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ORIGINAL RESEARCH

Comparison of Echocardiographic Assessment of Tricuspid Regurgitation Against Cardiovascular Magnetic Resonance

Yang Zhan, MD,[a] Alpana Senapati, DO,[a] Pimprapa Vejpongsa, MD,[a] Jiaqiong Xu, PhD,[a,b] Dipan J. Shah, MD,[a] Sherif F. Nagueh, MD[a]

ABSTRACT

OBJECTIVES The aim of this study was to compare echocardiographic methods of determining tricuspid regurgitation (TR) severity against TR regurgitant volume (TR_{RV}) by cardiovascular magnetic resonance (CMR).

BACKGROUND TR is usually assessed using echocardiography, but it is not known how this compares with quantitative measurements of TR severity by CMR.

METHODS Echocardiographic and CMR methods were compared in 337 patients. Echocardiographic methods included jet size, hepatic vein flow, inferior vena cava diameter, percentage change in inferior vena cava diameter with inspiration, right atrial end-systolic area and volume, right ventricular end-diastolic and end-systolic areas and fractional area change, vena contracta diameter, effective regurgitant orifice area, and TR_{RV} using the proximal isovelocity surface area method. TRRV by CMR was calculated as the difference between right ventricular end-diastolic and end-systolic volumes and systolic flow through the pulmonic valve.

RESULTS Echocardiographic parameters of TR severity had variable accuracy against TR_{RV} by CMR (area under the curve range 0.58 for jet area/right atrial end-systolic area to 0.79 for hepatic vein flow). A multiparametric approach to assessing TR severity according to the 2017 American Society of Echocardiography criteria had 65% agreement with TR severity by CMR. A hierarchal approach based on signals with higher feasibility and accuracy against CMR had 68% agreement, without missing cases of severe TR by CMR. Agreement with CMR by the hierarchal approach was higher than that by the 2017 American Society of Echocardiography guidelines ($p = 0.016$).

CONCLUSIONS Several individual echocardiographic parameters of TR severity have satisfactory accuracy against TR_{RV} by CMR. A multiparametric hierarchal approach resulted in 68% agreement with CMR and 100% agreement when a 1-grade difference in TR severity is considered acceptable. (J Am Coll Cardiol Img 2020;13:1461–71)
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Trace or mild tricuspid regurgitation (TR) commonly occurs (1), but increasing TR severity has adverse effects on the right ventricle, causing systemic congestion and decreased cardiac output. In severe TR, surgery or percutaneous intervention may be needed (2). Therefore, correct assessment of TR severity is important. For most patients, echocardiography is the imaging modality that is used. Recently, the American Society of Echocardiography (ASE) updated its guidelines (3). The

From the [a]Department of Cardiology, Houston Methodist DeBakey Heart & Vascular Center, Houston, Texas; and the [b]Center for Outcomes Research, Houston Methodist Research Institute, Houston, Texas. The authors have reported that they have no relationships relevant to the contents of this paper to disclose.
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ABBREVIATIONS AND ACRONYMS

ASE = American Society of Echocardiography

AUC = area under the receiver-operating characteristic curve

CMR = cardiac magnetic resonance

CW = continuous-wave

EDA = end-diastolic area

EF = ejection fraction

EROA = effective regurgitant orifice area

ESA = end-systolic area

FAC = fractional area change

LV = left ventricular

PISA = proximal isovelocity surface area

RA = right atrial

RV = right ventricular

SV = stroke volume

TR = tricuspid regurgitation

TR_{RV} = tricuspid regurgitation regurgitant volume

TVI = time-velocity integral

V_a = aliasing velocity

VC = vena contracta

V_p = peak tricuspid regurgitation velocity

recommendations were based on consensus opinion of experts, but without validation. Unlike mitral regurgitation, few studies have reported on the clinical application of echocardiographic measurements without comparison against cardiac magnetic resonance (CMR).

CMR provides accurate measurements of flow and has been validated in vitro and in vivo (4,5). CMR methodology is not affected by regurgitant orifice shape and quantifies TR regurgitant volume (TR_{RV}). Furthermore, blood flow velocities can be measured from the entire region of interest without assuming a flat flow profile. For example, CMR measurements of mitral regurgitation volume successfully identified patients with severe MR and adverse outcomes (6). Likewise, CMR is the gold standard for right ventricular (RV) size and ejection fraction (EF) (7). TR_{RV} is obtained on CMR as the difference between the stroke volume (SV) ejected by the right ventricle with each cardiac cycle and systolic blood flow through the pulmonic valve (3). Therefore, we sought to compare echocardiographic indexes of TR severity against CMR TR_{RV} and derive an algorithm to grade TR severity on the basis of the performance of echocardiographic measurements against CMR. The partition values for severity recommended in the ASE guidelines were applied: mild, TR_{RV} <30 ml; moderate, TR_{RV} 30 to 44 ml; and severe, TR_{RV} ≥45 ml (3).

METHODS

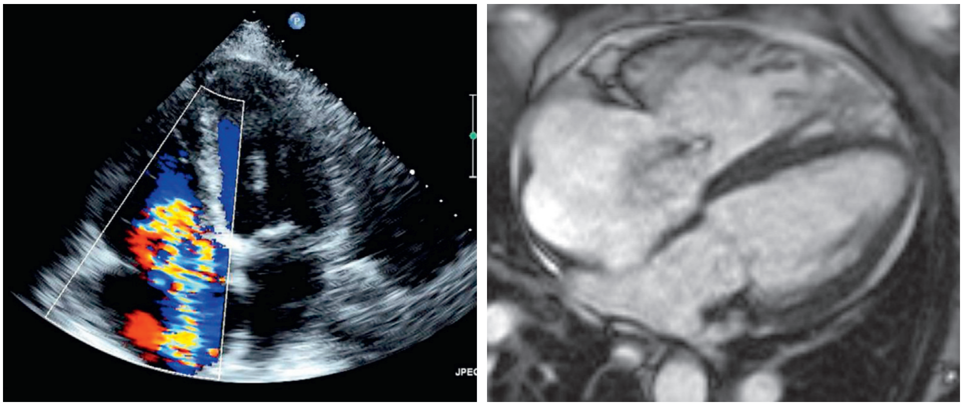
PATIENT POPULATION. Between 2008 and 2017, all patients with TR who underwent CMR and echocardiographic imaging within 60 days, without apparent differences in hemodynamic status, were included. Imaging was obtained for clinical indications. None had greater than mild pulmonic regurgitation, congenital heart disease, or left-to-right shunts. Patients with pacemakers or implantable cardioverter-defibrillators were excluded because leads interfere with CMR measurements of RV volumes through metallic void and shadowing artifacts. Patients with atrial fibrillation were excluded because of beat-to-beat variation in RV volumes and flow measurements by CMR.

ECHOCARDIOGRAPHIC IMAGE ACQUISITION. Image acquisition was performed in standard views. Color/pulsed-wave and continuous-wave (CW) Doppler was used. TR was evaluated in RV inflow, parasternal short-axis at the aortic valve level, and apical 4-chamber views. Efforts were made to capture the complete jet, including the proximal flow convergence zone, vena contracta (VC), and jet area. The TR jet was interrogated using CW Doppler in multiple views. Hepatic venous flow was sampled using pulsed-wave Doppler. Inferior vena cava maximal diameter was acquired at 2 cm from the junction with the right atrium during spontaneous respiration and sniffing (if there was no spontaneous collapse). Sonographers obtained additional images as needed, to optimize TR jet visualization.

ECHOCARDIOGRAPHIC ANALYSIS. RV end-diastolic area (EDA), end-systolic area (ESA), and right atrial (RA) ESA were measured in the apical 4-chamber view and indexed to body surface area following chamber quantification guidelines (8). RV fractional area change (FAC) was calculated as (RV EDA − RV ESA)/RV EDA, with normal FAC ≥35% (8). Jet area, VC, and proximal flow convergence were measured in all views with satisfactory imaging. The TR jet was classified as central or eccentric, and the ratio of jet area to RA ESA was obtained. TR effective regurgitant orifice area (EROA) and TR_{RV} were computed offline after proximal isovelocity surface area (PISA) radius and aliasing velocity (V_a) were tabulated. EROA was derived with the correction factor as $2 \times \Pi \times \text{radius}^2 \times V_a/(V_p - V_a)$, where V_p is peak TR velocity by CW Doppler (9). The correction factor $[V_p/(V_p - V_a)]$ was used to minimize PISA flow rate underestimation. TR_{RV} was the product of EROA and the time-velocity integral (TVI) of the TR jet by CW Doppler. Feasibility of satisfactory measurements was highest in the apical 4-chamber view and lowest in the parasternal short-axis view.

The CW signal of the TR jet was graded according to whether it was incomplete (grade 1), complete but less dense than tricuspid inflow (grade 2), or of equal brightness to tricuspid inflow (grade 3). Jet contour by CW Doppler was parabolic (grade 1) or early peaking triangular contour (grade 2). Hepatic venous flow was graded on the basis of systolic and diastolic flow signals with the average of 5 cardiac cycles into 1 of 4 categories: systolic dominance (grade 1), systolic TVI = diastolic TVI (grade 2), diastolic dominance (grade 3), and systolic flow reversal (grade 4). RV enlargement was present if RV EDA index was >12.6 cm²/m² in men and >11.5 cm²/m² in women (8). RA enlargement was present if RA volume index was >39 ml/m² in males and >33 ml/m² in women (8). Echocardiographic analyses were performed without knowledge of CMR measurements.

FIGURE 1 **Severe TR by Color Doppler Echocardiography and CMR**



(Right) Color Doppler of severe tricuspid regurgitation (TR) showing a large TR jet that fills the right atrium. **(Left)** Four-chamber view showing dilated right atrium, dilated right ventricle, and dilated tricuspid annulus from the same patient. CMR = cardiovascular magnetic resonance.

IMPACT OF $[V_p/(V_p - V_a)]$ on EROA AND TR_{RV}. ASE cutoff values for TR severity using PISA were based on a study that applied the correction factor (10). In several patients, underestimation of EROA and regurgitant volume occurs. Therefore, the previously validated correction factor is needed (9,10).

To assess whether different aliasing velocities affect corrected EROA and TR_{RV}, we measured in 20 patients with varying degrees of TR proximal flow convergence radius in the apical 4-chamber view at aliasing velocities of 35, 45, 55, and 65 cm/s. V_p and TVI were measured to calculate instantaneous flow rate, EROA, and TR_{RV} at each of the 4 velocities. The correction factor $[V_p/(V_p - V_a)]$ was then applied, and "corrected" values were computed.

ECHOCARDIOGRAPHIC CRITERIA USED FOR TR SEVERITY BY 2017 GUIDELINES. TR severity was graded first by looking for specific criteria of mild and severe TR (**Figures 1 and 2**). The following were considered consistent with mild TR: 1) VC <0.3 cm; 2) incomplete TR jet by CW Doppler; 3) systolic flow dominance in the hepatic veins; 4) normal RA volume index and normal RV EDA index (3); and, although not included in the algorithm of the 2017 update; and 5) jet area <5 cm^2, which was considered consistent with mild TR on the basis of 2003 guidelines (11). TR was severe if the following criteria were met: 1) VC ≥0.7 cm; 2) central jet area/RA ESA ratio ≥50%; 3) dense TR jet by CW Doppler with triangular or sine wave pattern; 4) systolic flow reversal in the hepatic veins; and 5) enlarged RV with FAC ≥35%. TR was mild or severe if >50% of available mild or severe parameters were met (all parameters having equal weight). If ≤50% of signs of mild or severe TR were present, VC diameter, EROA, and TR_{RV} were considered, and TR severity was determined by the majority of the 3 measurements (3).

HIERARCHICAL MODEL FOR GRADING TR SEVERITY ON THE BASIS OF THE RECOMMENDED VARIABLES IN THE 2017 ASE GUIDELINES. The 2017 guidelines do not specify an order in which measurements may be applied. We devised a hierarchal approach based on starting with variables with high feasibility and accuracy against CMR. VC, EROA, and TR_{RV} were used in later steps, if needed, to arrive at a final conclusion (**Central Illustration**). The model was derived from the first 237 patients and validated in the last 100 patients, using CMR measurements of TR_{RV} as the reference method.

The first parameter evaluated was CW Doppler of the TR jet. In the presence of a dense and triangular jet, the next step is to examine hepatic vein flow. With systolic reversal, severe TR was present. In the absence of hepatic vein flow signal or absence of systolic flow reversal, and if RV size was enlarged with normal FAC, severe TR was present. If RV size was normal or the right ventricle was enlarged but with reduced FAC, quantitation with VC, EROA, and TRRV was sought to determine TR severity.

If the CW Doppler jet was faint and incomplete or dense but rounded, the next step was evaluation of RV size. With normal RV size, hepatic vein flow was examined. In the presence of predominant systolic flow, mild TR was concluded. If other findings were present in hepatic vein flow (systolic TVI = diastolic TVI or predominant diastolic flow), quantitation with

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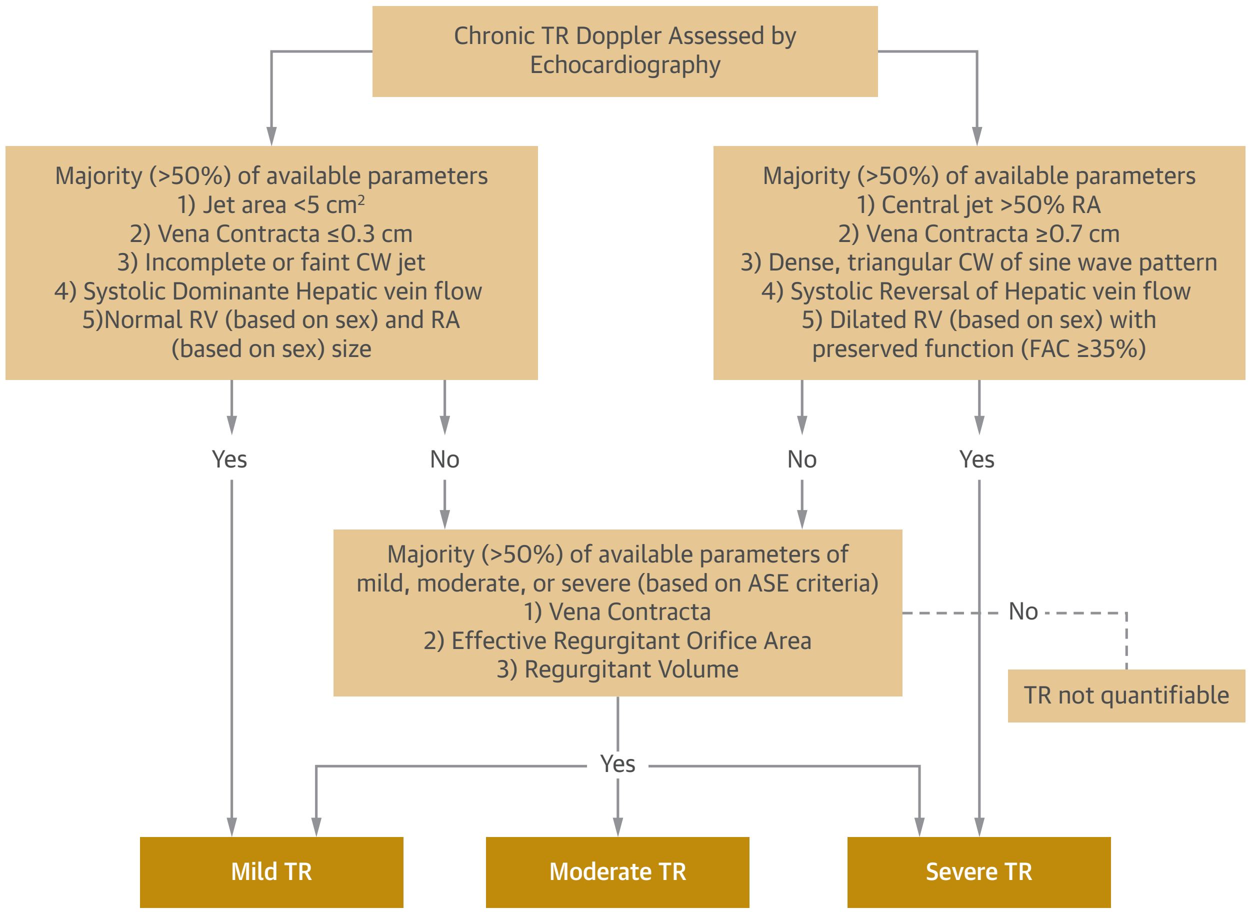
FIGURE 2 The 2017 ASE Recommendations for Assessment of TR Severity



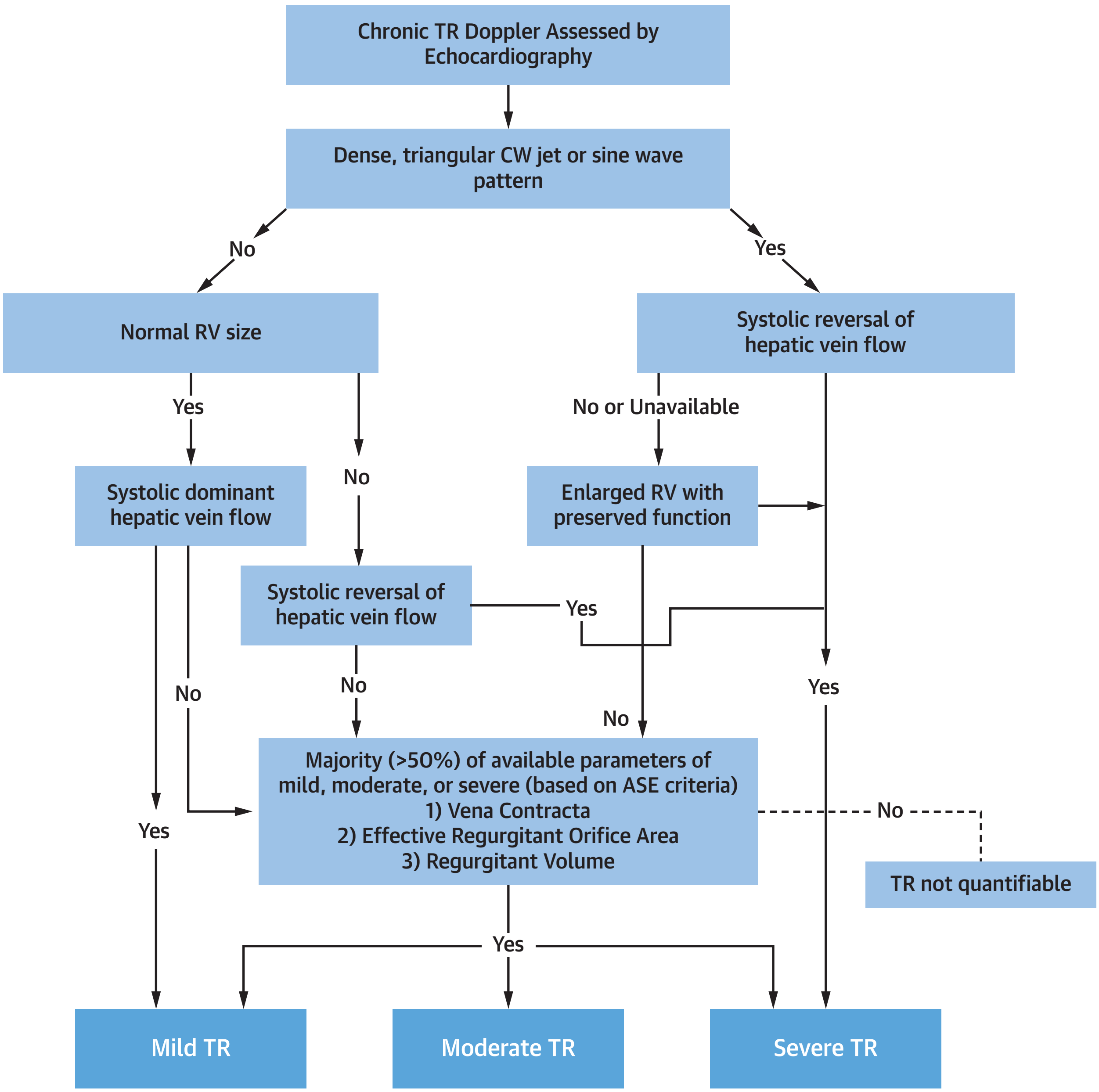
Modified with permission from Zoghbi et al. (3). ASE = American Society of Echocardiography; CW = continuous-wave; FAC = fractional area change; RA = right atrial; RV = right ventricular.

VC, EROA, and TR_{RV} was sought. However, an enlarged right ventricle with systolic flow reversal in hepatic vein flow, severe TR was present. If the right ventricle was enlarged and there was no systolic reversal in hepatic vein flow, VC, EROA, and TR_{RV} were considered. In the absence of the latter signals and for central jets, jet area and the ratio of jet area to RA ESA were used to draw conclusions about TR severity. For eccentric jets in the absence of quantitative signals, jet area findings were used to support severe TR if, despite being eccentric, jet area was >10 cm^2 or the ratio of jet area to RA end-systolic area was at least 50%.

CMR IMAGING AND ANALYSIS. CMR images were acquired using 1.5- or 3.0-T clinical scanners (Siemens Avanto, Aera, and Skyra, Siemens Healthineers, Erlangen, Germany) with phased-array coil systems. RV imaging was acquired via short-axis stacks with colocalization using 4-chamber and RV inflow-outflow views using steady-state free precession sequences with a typical flip angle of 65° to 85°, 3-ms repetition time, 1.3-ms echo time, 1.7 to 2.0 mm × 1.4 to 1.6 mm in-plane spatial resolution, 6-mm slice thickness, 4-mm interslice gap, and temporal resolution of 35 to 40 ms. Slices were prescribed from basal RV slice to apex. Flow across the pulmonic valve was assessed using phase-contrast imaging with a flip angle of 25° to 30°, repetition time of about 5 ms, 2.4-ms echo time, reconstructed in-plane spatial resolution of about 2.0 × 2.4 mm, 6-mm slice thickness, and temporal resolution of about 40 to 50 ms.

Left ventricular (LV) and RV volumes, mass, and EF were measured per CMR guidelines (12). LV

CENTRAL ILLUSTRATION Hierarchal Approach to Assess TR Severity



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Echocardiographic variables and their sequence on the basis of signals with highest feasibility and accuracy against TR regurgitant volume by CMR. Quantitative measurements are used later, if qualitative indicators are absent, equivocal, or discrepant with one another. Abbreviations as in Figure 1.

replacement fibrosis was assessed (13). Left atrial and RA volumes were measured using biplane area-length and single plane area-length methods, respectively (14). Tricuspid annular diameter was measured in the 4-chamber view in early diastole (15).

RV SV was determined by subtracting RV end-systolic volume from end-diastolic volume. RV EF was calculated as SV/end-diastolic volume. Pulmonary artery forward flow was computed by tracing pulmonary artery borders on phase-contrast imaging

TABLE 1 Baseline Characteristics of Patient Population Stratified by TR Regurgitant Volume Measured by CMR

		Regurgitant Volume			
	All (N = 337)	Mild (n = 209)	Moderate (n = 67)	Severe (n = 61)	p Value
Age (yrs)	58 ± 15	59 ± 15	59 ± 15	57 ± 16	0.734
Male	178 (53)	110 (53)	37 (55)	31 (50)	0.85
Body mass index (kg/m^2)	27.6 ± 6.3	27 ± 6	28.5 ± 6.6	28 ± 6.8	0.239
Systolic BP (mm Hg)	123 ± 19	124 ± 20	124 ± 19	120 ± 16	0.396
Diastolic BP (mm Hg)	72 ± 14	72 ± 14	72 ± 13	71 ± 12	0.834
Heart rate (beats/min)	78 ± 16	79 ± 17	75 ± 14	75 ± 17	0.07
GFR (ml/min/1.73 m^2)	75 ± 34	79 ± 31*	68 ± 35	69 ± 39	0.027
History of atrial fibrillation	72 (23)	35 (18)*	18 (32)	19 (35)	0.009
Hypertension	206 (61)	128 (62)	40 (60)	38 (61)	0.974
Hyperlipidemia	144 (43)	102 (49)*	21 (31)	21 (34)	0.011
Family history of CAD	158 (47)	103 (50)	27 (40)	28 (45)	0.405
Diabetes mellitus	76 (23)	48 (23)	15 (23)	13 (21)	0.965
History of smoking					0.161
Current	123 (37)	82 (39)	18 (27)	23 (38)	
Former (>1 yr)	23 (7)	10 (5)	7 (10)	6 (10)	
Never	191 (57)	117 (56)	42 (63)	32 (52)	
CAD	76 (23)	43 (21)	19 (30)	14 (23)	0.337
Myocardial infarction	46 (14)	27 (13)	11 (16)	8 (13)	0.748
Dyspnea	181 (58)	112 (57)†	28 (49)	41 (73)	0.025
Heart failure	147 (44)	87 (42)	25 (37)	35 (57)	0.069
ACE inhibitor or ARB	123 (37)	81 (39)	22 (33)	20 (32)	0.489
Aspirin	137 (41)	92 (44)	23 (34)	22 (35)	0.231
Diuretic agents	172 (51)	99 (47)	28 (42)	45 (74)	<0.001
Beta-blockers	175 (52)	108 (52)	34 (52)	33 (54)	0.975
Spironolactone	59 (18)	33 (16)	9 (13)	17 (27)	0.084
Statin	123 (37)	86 (42)	19 (28)	18 (29)	0.064

Values are mean ± SD or n (%). Diagnosis of heart failure was based on symptoms and signs of pulmonary or systemic congestion along with chest radiographic findings, serum natriuretic peptide levels, and echocardiographic findings. *$p < 0.05$ vs. patients with moderate or severe TR. †$p < 0.05$ vs. patients with severe TR.

ACE = angiotensin-converting enzyme; ARB = angiotensin receptor blocker; BP = blood pressure; CAD = coronary artery disease; CMR = cardiovascular magnetic resonance; GFR = glomerular filtration rate; TR = tricuspid regurgitation.

in every frame to determine flow and then summating flows during systole. TR_{RV} was calculated by subtracting pulmonary artery forward flow from RV SV. CMR analysis was performed without knowledge of echocardiographic findings. CMR post-processing was conducted using WEBPACS (HeartIT, Durham, North Carolina).

STATISTICAL ANALYSIS. Continuous variables are presented as mean ± SD and categorical variables as number (percentage). Differences among patients with mild, moderate, and severe TR were compared using one-way analysis of variance for continuous variables, followed by pairwise comparison using Bonferroni correction. The Shapiro-Wilk test was applied to test for normal distribution. Chi-square or Fisher exact tests were used for categorical variables. Pairwise Student's *t*-tests were used to compare blood pressure and heart rate at the time of CMR and echocardiographic examinations. Receiver-operating characteristic curve analysis was applied to assess the area under the receiver-operating characteristic curve (AUC) and accuracy analysis for the individual echocardiographic variables for severe TR. Repeated-measures analysis of variance followed by Wilcoxon matched-pairs signed rank test were applied to compare flow rate, EROA, and TR_{RV} at the 4 aliasing velocities. The McNemar test was used to compare agreement between echocardiographic algorithms and CMR for TR severity. All analyses were performed using Stata version 15 (StataCorp, College Station, Texas). Statistical significance was defined as $p < 0.05$.

RESULTS

There were 355 patients in this cohort, with a mean time difference of 10 ± 14 days between the 2 examinations. Suboptimal echocardiographic images led to the exclusion of 18 patients. Baseline characteristics of the remaining 337 patients are listed in Table 1. There were 16 patients with primary TR, and the remainder had secondary TR. There were 2 patients with tricuspid valve prolapse. The other patients with primary TR had infective endocarditis, carcinoid heart disease, and TR after heart transplantation. Patients with secondary TR had group I, II, or III pulmonary hypertension.

On the basis of CMR, there were 209 patients with TR_{RV} <30 ml, 67 with TR_{RV} 30 to 44 ml, and 61 with TR_{RV} ≥45 ml. There were no significant differences in blood pressure and heart rate at time of the 2 examinations ($p > 0.10$).

CMR FINDINGS. A small proportion of patients had LV replacement fibrosis. Although left atrial maximum volume index, LV mass index, and RV EF were not significantly different among the 3 groups (Table 2), RV volumes, RA maximum volume index, and tricuspid annular diameter increased significantly with TR progression.

ECHOCARDIOGRAPHIC FINDINGS. RA volumes and RV EDA and ESA increased with progression of TR severity (Table 2), but similar to RV EF by CMR, there was no difference in RV FAC among the 3 groups. Jet area, jet area/RA ESA ratio, VC, EROA, and TR_{RV} increased with increasing TR severity. TR jet area/RA ESA for eccentric jets was not statistically different among the 3 groups, highlighting the limitations of jet size in patients with eccentric jets.

PISA CALCULATION AND FLOW CORRECTION. After correction, instantaneous flow rate, EROA, and TR_{RV} were not significantly different at the 4 aliasing velocities (Table 3). There were no statistically

TABLE 2 Echocardiographic and CMR Measurements in Patient Groups Stratified by CMR-Determined TR Regurgitant Volume

		Regurgitant Volume			
	All (N = 337)	Mild (n = 209)	Moderate (n = 67)	Severe (n = 61)	ANOVA p Value
CMR measurements					
LA volume index (ml/m^2)	65 ± 31	63 ± 24	67 ± 33	69 ± 44	0.352
LV EDV index (ml/m^2)	93.3 ± 41.5	96.9 ± 40	91.6 ± 48.3	83.3 ± 37.2	0.071
LV ESV index (ml/m^2)	48.3 ± 40	52.4 ± 41.5	42.5 ± 42	40.7 ± 30.3	0.053
LV EF (%)	53.5 ± 19.3	51.6 ± 20.8*	58.2 ± 15.5	55.1 ± 16.5	0.04
LV mass index (g/m^2)	77.1 ± 27.6	77.5 ± 26.2	79.0 ± 34	73.6 ± 24.5	0.516
LV scar size (%)	3.8 ± 8.1	3.7 ± 7.2	3.1 ± 7.6	4.9 ± 11.5	0.543
RA volume index (ml/m^2)	62 ± 37	49 ± 22*	65 ± 28†	100 ± 55	<0.001
TV annular diameter (mm)	36 ± 7.7	34 ± 7.1*	38 ± 5.8†	42 ± 8.0	<0.001
RV EDV index (ml/m^2)	109.9 ± 42.3	95.8 ± 30.6*	114.8 ± 31.6†	152.0 ± 55.4	<0.001
RV ESV index (ml/m^2)	62.3 ± 38.1	55.1 ± 31.9*	64.2 ± 32.4†	84.4 ± 52.3	<0.001
RV EF (%)	46.4 ± 15.1	45.8 ± 16.2	46.6 ± 13.5	48.0 ± 13.2	0.614
Echocardiographic measurements					
TR jet area (cm^2)	5.4 ± 5	3.3 ± 3.1*	6.6 ± 5.1†	10.5 ± 5.7	<0.001
TR jet area/RA area (%)	22 ± 18	16 ± 13*	28 ± 22†	35 ± 18	<0.001
Central jets	23 ± 19	17 ± 14*	31 ± 23†	37 ± 19	<0.001
Eccentric jets	27 ± 15	21 ± 14	27 ± 17	34 ± 15	0.095
Vena contracta (cm)	0.5 ± 0.3	0.4 ± 0.2*	0.6 ± 0.3†	0.8 ± 0.4	<0.001
Corrected EROA (cm^2)	0.53 ± 1	0.27 ± 0.2*	0.66 ± 1.5†	1.1 ± 1.4	<0.001
Corrected regurgitant volume (ml)	39 ± 45	24 ± 19*	43 ± 45†	72 ± 66	<0.001
RA volume index (ml/m^2)	44 ± 28	34 ± 19*	48 ± 25†	70 ± 39	<0.001
RV EDA index (cm^2/m^2)	12.8 ± 4.5	11.6 ± 3.6	13.5 ± 3.7†	16.5 ± 5.9	<0.001
RV ESA index (cm^2/m^2)	8.3 ± 4.2	7.4 ± 3.4	8.8 ± 3.2†	10.9 ± 5.9	<0.001
RV fractional area change (%)	37 ± 14	38 ± 14	36 ± 14	37 ± 15	0.567

Values are mean ± SD. *$p < 0.05$ vs. moderate and severe TR. †$p < 0.05$ vs. severe TR.

ANOVA = analysis of variance; EDV = end-diastolic volume; EF = ejection fraction; EROA = effective regurgitant orifice area; ESV = end-systolic volume; LA = left atrial; LV = left ventricular; RA = right atrial; RV = right ventricular; TV = tricuspid valve; other abbreviations as in Table 1.

significant differences between color Doppler measurements when compared in patients with satisfactory data available from all 3 views or when 2 of 3 views were available. Conclusions about TR severity were the same when the mean or largest value was considered in the analysis, as all sets (2 or 3 sets) were largely concordant after excluding suboptimal images.

ACCURACY OF INDIVIDUAL MEASUREMENTS IN IDENTIFYING TR SEVERITY. Table 4 shows sensitivity, specificity, and AUC of the individual echocardiographic measurements with cutoff values recommended in the 2017 ASE guidelines on the basis of TR_{RV} by CMR (cutoff values for corrected EROA and TR_{RV} in Table 4 had the largest AUCs). Significant but modest correlations were present between quantitative echocardiographic measurements (VC, corrected and uncorrected EROA and TR_{RV}) and TR_{RV} by CMR, ranging from 0.36 to 0.49 ($p < 0.05$ for all).

ACCURACY OF THE 2017 GUIDELINES IN CLASSIFYING TR SEVERITY. Using the 2017 ASE guidelines, 36 patients (11%) had >50% of the signals with findings meeting criteria for severe TR, while 136 patients (40%) had >50% of the signals with findings of mild TR. TR severity was determined in 165 patients (49%) on the basis of quantitation. Among these 165 patients, final conclusions could not be reached in 34 (10% of the cohort), because of equal numbers of discordant criteria, where VC, EROA, and TR_{RV} corresponded to different degrees of TR severity.

Therefore, in 303 of 337 patients (90%), conclusions about TR severity could be reached. In 197 patients (65%), echocardiography and CMR were concordant in assigning the same grade of TR severity. Considering a 1-grade difference acceptable, echocardiography agreed with CMR in 287 (95%). In the remaining cases, 2 patients had severe TR by CMR but mild TR by echocardiography, and 14 patients with mild TR by CMR had severe TR by echocardiography (Table 5). The conclusions pertaining to TR severity in the 14 patients misclassified by echocardiography were based on color Doppler in the absence of satisfactory hepatic vein recordings.

HIERARCHICAL APPROACH TO GRADE TR SEVERITY. In the derivation cohort of 237 patients, there were 142 cases of mild, 51 of moderate, and 44 of severe TR

TABLE 3 Correction of Flow Rate Using $V_p/(V_p - V_a)$ in 20 Patients With Varying TR Severity

	Aliasing Velocity (cm/s)				
	35	45	55	65	p Value
PISA radius	0.47 ± 0.4	0.41 ± 0.4	0.37 ± 0.3	0.33 ± 0.3	<0.001
Instantaneous flow rate (ml/s)					
Uncorrected	91 ± 222	85 ± 193	77 ± 167	75 ± 170	0.005
Corrected	110 ± 276	109 ± 257	104 ± 241	110 ± 266	0.502
EROA (cm^2)					
Uncorrected	0.44 ± 1.2	0.40 ± 1.08	0.36 ± 0.94	0.36 ± 0.94	0.006
Corrected	0.53 ± 1.6	0.52 ± 1.4	0.49 ± 1.4	0.53 ± 1.5	0.455
TR_{RV} (ml)					
Uncorrected	27 ± 61	25 ± 53	23 ± 46	22 ± 47	0.004
Corrected	32 ± 76	32 ± 71	30 ± 66	32 ± 73	0.601

Values are mean ± SD.

PISA = proximal isovelocity surface area; TR_{RV} = tricuspid regurgitation regurgitant volume; V_a = aliasing velocity; V_p = peak TR velocity by continuous-wave Doppler; other abbreviations as in Tables 1 and 2.

by CMR. Echocardiography was concordant with CMR in assigning the same grade in 163 patients (69%). When a 1-grade difference in severity was considered acceptable, the concordance rate was 98% (233 patients). There were only 4 patients with mild TR by CMR (TR_{RV} 19, 23, 25, and 26 ml) who were classified with severe TR by echocardiography (Table 5). Echocardiography correctly identified 36 of the 44 patients with severe TR by CMR, but 8 were thought to have moderate TR. Of the 8 patients deemed to have moderate TR by echocardiography but severe TR by CMR, TR_{RV} by CMR was 47 ml in 2, 48 ml in 2, and 50 to 57 ml in the remaining patients. Of the 15 patients deemed to have severe TR by echocardiography but moderate TR by CMR, TR_{RV} by CMR was 40 ml in 2 patients, 41 ml in 1 patient, 42 ml in 2 patients, 44 ml in 2 other patients, and 31 to 38 ml in the remaining patients. Of the 21 patients with moderate TR by CMR but mild TR by echocardiography, CMR TR_{RV} was 30 ml in 3, 31 ml in 2, 32 ml in 1, 33 ml in 4, and 34 to 43 ml in the remaining patients.

In the validation cohort of 100 patients, there were 67 cases of mild TR, 16 cases of moderate TR, and 17 cases of severe TR by CMR. Echocardiography correctly graded TR severity, compared with CMR, in 72 patients (72%). When a 1-grade difference in severity was considered acceptable, the concordance rate increased to 100%. Importantly, there were no patients with severe TR by CMR who were considered to have mild TR by echocardiography, and there were no patients deemed to have severe TR by echocardiography but only mild TR by CMR (Table 5). Of the 5 patients with moderate TR by echocardiography and severe TR by CMR, TR_{RV} by CMR was 47 ml in 1 patient and 52 to 65 ml in the remaining patients.

Next, all patients included in the analysis of hierarchal approach accuracy (n = 337) and the 303 patients (in whom conclusions about TR severity could be reached) included in the analysis of the 2017 ASE guidelines were evaluated for agreement with CMR. The hierarchal approach had significantly higher agreement with CMR ($p = 0.016$). Table 6 presents the agreement between echocardiography and CMR with patients classified into 2 groups: severe and nonsevere TR.

The agreement between echocardiography (hierarchal approach) and CMR was evaluated in the subgroup of 33 patients with eccentric TR jets. There were 11 patients with severe TR by CMR. TR was deemed severe in 9 of the 11 patients by echocardiography, and in the other 2, TR was graded as moderate. There were 7 patients with moderate TR by CMR, and 5 of the 7 were deemed to have moderate

TABLE 4 Accuracy of Echocardiographic Parameters for Severe TR (Defined as TR_{RV} ≥45 ml)

	n	Guideline Threshold	AUC (95% CI)	Sensitivity (%)	Specificity (%)
VC diameter	236	≥7 mm	0.65 (0.59–0.72)	39	91
EROA	216	≥0.4 cm^2	0.75 (0.68–0.81)	80	70
TR_{RV}	216	≥45 m	0.72 (0.64–0.79)	61	82
Jet area/RA area	294	>50% (for central jets)	0.58 (0.52–0.64)	27	92
Jet contour	335	Triangular	0.69 (0.62–0.75)	40	97
Jet density	335	Dense	0.67 (0.61–0.73)	39	96
Jet contour and density	335	Triangular and dense	0.63 (0.57–0.68)	26	99
Hepatic vein	265	Systolic reversal	0.79 (0.73–0.86)	72	87
Dilated right ventricle with normal FAC	183	RV EDA index >12.6 for men and >11.5 for women with FAC ≥35%	0.74 (0.66–0.82)	76	73
Jet area (both central and eccentric jets)	300	>10 cm^2	0.70 (0.63–0.76)	48	92
IVC maximal dimension	301	>2.5 cm	0.66 (0.59–0.73)	45	87

AUC = area under the receiver-operating characteristic curve; CI = confidence interval; FAC = fractional area change; IVC = inferior vena cava; n = number of patients in whom satisfactory measurements were feasible in the apical 4-chamber view, VC = vena contracta; other abbreviations as in Tables 2 and 3.

TR by echocardiography, while 1 patient was graded mild and the second patient was graded severe (TR_{RV} by CMR was 40 ml in the latter patient, graded as severe by echocardiography). There were 15 patients with mild TR by CMR. Of these, 13 were graded as having mild lesions, and 2 were graded as having moderate lesions by echocardiography. Thus, echocardiography correctly graded the severity of TR, compared with CMR, in 27 of 33 patients (82%). When a 1-grade difference in severity was considered acceptable, the concordance rate increased to 100%. There were 16 patients with primary TR, of whom 11 had severe TR and 5 had moderate TR. Good agreement was present between the 2 imaging modalities at 81%.

DISCUSSION

Several individual echocardiographic parameters of TR severity have satisfactory accuracy when compared against TR_{RV} by CMR. Using a hierarchal approach, conclusions about TR severity could be reached in all patients. Using the hierarchal approach, there were no patients with severe TR by CMR who were classified with mild TR by echocardiography.

CW DOPPLER OF THE TR JET. The brightness and contour of the TR jet by CW Doppler were highly specific for severe TR. Nevertheless, improper alignment with the direction of the TR jet can lead to underestimation of severity, which can be difficult to avoid in eccentric jets. Likewise, proper alignment with a central jet can result in a bright signal in mild TR. Finally, the contour of the TR jet, while influenced by TR severity, is also affected by the systolic RV-RA pressure gradient and therefore RV systolic function and loading conditions as well as RA stiffness, which can be abnormally elevated in the absence of severe TR. Thus, it is advantageous to consider both aspects of the TR jet by CW Doppler. In particular, when both findings were present, specificity was excellent at 99% for severe TR.

PULSED-WAVE Doppler OF HEPATIC VENOUS FLOW. Systolic flow reversal is seen with severe TR. One must pay attention not to confuse systolic flow reversal due to TR with the small mid-systolic reversal signal or late diastolic reversal seen with RA contraction. Systolic reversal had good accuracy, though specificity was not 100% (87% specificity for severe TR), as systolic reversal can occur because of markedly increased RA stiffness and thus highly elevated RA "V"-wave pressure despite a TR lesion that is not severe. Likewise, patients with RV pacing and atrioventricular dyssynchrony can have some cardiac cycles with systolic reversal when the right atrium contracts against the closed tricuspid valve because of RV contraction at the same time. Thus, cardiac rhythm should be considered in the exercise to grade TR severity using hepatic venous flow. Although blunting of forward systolic flow may be seen with moderate TR and at times severe TR, a similar flow pattern occurs with elevated RA pressure with only trivial or mild TR (16), thus the limited specificity of diastolic flow dominance for severe TR in patients with systemic congestion and elevated mean RA pressure.

TABLE 5 Comparison of CMR and Echocardiography

	CMR Mild	CMR Moderate	CMR Severe	Total
Using ASE 2017 guidelines				
Echocardiography mild	147 (49)	30 (10)	2 (<1)	179 (59)
Echocardiography moderate	28 (9)	8 (3)	10 (3)	46 (15)
Echocardiography severe	14 (5)	22 (7)	42 (14)	78 (26)
Total	189 (62)	60 (20)	54 (18)	303 (100)
In 237 patients of the derivation cohort using the hierarchal approach				
Echocardiography mild	112 (47)	21 (9)	0 (0)	133 (56)
Echocardiography moderate	26 (11)	15 (6)	8 (3)	49 (21)
Echocardiography severe	4 (2)	15 (6)	36 (15)	55 (23)
Total	142 (60)	51 (22)	44 (19)	237 (100)
In 100 patients of the validation cohort using the hierarchal approach				
Echocardiography mild	54 (54)	8 (8)	0 (0)	62 (62)
Echocardiography moderate	13 (13)	6 (6)	5 (5)	24 (24)
Echocardiography severe	0 (0)	2 (2)	12 (12)	14 (14)
Total	67 (67)	16 (16)	17 (17)	100 (100)

Values are n (%).
ASE = American Society of Echocardiography; CMR = cardiovascular magnetic resonance.

TABLE 6 Comparison of CMR and Echocardiography

	CMR Nonsevere	CMR Severe	Total
Using ASE 2017 guidelines with patients classified as severe or nonsevere TR			
Echocardiography nonsevere	213 (70)	12 (4)	225 (74)
Echocardiography severe	36 (12)	42 (14)	78 (26)
Total	249 (82)	54 (18)	303 (100)
In 237 patients of the derivation cohort using the hierarchal approach with patients classified as severe or nonsevere TR			
Echocardiography nonsevere	174 (73)	0 (0)	174 (73)
Echocardiography severe	19 (8)	44 (19)	63 (27)
Total	193 (81)	44 (19)	237 (100)
In 100 patients of the validation cohort using the hierarchal approach with patients classified as severe or nonsevere TR			
Echocardiography nonsevere	81 (81)	5 (5)	86 (86)
Echocardiography severe	2 (2)	12 (12)	14 (14)
Total	83 (83)	17 (17)	100 (100)

Values are n (%).
Abbreviations as in Tables 1 and 5.

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RA SIZE AND RV SIZE. RA and RV size can be used to draw inferences about TR severity in patients with chronic but not acute TR, as there is no time for compensatory changes in acute lesions. Patients with mild TR usually have normal RA and RV volumes, whereas severe chronic TR is accompanied by enlarged chambers. We noted several patients in our study with mild TR but with enlarged right atria and right ventricles. This finding occurs in patients with secondary TR due to RV enlargement with or without RV systolic dysfunction. Therefore, the mere presence of chamber enlargement with reduced FAC should be carefully considered along with other indexes of TR severity as well as the clinical setting. Notwithstanding, as recommended in guidelines (3), the presence of an enlarged right ventricle with normal FAC has acceptable accuracy, with an AUC of 0.74 in our study for severe TR, and should trigger more careful evaluation of other signals to confirm the presence of severe TR.

VC- AND PISA-BASED MEASUREMENTS OF TR SEVERITY. VC measurements had good specificity in identifying patients with mild and severe TR. However, many patients with severe TR had VC <7 mm, and additional variables were needed to identify these patients.

Overall, corrected EROA and TR_{RV} had reasonable accuracy in identifying patients with severe TR (AUCs of 0.75 and 0.72, respectively). The accuracy of TR_{RV} is particularly acceptable given the variability of the method and the small difference in TR_{RV} between mild and severe TR advocated in the 2017 ASE guidelines (16-ml difference between mild and severe TR). Given the additional time needed to perform these calculations along with their variability, we considered PISA-based measurements as a later step, if needed, in the hierarchal approach, as opposed to relying on both measurements in the first set of criteria. This is in line with the 2017 guidelines, which recommend VC, TR_{RV}, and EROA as a second step for determining the presence of moderate TR (3).

COMPARING THE 2017 GUIDELINES WITH A HIERARCHAL APPROACH FOR TR ASSESSMENT. TR assessment by the 2017 ASE guidelines and by the hierarchal approach were concordant with CMR in 65% to 68% of cases, with 95% to 100% agreement when accepting a difference of 1 grade. The hierarchal approach classified TR severity in all patients, while the 2017 guidelines classified TR in 90% of patients because of suboptimal signals or an equal number of discordant variables. In addition, there were no patients in the hierarchal approach, in both the derivation and validation groups, in whom severe TR by CMR was graded mild by echocardiography. However, severe TR by CMR TR_{RV} was graded mild by echocardiography in 2 patients (0.7%) using the 2017 guidelines. Overall, the hierarchal approach had significantly higher agreement with CMR classification of TR severity, albeit with small overall difference with 2017 guidelines.

STUDY LIMITATIONS. To reliably assess TR using CMR, factors that affect the accuracy of RV volumes measurement and pulmonary blood flow were excluded (pacemakers or implantable cardioverter-defibrillators and atrial fibrillation). With respect to echocardiography, 18 patients (5.1%) had technically challenging studies that precluded echocardiographic evaluation of TR severity. In addition, we could not assess all echocardiographic variables in all patients, with somewhat lower feasibility for PISA-based measurements. Lower feasibility of PISA-derived EROA and TR_{RV} was seen in patients with mild but not moderate or severe TR, for which quantitative measurements have greater importance to judge response to treatment. In patients with mild TR, one can usually grade TR severity without the need to proceed to quantitative measurements. Importantly, it was possible to classify TR severity in all patients using the hierarchal approach with acceptable accuracy.

The time interval between echocardiography and CMR was 10 $\pm$ 14 days. Although we noted that heart rate and systemic blood pressure were similar between the 2 examinations, pre-load and afterload conditions might have been different. The hierarchal approach was prospectively validated in 100 patients, and additional studies are needed. Clinical outcomes could be of value in understanding discrepant findings between CMR and echocardiographic assessment of TR severity, the objective of future studies. Characterization of RV structure using late gadolinium enhancement could shed additional light on RV pathology in patients with TR.

ADDRESS FOR CORRESPONDENCE: Dr. Sherif F. Nagueh, Methodist DeBakey Heart & Vascular Center, 6550 Fannin, SM-677, Houston, Texas 77030. E-mail: snagueh@houstonmethodist.org.

PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: Assessment of TR severity by echocardiography is feasible and has acceptable accuracy compared with TR_{RV} measured by CMR. Higher feasibility and accuracy can be achieved by starting with qualitative signals that place a given patient into either the mild or severe group and then using quantitative parameters as a second step when the qualitative signals are either absent or equivocal.

TRANSLATIONAL OUTLOOK: TR assessment using a hierarchal approach based on routinely acquired signals is an appealing method to grade TR. Its performance in prospective patient groups with a wide range of TR severity should be evaluated against that of CMR. Its utility to judge response to treatment is of interest.

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