



# Comparison of biplanar- with 3D-vena contracta and vena contracta area for the assessment of tricuspid valve regurgitation by intraoperative transesophageal echocardiography

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**Background:** Tricuspid regurgitation (TR) is often incidentally detected at intraoperative transesophageal echocardiography (TEE), resulting in possible changes in the surgical plan. The aim of this study was to compare 2D and 3D measurements of TR vena contracta width (VCW) and the degree of TR severity using TEE from the three standard mid-esophageal (ME) views.

**Methods:** In a prospective observational study, we analyzed 3D and 2D TEE datasets from 30 adult patients undergoing elective tricuspid valve (TV) repair. 2D and 3D TEE color flow Doppler (CFD) loops of the TV in the three standard ME views (4Chamber, RV inflow-outflow (inflow) and modified bicaval) were recorded immediately after induction of anesthesia. VCW from single views and the average of the measurement of biplane VCW (2D biplane VCW) from each standard view were compared with the maximum and minimum diameters of the 3D vena contracta area (VCA) and their average (3D average VCW). TR severity classification was compared between 2D biplane VCW and 3D average VCW and VCA. Correlation between measurements was analyzed using Pearson coefficient and agreement assessed using the Bland-Altman method. Cohen's Kappa correlation was used to assess TR severity concordance.

**Results:** Biplane VCW in all three ME views underestimated 3D average VCW measurement, with VCW from ME inflow view showing the best agreement. VCW measurements in single standard views systematically underestimated the maximum 3D VCA diameter. We detected very good agreement in TR grading between 3D average VCW and 3D VCA, and an underestimation by 2D biplane VCW (moderate agreement for inflow and fair for the other views). Intra- and inter-observer correlation when repeating 2D measurements was more reliable than that for 3D measurements.

**Conclusions:** Our study shows that 2D biplane VCW from the ME inflow view best agrees with 3D average VCW and allows the most accurate classification of TR severity compared to 3D average VCW.

**Keywords:** Tricuspid valve regurgitation (TV regurgitation); vena contracta; transesophageal echocardiography (TEE); cardiac surgery; 3D echocardiography



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## Introduction

Preoperative evaluation of tricuspid regurgitation (TR) should be based on transthoracic echocardiography (TTE) in euvoletic, awake, spontaneously breathing patients (1-3).

However, incidental finding of TR by intraoperative transesophageal echocardiography (TEE) in patients undergoing left-sided valve surgery is not uncommon and should prompt a change in the surgical plan (4-7).

Guidelines recommend concomitant tricuspid valve (TV) surgery when TR is severe, and should be considered for moderate primary TR or mild-to-moderate secondary TR in cases of TV annular dilatation (1). Intraoperative quantification of TR severity is challenging as current guidelines are based on TTE; however, a multi-parametric approach has been recently suggested for TEE (3,5).

The most commonly used and technically simpler parameter to grade TR severity is the quantification of the regurgitant jet vena contracta width (VCW) by color flow Doppler (CFD). VCW measurement in a single imaging plane assumes that the regurgitation orifice is circular (8). However, in patients with TR, due to the variable anatomy of the TV, the lack of leaflet coaptation results in non-uniform complex geometrical regurgitant orifices (9,10), which leads to inaccuracies in TR grading based on a single-plane linear measurement (9,11,12). Averaging the VCW width obtained from two orthogonal TEE views (biplane imaging) has been proposed to increase quantification accuracy (2,13,14).

Three-dimensional color Doppler analysis using multiplanar reconstruction (MPR) allows measurement of the anatomical TR vena contracta area (3D VCA) and the maximum and minimum diameters independent of its shape (2,15-18). Although the direct relationship between 3D VCA cutoffs and outcomes is still debated, this measurement has been increasingly used (9,19-21) and is included in the latest expert recommendations (2,20,22).

Measurement of the average VCW using biplane imaging (2D biplane VCW), is simpler and faster, however, the standard mid-esophageal (ME) TEE view that allows the most accurate 2D biplane VCW measurement is yet to be defined.

The primary aim of our study was to compare 2D biplane VCW from each standard ME TV view with the average VCW by 3D Color Doppler (3D average VCW). We hypothesized that the 2D biplane VCW from one of the three standard ME TV views would best correlate with 3D average VCW. The secondary aim was to compare 2D VCW from each single standard ME view with the maximum and minimum 3D VCW diameters. Finally, we compared the TR severity using 2D biplane VCW, 3D average VCW, and 3D VCA (2,13).

## Methods

We conducted a prospective observational study in a tertiary care cardiac surgical center. The study was approved by the

university research ethics board (number 489/19-ek) and was conducted following the principles of the Declaration of Helsinki.

All consecutive adult patients with TR, planned for elective TV surgery (isolated or in combination with other cardiac procedures), from October 2020 to October 2022 were considered for recruitment in this study. Patients younger than 18 years, those with prior TV surgery or transcatheter interventions, contraindication to TEE, and those who did not provide written consent were excluded from the study.

## Data acquisition

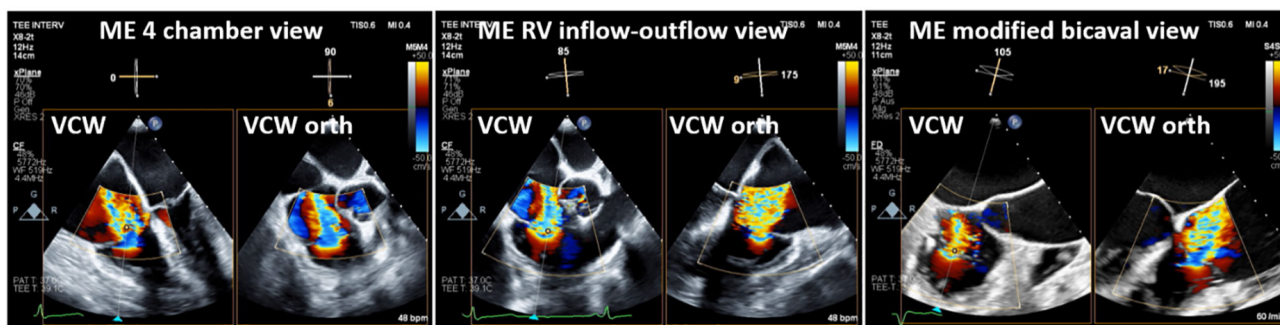
All echocardiographic datasets were obtained using an EPIQ CVX™ ultrasound system and a X8-2t™ TEE probe (Philips Medical Systems, Andover, MA, USA). All echo loops were acquired by certified echocardiographers following the same acquisition protocol.

After induction of general anesthesia and tracheal intubation, but before skin incision, a comprehensive TEE examination was performed according to current guidelines (5). The 2D and 3D images of the TV with and without CFD were acquired at the beginning of the examination to minimize any changes in physiological conditions using the following sequence: ME four chamber view (ME 4CH), ME inflow-outflow view (ME inflow), and ME modified bicaval view (ME mBC).

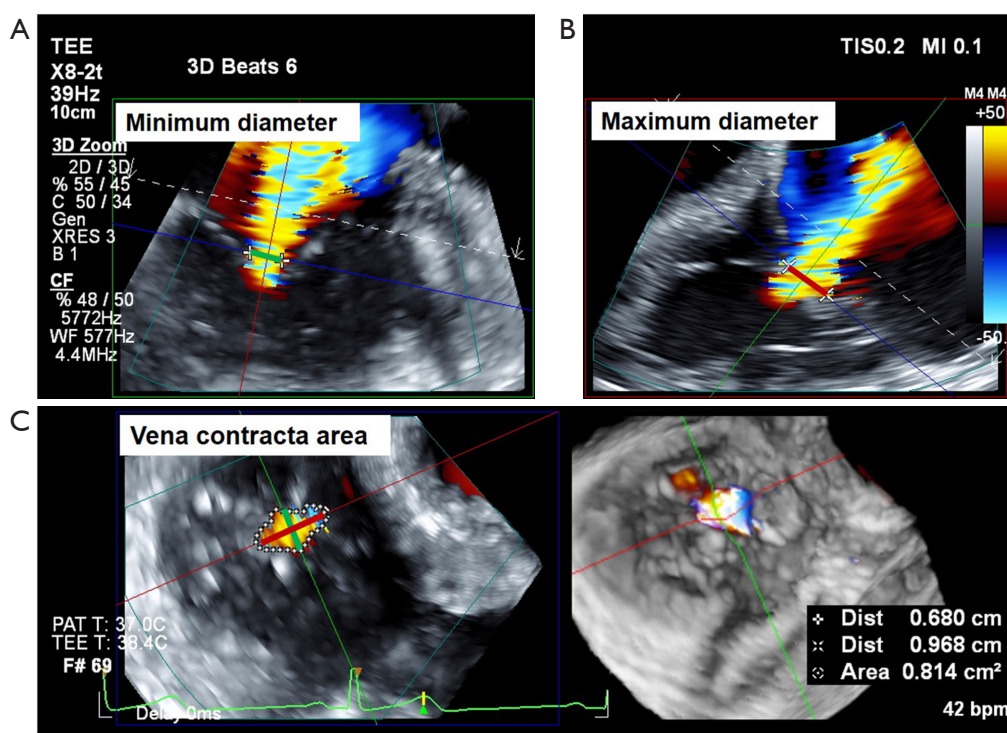
In each standard view, 2D images were optimized adjusting focus, depth, and gain. The color Doppler sector was then centered at the origin of the TR jet to include the flow convergence. For biplane acquisition the color sector was adjusted to include the VCW and the orthogonal plane was placed through the center of the TR jet. Nyquist limit was set to 50 cm/s, color gain adjusted to the highest limit that avoided tissue artifacts, and the wall filter was set to “high” (*Figure 1*).

3D color volumes were acquired from ME inflow view during apnea using 3D zoom acquisition mode. The region of interest was set to include the entire TR jet. ECG-gated multi-beat acquisition was used with the same color Doppler settings as for 2D views. Datasets with a volume rate of less than 15 Hz or with stitch artifacts were excluded.

All TEE datasets were digitally stored in the Image Arena workstation (TomTec, Unterschleissheim, Germany) for later offline analysis. 2D and 3D measurements were performed by the main study investigator offline using 3DQ 15.0 cardiac software from the Phillips QLAB package



**Figure 1** 2D color Doppler biplane acquisition of ME standard views: ME 4Chamber, ME RV inflow-outflow and ME modified bicaval view. 2D, 2-dimensional; ME, midesophageal; orth, orthogonal; RV, right ventricle; VCW, vena contracta width.



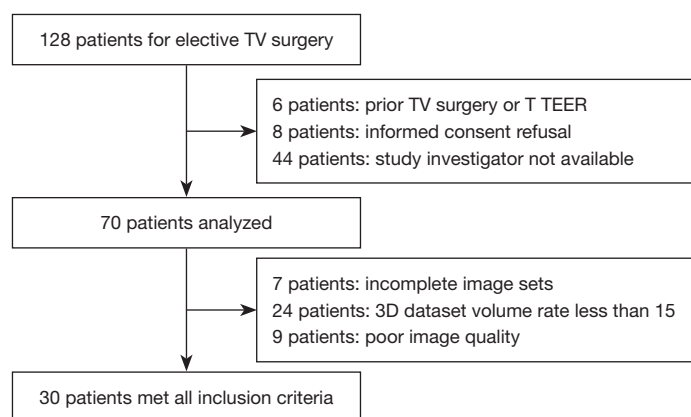
**Figures 2** Offline multiplanar reconstruction of a 3D Color Doppler dataset. 3D color multiplanar reconstruction of tricuspid regurgitant jet from a mid-esophageal 3D view. (A) Minimum VCW diameter (green). (B) Maximum VCW diameter (red). (C) Cross-sectional area with both diameters superimposed (blue). 3D, 3-dimensional; VCW, vena contracta width.

(Philips Medical Systems, Handover, MA, USA).

All measurements were done on the frame with the maximum TR jet size during systole.

The 3D average VCW was calculated on 3D color Doppler volume sets using MPR (Figure 2). The green (Figure 2A) and red (Figure 2B) planes were positioned to align with the center of the TR jet. The blue plane was then set at the level of the VCW in the green and the red plane

(Figure 2A,2B). In the VCA displayed on the blue panel, the green and red planes were adjusted to cut through the maximum and minimum diameter of the 3D VCA (Figure 2C). The 3D average VCW was calculated as the average of the VCW measured on the green and red panels. The 3D VCA was traced manually on the blue panel (Figure 2C) by planimetry of the color Doppler jet along the highest velocity-aliased core.



**Figure 3** Study flowchart for patients included in the study. T TEER, tricuspid transcatheter edge-to-edge repair; TV, tricuspid valve.

The sphericity index of the 2D biplane VCW and 3D average VCW was calculated by dividing the larger by the smaller VCW diameter (19). TR grading was performed for each view. For 2D biplane VCW and 3D average VCW, the suggested cut-off value of  $\geq 9$  mm for severe TR was used (2,20). For 3D VCA, a cut-off value of  $>75$  mm<sup>2</sup> defined severe TR (4,17).

The reliability of the measurements was assessed by performing intra- and inter-observer variability analysis. In a subgroup of ten randomly selected patients, the measurements were repeated two weeks later by the same observer and by a second one, both unaware of the previous results.

### Statistical analysis

As no previous studies were available to facilitate its direct calculation, to determine the study sample size, we performed an estimation of the two-sided expected correlation between 2D biplane VCW and the 3D average VCW. Assuming a target correlation of 0.8 and a minimum correlation of 0.5, with an alpha risk of 0.05 and a power of 80%, the required sample size was estimated to be 29 patients.

Continuous variables are presented as mean and standard deviation (SD) or 95% confidence interval (95% CI). Categorical variables are presented as numbers and percentages and are compared using Chi-squared test.

The correlation between 2D biplane VCW and 3D average VCW, as well as correlation between 2D VCW from single views and the maximum and minimum 3D VCA diameters, was analyzed using the Pearson method. Agreement between each of the two sets of measurements

was analyzed using the Bland-Altman method.

To determine the clinical relevance of the agreement and precision of our measurements for this study, we decided that a variation of the mean difference of  $\pm 15\%$  ( $\pm 0.2$  cm) and limits of agreement of  $\pm 40\%$  ( $\pm 0.5$  cm) were acceptable. Cohen's Kappa correlation was calculated to quantify concordance of TR severity classification between 2D biplane VCW, 3D average VCW, and VCA. Intra- and inter-observer interclass correlation coefficients (ICCs) were calculated to assess variability in measurements for 2D biplane, 3D average VCW and VCA.

We applied the following grading when using the Pearson correlation coefficient, ICC coefficient and Cohen's Kappa correlation:  $<0.2$  "poor",  $0.2-0.4$  "fair",  $0.41-0.6$  "moderate",  $0.61-0.8$  "good", and  $>0.8$  "very good" correlation or reliability.

## Results

### Patient data

During the 2-year recruiting period, 128 patients were referred for elective TV surgery. Seventy patients were included in the study from whom intraoperative TEE images of 30 patients met the inclusion criteria (Figure 3).

Demographics and clinical characteristics of the study group are summarized in Table 1.

### 2D biplane VCW and 3D average VCW of TR

The absolute values of the 2D biplane VCW measurements from ME 4CH and ME mBC were smaller than that from ME inflow view. All biplane VCW measurements were

**Table 1** Clinical characteristics of the study population (n=30)

Variable	Value
Age (years)	70.0±8.8
Gender (male)	15 (50.0)
Height (cm)	170.1±11.5
Weight (kg)	78.5±19.1
Arterial hypertension	26 (86.6)
Diabetes mellitus	7 (23.3)
Coronary heart disease	8 (26.7)
Pulmonary hypertension	
No	5 (16.7)
Moderate	16 (53.3)
Severe	9 (30.0)
Renal function	
Normal	8 (26.7)
Moderate	11 (36.7)
Severe	11 (36.7)
Rhythm	
SR	2 (40.0)
AF	17 (56.7)
PM	1 (3.3)
NYHA	
I	1 (3.3)
II	6 (20.0)
III/IV	23 (76.7)
LVEF (%)	54.2±9.3
RVFAC (%)	37.1±10.3
TAPSE (mm)	19.3±6.3
RVEDD (mm)	45.4±9.2
RA diameter (mm)	59.2±15
TV annulus (mm)	45.7±6.2
PAPS (mmHg)	45.1±17.5
TR etiology <sup>†</sup>	
Primary	3 (10.0)
PM lead-related	1 (3.3)
Secondary	
Atrial	6 (20.0)
Ventricular	20 (66.6)

**Table 1** (continued)**Table 1** (continued)

Variable	Value
TR severity (preop TTE)	
Mild/moderate	11 (36.7)
Severe	19 (63.3)
Surgery	
Isolated TVR	5 (16.7)
MVR + TVR	19 (63.3)
AVR + MVR + TVR	3 (10.0)
AVR + TVR	3 (10.0)

Date are expressed as mean ± standard deviation or n (%). Pulmonary hypertension (no: PAPS <31 mmHg; moderate: PAPS 31–55 mmHg; severe: PAPS >55 mmHg) and renal impairment (normal: CC >85 mL/min; moderate impairment: CC 50–85 mL/min; severe impairment: CC <50 mL/min) defined according to the criteria from the European System for Cardiac Operative Risk Evaluation (EuroSCORE) II.<sup>†</sup>, tricuspid regurgitation etiology defined according to the criteria published by the Tricuspid Valve Academic Research Consortium (23). AF, atrial fibrillation; AVR, aortic valve repair/replacement; CC, creatinine clearance; LVEF, left ventricle ejection fraction; MVR, mitral valve repair/replacement; NYHA, New York Heart Association; PAPS, systolic pulmonary artery pressure; PM, pacemaker; preop TTE, preoperative transthoracic echocardiography; RA, right atrium; RVEDD, right ventricle mid-ventricular end-diastolic diameter; RVFAC, right ventricular fractional area change; SR, sinus rhythm; TAPSE, tricuspid annular plane systolic excursion; TR, tricuspid regurgitation; TV, tricuspid valve; TVR, tricuspid valve repair/replacement.

smaller than the 3D average VCW.

All sphericity indices of the 2D biplane and 3D average VCW demonstrated a non-spherical shape. The sphericity index of the 3D average VCW had the highest value. Within the 2D biplane views, that from ME inflow view was higher compared to the other views (*Table 2*).

### Correlation and agreement between 2D biplane VCW and 3D average VCW measurements

Pearson regression analysis showed a “very good” linear correlation between the 2D biplane and 3D average VCW for the ME RV inflow view ( $r=0.832$ ) and “good” correlations for ME 4CH ( $r=0.613$ ) and ME mBC ( $r=0.687$ ) views.

Using 3D average VCW as the reference standard, Bland-Altman analysis (*Table 3*; *Figure 4*) showed “moderate”

**Table 2** Mean values and sphericity index of 2D and 3D vena contracta width measurements

Variable	Mean (mm)	95% CI
<b>ME 4CH</b>		
VCW	8.70	7.54–9.86
VCW orthogonal	10.92	9.06–12.79
Biplane VCW	9.81	8.47–11.15
Sphericity index	1.54	1.35–1.72
<b>ME inflow</b>		
VCW	11.64	9.37–13.91
VCW orthogonal	9.33	7.59–11.08
Biplane VCW	10.49	8.79–12.19
Sphericity index	1.78	1.43–2.1
<b>ME mBC</b>		
VCW	8.53	7.25–9.81
VCW orthogonal	10.95	9.06–12.85
Biplane VCW	9.74	8.41–11.08
Sphericity index	1.61	1.42–1.80
<b>3D datasets</b>		
3D VCA diameter max	16.82	14.68–19.96
3D VCA diameter min	8.99	7.69–10.29
3D average VCW	12.91	11.38–14.44
Sphericity index	2.04	1.73–2.35

2D, 2-dimensional; 3D, 3-dimensional; CI, confidence interval; max, maximum diameter; ME 4CH, midesophageal four chamber view; ME inflow, midesophageal right ventricle inflow-outflow view; ME mBC, midesophageal modified bicaval view; min, minimum diameter; VCA, vena contracta area; VCW, vena contracta width.

agreement with 2D biplane VCW from all three TEE views, with a mean difference of 24% (95% CI: -15% to +34%) for the 4CH view, 19% (95% CI: -11% to +26%) for the inflow view, and 25% (95% CI: -16% to +33%) for the mBC view.

The 2D biplane VCW systematically underestimated the 3D average VCW in all 3 standard imaging planes. The limits of agreement ranged between -20% and +75% indicates “poor precision” (Figure 3).

### Correlation and agreement between 2D VCW from single standard views and maximum and minimum 3D VCA diameters

Pearson regression for 2D VCW measurements from single views showed “good” linear correlation for ME inflow view and the maximum diameter of the 3D VCA ( $r=0.706$ ) but “moderate” correlation ( $R=0.428$  to  $0.600$ ) for the other two views.

Bland-Altman analysis between single 2D VCW in all three standard views and the maximum 3D VCA diameter measurement showed “poor” agreement and “poor” precision. The 2D VCW measured on single standard views systematically underestimated the maximum 3D VCA diameter.

Comparison of 2D VCW from single views with the minimum 3D VCA diameter showed “very good” agreement for ME 4CH and ME mBC, and “moderate” for ME inflow view. The limits of agreement showed “very poor” precision. The 2D VCW measured in ME 4CH and ME mBC single views agreed with the minimum 3D VCA diameter. The 2D VCW measured in ME inflow view overestimated the minimum diameter (Table 3).

### Grading the severity of TR

The grade of TR was assessed as at least severe in 80% of patients using 3D average VCW and in 83.3% of patients using 3D VCA [“very good” correlation ( $k=0.889$ ); sensitivity 96% and specificity 100%]. Using 2D biplane VCW, the TR was assessed as severe in 53.3% of patients when the measurement was done in ME 4CH, in 63.3% in ME inflow and in 60% in ME mBC view (Table 4).

### Intra- and inter-observer variability

The ICC coefficient showed a “good” to “very good” reliability when repeating all 2D VCW and 2D biplane VCW measurements with a “moderate” to “very good” 95% CI. When repeating the 3D average VCW and VCA measurements the ICC showed a “good” to “very good” reliability but with a “fair” to “very good” 95% CI (Table 5).

### Discussion

Our study showed that the 2D biplane VCW from the ME

**Table 3** Bland-Altman analysis comparing 2D and 3D vena contracta width measurements

VCW in mm	Mean Diff (95% CI)	95% LOA	
		(95% CI) LB	(95% CI) UB
2D biplane VCW and 3D average VCW			
ME 4CH bp VCW	3.09 (1.82 to 4.37)	-3.59 (-5.79 to -1.39)	9.77 (7.58 to 11.98)
ME RV inflow bp VCW	2.42 (1.47 to 3.37)	-2.56 (-4.21 to -0.92)	7.40 (5.76 to 9.05)
ME mBC bp VCW	3.17 (2.02 to 4.31)	-2.85 (-4.83 to -0.87)	9.18 (7.20 to 11.66)
2D VCW from single planes and maximal diameter of 3D VCA			
ME 4CH VCW	8.11 (6.28 to 9.94)	-1.52 (-4.69 to 1.65)	17.74 (14.58 to 20.92)
ME RV inflow VCW	5.18 (3.48 to 6.87)	-3.72 (-6.651 to -0.79)	14.07 (11.14 to 17.00)
ME mBC VCW	8.29 (6.47 to 101.10)	-1.23 (-4.36 to -1.90)	17.81 (14.67 to 20.94)
2D VCW from single planes and minimal diameter of 3D VCA			
ME 4CH VCW	0.29 (-1.03 to 1.62)	-6.65 (-8.94 to -4.36)	7.24 (4.95 to 9.53)
ME RV inflow VCW	-2.64 (-4.44 to -0.85)	-12.07 (-15.18 to -8.97)	6.79 (3.68 to 9.89)
ME mBC VCW	0.47 (-0.71 to 1.64)	-5.70 (-7.73 to -3.67)	6.64 (4.61 to 8.67)

The Bland-Altman analysis shows the mean difference or bias (with 95% CI) and the 95% lower and upper limits of agreement (with 95% CI) between 2D biplane VCW and 3D average VCW, between 2D VCW from single planes and maximal diameter of 3D VCA and between 2D VCW from single planes and minimal diameter of 3D VCA measurements. 2D, 2-dimensional; 3D VCA, 3-dimensional vena contracta area; 95% LOA LB (95% CI of the LOA), Bland-Altman 95% limits of agreement lower boundary (95% confidence intervals of the limits of agreement); 95% LOA UB (95% CI of the LOA), Bland-Altman 95% limits of agreement upper boundary (95% confidence intervals of the limits of agreement); bp, biplane; CI, confidence interval; ME 4CH, midesophageal four chamber view; ME inflow, midesophageal right ventricle inflow-outflow view; ME mBC, midesophageal modified bicaval view; mean diff, mean difference (bias); RV, right ventricle; VCW, vena contracta width.

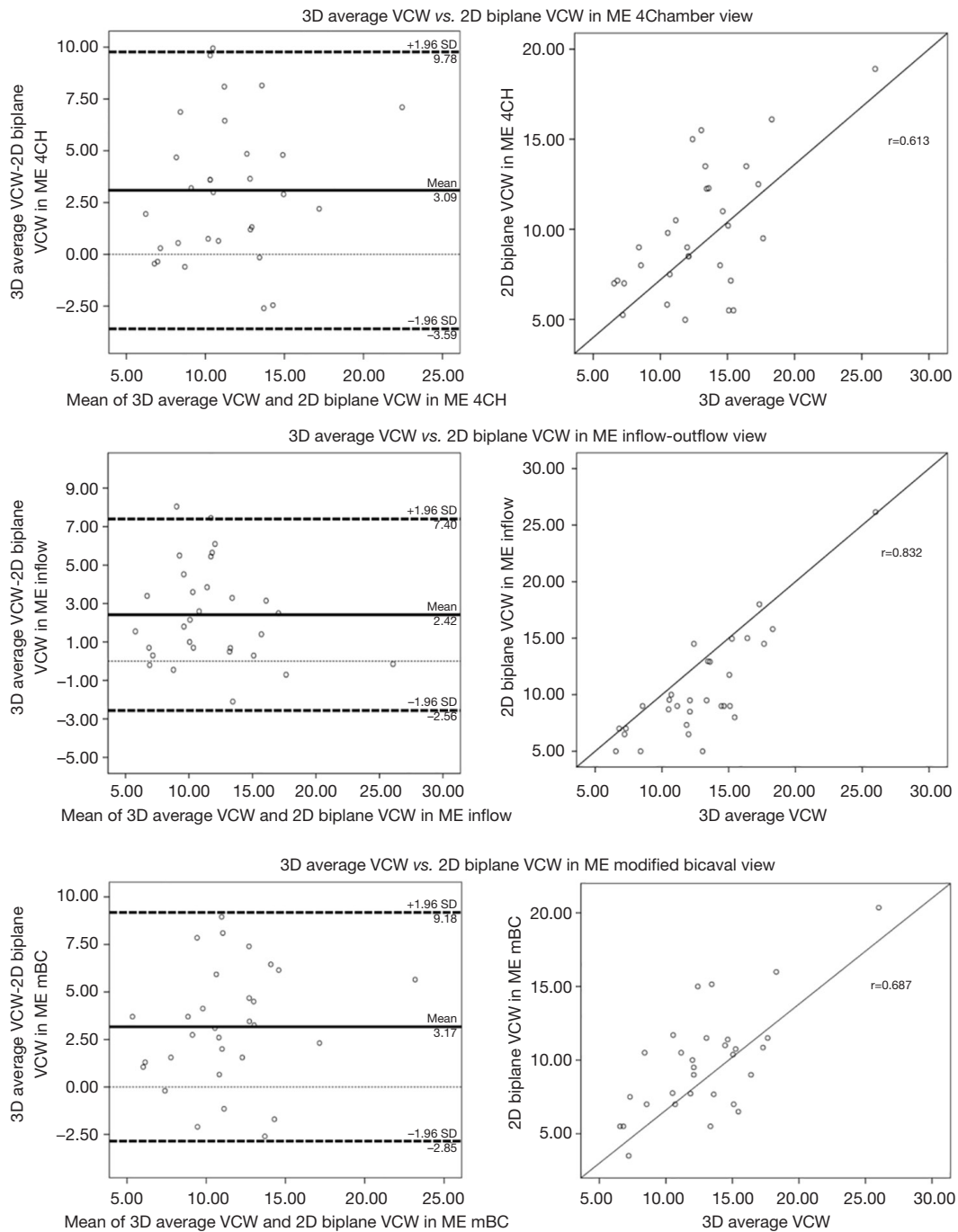
inflow view best correlates with 3D average VCW. We confirmed a non-circular shape of the tricuspid regurgitant orifice area in all our patients, with the highest sphericity index measured on 3D color Doppler datasets. This reflects that none of the 2D views cut through the maximum or minimum diameter of the 3D VCA. Nevertheless, among the 2D views, the sphericity index measured from the biplane ME inflow view was the highest, which may explain why the 2D biplane VCW measurement from this view best agrees with the 3D average VCW. To the best of our knowledge, this is the first study comparing 2D biplane VCW with 3D average VCW using intraoperative TEE.

Several studies have demonstrated that in functional TR, the annulus dilates mostly along the posterior border, causing an elongated and posteriorly displaced regurgitant jet, or along the anterolateral border, causing a gap between the septal leaflet and the other two leaflets (21-24). This creates an ellipsoidal or irregular regurgitant orifice along the septal leaflet's coaptation edge, and explains

the inaccuracy of single-plane 2D VCW measurements in functional TR, as already reported by TTE studies comparing 2D and 3D VCW measurements (9,10,12,19). In our study, we confirmed this observation using TEE. We found very good agreement between the ME 4CH and mBC VCW with minimum 3D VCA diameter. This can be explained by the fact that the ME 4CH view cuts mostly through the septal and anterior leaflet, and the mBC view through anterior and posterior leaflets. The ME inflow view, which cuts through the commissure between the septal and the other two leaflets, best correlated with the maximum 3D VCA diameter.

Three-dimensional echocardiography overcomes the limitations of 2D imaging in irregularly shaped jets. MPR enables display of the cross-sectional area of the regurgitant jet, thus allowing the measurement of 3D VCA and its maximum and minimum diameters.

The use of 3D color flow imaging has some limitations that make its routine use challenging. It requires a



**Figure 4** Bland-Altman plot and Pearson correlation comparing the 2D biplane VCW from each mid-esophageal standard view and the 3D average VCW as reference. Left: Bland-Altman plot assessing the agreement between the measurement of 3D average VCW and 2D biplane VCW in ME 4Chamber, inflow-outflow and modified bicaval views. The solid line represents the average difference from the mean scores (bias or agreement). The dashed lines represents the 95% limits of agreement from  $-1.96$  to  $+1.96$  SD (precision). Each point represents a single paired measurement. The positive bias in the 3 comparisons indicates that 2D biplane VCW tends to underestimate 3D average VCW measurements. Right: Pearson correlation between 3D average VCW and 2D biplane VCW in ME 4CH, inflow-outflow and modified bicaval views. 3D average VCW, average of minimal and maximum diameter of the 3D vena contracta area; ME 4CH, mid esophageal 4Chamber view; ME inflow, mid-esophageal TV inflow-outflow view; ME mBC, mid-esophageal modified bi-caval view; SD, standard deviation; VCW, vena contracta width.

**Table 4** Comparison of TR severity assessed using 2D biplane VCW, 3D average VCW and 3D VCA

Variable	3D average VCW			VCA		
	k	Sensitivity (%)	Specificity (%)	k	Sensitivity (%)	Specificity (%)
ME 4CH bp VCW	0.306	62.5	83.3	0.233	60	80
ME RV inflow bp VCW	0.440	75	83.3	0.401	72	80
ME mBC bp VCW	0.394	70.8	83.3	0.308	68	80

The table shows Cohen's kappa coefficients assessing the agreement on TR severity between 2D biplane VCW from each ME standard view and 3D measurements: VCA and 3D average VCW. Sensitivity and specificity are also reported for each comparison. 2D, 2-dimensional; 3D VCA, 3-dimensional vena contracta area; bp, biplane; k, Cohen's kappa coefficient; ME 4CH, midesophageal four chamber view; ME inflow, midesophageal right ventricle inflow-outflow view; ME mBC, midesophageal modified bicaval view; RV, right ventricle; TR, tricuspid regurgitation; VCW, vena contracta width.

**Table 5** Intra-observer and inter-observer variability of the 2D biplane VCW, 3D VCW and 3D VCA

Variable	ICC (95% CI)	
	Intra-observer variation	Inter-observer variation
ME 4CH bp VCW	0.943 (0.769–0.986)	0.898 (0.575–0.975)
ME RV inflow bp VCW	0.971 (0.897–0.993)	0.944 (0.774–0.986)
ME mBC bp VCW	0.995 (0.982–0.999)	0.865 (0.434–0.967)
3D VCA max diameter	0.838 (0.320–0.960)	0.820 (0.309–0.955)
3D VCA min diameter	0.880 (0.498–0.971)	0.878 (0.513–0.970)
3D VCA	0.896 (0.596–0.974)	0.899 (0.582–0.975)

2D, 2-dimensional; 3D VCA, 3-dimensional vena contracta area; bp, biplane; CI, confidence interval; ICC, intra-class correlation coefficient; ME 4CH, midesophageal four chamber view; ME inflow, midesophageal right ventricle inflow-outflow view; ME mBC, midesophageal modified bicaval view; RV, right ventricle; VCW, vena contracta width.

combination of appropriate equipment, expertise, and time availability both for image acquisition and off-line analysis (25). Measurement of 3D VCA is further affected by the relatively poor temporal and spatial resolution and lower frame rates. Furthermore, when the regurgitant orifice is in the far field and does not lie perpendicular to the ultrasound beam, it may be difficult to precisely identify the edges of the color jet (2,10,26). This may lead to inaccuracies in 3D VCA measurements, with an overestimation of the 3D VCA (27) and may be reflected in our study by the lower reliability observed when repeating 3D MPR and VCA measurements compared to 2D measurements. Nevertheless, although prognostic data are lacking, 3D VCA is increasingly used to quantify TR in clinical practice (9,19-21).

Given the above described limitations, intraoperative use of biplane imaging could be considered a reliable

alternative.

Although a VC  $\geq 7$  mm measured in the TTE apical 4CH view remains the cutoff for severe TR in current surgical decision making guidelines (1,28,29), this view only captures the septal-lateral dimension of the VCW. Our study shows that VCW from the ME 4CH view more often correlates with the minor diameter of the 3D VCA. VCW measurements in the ME 4CH view would therefore underestimate the severity of the TR and may be one of the reasons for delayed patients' referral.

Furthermore, to improve the identification of the regurgitant orifice area using 2D biplane VCW, it has been recommended to rotate the multiplane angle from 0 to 150° from the ME 4CH view focused on the TV to capture the maximal diameter of the regurgitant jet. Adding an orthogonal plane helps to further increase the accuracy of VCW measurement with 2D imaging (3,11,18,20).

In regard to the impact of different measurements on grading TR severity, we reported that there was a very good correlation in the TR grading comparing 3D average VCW and 3D VCA, while all 2D biplane VCW measurements underestimated it. Of all the 2D biplane measurements, that from the ME inflow view was the most precise in defining severe TR. This is reflected in the correlation of 2D biplane VCW in the ME inflow view with 3D average VCW.

The incidence of severe TR by preoperative TTE (63.2%) was comparable to that measured by intraoperative TEE using 2D biplane VCW (53% to 63%), but lower than that assessed by 3D VCA. Preoperative TTE was performed on awake patients which should have resulted in higher degree of TR, and this quantification was based on single plane measurements only. The higher severity of TR measured intraoperatively may also reflect disease progression due to the time elapsed between the two measurements.

### Limitations

Our study has several limitations. First, it is an observational single-center study. Second, the sample size is limited and the etiology of TR is heterogeneous with different TR mechanisms. Both factors do not allow to analyze the impact of the different regurgitant orifice geometry on our measurements. Third, the measurements were done under general anesthesia. Although we performed the examination before the skin incision with minimal hemodynamic variability and in short intervals of apnea, loading conditions and the afterload of the right ventricle may not be comparable to awake conditions. Nevertheless, both 2D and 3D images were acquired almost simultaneously within the same hemodynamic situation. Fourth, the measurements were done in the frame with the maximum jet size during systole for all patients regardless of etiology, which may have led to overestimation of TR. Fifth, as all patients presented with at least moderate TR, our results cannot be extrapolated to lesser degrees of TR since the reproducibility of 2D biplane VC and 3D VCA increases with increasing severity of TR (30). Sixth, we included only patients with good-quality images with clearly defined VCA in 3D, so there may be a selection bias, which may also contribute to low variability in repeated measurements. Finally, our study does not have a gold standard to quantify TR severity. While MRI is the reference standard, the comparison with intraprocedural setting is limited by its performance in awake patients under completely different

hemodynamic conditions. This may have a significant impact on the degree of TR given its very dynamic nature especially in secondary TR.

### Conclusions

Our study shows that 2D biplane VCW from the ME inflow view best agrees with 3D average VCW and allows most accurate classification of TR severity compared to 3D average VCW. No single 2D TEE standard view reflects the maximum or minimum diameter of the 3D VCA. The intraoperative use of 2D biplane CFD from the ME inflow view may increase the accuracy of TR grading and help assist surgical decision making in the operating room when 3D technology and/or expertise is not available. These findings have to be confirmed in a prospective trial.

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### Footnote

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