Advances in the Assessment of Patients With Tricuspid Regurgitation: A State-of-the-Art Review on the Echocardiographic Evaluation Before and After Tricuspid Valve Interventions

Luigi P. Badano, MD, PhD, Michele Tomaselli, MD, Denisa Muraru, MD, PhD, Xavier Galloo, MD, Chi Hion Pedro Li, MD, and Nina Ajmone Marsan, MD, PhD, *Milan, Italy; Leiden, The Netherlands; Brussels, Belgium; and Barcelona, Spain*

Tricuspid regurgitation (TR) can have a significant impact on the health and mortality of a patient. Unfortunately, many patients with advanced right-sided heart failure are not referred for isolated tricuspid valve (TV) surgery in a timely manner. This delayed referral has resulted in a high in-hospital mortality rate and significant undertreatment. Fortunately, transcatheter TV intervention (TTVI) has emerged as a safe and effective alternative to surgery, successfully reducing TR severity and improving patients' quality of life. Current guidelines emphasize the importance of assessing TR severity and its impact on the right heart chambers for selecting the appropriate intervention. However, the echocardiographic assessment of both right chambers and TV anatomy, along with TR severity, poses specific challenges, leading to the underestimation of TR severity. Recently, three-dimensional echocardiography has become crucial to enhance the characterization of TR severity. Moreover, it is essential to evaluate residual TR after TTVI to gauge the intervention's success and predict the patient's prognosis. This review provides a thorough evaluation of the echocardiographic parameters used to assess TR severity before and after TTVI. It presents a critical analysis of the accuracy and reliability of these parameters, highlighting their strengths and limitations to establish standardized diagnostic criteria and treatment protocols for TR, which will inform clinical decision-making and improve patient outcomes. (J Am Soc Echocardiogr 2024;37:1083-102.)

Keywords: Native tricuspid valve, Transcatheter tricuspid valve intervention, Tricuspid regurgitation grading, Right ventricle, Right atrium

From the Department of Medicine and Surgery, University of Milano-Bicocca (L.P.B., M.T., D.M.), Department of Cardiology, Istituto Auxologico Italiano, IRCCS (L.P.B., D.M.), Milan, Italy; the Department of Cardiology, Leiden University Medical Center, Leiden, The Netherlands (X.G., N.A.M.); the Department of Cardiology, University Hospital Brussels, Brussels, Belgium (X.G.); and the Department of Cardiology, Hospital de la Santa Creu i Sant Pau, Biomedical Research Institute, Barcelona, Spain (C.H.P.L.).

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Reprint requests: Michele Tomaselli, MD, Department of Cardiology, Istituto Auxologico Italiano, IRCCS, Piazzale le Brescia 20, 20149 Milan, Italy (E-mail: *michetomaselli@gmail.com*).

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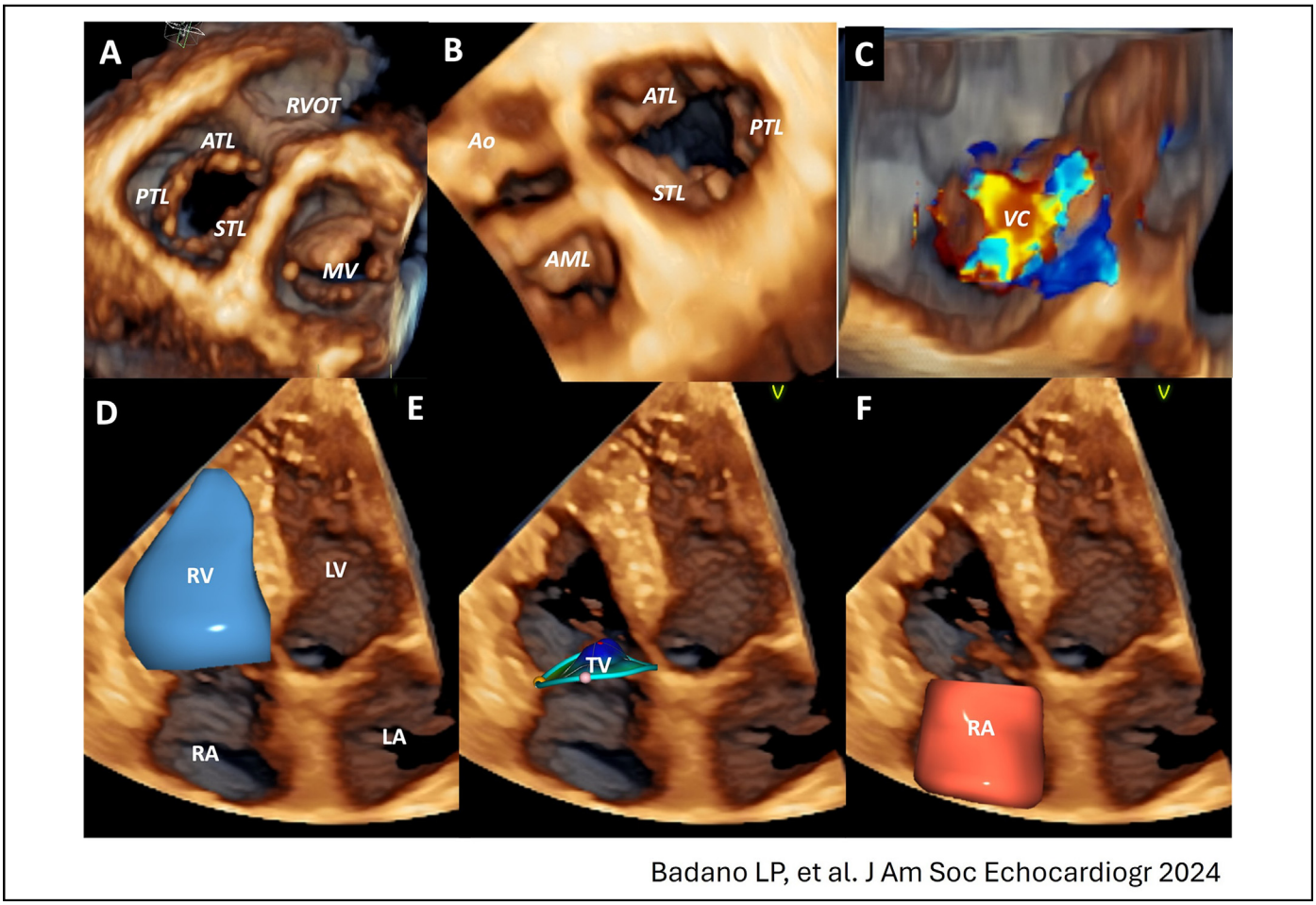
Tricuspid regurgitation (TR) is an independent determinant of patients' morbidity and mortality.[1,2] The high in-hospital mortality for isolated tricuspid valve (TV) surgery, related to the late referral of patients with intractable right-sided heart failure and end-organ failure, led to significant undertreatment of these patients.[3] In recent years, transcatheter TV intervention (TTVI) has been reported to be safe and effective in reducing TR severity, relieving symptoms, and improving quality of life.[4-7] According to current guidelines,[8-11] assessing TR severity and its effects on the right heart chambers is crucial for selecting patients for appropriate interventions. Moreover, the assessment of residual TR after TTVI is the main parameter used to evaluate the success and durability of the intervention,[12,13] and it is also an important prognostic factor after the procedures.[14] Echocardiography is the first-line imaging modality to assess TV anatomy, TR severity, and the extent of right ventricular (RV) and right atrial (RA) remodeling in patients with TR (Central Illustration).[10,11,13,15-17] However, assessing the severity of TR remains a challenging task for the echocardiographer, and recent data have highlighted significant limitations of the current recommendations about the echocardiographic assessment of TR severity.[10,11,15,16,18] Moreover, there are scant data on evaluating residual TR after TTVI, as implanted devices may challenge the conventional echocardiographic parameters because of the presence either multiple or eccentric jets or shadowing by the implanted devices.[19]



Central Illustration Use of transthoracic 3DE to characterize patients with STR. This technique provides an accurate assessment of the valve's anatomy from both the ventricular **(A)** and atrial **(B)** perspectives; it offers precise measurements of regurgitation severity, which are independent of geometric assumptions and the orientation of the 2D view, even in the presence of complex jet shapes **(C)**; and it enables the measurement of right ventricular volumes and RVEF **(D)**, tricuspid annular size and shape **(E)**, and right atrial volume and function **(F)**, all of which are accurately measured without any reliance on geometric assumptions. *AML*, Anterior mitral leaflet; *Ao*, aortic valve; *ATL*, anterior tricuspid leaflet; *LA*, left atrium; *LV*, left ventricle; *MV*, mitral valve; *PTL*, posterior tricuspid leaflet; *RA*, right atrium; *RV*, right ventricle; *RVOT*, right ventricular outflow tract; *STL*, septal tricuspid leaflet.

In this review we aim to provide an overview of the most recent evidence concerning the strengths and limitations of the current guideline-recommended multiparametric echocardiographic approach. Additionally, we explore new methods and algorithms for assessing TR severity in patients with native TV and those who have undergone TTVI, improving the evaluation and overall management of patients with TR.

ESSENTIAL ANATOMIC EVALUATION AND CLASSIFICATION OF TR

The TV is the largest (the normal valve orifice area ranges between 7 and 9 cm^2) and the most anteriorly and inferiorly positioned cardiac valve.[20] Two-dimensional echocardiography (2DE) and three-dimensional echocardiography (3DE) have improved our appreciation of the anatomic variability of the TV.[15,21]

TR may be classified as primary or secondary or as related to or associated with a cardiac implantable electronic device (CIED).[11,13,15,16] This classification is essential to characterize a patient's prognosis and guide TTVI device selection.[22-25] Primary TR involves abnormalities of the TV leaflets and encompasses congenital abnormalities, fibroelastic degeneration, endocarditis, rheumatic disease, traumatic damage, and carcinoid disease.[10,11,16] Secondary TR (STR) is characterized by impaired valve coaptation caused by dilatation of the right ventricle and/or of the tricuspid annulus (TA) due to left-sided heart valve diseases, left ventricular dysfunction, pulmonary hypertension, congenital heart defects, and atrial fibrillation.[26] STR accounts for >80% of cases[27] and is further divided into two phenotypes: atrial STR (A-STR) and ventricular STR (V-STR)[13] (Figure 1). Recently, parameters to define A-STR and V-STR have been proposed by a consensus of the Tricuspid Valve Academic Research Consortium (TVARC) and the PCR Tricuspid Focus Group.[13,28] A-STR is characterized by the absence of significant leaflet tethering in the setting of a dilated right atrium and normal RV size and function. Conversely, V-STR requires the presence of significant leaflet tethering and RV dilation and/or dysfunction.[13,28] The definition of these phenotypes is pivotal, as patients with A-STR have a more favorable natural history and post-procedural outcomes than patients with V-STR.[22-24] A-STR may be amenable to any class of TR therapy without prohibitive annular

Abbreviations

2D = Two-dimensional

2DE = Two-dimensional echocardiography

3D = Three-dimensional

3DE = Three-dimensional echocardiography

A-STR = Atrial secondary tricuspid regurgitation

AROA = Anatomic regurgitant orifice area

CIED = Cardiac implantable electronic device

CMR = Cardiac magnetic resonance

CT = Computed tomography

EROA = Effective regurgitant orifice area

FAC = Fractional area change

PA = Pulmonary artery

PASP = Pulmonary artery systolic pressure

PISA = Proximal isovelocity surface area

PRL = Para-ring leakage

RA = Right atrial

RegFr = Regurgitant fraction

RegVol = Regurgitant volume

RV = Right ventricular

RVEF = Right ventricular ejection fraction

STR = Secondary tricuspid regurgitation

SV = Stroke volume

TA = Tricuspid annulus

TAPSE = Tricuspid annular plane systolic excursion

TEE = Transesophageal echocardiography

TEER = Transcatheter edge-to-edge repair

TR = Tricuspid regurgitation

TTE = Transthoracic echocardiography

T-TEER = Tricuspid transcatheter edge-to-edge repair

TTVI = Transcatheter tricuspid valve intervention

TV = Tricuspid valve

TVARC = Tricuspid Valve Academic Research Consortium

VC = Vena contracta

VCA = Vena contracta area

V-STR = Ventricular secondary tricuspid regurgitation

dilation or leaflet coaptation defect.[12,29] Severe TV leaflet tethering (defined as tethering height > 0.76 cm and tenting area > 1.63 cm^2) is a strong predictor of recurrent TR following surgical repair.[30] Moreover, V-STR anatomy is typically less suitable for transcatheter annuloplasty devices and more favorable for transcatheter TV replacement[6,7] or tricuspid transcatheter edge-to-edge repair (T-TEER) depending on anatomy.[12,31,32] CIED-related TR is a burdensome problem with a prevalence expected to increase in the next decades.[33] CIED-related TR may be subcategorized into lead-associated TR type A when CIEDs determine mechanical interference on leaflet excursion or coaptation (impingement, adherence, or entanglement) or leaflet perforation or laceration and lead-associated TR type B in the absence of significant interference on TV apparatus.[13,33,34] Recent data from a national Australian database[2] showed that CIEDs were associated with a twofold increased probability of moderate or severe TR compared with patients without CIEDs. TR worsening after CIED implantation is an independent risk factor for experiencing cardiovascular events.[35] Patients with high surgical risk and lead-associated TR type A with significant leaflet impingement are unfavorable for annuloplasty or T-TEER and could be considered for transvenous lead extraction and transcatheter TV replacement.[12,13,34]

THE TA

Dilation of the TA is among the main determinants of the development and severity of STR, particularly in patients with A-STR.[26,36-38] Moreover, the size of the TA is critical in determining the need for concomitant TV interventions in patients undergoing left-sided valve surgery[8,9] and in the patient selection for transcatheter procedures to repair the regurgitant TV.[39] Current guidelines for TV repair recommend tricuspid annular sizing on 2DE by measuring tricuspid annular diameter during diastole from an apical four-chamber view.[8,9] However, the TA is a highly dynamic, saddle-shaped structure, and because of this complex three-dimensional (3D) geometry, it is unlikely that a single linear dimension can account for its actual size.[40,41] Moreover, as there is no anatomic landmark to standardize the position of the apical four-chamber view, small rotations of the probe during image acquisition can result in significant variations of the measured diameter (Figure 2). Finally, tricuspid annular dilation commonly occurs in the anteroposterior direction, which is not explored in the conventional two-dimensional (2D) echocardiographic apical four-chamber view.[42] Accordingly, the most suitable echocardiographic technique to obtain accurate measurements of tricuspid annular size is 3DE[15,21,40,43] (Figure 3). Three-dimensional echocardiographic studies have reported that reference values for tricuspid annular geometry should be sex specific and indexed to the body surface area.[40,43] The dynamic changes during the cardiac cycle identify a minimum tricuspid annular size in midsystole, then increase during early diastole and reach a maximum value during end-diastole.[40,41,43]

RV AND RA ANATOMY AND FUNCTION

The chronic volume overload determined by TR causes a gradual maladaptive RV remodeling, leading to a vicious cycle characterized by progressive RV remodeling, worsening TR, and adverse prognosis.[16,44] Consequently, current guidelines suggest that the accurate assessment of RV remodeling in patients with TR is essential to guide TV surgical and transcatheter interventions.[8,9,45] However, the conventional 2D echocardiographic parameters used to evaluate RV size and function, such as tricuspid annular plane systolic excursion (TAPSE), RV fractional area change (FAC), RV tissue Doppler S-wave velocity,[46,47] are not accurate enough to encompass the complex morphologic and functional remodeling of the right ventricle in response to TR.[48] Conversely, 3DE allows a comprehensive analysis of RV size, shape, and function, regardless of geometric assumptions.[21,49] RV volumes and RV ejection fraction (RVEF) by 3DE showed an excellent correlation with cardiac magnetic resonance (CMR).[45,49-51] In a recent study[52] including 75 patients with severe STR undergoing transcatheter edge-to-edge repair (TEER), impaired preprocedural RVEF (<45%) was associated with an increased mortality rate, but the postprocedural decrease of 3D RVEF after transcatheter TV replacement was not. Moreover, RVEF predicted outcomes better than TAPSE.[52] Finally, RV free wall longitudinal strain by 2D speckle-tracking echocardiography, overcoming most of the limitations inherent in the conventional echocardiographic parameters of RV function, may predict outcomes in patients with isolated STR.[53] However, both the traditional and the advanced indexes of RV function are highly influenced by the volume and pressure overload associated with significant

HIGHLIGHTS

- The TV has a peculiar anatomy and works in a unique hemodynamic environment.
- Measuring TR severity and its impact on the right heart is key to managing patients.
- Evaluating residual TR after TTVI is key to assessing the procedure's success.

TR,[17,54] potentially overestimating RV function.[13] Thus, compared with the general population, upper limits of normality to identify RV dysfunction have been advocated in patients with severe TR.[13] Conversely, the load dependency of the "shortening" indices of RV function can be partially overcome by evaluating imaging surrogates of the RV–pulmonary artery (PA) coupling.[55] The ratio between TAPSE and PA systolic pressure (PASP) measured by echocardiography has recently correlated to outcomes in the setting of severe STR.[56,57] However, compared with other echocardiographic indexes of RV-PA coupling, the TAPSE/PASP ratio showed the lowest prognostic value in model fit and discrimination ability. In contrast, the model with 3D echocardiographic RVEF/PASP ratio exhibited the highest prognostic value.[58,59] Moreover, the accuracy of PASP estimation with 2D Doppler echocardiography in patients with severe STR is questionable,[60,61] and the predictive value of TAPSE/PASP ratio is significantly higher when invasively measured PASP is used in the calculation.[62] In addition to the underestimation of the RV-RA gradient, in patients with severe TR, the rapid equalization of RV and RA pressures creates large RA V waves, and RA pressure becomes much more dynamic, and it is grossly underestimated using the conventional "static" noninvasive echocardiographic parameters.[61,63] Importantly, the extent of the underestimation will be more significant with a larger effective regurgitant orifice area (EROA), a more dysfunctional right ventricle, and worse RA compliance. Recently, the ratio between RV forward stroke volume (SV) and RV end-systolic volume has been proposed as an index of RV-PA coupling obtained using RV volumes measured by 3DE.[59] This index is independent of PASP estimation and provides a stronger association with outcome than TAPSE/PASP ratio in patients with STR.[59]

Until recently, the right atrium has been considered an innocent bystander that passively dilates because of the chronic volume overload imposed by TR.[64] Growing evidence suggests that RA enlargement and subsequent tricuspid annular dilation[36,65] may be the strongest determinant of A-STR pathophysiology.[38] Therefore, the precise evaluation of RA size is pivotal to defining STR phenotypes and refining patient prognosis.[66] Although 2DE underestimates actual RA volumes, measurements of RA volumes using the RV-focused apical view may improve the correlation with CMR.[67] Finally, recent data support the use of RA longitudinal strain analysis by 2D speckle-tracking echocardiography as an independent predictor of cardiovascular events in patients with STR.[22,23,68-70]

DETERMINATION OF TR SEVERITY AND EXTENDED TR GRADING SCHEME: STRENGTHS AND LIMITATIONS OF CURRENT METHODS

Transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) are the most widely used imaging modalities to assess TV valve anatomy, the etiology and severity of TR, and the extent of RV and RA remodeling associated with TR.[16,18] TTE is the recommended technique to assess severity, while TEE is performed mainly to evaluate the mechanism, anatomy, and feasibility of transcatheter procedures. Additional advanced imaging may be of value when the echocardiographic study is either insufficient or inconclusive.[11,16] The American Society of Echocardiography and

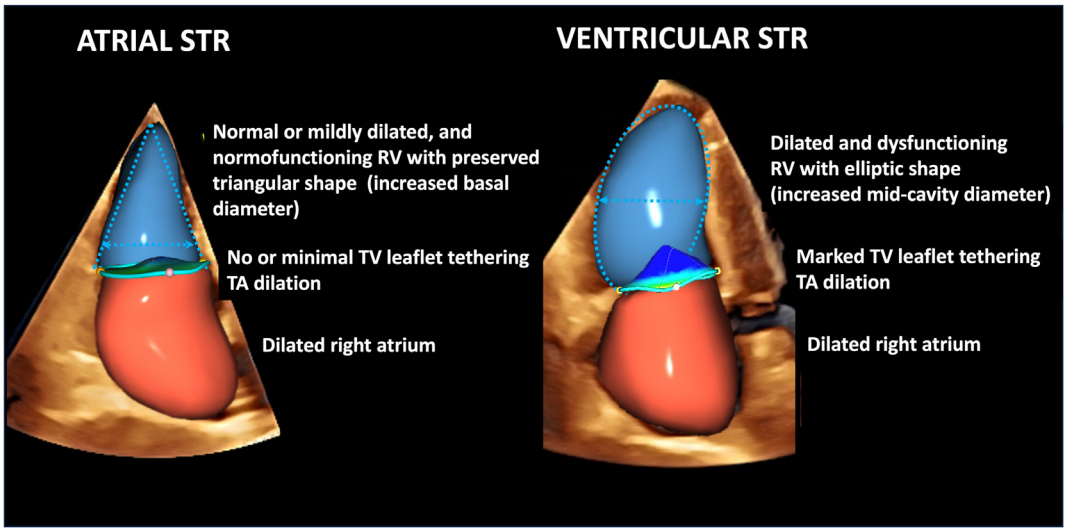


Figure 1 Morphologic characteristics of A-STR and V-STR. The main morphologic and functional characteristics of A-STR include isolated TR (no left ventricular dysfunction or significant left-sided valve diseases), tricuspid annular dilation with minimal or no TV leaflet tethering, marked RA dilatation, a normal triangular shape of the right ventricle (RV) with enlarged basal diameter, normal or only mildly increased right ventricular volume, and normal right ventricular function. In contrast, V-STR is characterized by significant TV leaflet tethering, associated with an elliptical shape of the RV (increased midcavity diameter) and significant right ventricular dilation and/or dysfunction associated with dilated TA and right atrium.

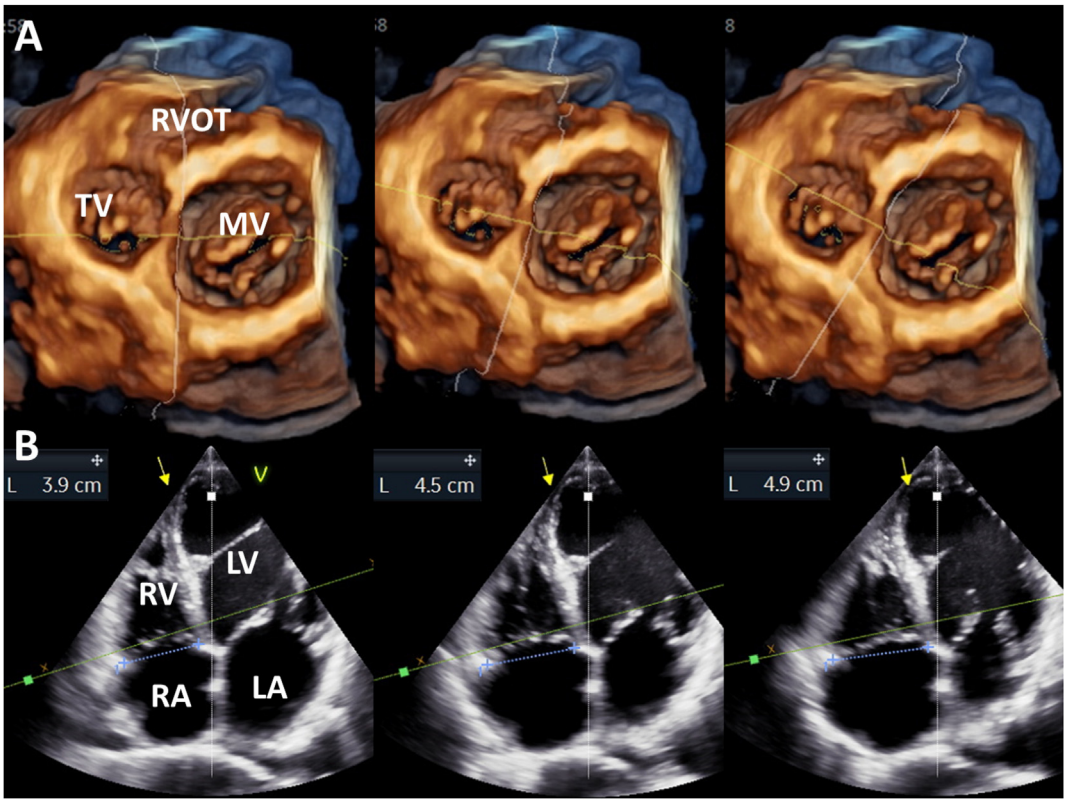


Figure 2 Variability in tricuspid annular diameter measurement by 2DE. *(Top)* Three-dimensional en face view of the mitral and the TV, with a *yellow line* showing the position of the corresponding apical four-chamber cut planes shown in the *bottom panels*. The *bottom panels* show the tricuspid annular diameter obtained from the same 3D data set by rotating the cutting plane in three dimensions to simulate the rotation of the probe. *LA*, Left atrium; *LV*, left ventricle; *MV*, mitral valve; *RA*, right atrium; *RV*, right ventricle; *RVOT*, right ventricular outflow tract.

the European Association of Cardiovascular Imaging recommend a multiparametric and hierarchical approach to TR assessment based on qualitative, semiquantitative, and quantitative parameters (Table 1).[10,11] The application of the American Society of Echocardiography's 2017 guidelines for the assessment of TR severity was shown to be concordant with CMR (using a regurgitant volume [RegVol] of ≥45 mL measured by CMR to define severe TR) in 65% if one grade of difference in severity between the two imaging modalities was deemed acceptable.[71] However, when a hierarchical order (starting from the appearance of the continuous-wave Doppler spectrum, the size of the right ventricle, and the presence of systolic reverse flow in the hepatic veins) is used, the agreement between echocardiography and CMR increases to 100%.

Before discussing the strengths and limitations of the various echocardiographic parameters (Table 2), it is essential to acknowledge that TR severity is extremely sensitive to changes in loading conditions, potentially leading to overestimation of TR severity in fluid overload states.[15,16] Moreover, the respiratory cycle's dramatic influence on RV and pulmonary physiology determines an increase in TV leaflet tenting volume and TR regurgitant orifice area during inspiration.[72] Thus, to obtain comparable interpatient and interstudy measurements, TR assessment should ideally be performed in euvolemic patients, and all measurements should be performed at end-expiration in spontaneously breathing patients.

Qualitative and Semiquantitative Methods

Qualitative evaluation of the TV apparatus and the surrounding structures helps define the severity of TR,[10,11,16,18] select the most appropriate strategy for TTVI, and predict postprocedural outcomes.[12,13,15] In particular, structural abnormalities of the TV leaflets such as perforations, flail segments, leaflet retraction with a large coaptation gap, or marked tethering of leaflets with loss of coaptation are considered specific characteristics of severe TR.[10,11] Concerning preprocedural planning, a coaptation depth larger than 1 cm was associated with a reduced success rate regardless of the devices used for TTVI.[73] Moreover, a TV leaflet coaptation gap >8.5 mm may be associated with procedural failure following T-TEER.[12] Finally, a TV coaptation gap >10 mm identified patients at the highest risk for cardiovascular events among 606 patients with severe isolated STR.[74]

Among the qualitative and semiquantitative echocardiographic Doppler parameters, the presence of a dense and triangular continuous-wave Doppler jet, systolic reversal of the hepatic vein flow, a large holosystolic flow convergence zone, a large central or eccentric wall-impinging jet, and a TR jet area >10 cm^2 are specific for severe TR.[10,11] Careful consideration should be paid to eccentric, wall-impinging jets that appear significantly smaller than centrally directed jets of similar hemodynamic severity.[10,11] However, the expansion of the TR regurgitant jet into the right atrium is only partially related to the RegVol. Conversely, it depends primarily on the conservation of the jet's momentum and is proportional to the square of TR jet velocity.[18,75] Thus, as the right ventricle is a

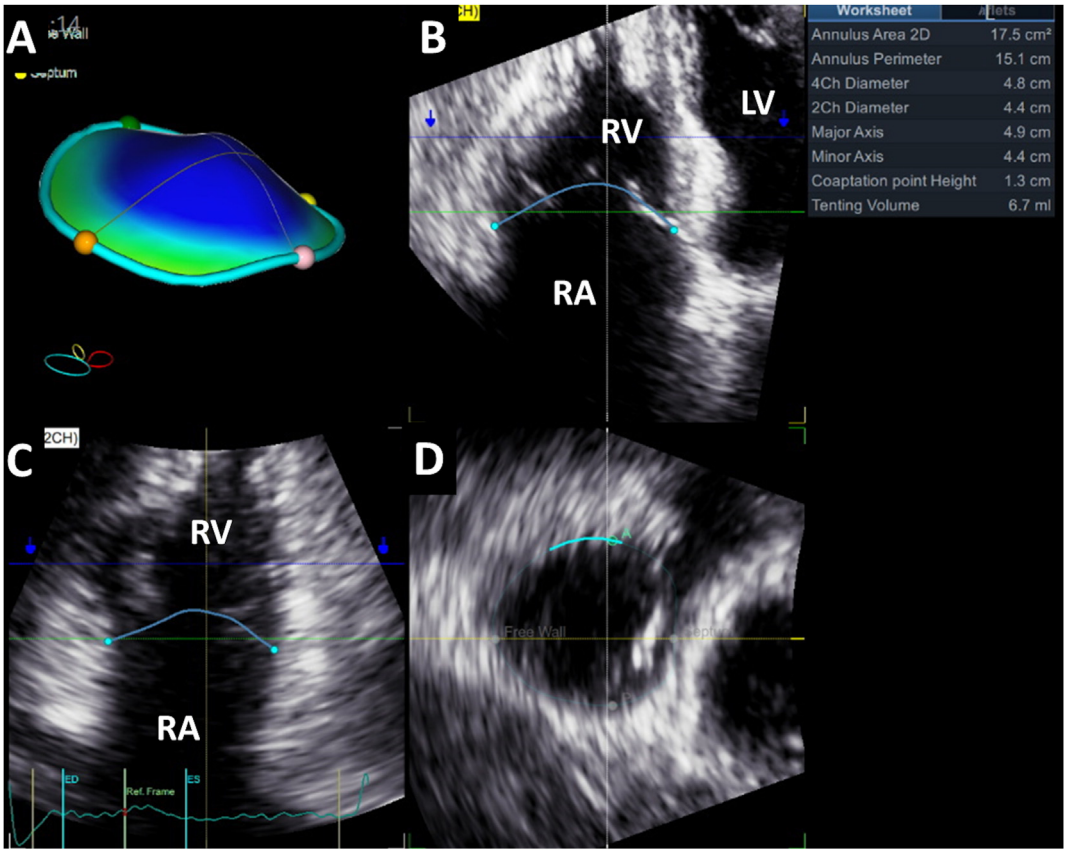


Figure 3 Quantitative analysis of tricuspid annular geometry using a dedicated software package on a transthoracic 3D data set. **(A)** Surface rendering of the TV in a patient with STR that allows appreciation of its complex 3D shape. The *colored dots* are used for spatial orientation (*yellow*, septum; *orange*, RV free wall; *pink*, posterior; *green*, anterior). Indexing of the TV model is done using different cut planes (**B**, four-chamber view; **C**, 90° cut plane shown by the *white vertical line* in the four-chamber view; **D**, transverse cut plane whose position is shown by the *blue horizontal line*). *2Ch*, Two-chamber; *4Ch*, four-chamber; *LV*, left ventricle; *RA*, right atrium; *RV*, right ventricle.

low-pressure chamber, in patients with significant TR (relatively large EROA), the gradient between the right ventricle and the right atrium will be relatively low, and consequently, the TR jet color area may underestimate TR severity[18] (Figure 4). Importantly, the extent of the underestimation will be more significant with larger EROA and a more dysfunctional right ventricle. Accordingly, color flow imaging is not reliable for assessing TR severity. It should be used only to detect the presence of TR, localize the origin of the jet, and identify those that are obviously mild (central jets with laminar flow extending just beyond the TV leaflets) from obviously severe (large and turbulent jets, filling >50% of the RA area with reverse flow into the hepatic veins). Notably, a severe TR jet in the central or anteroseptal position independently predicted procedural success after TEER.[31]

The vena contracta (VC) is the narrowest portion of the regurgitant jet that occurs at or immediately downstream of the TR orifice.[10,11,18] VC width represents a surrogate of the EROA.[10,11,76] A TR VC width >7 mm, obtained from the apical four-chamber view, identifies severe TR,[10,11,76] and it is a marker of adverse prognosis.[77] However, because in TR, the regurgitant orifice often presents a complex and unpredictable shape (often elliptical or star shaped; Figure 5), the assessment of VC width using a single linear measurement may not accurately describe the complexity of the TR orifice[15] (Figure 6). Accordingly, it has been proposed to average the measurements obtained from two orthogonal views (the apical four-chamber and the parasternal inflow views) to obtain a biplane VC and improve the accuracy of this parameter.[16] In a recent study including 284 patients with severe TR, a biplane VC >9.2 mm was identified as the most accurate threshold value associated with adverse RV remodeling and increased mortality.[78]

Three-dimensional echocardiography may also help improve the accuracy of quantitative Doppler methods and provide integrative criteria for the 2D echocardiographic assessment of TR grade. Several studies have shown that the planimetry of the VC area (VCA) on 3D echocardiographic color data sets can improve the assessment of TR severity, as it is independent of geometric assumptions about the shape of the regurgitant orifice (Figure 6,D).[79-82] However, several limitations must be acknowledged.[18] First, color 3DE is limited by the low volume rate in single-beat acquisitions, with the need to acquire multiple cardiac cycles that may compromise 3D reconstruction quality (i.e., stitching artifacts) in case of arrhythmias. Second, the planimetry of the VCA in a 3D color Doppler data set depends both on the resolution of the color pixel size, with the potential "spillage" of the color at the edges, and on color gain settings, making it difficult to standardize it for interpatient comparison. Third, planimetry of the 3D VCA is a single-frame measurement and does not consider the large variability of the regurgitant flow during the cardiac systole in patients with STR. Finally, in STR, the regurgitant orifice surface is generally not flat. Using a planimetry

Table 1 Strengths and limitations of the various echocardiographic parameters used to assess the severity of TR

Parameter	Strengths	Limitations
Jet area	• Easy to measure	• Dependent on color gain settings • Dependent on the driving pressure (for the same RegVol, smaller TR jet area and larger mitral regurgitation jet area because of different regurgitant jet velocities) and jet direction (overestimation of central jets and underestimation of eccentric jets) • Overestimation of TR in nonholosystolic jets • Single-view, tomographic estimation of a complex 3D phenomenon
RA area/jet area	• Specific in identifying severe TR when ≥50%	• See the limitations of TR jet area • Use of the apical four-chamber view may underestimate RA area
Density of the TR CW Doppler spectrum	• The density of the Doppler spectrum is proportional to the TR RegVol • Faint or incomplete jet is suggestive of mild TR	• Central jets may appear denser than more severe eccentric jets • Overlap between moderate and severe TR
Shape of the TR CW Doppler spectrum	• The early-peaking, dense, and triangular-shape CW Doppler spectrum is a specific sign of pressure equalization at low velocity	• Affected by changes that modify RV and RA pressures
Hepatic vein flow reversal	• Specific sign of severe TR	• Depends on compliance of the right atrium • May not be reliable in patients with atrial fibrillation, paced rhythm with retrograde atrial conduction
VC	• A surrogate for the regurgitant orifice area • Can be used in eccentric jets and in multivalvular diseases • Partially dependent on flow rate and the driving pressure for dynamic orifices • Less dependent on technical factors • Good at identifying mild (<3 mm) or severe (≥7 mm) TR	• It assumes a circular shape of the regurgitant orifice and that the linear measurement is the diameter of that circle; not valid in noncircular regurgitant orifices • Not valid for multiple jets • Inaccurate in nonholosystolic jets • Small errors in its measurement may lead to a large misclassification of TR severity
VCA	• Multiple jets can be measured. • Independent of geometric assumptions about the shape of the regurgitant orifice area	• Depends on color gain settings • Depends on the spatial resolution of the 3D echocardiographic color • Time consuming • Limited temporal resolution of the single-beat 3D data sets • Interobserver variability • Dynamic jets may be over- or underestimated • Requires 3D echocardiographic machines and expertise in acquiring 3D color data sets of the TRs
PISA	• Can be used in eccentric jets • Feasible in patients with multivalvular disease. • Strong evidence about the independent prognostic impact of PISA-derived EROA and RegVol	• PISA calculation provides a instantaneous (single-frame) peak flow rate and ignores the variability of the PISA radius during the systolic phase • Overestimation of TR in nonholosystolic jets • Difficult alignment of the ultrasound beam in eccentric jets. • Cannot be applied in multiple jets. • In STR, the tethering subtended by TV leaflets and the low flow velocities of the right heart may flatten PISA convergence and underestimate TR severity

(*Continued*)

Table 1 (*Continued*)

Parameter	Strengths	Limitations
Doppler volumetric method	• Can be applied in multiple or eccentric jets	• Cannot be applied in multivalvular regurgitations • Relies on geometric assumptions about the shape of the TA and of the left or RV outflow tract • Time consuming
3D echocardiographic volumetric method	• Can be applied in multiple or eccentric jets • Independent of geometric assumptions • Easy to use	• Cannot be applied in multivalvular regurgitations • Limited temporal resolution of single-beat 3D echocardiographic data sets in atrial fibrillation • Requires 3D echocardiographic machines and expertise in measuring RV volumes

CW, Continuous-wave.

on a tomographic plane to measure it may not be accurate. However, the new 3D echocardiographic systems have significantly improved the temporal and spatial resolution of the 3D echocardiographic color acquisitions. Color gain should be set at the highest value that does not create tissue artifacts and should not be changed during the planimetry (to provide consistent interpatient and interstudy comparison). Multiple 3D echocardiographic color frames can be planimetered to average results to account for the intrabeat variability of TR.

Different cutoff values of 3D echocardiographic VCA have been proposed to identify severe TR, ranging from 0.36 cm^2 (sensitivity, 89%; specificity, 84%)[80] to 0.60 cm^2 (sensitivity, 92%; specificity, 75%)[81] and 0.75 cm^2 (sensitivity, 85.2%; specificity, 82.1%).[79] This variability can be explained by the different

Table 2 Established threshold values for the echocardiographic parameters used to grade TR severity within a five-grade scheme

	Mild (1+)	Moderate (2+)	Severe (3+)	Massive (4+)	Torrential (5+)
Qualitative					
Tricuspid morphology	Normal or mildly abnormal	Moderately abnormal		Severely abnormal (flail leaflet, large coaptation gap, marked tethering)	
Color flow jet area	Small, narrow, central	Moderate central		Large central, or eccentric, wall impinging	
Flow convergence zone	Not visible, transient, or small	Intermediate in size and duration		Large throughout systole	
CW Doppler contour	Faint, partial, parabolic	Dense, parabolic	Dense, parabolic or triangular	Dense, often triangular, may have low peak velocity	Dense, usually triangular, often low peak velocity
Right heart dimensions	Usually normal	Normal or mild dilation	Usually dilated	Dilated	
Semiquantitative					
VC width, mm	<3	3-6.9	7-13.9	14-20.9	≥21
PISA radius, mm	≤5.4	5.5-8.9		≥9	
Hepatic vein flow	Systolic dominant	Systolic blunting		Systolic flow reversal	
Tricuspid inflow	A-wave dominant	Variable		E-wave dominant (≥1 m/s)	
Quantitative					
PISA EROA, mm^2	<20	20-39	40-59	60-79	≥80
Doppler volumetric EROA, mm^2			75-94.9	95-114.9	≥115
PISA RegVol, mL	<30	30-44	45-59	60-74	≥75
RegFr, %	<15	16-49		≥50	
3D VCA, mm^2			75-94.9	95-114.9	≥115

CW, Continuous-wave.

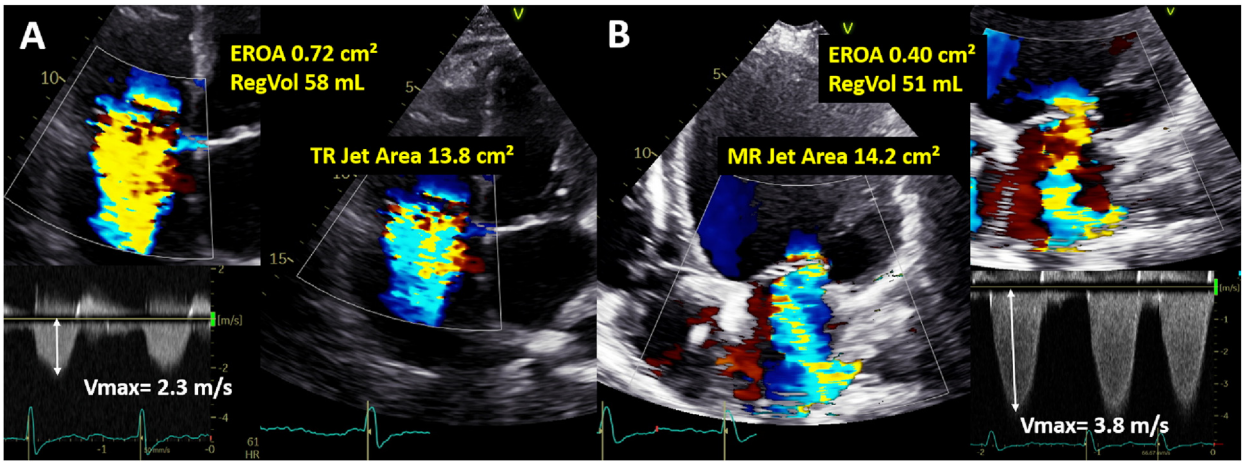


Figure 4 The relationship between tricuspid regurgitant orifice size and the expansion of the jet into the right atrium is governed by the conservation of momentum (*M*), which is proportional to the product of EROA and the square of jet velocity (v^2). In these cases, although the color flow jet area was comparable for the mitral and the tricuspid regurgitant jets (13.8 vs 14.2 cm^2), the patient with TR **(A)** displayed larger EROA (0.72 vs 0.40 cm^2) and RegVol (58 vs 51 mL) compared with the patient with mitral regurgitation (MR; **B**). These differences arose mainly from the lower velocity of the TR jet (2.3 vs 3.8 m/s). *MR*, Mitral regurgitation; *Vmax*, maximal regurgitant jet velocity on continuous-wave Doppler.

2D criteria used to define severe TR. In a single-center study performed using TEE, a 3D VCA cutoff value of 0.61 cm^2 discriminated severe TR with sensitivity of 78% and specificity of 97% (area under the curve, 0.93; $P < .001$).[82] Although the current guidelines suggest a lower cutoff (0.4 cm^2),[10,11] the TVARC adopted the threshold of 0.75 cm^2 for 3D echocardiographic VCA to define severe TR.[13]

Quantitative Methods

The quantitative parameters used to measure TR severity include EROA, RegVol, and regurgitant fraction (RegFr). EROA ≥ 0.40 cm^2, RegVol ≥ 45 mL, and RegFr ≥ 50% are recommended as indicative of severe TR.[8,10,11] However, the threshold values that identify hemodynamically severe TR may be different from those identifying high-risk TR (in terms of poor prognosis).[56]

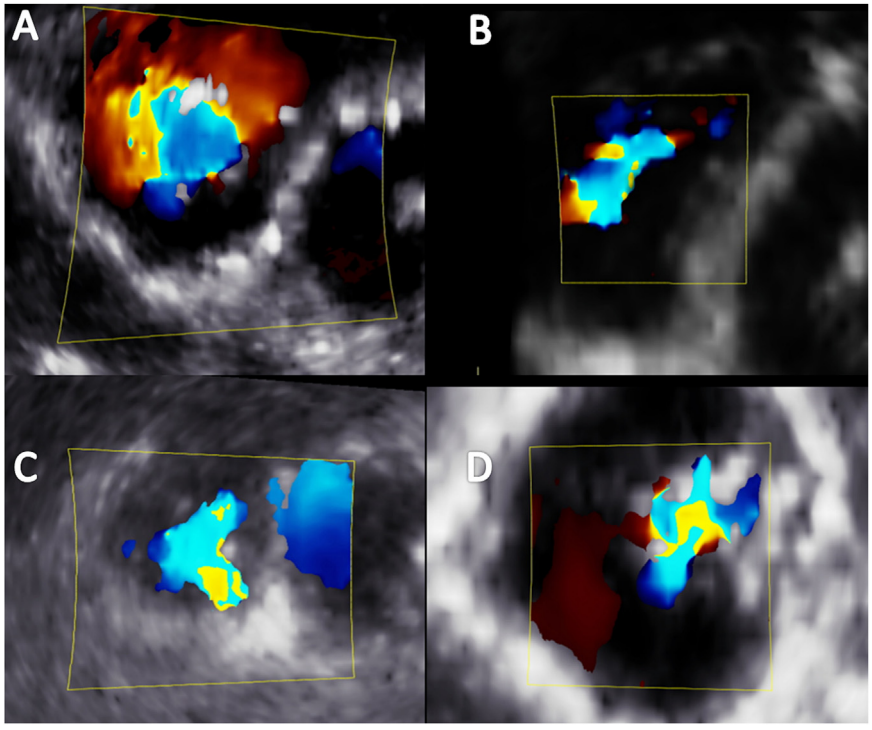


Figure 5 Variability of the shape of the VC among patients with STR. Transthoracic 3D color Doppler echocardiography with transverse cut planes obtained at the level of the VC of the regurgitant jet. The panels show distinct morphologies of the VC: circular **(A)**, ellipsoid **(B)**, crescent **(C)**, and stellate **(D)**.

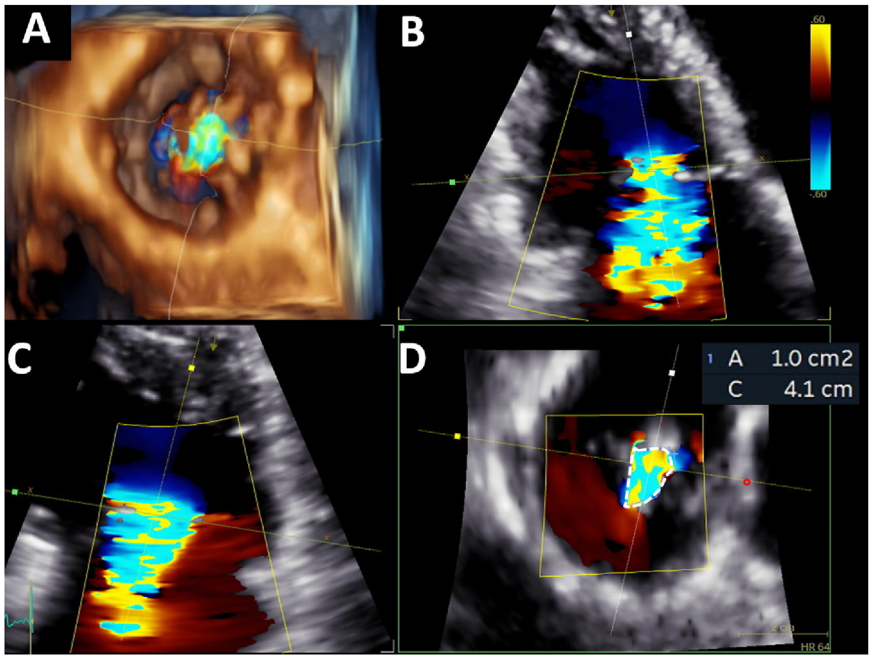


Figure 6 Effects of the orientation of the 2D cut plane on the measurement of the VC diameter. **(A)** Transverse section of a transthoracic 3D color Doppler data set to show the VC of the regurgitant jet from the ventricular perspective. The shape is elliptical. **(B** and **C)** Four-chamber and anteroposterior longitudinal cut planes obtained by slicing the data set in **(A)** (*yellow line*, four-chamber view; *white line*, 2D view at 90° from the four-chamber view). The diameter of the VC in the four-chamber is smaller than the one that could be measured in its orthogonal view. Data sets are intentionally sliced to facilitate planimetry of the VCA. **(D)** Planimetry of the VC drawn on a transverse cut plane obtained by slicing the 3D color data set at the level of the VC and perpendicular to the longitudinal axis of the regurgitant jet. *A*, Area; *C*, circumference.

The Proximal Isovelocity Surface Area Method

The primary quantitative method recommended is the proximal isovelocity surface area (PISA) method, based on the conservation of mass principle, which makes it possible to obtain both TR EROA and RegVol.[10,11,18] Using these measurements alone will not allow the calculation of RegFr, as the total RV SV is not measured. However, the RV SV can be measured by either Doppler or 3DE, and RegFr can be calculated.[83] However, the main anatomic and fluid-dynamic assumptions inherent in the 2D echocardiographic PISA method (i.e., the hemispheric shape of the PISA and an infinitesimally tiny and circular regurgitant area lying on a flat plane) are seldom met in patients with TR: (1) As the regurgitant orifice is relatively large and has an unpredictable shape, and the flow velocity is relatively low compared with that of the mitral regurgitation jet, the geometry of the PISA is frequently flat (elliptical) in patients with moderate or severe TR; (2) the regurgitant orifice is usually large, star shaped, or ellipsoid and generally develops within a nonplanar surface depending on the extent and symmetry of TV leaflet tethering; and (3) the regurgitation is often dynamic and variable throughout systole, so the instantaneous PISA radius measured on a single frame may not be representative of the average PISA radius during the systolic phase of the cardiac cycle.[15,18] These limitations are known to result in underestimation of TR severity in up to 20% to 30% of patients with STR.[15,18] Compared with both volumetric Doppler EROA and 3D VCA, PISA EROA was consistently smaller, especially in patients with atrial fibrillation and more elliptical regurgitant orifices (defined as maximal VC/minimal VC < 1.6).[80,81] However, the underestimation of EROA by PISA may be reduced by correcting for the valve leaflet's tethering angle and the TR jet's relatively low velocity.[84] The susceptibility to an increase in TR severity degree is notably higher in cases in which the TV exhibits a tenting height of 5.5 mm, a tenting area of 1.42 cm^2, and a leaflet angle of 217.5°, particularly following angle correction (Figure 7).[84] This becomes pivotal in patients with V-STR.[84] More recently, 3D PISA has been used to quantify EROA in TR, with a good correlation with 3D VCA ($r = 0.97$).[85] However, irrespective of these issues, PISA-derived EROA and RegVol have been demonstrated to be powerful independent predictors of outcomes.[83,86,87] Additionally, as the progression of patients with mild or moderate TR is not always linear, quantitating the severity of TR enables the identification of patients whose condition is likely to progress to more severe grades, remain stable over time, or improve to mild or trivial TR.[88,89] By identifying these patients and accurately measuring changes in TR severity, we can gain a better understanding of the underlying pathophysiology and the impact of medical treatment.[90]

Directly measuring the planimetry of the TV anatomic regurgitant orifice area (AROA) using 2DE, 3DE, or computed tomography (CT) is a promising tool for assessing TR severity. In a recent study[91] that included 60 patients with symptomatic severe TR undergoing TTVI, tricuspid AROA by CT showed an excellent correlation ($r = 0.93$, $P < .001$) with 3D echocardiographic VCA by TEE, with a stepwise increase in the tricuspid AROA values observed across the expanded TR grades. However, cutoffs of severity are less well defined than for EROA, and its clinical use is still limited.

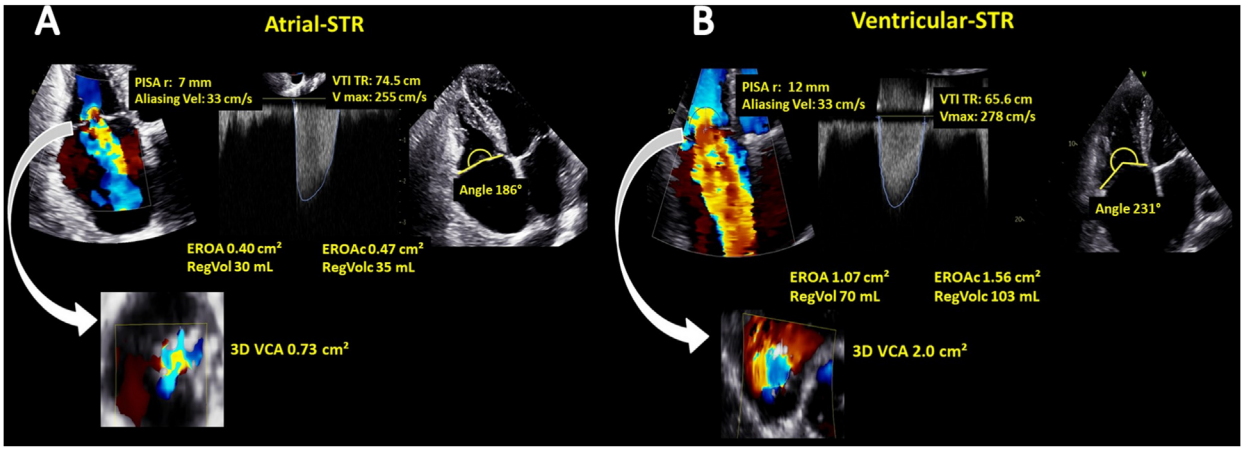


Figure 7 Impact on the quantitative parameters of severity of correcting the conventional PISA method by the leaflet tethering angle and the regurgitant jet velocity in patients with STR. The application of angle correction is more clinically relevant in patients with ventricular **(B)** than atrial **(A)** STR, as the larger tenting of the TV leaflets may lead to the flattening of the PISA hemisphere, resulting in a larger underestimation of TR severity in ventricular than in A-STR compared with the assessment based on the 3D VCA. *EROAc*, Corrected EROA; *RegVolc*, corrected RegVol; *Vmax*, maximal velocity.

Volumetric Methods

The volumetric approach calculates RegVol by subtracting RV forward SV from total RV SV.[10,11,18] These methods can calculate TR RegVol even in the presence of multiple jets and irregular orifices, overcoming the limitations of the PISA method.[10,11,18] The main limitation is that they require the absence of significant concomitant regurgitations of the pulmonary and/or aortic and mitral valves used to measure forward RV SV.[10,11,18] The original Doppler volumetric method calculated RV total SV by multiplying tricuspid annular area (calculated using tricuspid annular diameter obtained from the apical four-chamber view and assuming a circular tricuspid annular shape) by the TV inflow velocity-time integral (obtained by placing the pulse-wave sample volume at the level of the tricuspid annular plane).[92] Forward RV SV (from either the RV or left ventricular outflow tract) was subtracted from RV total SV to obtain RegVol.[92] Dividing RegVol by the velocity-time integral of the continuous-wave Doppler spectrum of the TR jet provides EROA, and dividing RegVol by total RV SV provides RegFr.[92] This method relies on the geometric assumptions of a circular TA and the fact that the tricuspid annular diameter measured in the apical four-chamber view is the actual diameter of that circle. Both are untrue, as discussed above.[15,40] TA is irregularly elliptical except in patients with severe TR, in whom the TA could be more circular and posteriorly displaced.[93] An improvement of the original volumetric method requires the measurement of tricuspid annular diameters as an average of measurements obtained from orthogonal planes (typically parasternal RV inflow and apical four-chamber views) at early diastole and using an ellipse formula to calculate the tricuspid annular area.[18] The latter has been used in a few studies,[5,81] showing a good correlation with 3D VCA ($r = 0.92$, $P < .0001$). However, this method is also based on the geometric assumption of the elliptical geometry of TA and is time consuming. Finally, forward RV SV calculation by Doppler is based on the erroneous assumption of a circular RV outflow tract area.[94] Thus, because of these technical issues, the original Doppler volumetric method was deemed useless in recent guidelines.[11] However, Praz *et al.*[95] have reported that measuring actual tricuspid annular area on transesophageal 3DE allows accurate calculation of the RV filling volume to be used to calculate RegVol and EROA for TR severity grading in comparison with 3D echocardiographic VCA as a reference.

A way to overcome the geometric assumptions of the previous formulas relies on acquiring a 3D data set of the right ventricle and the left ventricle to measure total RV and left ventricular SV. In patients with isolated TR, TR RegVol can be obtained by the difference between 3D RV and left ventricular SVs.[84]

Extended TR Grading Scheme

Recently, it has been proposed to extend the grading of TR severity by including the massive and torrential grades to characterize better patients referred to TTVI.[11,13,16,96] A five-grade scheme has been suggested to assess the results of the first studies assessing the efficacy of TTVI, often leaving patients with severe residual TR after the procedure.[5,97] For example, in the SCOUT (Percutaneous Tricuspid Valve Annuloplasty System for Symptomatic Chronic Functional Tricuspid Regurgitation) trial, a reduction in EROA of -0.22 ± 0.29 mm^2 (from a baseline EROA of 0.85 ± 0.22 mm^2 to a postprocedural EROA of 0.63 ± 0.29 mm^2) was reported.[5] Using the conventional three-grade scheme (i.e., mild, moderate, and severe), the trial would not have shown any hemodynamically significant reduction of TR severity after the procedure,[5,97] highlighting the need to revise TR severity grading.[96] Recent studies outlined the clinical value of the new grading scheme, confirming the prognostic impact of massive and torrential TR.[4,77,98-101] However, looking at the spline curves for various quantitative parameters of TR severity vs all-cause mortality, they do not show any distinct change in the slope that can be used as an argument to justify a categorical grading scheme.[77,83,102] Conversely, the spline curves show a continuous increase in the risk with a tendency to plateau at the highest values of the quantitative parameters that have been evaluated. Accordingly, although it is evident that patients with massive TR, as a group, have a worse prognosis than patients with severe TR, it is crucial to provide an accurate quantitative assessment of TR severity because a patient with EROA of 61 mm^2 (massive TR) does not necessarily have a worse prognosis than a patient with EROA of 58 mm^2 (severe TR).[103]

TREATMENT OPTIONS: TR ASSESSMENT AFTER INTERVENTION

There is limited clinical evidence to support the use of medical therapy for symptomatic patients with significant TR. Current guidelines recommend (class 2a) diuretic agents for patients presenting with right heart failure due to significant TR.[8,9] The recent TVARC recommendations state that the goals of optimal medical therapy should be similar to those of interventional therapy (e.g., to reduce TR severity to less than moderate).[13] However, medical therapy is often not sufficient to reduce TR severity to a moderate grade. In such cases, patients with isolated severe TR who remain symptomatic, or those with moderate to severe TR and tricuspid annular dilatation ≥ 40 mm (≥21 mm/m^2) due to left-sided valve disease should be referred for TV intervention.[8,9] However, probably because of late referral, in-hospital mortality for isolated TV surgery was traditionally reported to be higher (about 10%) compared with other single-valve surgery,[3] which discouraged clinicians from referring patients for TV surgery. Leaving TR untreated will lead to a vicious cycle of "TR begetting more TR," resulting in patients' presenting with high morbidity (ranging around 30%), more advanced stages of right heart failure, and aggravated end-organ damage.[3] The high morbidity and mortality risk among patients referred for TR intervention has led to the development of various transcatheter procedures, including (1) leaflet approximation, (2) direct or indirect annuloplasty, (3) orthotopic valve replacement, and (4) heterotopic valve implantation (caval valve devices).[13,104] Leaflet approximation devices (T-TEER) are currently the most frequently used, but numerous other transcatheter approaches have also shown promising results. However, each TTVI device has a distinctive mechanism of action and requires dedicated postprocedural imaging evaluation to assess its safety and efficacy. Heterotopic valve implantation devices do not act on the TV leaflets themselves or replace the TV valve. Instead, they ventricularize the right atrium by implanting valves upstream of the TV. These devices do not reduce TR severity, and postprocedural TR grading after heterotopic valve implantation does not apply and will therefore not be discussed.

Determination of TR Severity After TTVI

Two-dimensional echocardiography and 3DE are commonly used to assess the severity of TR after TTVI because of their widespread availability. However, it is important to note that even after TTVI, the severity of TR and the extent of the RV and RA remodeling can still be affected by various factors, such as arrhythmias, the respiratory cycle, and volume status. Therefore, it is necessary to assess the results of the procedure under stable loading conditions, which should be similar to those during the preprocedural study. Additionally, the different types of implanted TTVI devices reduce the severity of TR through distinct mechanisms, which may affect the quantitation of TR severity differently. Therefore, it is essential to interpret TR severity with consideration to the implanted TTVI device type and its distinct mechanisms (Table 3).

Evaluation of the reduction of TR after TTVI relies on a comprehensive, predominantly transthoracic, echocardiographic study, such as the one performed before the procedure.[11,13,19] However, it is important to note that some (semi)quantitative and quantitative parameters of TR severity may have limited applicability after TTVI because of residual multiple regurgitant jets after T-TEER or deformation of the annulus and proximal flow convergence by other TTVI devices.[13] Nevertheless, it is still crucial to properly grade TR severity after TTVI, as moderate or more residual TR is associated with adverse outcomes.[14,105,106]

Other imaging modalities may be used to evaluate patients with TR. CMR is also a valid alternative for quantifying TR severity, as well as assessing reverse remodeling, although the cutoffs may vary compared with echocardiographic grading.[19,107] Direct measurement of TV flow is possible with CMR, but it is still of limited use. Instead, indirect quantitative techniques are widely applied to assess TR severity, such as calculating RegVol by subtracting either pulmonic forward SV or left ventricular forward SV (in the absence of other concomitant regurgitant valve lesions) from RV SV, from which RegFr can be derived.[19] Although the use of CMR for TR severity quantitation after TTVI is feasible, further validation is needed. Most TTVI devices are CMR proof, and patients can safely undergo CMR imaging after the TTVI. To date, the Circulatory Systems Device Panel of the TRILUMINATE pivotal trial is the only available evidence on post–T-TEER CMR evaluation, and the preliminary results show that CMR-derived RegVol and RegFr can be used after T-TEER.[108] However, results need to be confirmed in larger cohorts with real-world data, and it remains to be investigated whether the other TTVI devices cause significant artifacts that hinder the accurate CMR quantitation of TR severity. Cardiac CT can be used after TTVI, preferably to assess changes in cardiac size and/or function. However, in the absence of other concomitant valve regurgitation, CT can also provide an estimate of RegVol and RegFr by comparing RV and left ventricular forward SVs.[109] The Circulatory Systems Device Panel of the TRILUMINATE pivotal trial also showed good feasibility of RA and RV assessment after T-TEER.[108] The preliminary data from the CMR and CT imaging substudy confirm a significant TR reduction, favorable right heart reverse remodeling, and improved RV function in patients treated by T-TEER compared with the control group. Both CMR and CT support reverse remodeling after T-TEER relative to the control group. However, measurements by CT were slightly different compared with CMR, with CT showing larger reductions than CMR after T-TEER.

Echocardiographic Qualitative and Semiquantitative Methods. Qualitative parameters, such as TV leaflet morphology, flow convergence zone, and color Doppler signal density and shape, can still be useful after TTVI[13] to estimate TR severity. However, even after TTVI, semiquantitative and quantitative measures are the preferred approaches. Color Doppler imaging can be used among the semiquantitative parameters to identify the presence of TR, the origin of the jet (e.g., multiple jets after T-TEER), and its direction. However, color flow jet area needs to be used with caution, and (as explained earlier) it cannot be used to assess TR severity. Hepatic vein flow pattern is affected by several conditions, such as atrial arrhythmias and RA compliance. As RA compliance may change significantly after TTVI, and new atrial fibrillation can also occur, hepatic vein flow pattern may be less reliable to evaluate TR severity than during preprocedural assessment. However, it could be considered within the multiparametric evaluation. VC width (preferably by averaging measurements obtained from two orthogonal views) and PISA radius remain useful measures to assess TR severity after TTVI.

Echocardiographic Quantitative Methods. One of the most reliable parameters for assessing TR after TTVI is considered 3D VCA planimetry, which is less affected by the different TTVI devices used.[13] On the other end, using quantitative parameters derived from the flow convergence method (PISA EROA and RegVol) can be used

Table 3 Overview of the strengths and limitations of the various echocardiographic parameters used to assess (residual) TR severity or paravalvular leak after TTVI and divided per type of TTVI

Parameter	T-TEER	TV annuloplasty	TTVR
Qualitative parameters			
Jet area	• Remains dependent on color gain settings and the driving pressures • Preferably used to define the origin of the jet (e.g., multiple jets after T-TEER) and jet direction • No validation yet of jet area quantification	• Remains dependent on color gain settings and the driving pressures • Preferably used to define the origin of the jet and jet direction	• Remains dependent on color gain settings and the driving pressures • Normally no residual valvular TR, yet mainly used to detect (the origin of) paravalvular leakage
Density and shape of the TR CW Doppler spectrum	Analogous to preprocedural evaluation • T-TEER devices can potentially create TS, which should be checked before clip-release and during follow-up	Analogous to preprocedural evaluation	Analogous to preprocedural evaluation • Postprocedural inflow gradient dependent on loading conditions, yet longitudinal follow-up may be used to evaluate prosthetic valve thrombosis
Hepatic vein flow reversal	Analogous to preprocedural evaluation • Depends on RA compliance, which may be altered after TTVI • May not be reliable in patients with atrial fibrillation (de novo induced after TTVI) and paced rhythm with retrograde atrial conduction	Analogous to preprocedural evaluation • Depends on RA compliance, which may be altered after TTVI • May not be reliable in patients with atrial fibrillation (de novo induced after TTVI) and paced rhythm with retrograde atrial conduction	Analogous to preprocedural evaluation • Depends on RA compliance, which may be altered after TTVI • May not be reliable in patients with atrial fibrillation (de novo induced after TTVI) and paced rhythm with retrograde atrial conduction
RA/RV and annular remodeling	• Leaflet approximation may cause reduction in TV annular size • TV annular size reduction is best assessed in biplane mode (noncircular annulus) • Mandatory evaluation after TTVI to evaluate reduction in RA and RV size as well as longitudinal and radial function (longitudinal function may be more altered after T-TEER compared with radial function; importance of longitudinal follow-up) • Acute postprocedural decrease in RV FAC, (partly) recovering during follow-up • Clips may cause acoustic shadowing/artifacts complicating adequate RA endocardial delineation • Measures of RV-PA coupling could be useful, taking into account the change in loading conditions after TTVI	• TV annuloplasty causes significant reduction in TV annular size • TV annular size reduction best assessed in biplane mode (noncircular annulus) • Mandatory evaluation after TTVI to evaluate reduction in RA and RV size as well as longitudinal and radial function (longitudinal function may be more altered after TV annuloplasty compared with radial function; importance of longitudinal follow-up) • Acute postprocedural decrease in RV FAC, (partly) recovering during follow-up • Annuloplasty band causes acoustic shadowing/artifacts complicating adequate RA and/or RV endocardial delineation • Measures of RV-PA coupling could be useful, taking into account the change in loading conditions after TTVI	• Acute postprocedural decrease in RV FAC, (partly) recovering during follow-up • Significant acoustic showing/artifacts due to the prosthesis complicating adequate RA and/or RV endocardial delineation

(*Continued*)

Table 3 (*Continued*)

Parameter	T-TEER	TV annuloplasty	TTVR
(Semi)quantitative parameters			
VC	• Remains partially dependent on flow rate and the driving pressure • Preferably the average of two orthogonal views should be used: cave at acoustic shadowing/artifacts • The use of the biggest VC measure has been proposed; adding multiple measures of VC width from multiple jets is not yet validated	Analogous to preprocedural evaluation	If residual TR is present, then analogous to preprocedural evaluation
VCA (3D)	• Remains dependent on color gain settings and the spatial resolution of 3D echocardiographic color • Multiple jets can be measured and summed	Analogous to preprocedural evaluation	If residual TR is present, then analogous to preprocedural evaluation
PISA	• Device will mechanically interfere with the shape of the proximal flow, deviating it even more from the hypothetical hemispheric shape, resulting in an overestimation of the TR severity	Analogous to preprocedural evaluation • Annuloplasty band may cause acoustic shadowing/artifacts complicating adequate PISA evaluation	If residual TR is present, then analogous to preprocedural evaluation • Useful for central TR
Doppler volumetric method	• Can be applied in multiple or eccentric jets • Diastolic flow restriction caused by the TTVI device results in diastolic SV overestimation • Can be used when RV SV is measured by 3D echocardiographic volumetric methods or CMR measurements • Difficult to use intraprocedurally	• Annuloplasty band causes acoustic shadowing/artifacts complicating adequate TV annular sizing • Diastolic flow restriction caused by the TTVI device results in diastolic SV overestimation • Can be used when RV SV is measured by 3D echocardiographic volumetric methods or CMR measurements • Difficult to use intraprocedurally	• TV prosthesis may cause acoustic shadowing/artifacts complicating adequate TV annular sizing • Difficult to use intraprocedurally
3D echocardiographic volumetric method	• Most trustworthy parameter after TTVI and least influenced by the various TTVI devices • Can be applied in multiple or eccentric jets • Difficult to use intraprocedurally	• Most trustworthy parameter after TTVI and least influenced by the various TTVI device • Difficult to use intra-procedure	• Most trustworthy parameter after TTVI and least influenced by the various TTVI devices • Difficult to use intraprocedurally

CW, Continuous-wave; *TS*, tricuspid stenosis; *TTVR*, transcatheter TV replacement.

in TR grading after TTVI, especially in patients who have undergone T-TEER, annuloplasty, or orthotopic valve implantation. In the SCOUT trial, PISA EROA was found to underestimate quantitative EROA by >50%.[5,19] The calculation of RegFr may also be affected by TTVI, as the diastolic flow restriction caused by the TTVI device may lead to an overestimation of diastolic SV. However, it is still possible to calculate RegFr after TTVI if total RV SV is measured using other methods, such as 3DE or CMR, and RegVol is quantified by 3D VCA.[13]

RV and RA Reverse Remodeling. Following TTVI, it is important to consider the changes in the size and function of the right chambers as part of the assessment of TR severity. However, there are conflicting results published regarding RV reverse remodeling after TTVI, and no data are available regarding RA reverse remodeling.[14] These contradictory results may be related to the nonstandardized approach and different imaging techniques used to measure RV dimension and function after TTVI. Both T-TEER devices (by exerting traction on the TA through leaflet approximation) and transcatheter annuloplasty devices can reduce annular size, thereby reducing basal RV diameters.[110-114] However, TTVI procedures, particularly TV annuloplasty,[110,115] may affect longitudinal RV function, as measured by TAPSE or Doppler tissue imaging S, similar to surgical annuloplasty.[116] RV FAC encompasses both longitudinal and radial function and may therefore better assess RV function. However, RV FAC has shown low reproducibility and also depends on geometric assumptions and loading conditions. In the presence of significant TR, RV FAC often overestimates

actual RV myocardial function because of the increased preload.[117] By treating significant TR with TTVI, RV preload will reduce together with RV dimensions. However, RV end-diastolic dimensions are more preload dependent, whereas RV end-systolic dimensions are more afterload dependent.[118] As a result, RV end-diastolic area will decrease to a greater extent than RV end-systolic area, resulting in a postprocedural decrease in RV FAC. Measures of RV-PA coupling could be useful considering the change in loading conditions after TTVI. In a subanalysis of the TriValve registry, analyzing 234 patients undergoing TTVI, 30-day RV-PA coupling (assessed using TAPSE/PASP ratio) did not change significantly (baseline TAPSE/PASP − 30-day TAPSE/PASP = −0.04 ± 0.21 mm/mm Hg).[56]

Transcatheter TEER

Of all TTVI devices, leaflet approximation devices may interfere the most with TR jet assessment. By being placed in the center of the TR jet and grasping two of the TV leaflets, the T-TEER device will alter most of the normal physics of the TR jet. First, the device will mechanically interfere creating artifacts and/or abnormal shape of the proximal flow that lead to a nonhemispheric shape of the isovelocity surface. As a result, PISA radius length may result in an overestimation of the TR severity.[13]

Second, the T-TEER device often creates two or more orifices with multiple jets going in different directions, which must be evaluated separately for the assessment of TR severity. Whereas the summation of the 2D echocardiographic VCs of the multiple jets has yet to be validated, the best approach is currently considered the sum of the 3D echocardiography VCAs of all residual TR jets, which should therefore always be attempted (Figure 8).[13]

Third, the device causes significant acoustic shadowing, complicating TR assessment by echocardiography. The acoustic shadowing increases with the number of clips, which, in the TriValve registry, were on average 2 ± 1 (range, 0–5) clips.[111] In addition, T-TEER devices, by approximating two of the TV leaflets, create traction and consequent TA remodeling (significant reductions in septal-lateral diameter, planimetric area, and perimeter[112] and possibly RA and RV remodeling. In a study of 47 patients undergoing T-TEER, significant TA and RV reverse remodeling was observed, with reductions at 6-month follow-up in RV end-diastolic area of 12.3% (29.1 vs 25.2 cm^2), RV end-systolic area of 11.9% (18.5 vs 16.2 cm^2), and septal-lateral TV annular diameter of 6% (47.3 vs. 44.4 mm).[112,119] It is therefore important to assess the result of T-TEER immediately after the procedure and also during follow-up, as TR severity may vary over time because of ongoing RA, RV, and TA remodeling.

Finally, T-TEER devices can potentially, although rarely, create tricuspid stenosis when multiple clips are deployed. Continuous-wave Doppler measurements should include pressure half-time, peak and mean transtricuspid diastolic gradients, peak and mean transtricuspid systolic gradients and the diastolic velocity-time integral.[13] A periprocedural mean transtricuspid diastolic gradient ≥5 mm Hg should be considered to indicate significant stenosis, which should prevent the physician from deploying further clips, although no clear impact on outcomes has been so far demonstrated.[120]

Transcatheter TV Annuloplasty

Quantitation of TR severity after TV annuloplasty is generally not significantly different compared with preprocedural evaluation, as the TV will still consist of a single orifice, with an anatomy and pathophysiology similar to those of the native TV. Most Doppler measurements, except for the hepatic vein flow, which may be affected by changes in RA compliance, remain unaffected by TV annuloplasty for the assessment of residual TR.[19] However, the annuloplasty ring may cause acoustic shadowing, making it difficult in some cases to assess leaflet motion and coaptation. After TV annuloplasty, the position, geometry, and dimension of the annuloplasty band (and therefore of the TA annulus) should be assessed by using 2DE or preferably 3DE (Figure 9). In some cases, anchors may detach, altering the shape of the annulus and causing residual TR at an unusual location, mostly posterior to the annuloplasty device (causing para-ring leakage [PRL]).[19]

Miscellaneous

PRL may occur after transcatheter TV replacement and has been described as mild in about 10% of cases and moderate in 1.5% of cases.[6,7] It is important to perform adequate echocardiographic

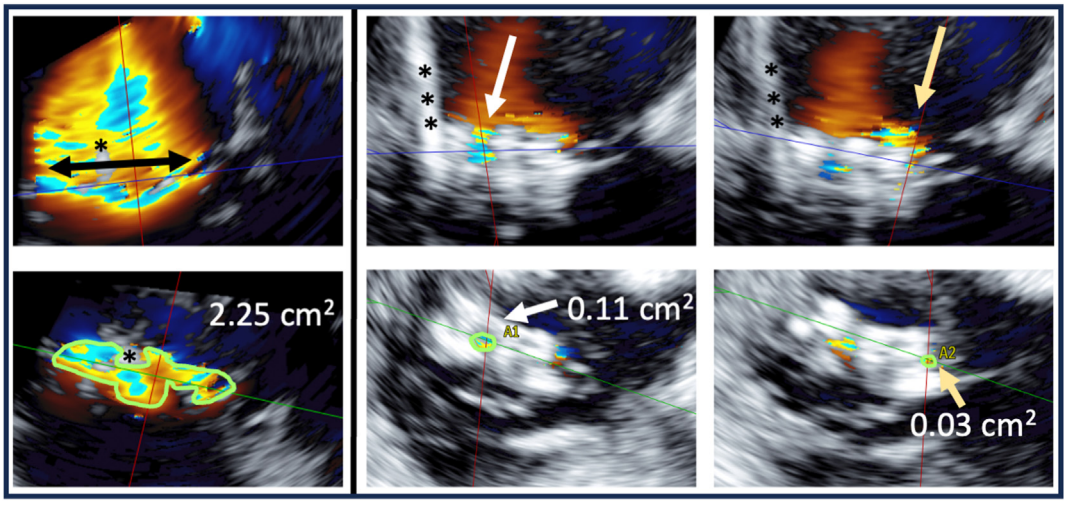


Figure 8 Three-dimensional echocardiography for TR quantification after T-TEER. Torrential (with also incidental presence of a pacemaker lead, *asterisks*) TR with a VCA of 2.25 cm^2 before the procedure *(left)*. After the implantation of three T-TEER devices, two mild residual jets were detected between the devices. The posterior jet had a VCA of 0.11 cm^2 *(middle)*, and the anterior jet had a VCA of 0.03 cm^2 *(right)*.

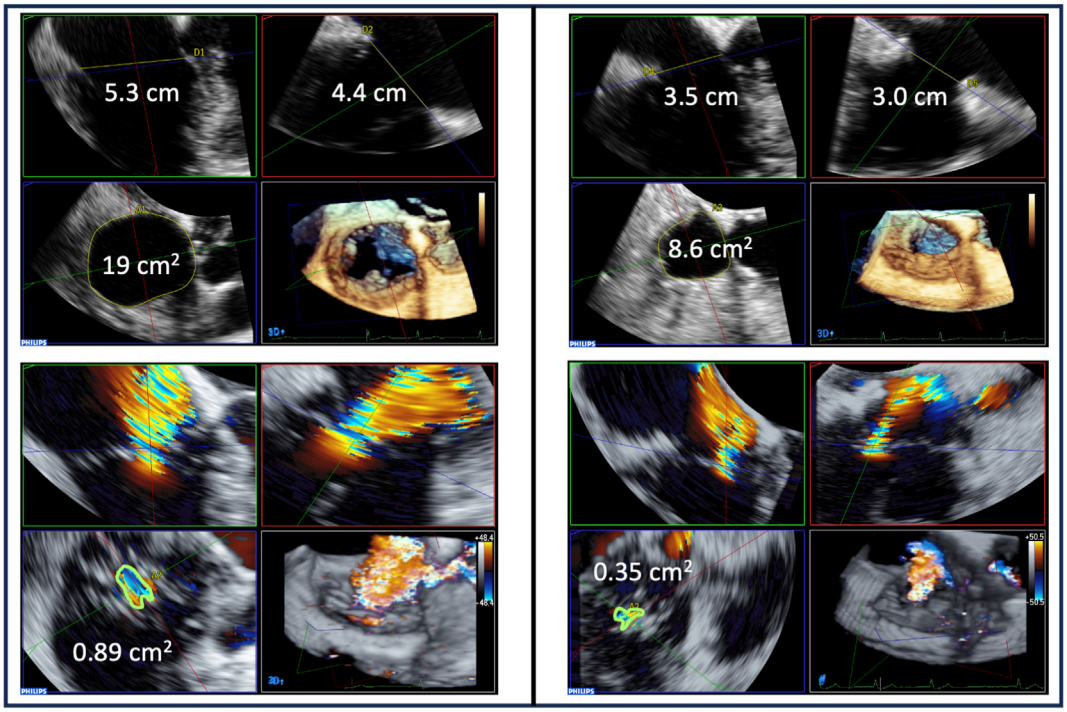


Figure 9 Three-dimensional echocardiography for TR severity quantification after TV annuloplasty. Annular size and VCA before *(left)* and after *(right)* TV annuloplasty are useful to quantify immediate annulare contraction (from 19 to 8.6 cm^2) and acute TR reduction (from 0.89 to 0.35 cm^2).

evaluation to determine the severity and the location of PRL both intraprocedurally and during follow-up, when subsequent transcatheter PRL closure may be required.

TTE can provide sufficient information in TV PRL cases compared with mitral valve PRL cases, in which TEE is the preferred imaging method. However, TEE or intracardiac echocardiography may be required to obtain additional anatomic and functional details. In both cases, 3DE is also of paramount importance for evaluating PRL.

When describing PRL on 3DE, it is crucial to standardize the views to identify the location of the TV PRL (Figure 10).[121] The interatrial septum should be positioned at 6 o'clock. When performing TTE, the 3D volume is normally rotated to image the TV leaflets from the right ventricle with the aorta to the right side. When performing TEE, the 3D volume is normally rotated to image the TV leaflets from the right atrium with the aortic valve to the left side.[121] Ideally, the assessment should be performed from both the RA and RV perspectives.

Next, the size and shape of the defect must be quantified. Color Doppler is used to identify and confirm defects and differentiate them from dropout or artifacts secondary to acoustic shadowing from the prosthesis. Additionally, CT and CMR can provide additional information when echocardiography is unclear.

CONCLUSION

The TV is not just another atrioventricular valve positioned on the right side of the heart, for which we are allowed to use the same echocardiographic techniques, parameters, and cutoff values we have developed for the mitral valve. The TV has a peculiar anatomy

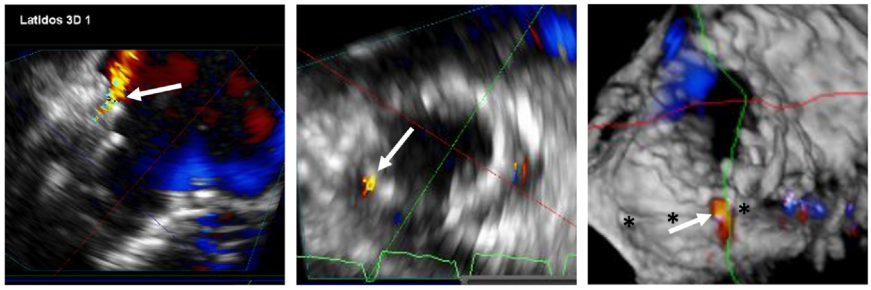


Figure 10 Three-dimensional echocardiography for TR quantification after transcatheter TV replacement in a severe lead-associated TR. After the implantation of an orthotopic Cardiovalve prosthesis, multiplanar reconstruction was useful to trace the residual jet *(arrow)* around the lead *(asterisks)*, with a small VCA (<10 mm^2).

and works in a hemodynamic environment (volumetric pump), which differs from the mitral valve (pressure pump). Accordingly, to assess the TV and the severity of TR, we need a dedicated multiparametric approach using the appropriate echocardiographic techniques and adapting the severity parameters to the peculiar hemodynamics of the TV. This approach becomes even more important in patients undergoing TTVI, as each TTVI will affect the assessment of TR severity with distinct mechanisms and specific limitations. This review describes the state-of-the-art use of echocardiography to assess the severity of TR and the geometry and function of the right heart structures before and after TTVI, which should be applied in a standardized fashion to obtain a consistent assessment and allow the comparison of data collected from different studies.

REVIEW STATEMENT

Given her role as *JASE* Editor-in-Chief, Patricia A. Pellikka, MD, and given their roles as *JASE* Associate Editors, Luigi P. Badano, MD, PhD, and Nina Ajmone Marsan, MD, PhD, had no involvement in the peer review of this article and have no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to James D. Thomas, MD.

CONFLICTS OF INTEREST

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