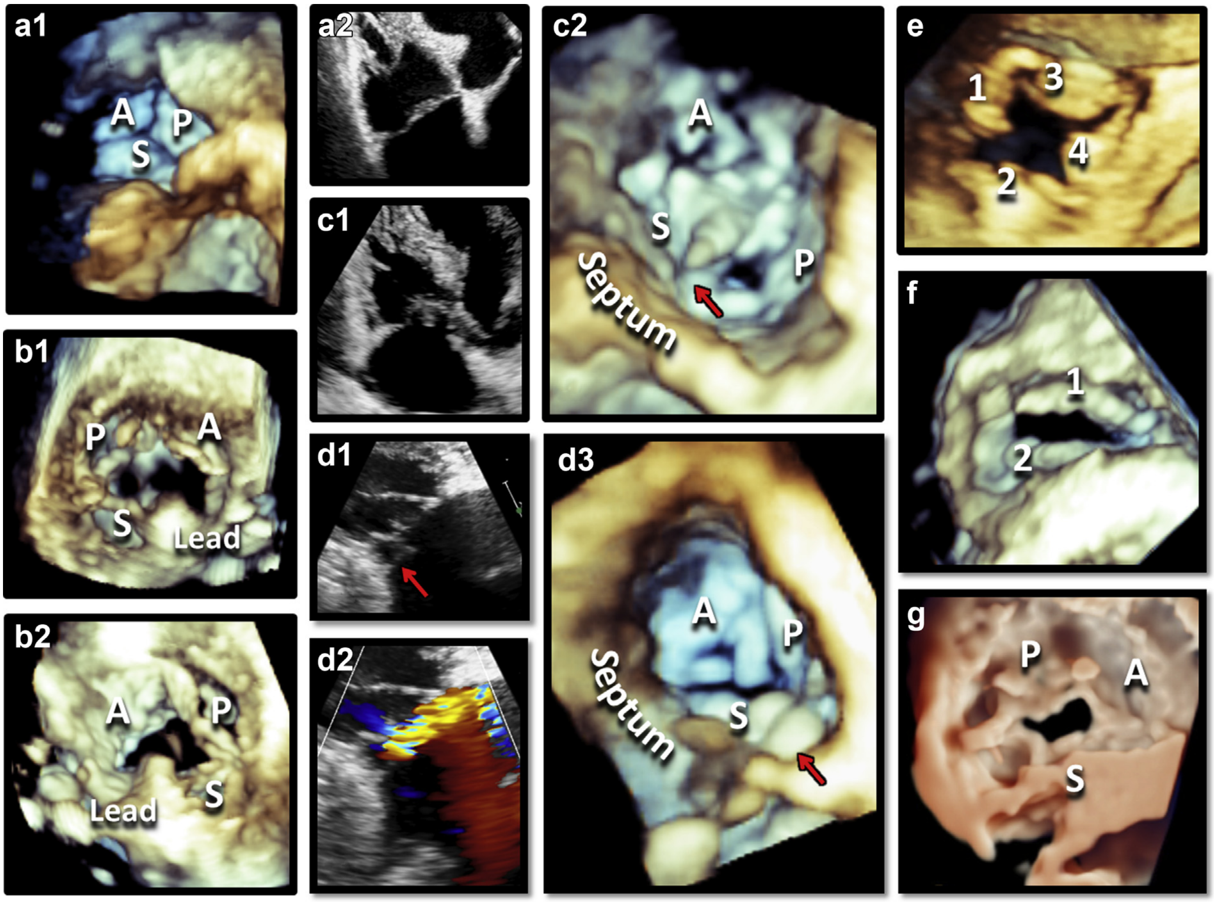

Figure 2. Etiologies of tricuspid valve dysfunction. Myxomatous degeneration of the tricuspid valve leading to prolapse shown by 3D from the right atrium perspective (a1) and by 2D TTE from the RV-focused view (a2); Impingement of a cardiac implantable electronic device in the septal leaflet of the TV seen by 3D from the ventricle (b1) and atrial orientation (b2); 2D TTE RV-focused view showing a mass in TV leaflets (c1), and 3D from the right atrium perspective of the TV, revealing a vegetation attached to the anterior leaflet (c2); Ruptured septal leaflet with flail chordae seen on 2D TTE (d1, red arrow), resulting in severe TR with eccentric jet (d2) and 3D from the right atrial orientation (d3) demonstrating the leaflets and the flail chordae (red arrow); From the ventricle perspective is illustrated a quadricuspid (e) and bicuspid (f) valve; At midsystole, on the ventricle perspective, using the technique of transillumination, it is possible to visualize the malcoaptation of the TV leaflets (g). See text for detailed information.
Abbreviations: 2D, 2-dimensional; 3D, 3-dimensional; A, anterior; P, posterior; RV, right ventricle; S, septal; TR, tricuspid regurgitation; TTE, transthoracic echocardiography.

consequently TR improvement.[49] The distinct phenotypic differences are likely to impact interventional treatment eligibility and prognosis, in procedures such as annuloplasty, TV leaflet augmentation, transcatheter repair, and ablation.[24,29,44]

TV Regurgitation: Assessment By Echocardiography

According to current guidelines, the recommended parameters for the evaluation of TR are mostly similar to those used for mitral regurgitation (MR) assessment, thus extrapolating experience and knowledge acquired from its left-side counterpart to apply in cases of TR.[24,26,38,50] In fact, the vena contracta (VC) and effective regurgitant orifice area (EROA) have similar thresholds for the definition of severe regurgitation (Table 2).[11,12,26,53] This recommendation persists despite the increasing evidence which highlights inherent differences unique to the TV, including its morphology, leaflet number, orifice size, and geometry.

TR grading presents even greater challenges owing to the impact of factors such as load dependency and respiratory variability, as well as the presence of an irregularly shaped dynamic regurgitant orifice. Moreover, TA size, the degree of tethering and tenting of the TV, and the geometry, size, and function of the RV and right atrium should also be considered in the assessment of TR.[11,12] A multiparametric approach, using quantitative and semiquantitative methods, is therefore recommended for grading TR.

Table 1
Contrast between right ventricular and atrial functional TR

Parameter	VFTR	AFTR
Leaflet tethering	+++	Normal or minimal
TA diameter	+	+++
RA volume	Variable degree of dilatation	+++
RV basal diameter	++	+++
RV mid diameter	+++	Normal or mildly dilated
RV length	Lengthened	Normal or diminished
RV shape	Elliptical/spherical	Conical
RV function	More dysfunctional	Less dysfunctional or normal
Pulmonary hypertension	Present or absent	Absent
Left heart disease	Present or absent	Absent

Notes. Data from Topilsky et al.[37] and Badano et al.[38]
AFTR = atrial functional tricuspid regurgitation, RA = right atrium, RV = right ventricle, TA = tricuspid annulus, VFTR = ventricular functional tricuspid regurgitation.

Table 2
Severe mitral valve regurgitation and tricuspid regurgitation grading, according to the guidelines, and the new proposed grading scheme for TR severity, in which severe TR is subclassified

Quantitative parameter	MR	TR			
	Severe	Moderate	Severe	Massive	Torrential
VC width (cm^2)	≥0.7[11,12]	0.3-0.69[11,12]	0.7-1.3[11,12]	1.4-2.0[10,52]	≥2.1[10,52]
3D VCA (cm^2)	>0.40[11]	0.5-0.75[51]	0.75-0.94[11,12]	0.95-1.14[10,52]	≥1.15[10,52]
PISA (cm^2)*	≥1.0[11]	0.6-0.9[11,12]	>0.9[11,12]	-	-
EROA by PISA (cm^2)	≥0.40[11,12]	0.20-0.39[11,12]	0.40-0.59[11,12]	0.60-0.79[10,52]	≥0.80[10,52]
Rvol by PISA (mL/beat)	≥60[11,12]	30-44[11]	45-59[11,12]	60-74[10]	≥75[10]

Notes. The grading scheme was proposed according to Hahn et al.,[10] Zoghbi et al.,[11] Lancellotti et al.,[12] and Velayudhan et al.[52]
3D VCA = three-dimensional vena contracta area, EROA = effective regurgitant orifice area, MR = mitral valve, PISA = proximal isovelocity surface area, Rvol = regurgitant volume, TR = tricuspid valve, VC = vena contracta.
* Nyquist limit of 28 cm/s.

Imaging the TV

The assessment of TV leaflet morphology using 2 dimensions alone can be challenging. Guidelines recommend interrogation using multiple imaging planes on transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE).[11–13] With TTE, specifically, the RV inflow, basal short axis, apical 4, and subcostal views should all be used. However, despite the use of all standard transthoracic views, in some cases, they may be insufficient to fully determine TV anatomy and leaflet morphology. In these cases, dedicated TTE imaging with expert knowledge of additional TV-specific views and associated landmarks, such as the aortic valve, coronary sinus, and interventricular septum, should be obtained as illustrated in Figure 3.[43,54]

Using TEE, the acquisition typically starts with mid-esophageal views, first at zero degrees in the 4-chamber view (rotating the probe clockwise and using right flexion to center the TV in the sector) in which the septal (adjacent to the septum) and anterior (juxtaposed to the RA appendage) leaflets are often seen. Following this, the angle should be increased from 60 to 90 degrees to acquire RV inflow-outflow views, in which the commissures can be interrogated further using biplane imaging. In the deep-esophageal views, the TEE operator can display the RV focused view, particularly useful for the visualization of the TA and TR VC, as well as RV function. Transgastric views offer particular advantages for imaging the TV and provide ideal views to confirm TV leaflet morphology and the subvalvular apparatus. At zero-degree rotation with anteflexion, the RV inflow and outflow can be visualized. Higher angulation at 20-60 degrees reveals the short axis plane, where the TV leaflet tips can be simultaneously assessed, along with the regurgitant orifice and the coaptation gap, if present. This view is particularly important in the setting of interventional procedures, particularly the TV edge-to-edge repair (Figure 4). Although deep transgastric views are used to assess TV leaflets, an additional advantage from these views is the coaxial alignment for Doppler assessment of TR, to obtain complete and peak TV continuous Doppler velocities allowing optimal beam alignment.[13]

3D imaging is unparalleled in its ability to delineate TV morphology using the unique "en-face" view, in which all 3 TV leaflets and TA are visualized from either the RA or RV perspective.[15,55] 3D images can be acquired from any acoustic window permitting optimal 2-dimensional

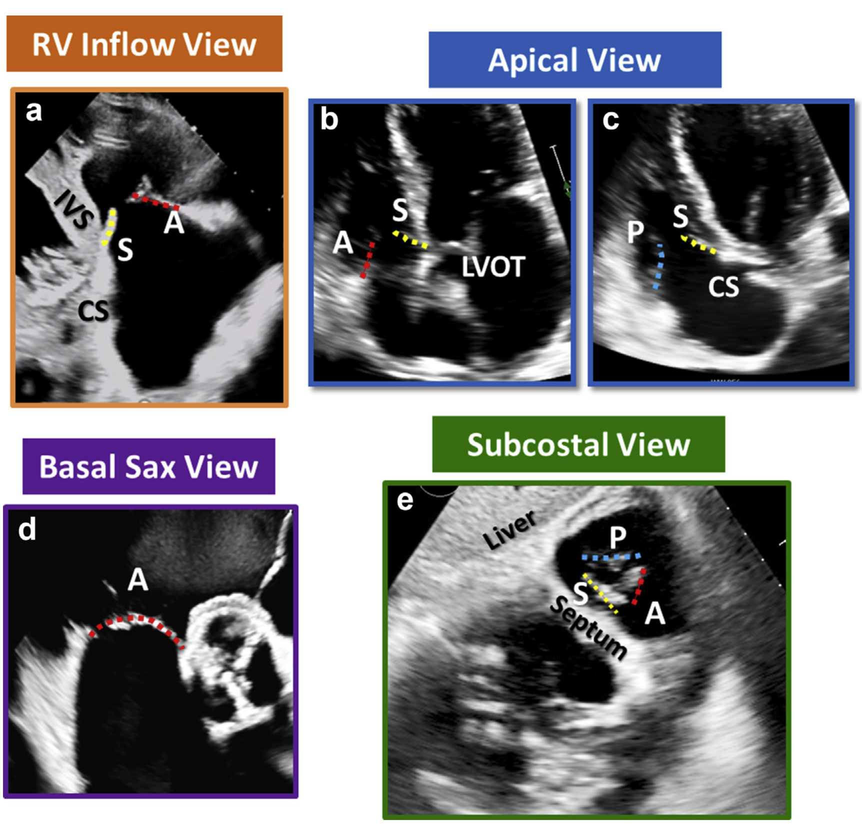

Figure 3. 2D transthoracic targeting image of the tricuspid valve. Using additional views and landmarks is possible to identify the tricuspid leaflets. The leaflets closest to the aorta are the anterior or the septal leaflets (never the posterior), the leaflet closest to the free wall is the posterior or the anterior (never the septal), and finally, the septal leaflet is the closest to the septum. In the RV inflow view, the yellow dots outline the septal leaflet, closest to the coronary sinus and the septum. The red dots mark the anterior leaflet closest to the transducer (a). When the RV apical view intersected the LVOT, the combination anterior (red dots) and septal leaflet (yellow dots) are present (b). However, when the coronary sinus is intersected, the posterior (blue dots) and septal (yellow dots) are seen (c). In the parasternal short axis view, the anterior leaflet is present if only a single leaflet is seen (d). In the subcostal short-axis view, the septal leaflet (yellow dots) is close to the septum, the posterior leaflet (blue dots) is closest to the liver, and lastly, the anterior leaflet is adjacent to the aortic valve (e). Abbreviations: A, anterior; CS, coronary sinus; IVS, interventricular septum; LVOT, left ventricular outflow tract; P, posterior; RV, right ventricle; S, septal.

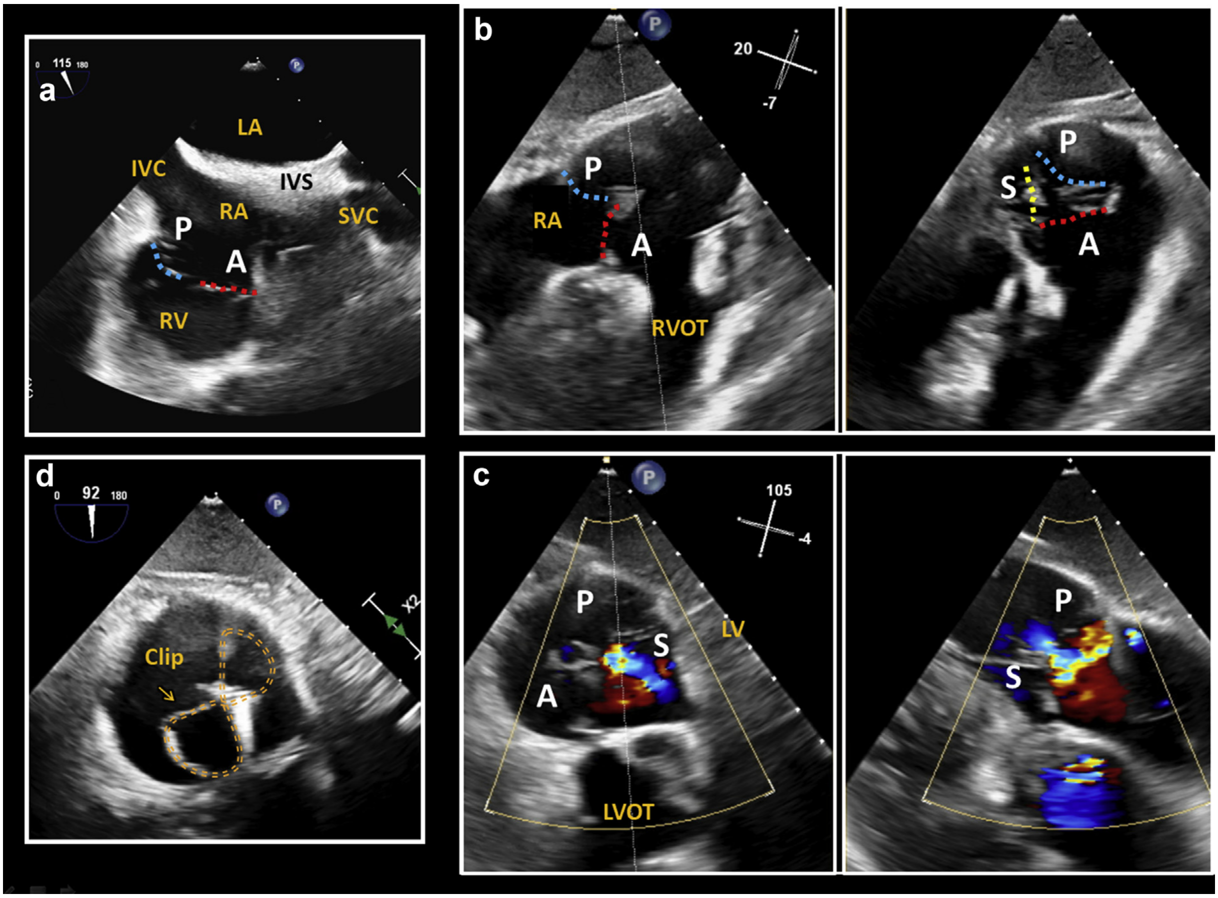

Figure 4. Important TEE views during TV percutaneous interventions: (a) Mid-esophageal bicaval view, wherein the right-side chambers, the posterior and anterior TV leaflets and its landmarks are appreciated. This view is particularly important owing to the optimal 3D acquisition and TR assessment due to ideal beam and coaxial flow alignment and also to guide the catheter through the IVS and toward the TV during intervention; Transgastric biplane image: (b) In the short-axis view, it is possible to visualize all the leaflets simultaneously, (c) to assess the coaptation gap, the regurgitant orifice, and the orientation of the jet. The biplane technique can aid in the appraisal. (d) In the left bottom image, a Clip can be seen grasping the septal and posterior leaflets.
Abbreviations: A, anterior; IVC, inferior vena cava; IVS, interventricular septum; LA, left atrium; LV, left ventricle; LVOT, left ventricular outflow tract; P, posterior; RA, right atrium; RV, right ventricle; RVOT, right ventricle outflow tract; S, septal; SVC, superior vena cava; TR, tricuspid regurgitation; TTE, transthoracic echocardiography; TV, tricuspid valve.

(2D) data, which is integral for the acquisition of high-quality 3D data sets. Because of the proximity of the TV to the transducer in the parasternal views, which allows for greater spatial resolution, the parasternal views are often the initial acquisition window of choice for 3D TV imaging with TTE. Selection of the 3D acquisition strategy depends upon the indication and aims of the imaging study. Real-time single-beat 3DE zoom of the TV is usually performed during interventional procedures. An alternative mode, used for diagnostic and grading purposes, is the full-volume multibeat acquisition with multiplanar reconstruction. The American Society of Echocardiography recommends a standard display of the septal leaflet at the 6 o'clock (inferior) position; however, this can be adjusted by individual operators, particularly during percutaneous TV procedures.[13,15,56]

Doppler Parameters

Color Doppler TR jet area by visual estimation is used more frequently in clinical practice than the flow convergence profile of the regurgitant jet, yet both have important limitations for grading TR severity.[11,57] Analysis of the jet area without simultaneous localization of the jet origin may result in underestimation of TR severity since the color Doppler jet area depends on conservation of momentum, which is usually lower in TR than in MR. Variations in hemodynamics, structural factors, and ultrasound system settings can alter the display of the jet and confound the interpretation of TR severity; abnormalities of the cardiac conduction system, heart rate, cardiac output, fluid viscosity, chamber hindrance, respiration variation, and jet geometry are a few examples. Moreover, machine elements, scanning variations, and technical missteps involving color scale, gain, frame rate, pulse repetition frequency, Doppler angle, wall filter, and artifacts may also significantly impact severity assessment.[11,57–61] Another shortcoming lies in the underestimation of eccentric TR jets and overestimation of central TR jets. Also, the jet-to-RA area ratio metrics have been found to underestimate TR severity owing to variable RA dilation patterns.[57]

In comparison, VC is independent of flow rate and driving pressure and is easy to measure, thus making it useful in determining TR severity regardless of whether the jet direction is central or eccentric (Figure 5). However, drawbacks exist in cases of multiple jets and/or measurement variability confounded by differing imaging planes. The latter can be understood in the context of the often nonplanar, ellipsoidal regurgitant orifice, in which a single 2D-derived VC width often makes nonvalid assumptions regarding the true regurgitant orifice geometry, as recently confirmed by 3D studies.[51,57,62] A 2D VC width greater than 6.5 mm has been validated for the definition of severe TR with a specificity of 93% and sensitivity of 88%.[63] Importantly, a VC equal to or greater than 5.5 mm is still associated with worse clinical outcomes and higher mortality rates.[41] In contrast, 3D planimetry of the VC area is more reliable for evaluating the complex shape of the VC.[35,52] (Figure 6) As might be

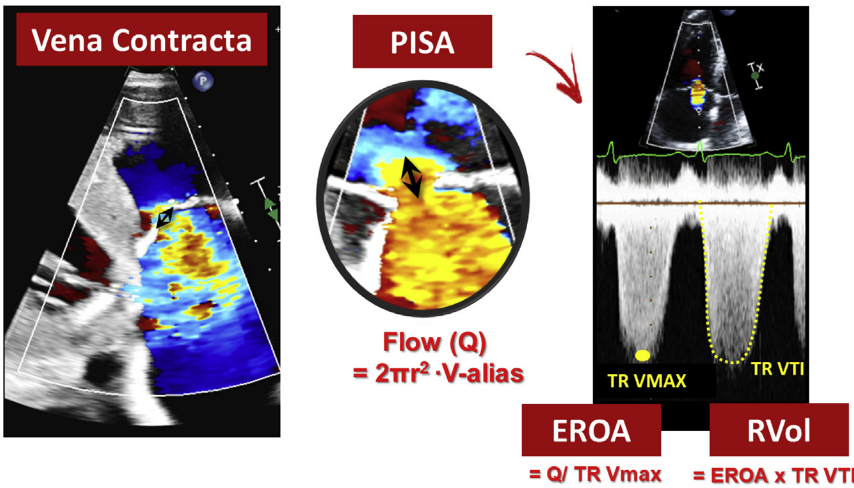

Figure 5. Multiparametric approach using quantitative and semiquantitative methods for grading TR. VC width (right image) is measured in midsystole, using zoom mode, with proper beam-flow orientation and Nyquist limit ranging between 35 and 60 cm/s, on parasternal RV inflow and apical 4-chamber views. The proximal isovelocity surface area [PISA] method calculates the radius of the convergence flow area. The radius must be measured from the top of the shell until the VC, after adjustment of the Nyquist limit baseline between 28 and 40 cm/s, and the PISA will be estimated through the formula presented above. The angle correction can be made by multiplying the Q by alpha/180. From the PISA and the TR regurgitant flow, quantitative techniques such as effective regurgitant orifice area (EROA) and the regurgitant volumes (Rvol) are derived.
Abbreviations: RV, right ventricle; TR, tricuspid regurgitation; VC, vena contracta.

expected, the maximal VC diameter obtained with 3D is often larger than that obtained with 2D.[51] Studies have reported mixed 3D VC area (VCA) thresholds for severe TR, ranging from 57 mm^2 [45,51,64] up to 75 mm^2.[10,52] Interestingly, in patients with secondary TR, the ratio between VC/TA has been specifically proposed to improve risk stratification. The underlying concept of this approach is to correct TR severity for right heart dimensions, similarly to the EROA/left ventricle end-diastolic volume ratio which has been studied in MR. In the study, the VC/TA ratio equal to or greater than 0.24 was independently associated with worse prognosis.[50]

Studies describing the diagnostic value of the flow convergence method (proximal isovelocity surface area [PISA]) and its associated quantitative measures such as the EROA and regurgitant volume (Rvol) also have relevant limitations (Figure 5). The guidelines suggest that an EROA >40 mm^2 or an RVol of >45 mL/beat indicates the presence of severe TR, while acknowledging that justification for these partition threshold values remains unclear. Partition values have been derived either in a similar fashion to mitral valve EROA or cross-validated in limited context with few studies validating the prognostic implications of these thresholds.[11,12] It is well known that 2D PISA has limitations which may result in EROA underestimation, particularly in cases of eccentric TR jets.[7,62,64] This was illustrated by Bartko et al.[41] in which the EROA and RVol thresholds associated with mortality in patients with heart failure with reduced ejection fraction were lower than those defined for clinical use, with cutoffs of ≥20 cm^2 and ≥20 mL/beat, respectively. Cases such as these underscore the need for an integrated approach in grading TR by including semiquantitative and quantitative parameters.[6,11,41] Advances in 3D quantification methods have been widely reported including 3D VCA, 3D PISA, regurgitant fraction (with 3D PISA and 3D RV stroke volume), and 3D EROA; however, all of these still warrant prospective validation to demonstrate incremental diagnostic value.[43,65]

While not entirely sensitive, hepatic venous systolic flow reversal is considered a surrogate finding specific for severe TR (Figure 7a). However, it must be interpreted in context, as hepatic vein flow is also influenced by RA compliance, RV function, and systemic venous pressures. Furthermore, hepatic vein flow may not be reliable in conditions such as atrial fibrillation or in the presence of pacemakers. In cases of severe TR, the jet envelope obtained using continuous wave (CW) Doppler is dense, with a triangular shape and low, early-peaking velocity owing to the rapid equilibration between the RA and RV pressures (Figure 7b). One of the limitations of CW in TR evaluation is that for central jets, CW may appear denser than for eccentric jets, which may confound the interpretation of qualitative TR grading.[11,12,57]

Tricuspid Annulus

TA dilatation is a reliable indicator of underlying TV pathology,[35,66,67] as evidenced by studies showing a good correlation between the TA diameter and TR regurgitant volumes. The current guidelines define significant TA dilatation when the end-diastolic diameter (measured in the apical 4-chamber view in the frame prior to TV closure) is ≥40 mm or ≥21 mm/m^2.[28] The dynamic variability

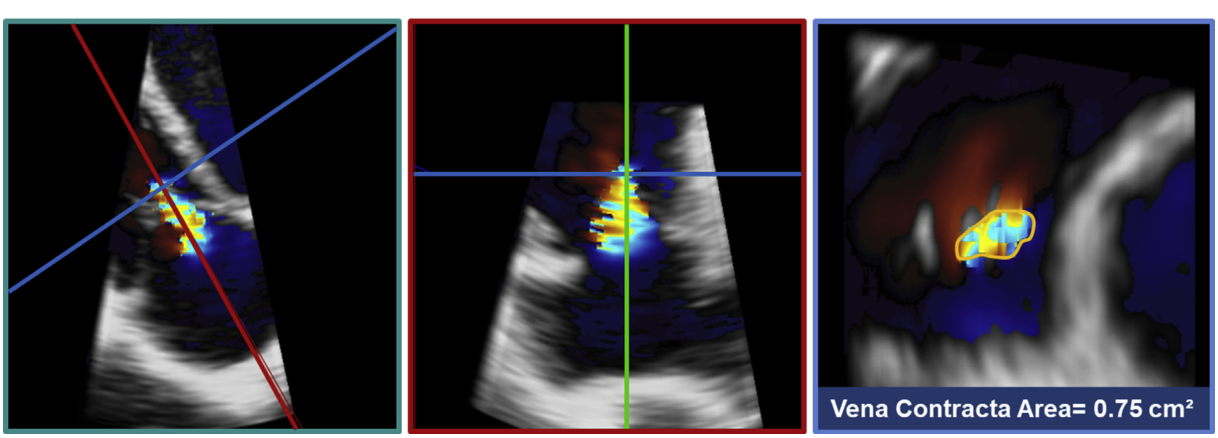

Figure 6. Multiplane imaging of the TR. The 3D color Doppler image aligns the green and red planes to image the vena contracta area in the blue plane.
Abbreviations: 3D, 3-dimensional; TR, tricuspid regurgitation.

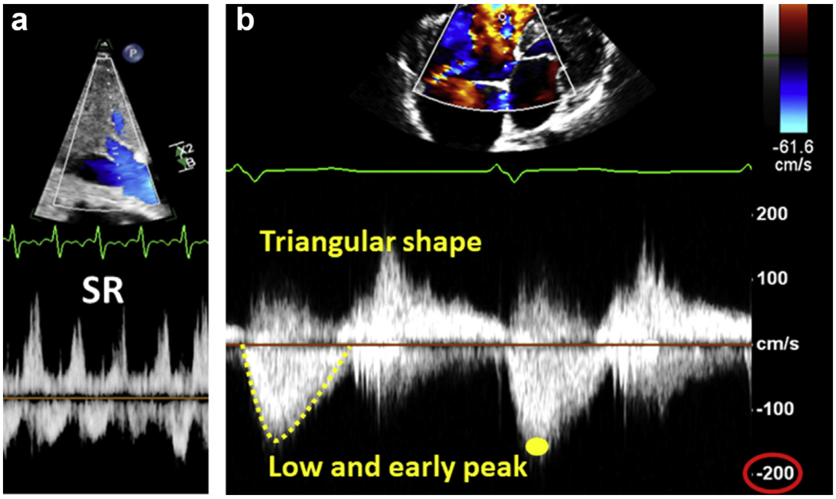

Figure 7. Supportive signs of severe TR. Systolic flow reversal in the hepatic veins detected by pulsed wave (PW) spectral Doppler from a subcostal view (a); Dense and triangular continuous wave (CW) spectral shape of TR jet with low (<2.5 m/s) and early peaking of the velocity representing the imminent equalization of the right ventricle and atrial pressure (b). Abbreviation: TR, tricuspid regurgitation.

of annular size and shape throughout various phases of the cardiac cycle and/or related to underlying loading conditions compounds challenges in aligning the probe with the major axis of the TA for the purpose of 2D measurements. These issues may partly explain why 2D echocardiography tends to underestimate TA dimensions, when compared to TA values derived from 3D and cardiovascular magnetic resonance techniques[24,68,69] (Figure 8). 3D outperforms 2D analysis with a comprehensive and reproducible evaluation of TA size, geometry, and function.[35,38,70] The benefit of employing routine 3D assessment in TA morphology has been shown in the postoperative setting, with the ability to predict adverse surgical outcomes.[7,42,66,71] However, dedicated software and studies based on the outcome are needed to define TA dilatation thresholds for surgical intervention recommendations.

TV leaflet coaptation is also an important factor in TR and thus should be routinely assessed. Tethering distance greater than 8 mm and tenting area greater than 1.6 cm^2 are indicative of severe TR.[24,38,40] Tenting volume obtained with 3D analysis was identified as a predictor of residual TR after annuloplasty.[72] Recently, the ratio of leaflet area-to-closure area lower than 1.78, in which the closure-to-area represents the annular area and tenting, was also reported to be predictive of severe TR.[44]

Right-Sided Chambers

Currently, attention has been drawn to the relationship between TR and RV chamber remodeling and the need to stratify RV dysfunction severity.[73,74] Accordingly, a comprehensive approach to the assessment

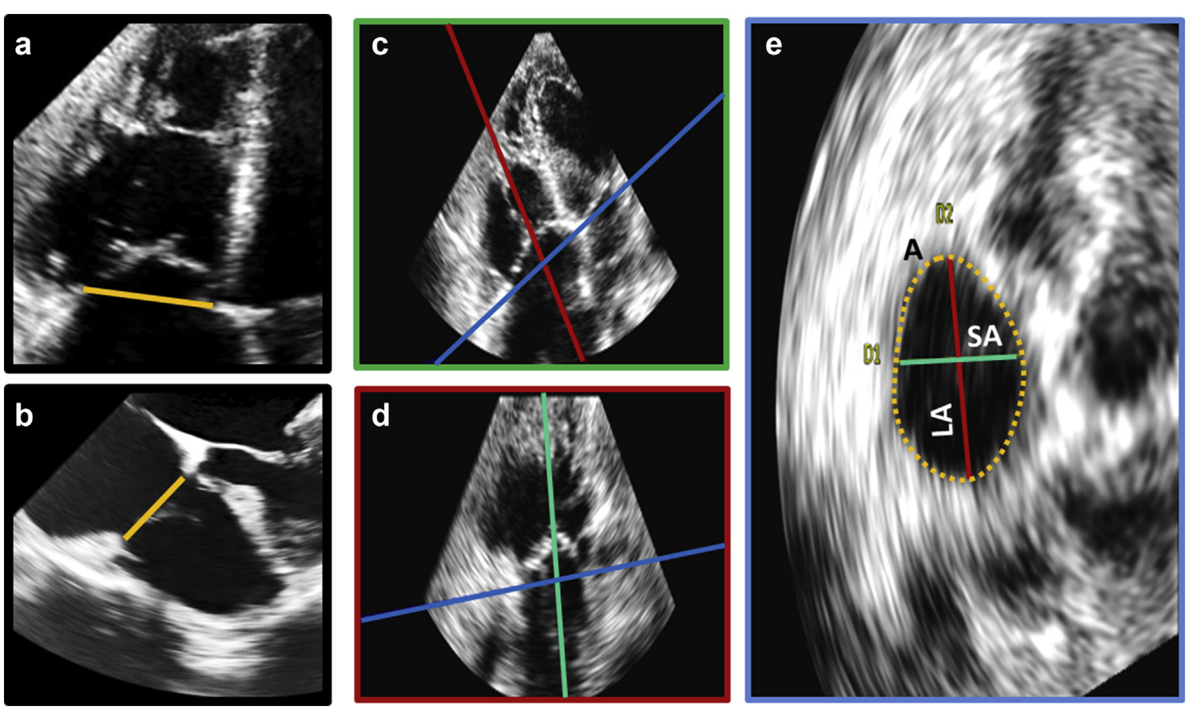

Figure 8. Measurements of the tricuspid annulus using different echocardiogram modalities. Two-dimensional measurements of the tricuspid annulus from transthoracic RV inflow view (a) and from the transesophageal midesophageal 4-chamber view (b) in which the annulus was measured from the hinge point to the hinge point at end-diastole (yellow lines). 3D full volume of RV-focused view derived from transthoracic echocardiogram was sliced and oriented (c and d) to obtain a planimetry of the tricuspid annulus. The yellow dotted line outlines the TA area (e), the red line represents the long-axis diameter (LA), and the green line represents the short-axis diameter (SA) measurement.
Abbreviations: RV, right ventricle; TA, tricuspid annulus.

of the RV is recommended including evaluation of dimensions, functional parameters, and pulmonary artery systolic pressure. This is due to the following: (1) changes in RV shape/geometry, which may independently determine functional TR severity[75], (2) understanding that the presence of RV dilatation and dysfunction is associated with worse outcomes in patients with TR[76], and (3) awareness that knowledge of RV and TA dimensions is important for surgical recommendations. Indeed, the presence of RV dysfunction associated with severe TR negatively impacts eligibility for surgery and attendant prognosis[28,77] owing to an increased risk of acute heart failure in early postoperative TV interventions.[73]

Measurement of RV basal and mid diameters and apical-to-basal lengths is useful to evaluate RV enlargement and assist in identifying the RV remodeling pattern associated with the underlying TR mechanism (Figure 9).

Frequently, individual 2D parameters are used to assess RV performance such as tricuspid annular plane systolic excursion (TAPSE), S′ wave, and fractional area change. These parameters have important limitations and must be interpreted with caution.[78–80] In the case of TAPSE, for example, it is known that this parameter is angle dependent, presumes that regional free wall motion reflects global function, and may be falsely elevated in the setting of severe TR.[73] In contrast, RV longitudinal strain (RV LS) measured with speckle tracking does not assume the RV to have a particular geometric shape, nor does it extrapolate global longitudinal function from a focal region of the RV. RV LS has a high sensitivity to detect RV dysfunction, with incremental value beyond TAPSE and fractional area change shown in the prognosis of patients with severe TR (Figure 9). More specifically, an RV free wall LS threshold of −23% was associated with death in patients with severe TR.[76] Interestingly, assessment of the RV–pulmonary artery coupling with echocardiography has been tested in patients with secondary TR and PH using the TAPSE/-pulmonary artery systolic pressure ratio in which mortality has been shown to be associated with a ratio lower than 31 mm/mmHg.[81] Lastly, assessment of the RV using 3D is preferable because it is independent of geometric assumptions and capable of quantifying RV volumes, ejection fraction, and stroke volume[79] (Figure 10). This methodology has good agreement with cardiovascular magnetic resonance, the current gold standard to evaluate RV size and function.[78,82–84]

Evaluation of RA volumes using Simpson's method is preferred for 2D chamber assessment. While not routinely used in clinical practice, the phasic function of the right atria can also be measured using longitudinal RA strain (Figure 9). 3D methods for RA quantification can accurately estimate RA volumes as well as function. Normative values of the RA were recently published that will aid in the standardization of RA reference values.[85] Independent of the method of choice, quantification of RA dimension and function must be assessed in cases of TR because the integration of RA dimensions and function is paramount for accurate assessment of TR severity.

Evaluation of TR Severity

An integrated approach is the current consensus for TR classification, with the incorporation of structural, qualitative, semiquantitative, and quantitative parameters. According to current guidelines, VC >0.7 mm^2, PISA >0.9 cm^2, EROA >40 mm^2, and RVol of >45 mL/beat are values diagnostic of severe TR, though caveats exist as outlined above.[11,12] Doppler metrics of severe TR accompanied by right ventricular enlargement and/or dysfunction, dilated TA and/or vena cava, tricuspid leaflet tenting, and hepatic venous systolic flow reversal are helpful in establishing the diagnosis of significant TR.

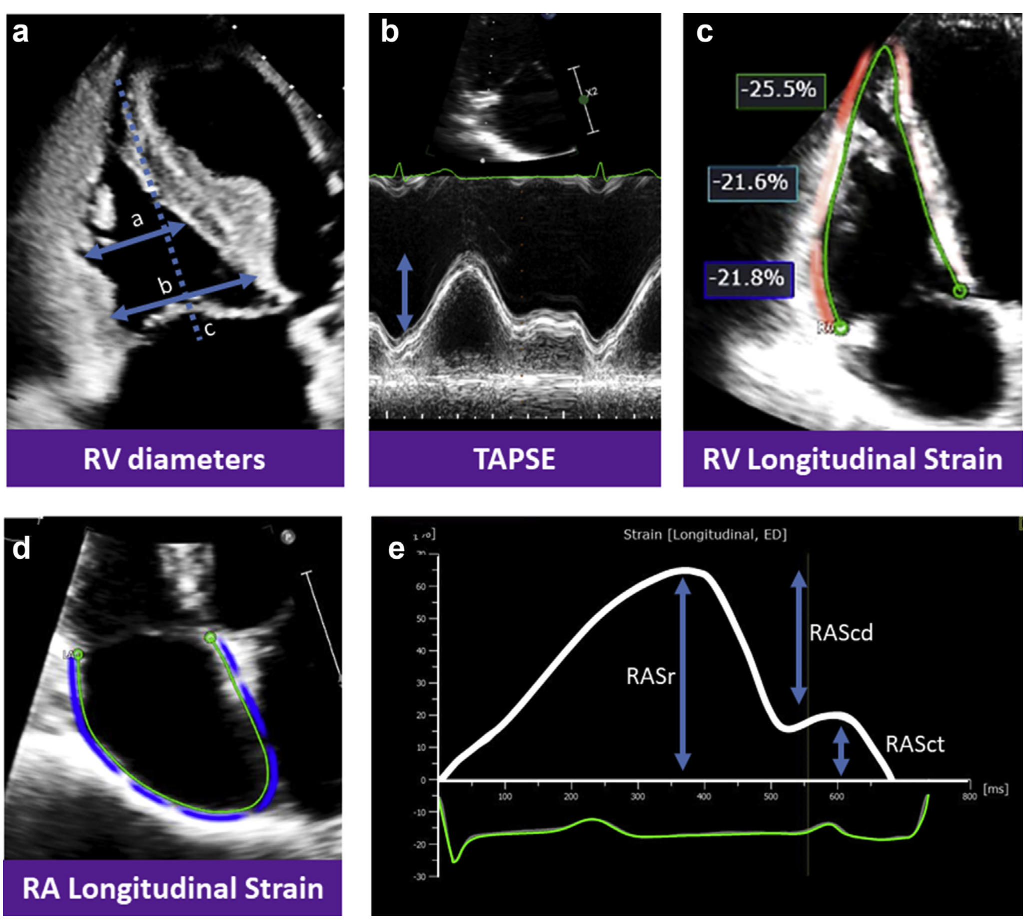

Figure 9. Right ventricular diameter and function metrics attained from the RV apical-focused view: (a) RV basal diameter (a), RV mid diameter (b), and RV length (c); (b) TAPSE; (**c**) RV free wall and global longitudinal strain. (d) Right atrial phasic function obtained through 2D speckle tracking; (e) When the QRS is used as the timing reference point, the phasic curve starts with the peak positive longitudinal atrial strain corresponding to the reservoir function (RASr_ED), followed by the early diastolic strain waves representing the conduit phase (RAScd_ED) and finally the late diastolic strain wave expressing the booster pump.
Abbreviations: 2D, 2-dimensional; RV, right ventricle; TAPSE, tricuspid annular plane systolic excursion.

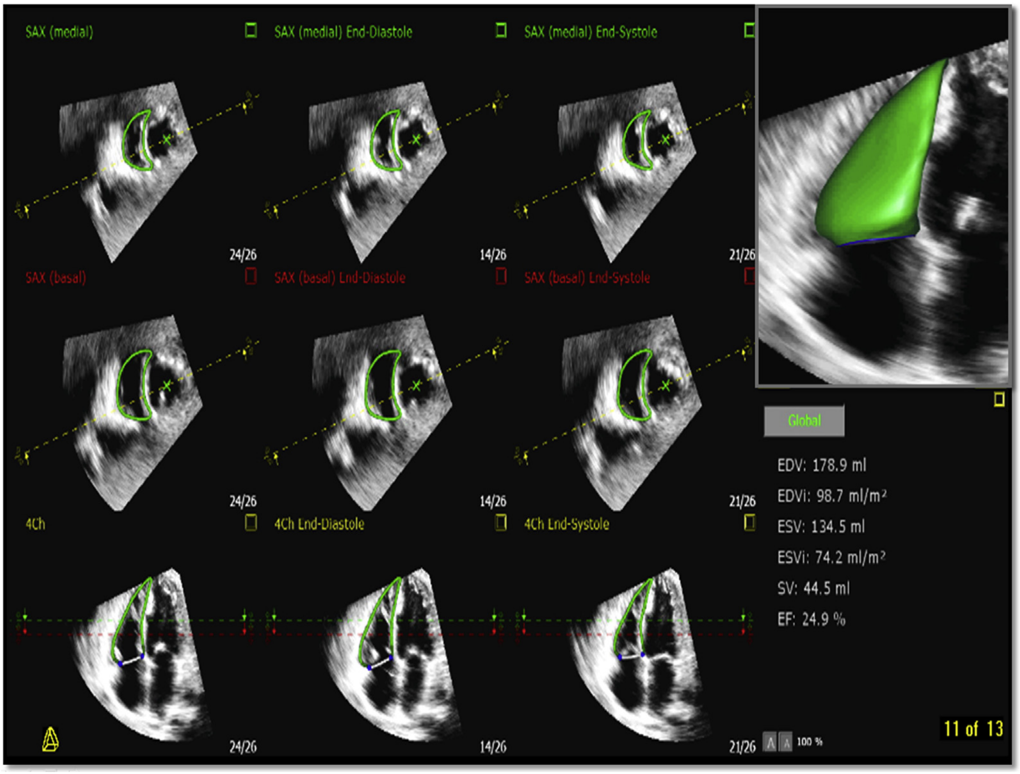

Figure 10. Right ventricle 3D analysis using dedicated software. After the TTE full-volume acquisition, the right ventricle planes were aligned and the TV annulus was marked, followed by the trace of the endocardial border on the short and long axis to obtain end-diastolic and end-systolic planes. The software estimates volume and function metrics. (RASct_ED).
Abbreviations: 3D, 3-dimensional; TTE, transthoracic echocardiography; TV, tricuspid valve.

The Need for a New Grading Scheme

Recent studies have demonstrated clinical TR cutoff values lower than those proposed by the guidelines and different prognoses for patients in the same umbrella of severity.[6,7,10,64] Additionally, there is a lack of data with regard to the need to weight each TR severity parameter in a differential fashion. An example of this has been demonstrated in the findings of increased mortality in TR patients with larger EROA and RVol but not VC.[41] Inherent limitations of 2D techniques as already discussed can serve to further confound this assessment.

By the time a patient becomes symptomatic with heart failure, the degree of TR severity may already exceed the guidelines' threshold of TR severity.[8,10] The relatively late presentation of patients with functional TR also underscores the clinical need for a more nuanced grading scheme to better capture TR severity. Beyond the benefit of earlier detection, this change could facilitate improvements in patient outcomes in light of advances in TR procedures[7–9] and their positive impact on prognosis and survival, particularly when patients are treated earlier in the course of their disease.[86–88]

Some investigators have suggested incorporating 2 additional TR grades to capture cases which extend beyond severe: "super severe"[89] or "massive and torrential".[10] In order to add cutoff values of TR, authors have proposed partition differences between "massive" and "torrential": 2D PISA-EROA $\geq$60 cm^2 and $\geq$80 cm^2, 2D VC >1.4 cm^2 and $\geq$2.1 cm^2, PISA-RVol $\geq$60 mL/beat and $\geq$75 mL/beat, and 3D VCA $\geq$95 cm^2 and $\geq$1.15 cm^2 (Table 2). Additionally, Dreyfus et al.[24] proposed that the classification of TR should incorporate morphologic information on TA diameter and leaflet coaptation (leaflet tethering). This staging system was specifically relevant for cases of functional TR and was applied toward refining the eligibility and patient selection for interventional TV procedures.

These expansions in categorization may permit the evaluation of novel therapeutic strategies and their efficacy and aid in tracking the evolution of TR after percutaneous and surgical treatment.[7,8,10,90,91] Potential applications for this novel scheme are illustrated by cases in which there is a numerical and significant reduction of EROA after TV repair, but by conventional grading classification, TR severity remains apparently unchanged from 'severe TR' to 'severe TR'; such situations fail to take into account the degree of TR improvement.[8,10,92] The thresholds for these grades are corroborated by limited trials, with small and highly selected group of patients undergoing percutaneous TV treatment. In other words, the grading scheme may need to be refined to be readily adapted into clinical practice.

Conclusion

The distinctive composition of the TV components and the right heart necessitate a unique set of criteria to better understand and express severity of TR. A comprehensive and systematic approach in the evaluation of TR mechanisms, including information on TA dimension, presence of leaflet malcoaptation or tenting, and RV chamber size, is recommended in addition to and beyond the already established practice of a multiparametric approach. Implementation of routine 3D assessment of the TV, along with an evolving understanding of TR assessment, will play a pivotal role in guiding the patient selection and imaging guidance of TV interventions.

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References

1 Topilsky Y, Maltais S, Medina Inojosa J, et al. Burden of tricuspid regurgitation in patients diagnosed in the community setting. *JACC Cardiovasc Imaging.* 2019;12:433-442.
2 Nath J, Foster E, Heidenreich PA. Impact of tricuspid regurgitation on long-term survival. *J Am Coll Cardiol.* 2004;43:405-409.

3 Wang N, Fulcher J, Abeysuriya N, et al. Tricuspid regurgitation is associated with increased mortality independent of pulmonary pressures and right heart failure: a systematic review and meta-analysis. *Eur Heart J*. 2019;40:476-484.
4 Guta AC, Badano LP, Tomaselli M, et al. The pathophysiological link between right atrial remodeling and functional tricuspid regurgitation in patients with atrial fibrillation: a three-dimensional echocardiography study. *J Am Soc Echocardiogr*. 2021;34:585-594.e1.
5 Topilsky Y, Nkomo VT, Vatury O, et al. Clinical outcome of isolated tricuspid regurgitation. *JACC Cardiovasc Imaging*. 2014;7:1185-1194.
6 Muraru D, Previtero M, Ochoa-Jimenez RC, et al. Prognostic validation of partition values for quantitative parameters to grade functional tricuspid regurgitation severity by conventional echocardiography. *Eur Heart J Cardiovasc Imaging*. 2021; 22:155-165.
7 Hahn RT, Meduri CU, Davidson CJ, et al. Early feasibility study of a transcatheter tricuspid valve annuloplasty: scout trial 30-day results. *J Am Coll Cardiol*. 2017;69: 1795-1806.
8 Miura M, Alessandrini H, Alkhodair A, et al. Impact of massive or torrential tricuspid regurgitation in patients undergoing transcatheter tricuspid valve intervention. *JACC Cardiovasc Interv*. 2020;13:1999-2009.
9 Taramasso M, Alessandrini H, Latib A, et al. Outcomes after current transcatheter tricuspid valve intervention: mid-term results from the International Trivalve Registry. *JACC Cardiovasc Interv*. 2019;12:155-165.
10 Hahn RT, Zamorano JL. The need for a new tricuspid regurgitation grading scheme. *Eur Heart J Cardiovasc Imaging*. 2017;18:1342-1343.
11 Zoghbi WA, Adams D, Bonow RO, et al. Recommendations for noninvasive evaluation of native valvular regurgitation: a report from the American Society of Echocardiography developed in collaboration with the Society for Cardiovascular Magnetic Resonance. *J Am Soc Echocardiogr*. 2017;30:303-371.
12 Lancellotti P, Tribouilloy C, Hagendorff A, et al. Recommendations for the echocardiographic assessment of native valvular regurgitation: an executive summary from the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging*. 2013;14:611-644.
13 Hahn R, Saric M, Faletra FF, et al. Recommended standards for the performance of transesophageal echocardiographic screening for structural heart intervention: from the American Society of Echocardiography. *J Am Soc Echocardiogr*. 2022;35:1-76.
14 Khalique OK, Cavalcante JL, Shah D, et al. Multimodality imaging of the tricuspid valve and right heart anatomy. *JACC Cardiovasc Imaging*. 2019;12:516-531.
15 Peters AC, Gong FF, Rigolin VH. Three-dimensional echocardiography for the assessment of the tricuspid valve. *Echocardiography*. 2020;37:758-768.
16 Dahou A, Levin D, Reisman M, Hahn RT. Anatomy and physiology of the tricuspid valve. *JACC Cardiovasc Imaging*. 2019;12:458-468.
17 Sakon Y, Murakami T, Fujii H, et al. New insight into tricuspid valve anatomy from 100 hearts to reappraise annuloplasty methodology. *Gen Thorac Cardiovasc Surg*. 2019;67:758-764.
18 Kawada N, Naganuma H, Muramatsu K, Ishibashi-Ueda H, Bando K, Hashimoto K. Redefinition of tricuspid valve structures for successful ring annuloplasty. *J Thorac Cardiovasc Surg*. 2018;155:1511-1519.e1.
19 Athavale S, Deopujari R, Sinha U, Lalwani R, Kotgirwar S. Is tricuspid valve really tricuspid? *Anat Cell Biol*. 2017;50:1-6.
20 Tretter JT, Sarwark AE, Anderson RH, Spicer DE. Assessment of the anatomical variation to be found in the normal tricuspid valve. *Clin Anat*. 2016;29:399-407.
21 Lama P, Tamang BK, Kulkarni J. Morphometry and aberrant morphology of the adult human tricuspid valve leaflets. *Anat Sci Int*. 2016;91:143-150.
22 Muresian H. The clinical anatomy of the right ventricle. *Clin Anat*. 2016;29:380-398.
23 Hahn RT, Waxman AB, Denti P, Delhaas T. Anatomic relationship of the complex tricuspid valve, right ventricle, and pulmonary vasculature: a review. *JAMA Cardiol*. 2019;4:478-487.
24 Dreyfus GD, Martin RP, Chan KM, Dulguerov F, Alexandrescu C. Functional tricuspid regurgitation: a need to revise our understanding. *J Am Coll Cardiol*. 2015;65:2331-2336.
25 Spinner EM, Shannon P, Buice D, et al. In vitro characterization of the mechanisms responsible for functional tricuspid regurgitation. *Circulation*. 2011;124:920-929.
26 Vieitez JM, Monteagudo JM, Mahia P, et al. New insights of tricuspid regurgitation: a large-scale prospective cohort study. *Eur Heart J Cardiovasc Imaging*. 2021;22:196-202.
27 Utsunomiya H, Itabashi Y, Mihara H, et al. Functional tricuspid regurgitation caused by chronic atrial fibrillation: a real-time 3-dimensional transesophageal echocardiography study. *Circ Cardiovasc Imaging*. 2017;10:e004897.
28 Otto CM, Nishimura RA, Bonow RO, et al. 2020 ACC/AHA guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. *Circulation*. 2021;143:e35-e71.
29 Muraru D, Parati G, Badano LP. The tale of functional tricuspid regurgitation: when atrial fibrillation is the villain. *Eur Heart J Cardiovasc Imaging*. 2020;21:1079-1081.
30 Prihadi EA, Delgado V, Leon MB, Enriquez-Sarano M, Topilsky Y, Bax JJ. Morphologic types of tricuspid regurgitation: characteristics and prognostic implications. *JACC Cardiovasc Imaging*. 2019;12:491-499.
31 Addetia K, Harb SC, Hahn RT, Kapadia S, Lang RM. Cardiac implantable electronic device lead-induced tricuspid regurgitation. *JACC Cardiovasc Imaging*. 2019;12:622-636.
32 Mediratta A, Addetia K, Yamat M, et al. 3d echocardiographic location of implantable device leads and mechanism of associated tricuspid regurgitation. *JACC Cardiovasc Imaging*. 2014;7:337-347.
33 Nappi F, Spadaccio C, Mihos C, Shaikhrezai K, Acar C, Moon MR. The quest for the optimal surgical management of tricuspid valve endocarditis in the current era: a narrative review. *Ann Transl Med*. 2020;8:1628.
34 Fuchs MM, Connolly HM. Ebstein anomaly in the adult patient. *Cardiol Clin*. 2020;38: 353-363.
35 Badano LP, Agricola E, Perez de Isla L, Gianfagna P, Zamorano JL. Evaluation of the tricuspid valve morphology and function by transthoracic real-time three-dimensional echocardiography. *Eur J Echocardiogr*. 2009;10:477-484.
36 Karagodin I, Yamat M, Addetia K, Lang RM. Visualization of number of tricuspid valve leaflets using three-dimensional transthoracic echocardiography. *J Am Soc Echocardiogr*. 2021;34:449-450.
37 Topilsky Y, Khanna A, Le Tourneau T, et al. Clinical context and mechanism of functional tricuspid regurgitation in patients with and without pulmonary hypertension. *Circ Cardiovasc Imaging*. 2012;5:314-323.
38 Badano LP, Hahn R, Rodriguez-Zanella H, Araiza Garaygordobil D, Ochoa-Jimenez RC, Muraru D. Morphological assessment of the tricuspid apparatus and grading regurgitation severity in patients with functional tricuspid regurgitation: thinking outside the box. *JACC Cardiovasc Imaging*. 2019;12:652-664.
39 Dreyfus GD, Chan KM. Functional tricuspid regurgitation: a more complex entity than it appears. *Heart*. 2009;95:868-869.
40 Fukuda S, Gillinov AM, McCarthy PM, et al. Determinants of recurrent or residual functional tricuspid regurgitation after tricuspid annuloplasty. *Circulation*. 2006;114: I582-I587.
41 Bartko PE, Arfsten H, Frey MK, et al. Natural history of functional tricuspid regurgitation: implications of quantitative Doppler assessment. *JACC Cardiovasc Imaging*. 2019;12:389-397.
42 Sukmawan R, Watanabe N, Ogasawara Y, et al. Geometric changes of tricuspid valve tenting in tricuspid regurgitation secondary to pulmonary hypertension quantified by novel system with transthoracic real-time 3-dimensional echocardiography. *J Am Soc Echocardiogr*. 2007;20:470-476.
43 Hahn RT. State-of-the-art review of echocardiographic imaging in the evaluation and treatment of functional tricuspid regurgitation. *Circ Cardiovasc Imaging*. 2016;9: e005332.
44 Afilalo J, Grapsa J, Nihoyannopoulos P, et al. Leaflet area as a determinant of tricuspid regurgitation severity in patients with pulmonary hypertension. *Circ Cardiovasc Imaging*. 2015;8:e002714.
45 Utsunomiya H, Harada Y, Susawa H, et al. Comprehensive evaluation of tricuspid regurgitation location and severity using vena contracta analysis: a color Doppler three-dimensional transesophageal echocardiographic study. *J Am Soc Echocardiogr*. 2019;32:1526-1527.e2.
46 Sagie A, Schwammenthal E, Padial LR, Vazquez de Prada JA, Weyman AE, Levine RA. Determinants of functional tricuspid regurgitation in incomplete tricuspid valve closure: Doppler color flow study of 109 patients. *J Am Coll Cardiol*. 1994;24:446-453.
47 Volpato V, Mor-Avi V, Veronesi F, et al. Three-dimensional echocardiography investigation of the mechanisms of tricuspid annular dilatation. *Int J Cardiovasc Imaging*. 2020;36:33-43.
48 Muraru D, Addetia K, Guta AC, et al. Right atrial volume is a major determinant of tricuspid annulus area in functional tricuspid regurgitation: a three-dimensional echocardiographic study. *Eur Heart J Cardiovasc Imaging*. 2021;22:660-669.
49 Muraru D, Caravita S, Guta AC, et al. Functional tricuspid regurgitation and atrial fibrillation: which comes first, the chicken or the egg? *CASE (Phila)*. 2020;4:458-463.
50 Fortuni F, Dietz MF, Prihadi EA, et al. Ratio between vena contracta width and tricuspid annular diameter: prognostic value in secondary tricuspid regurgitation. *J Am Soc Echocardiogr*. 2021;34:944-954.
51 Song JM, Jang MK, Choi YS, et al. The vena contracta in functional tricuspid regurgitation: a real-time three-dimensional color Doppler echocardiography study. *J Am Soc Echocardiogr*. 2011;24:663-670.
52 Velayudhan DE, Brown TM, Nanda NC, et al. Quantification of tricuspid regurgitation by live three-dimensional transthoracic echocardiographic measurements of vena contracta area. *Echocardiography*. 2006;23:793-800.
53 Tribouilloy CM, Enriquez-Sarano M, Capps MA, Bailey KR, Tajik AJ. Contrasting effect of similar effective regurgitant orifice area in mitral and tricuspid regurgitation: a quantitative Doppler echocardiographic study. *J Am Soc Echocardiogr*. 2002;15:958-965.
54 Addetia K, Yamat M, Mediratta A, et al. Comprehensive two-dimensional interrogation of the tricuspid valve using knowledge derived from three-dimensional echocardiography. *J Am Soc Echocardiogr*. 2016;29:74-82.
55 Muraru D, Hahn RT, Soliman OI, Faletra FF, Basso C, Badano LP. 3-Dimensional echocardiography in imaging the tricuspid valve. *JACC Cardiovasc Imaging*. 2019;12: 500-515.
56 Lang RM, Badano LP, Tsang W, et al. EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. *J Am Soc Echocardiogr*. 2012;25:3-46.
57 Hahn RT, Thomas JD, Khalique OK, Cavalcante JL, Praz F, Zoghbi WA. Imaging assessment of tricuspid regurgitation severity. *JACC Cardiovasc Imaging*. 2019;12:469-490.
58 Ebrahimi R, Gardin JM. Pitfalls in the color Doppler diagnosis of valvular regurgitation. *Echocardiography*. 1993;10:193-202.
59 Mutlak D, Carasso S, Lessick J, Aronson D, Reisner SA, Agmon Y. Excessive respiratory variation in tricuspid regurgitation systolic velocities in patients with severe tricuspid regurgitation. *Eur Heart J Cardiovasc Imaging*. 2013;14:957-962.
60 Papadopoulos CH, Oikonomidis D, Lazaris E, Nihoyannopoulos P. Echocardiography and cardiac arrhythmias. *Hellenic J Cardiol*. 2018;59:140-149.
61 Cape EG, Yoganathan AP, Levine RA. Increased heart rate can cause underestimation of regurgitant jet size by Doppler color flow mapping. *J Am Coll Cardiol*. 1993;21: 1029-1037.
62 Chen TE, Kwon SH, Enriquez-Sarano M, Wong BF, Mankad SV. Three-dimensional color Doppler echocardiographic quantification of tricuspid regurgitation orifice area:

comparison with conventional two-dimensional measures. *J Am Soc Echocardiogr*. 2013;26:1143-1152.
63 Tribouilloy CM, Enriquez-Sarano M, Bailey KR, Tajik AJ, Seward JB. Quantification of tricuspid regurgitation by measuring the width of the vena contracta with Doppler color flow imaging: a clinical study. *J Am Coll Cardiol*. 2000;36:472-478.
64 Dahou A, Ong G, Hamid N, Avenatti E, Yao J, Hahn RT. Quantifying tricuspid regurgitation severity: a comparison of proximal isovelocity surface area and novel quantitative Doppler methods. *JACC Cardiovasc Imaging*. 2019;12:560-562.
65 de Agustin JA, Viliani D, Vieira C, et al. Proximal isovelocity surface area by single-beat three-dimensional color Doppler echocardiography applied for tricuspid regurgitation quantification. *J Am Soc Echocardiogr*. 2013;26:1063-1072.
66 Dreyfus GD, Corbi PJ, Chan KM, Bahrami T. Secondary tricuspid regurgitation or dilatation: which should be the criteria for surgical repair? *Ann Thorac Surg*. 2005;79:127-132.
67 Nemoto N, Lesser JR, Pedersen WR, et al. Pathogenic structural heart changes in early tricuspid regurgitation. *J Thorac Cardiovasc Surg*. 2015;150:323-330.
68 Dreyfus J, Durand-Viel G, Raffoul R, et al. Comparison of 2-dimensional, 3-dimensional, and surgical measurements of the tricuspid annulus size: clinical implications. *Circ Cardiovasc Imaging*. 2015;8:e003241.
69 Addetia K, Muraru D, Veronesi F, et al. 3-dimensional echocardiographic analysis of the tricuspid annulus provides new insights into tricuspid valve geometry and dynamics. *JACC Cardiovasc Imaging*. 2019;12:401-412.
70 Huttin O, Voilliot D, Mandry D, Venner C, Juilliere Y, Selton-Suty C. All you need to know about the tricuspid valve: tricuspid valve imaging and tricuspid regurgitation analysis. *Arch Cardiovasc Dis*. 2016;109:67-80.
71 Matsunaga A, Duran CM. Progression of tricuspid regurgitation after repaired functional ischemic mitral regurgitation. *Circulation*. 2005;112:I453-I457.
72 Min SY, Song JM, Kim JH, et al. Geometric changes after tricuspid annuloplasty and predictors of residual tricuspid regurgitation: a real-time three-dimensional echocardiography study. *Eur Heart J*. 2010;31:2871-2880.
73 Preda A, Melillo F, Liberale L, Montecucco F, Agricola E. Right ventricle dysfunction assessment for transcatheter tricuspid valve repair: a matter of debate. *Eur J Clin Invest*. 2021;51:e13653.
74 Schlotter F, Miura M, Kresoja KP, et al. Outcomes of transcatheter tricuspid valve intervention by right ventricular function: a multicentre propensity-matched analysis. *EuroIntervention*. 2021;17:e343-e352.
75 Kim HK, Kim YJ, Park JS, et al. Determinants of the severity of functional tricuspid regurgitation. *Am J Cardiol*. 2006;98:236-242.
76 Prihadi EA, van der Bijl P, Dietz M, et al. Prognostic implications of right ventricular free wall longitudinal strain in patients with significant functional tricuspid regurgitation. *Circ Cardiovasc Imaging*. 2019;12:e008666.
77 Baumgartner H, Falk V, Bax JJ, et al. 2017 ESC/EACTS guidelines for the management of valvular heart disease. *Eur Heart J*. 2017;38:2739-2791.
78 Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *J Am Soc Echocardiogr*. 2015;28:1-39.e14.
79 Addetia K, Muraru D, Badano LP, Lang RM. New directions in right ventricular assessment using 3-dimensional echocardiography. *JAMA Cardiol*. 2019;4:936-944.
80 DiLorenzo MP, Bhatt SM, Mercer-Rosa L. How best to assess right ventricular function by echocardiography. *Cardiol Young*. 2015;25:1473-1481.
81 Fortuni F, Butcher SC, Dietz MF, et al. Right ventricular-pulmonary arterial coupling in secondary tricuspid regurgitation. *Am J Cardiol*. 2021;148:138-145.
82 van der Zwaan HB, Geleijnse ML, McGhie JS, et al. Right ventricular quantification in clinical practice: two-dimensional vs. three-dimensional echocardiography compared with cardiac magnetic resonance imaging. *Eur J Echocardiogr*. 2011;12:656-664.
83 Shimada YJ, Shiota M, Siegel RJ, Shiota T. Accuracy of right ventricular volumes and function determined by three-dimensional echocardiography in comparison with magnetic resonance imaging: a meta-analysis study. *J Am Soc Echocardiogr*. 2010;23:943-953.
84 Sugeng L, Mor-Avi V, Weinert L, et al. Multimodality comparison of quantitative volumetric analysis of the right ventricle. *JACC Cardiovasc Imaging*. 2010;3:10-18.
85 Soulat-Dufour L, Addetia K, Miyoshi T, et al. Normal values of right atrial size and function according to age, sex, and ethnicity: results of the world alliance societies of echocardiography study. *J Am Soc Echocardiogr*. 2021;34:286-300.
86 Patlolla SH, Schaff HV, Greason KL, et al. Early right ventricular reverse remodeling predicts survival after isolated tricuspid valve surgery. *Ann Thorac Surg*. 2021;112:1402-1409.
87 Calafiore AM, Foschi M, Kheirallah H, et al. Early failure of tricuspid annuloplasty. Should we repair the tricuspid valve at an earlier stage? The role of right ventricle and tricuspid apparatus. *J Card Surg*. 2019;34:404-411.
88 Wang TKM, Akyuz K, Xu B, et al. Early surgery is associated with improved long-term survival compared to class i indication for isolated severe tricuspid regurgitation. *J Thorac Cardiovasc Surg*. 2021. https://doi.org/10.1016/j.jtcvs.2021.07.036
89 Kebed KY, Addetia K, Henry M, et al. Refining severe tricuspid regurgitation definition by echocardiography with a new outcomes-based "massive" grade. *J Am Soc Echocardiogr*. 2020;33:1087-1094.
90 Karam N, Mehr M, Taramasso M, et al. Value of echocardiographic right ventricular and pulmonary pressure assessment in predicting transcatheter tricuspid repair outcome. *JACC Cardiovasc Interv*. 2020;13:1251-1261.
91 Muller DWM. Predicting the outcome of transcatheter tricuspid valve intervention: when is late too late? *JACC Cardiovasc Interv*. 2020;13:1262-1264.
92 Go YY, Dulgheru R, Lancellotti P. The conundrum of tricuspid regurgitation grading. *Front Cardiovasc Med*. 2018;5:164.