Quantification of Tricuspid Regurgitation by Measuring the Width of the Vena Contracta With Doppler Color Flow Imaging: A Clinical Study
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OBJECTIVE
We sought to evaluate the vena contracta width (VCW) measured using color Doppler as an index of severity of tricuspid regurgitation (TR).

BACKGROUND
The VCW is a reliable measure of mitral and aortic regurgitation, but its value in measuring TR is uncertain.

METHODS
In 71 consecutive patients with TR, the VCW was prospectively measured using color Doppler and compared with the results of the flow convergence method and hepatic venous flow, and its diagnostic value for severe TR was assessed.

RESULTS
The VCW was 6.1 ± 3.4 mm and was significantly higher in patients with, than those without, severe TR (9.6 ± 2.9 vs. 4.2 ± 1.6 mm, p < 0.0001). The VCW correlated well with the effective regurgitant orifice (ERO) by the flow convergence method (r = 0.90, SEE = 0.17 cm², p < 0.0001), even when restricted to patients with eccentric jets (r = 0.93, p < 0.0001). The VCW also showed significant correlations with hepatic venous flow (r = 0.79, p < 0.0001), regurgitant volume (r = 0.77, p < 0.0001) and right atrial area (r = 0.46, p < 0.0001). A VCW ≥6.5 mm identified severe TR with 85.3% sensitivity and 93.3% specificity. In comparison with jet area or jet/right atrial area ratio, the VCW showed better correlations with ERO (both p < 0.01) and a larger area under the receiver operating characteristic curve (0.98 vs. 0.88 and 0.85, both p < 0.02) for the diagnosis of severe TR.

The VCW measured by color Doppler correlates closely with severity of TR. This quantitative method is simple, provides a high diagnostic value (superior to that of jet size) for severe TR and represents a useful tool for comprehensive, noninvasive quantitation of TR.

CONCLUSIONS
The VCW measured by color Doppler allows specific determination of the degree of severity of TR in a clinical setting, and we prospectively examined, in a large series of patients, the relation of VCW with ERO simultaneously calculated by the proximal flow convergence method (18,19) is appealing but time consuming and requires multiple measurements. Therefore, the subjective visual assessment of TR often remains the only method used in routine clinical practice (20).

Recently, there has been considerable interest in color Doppler imaging of the vena contracta for quantifying valve regurgitation (21–23). The vena contracta is the smallest regurgitant flow area immediately beyond the flow convergence region and before expansion of the turbulent regurgitant jet (24) and corresponds hydrodynamically with the effective regurgitant orifice area (ERO) (25). In vitro studies support the concept that measurements of the color Doppler size of the vena contracta directly represent the size of the regurgitant orifice (26–29). Hence, recently, in vivo color Doppler measurements of the vena contracta width (VCW) have been used to assess severity of mitral (21,22,30–32) and aortic regurgitation (23,24). Pilot data in TR appear promising (33). Therefore, the VCW has considerable potential as a simple but physiologically meaningful index of severity of TR but remains to be validated.

Consequently, we hypothesized that the VCW measured by color Doppler allows specific determination of the degree of TR in a clinical setting, and we prospectively examined, in a large series of patients, the relation of VCW with ERO simultaneously calculated by the proximal flow convergence method (18,19) is appealing but time consuming and requires multiple measurements. Therefore, the subjective visual assessment of TR often remains the only method used in routine clinical practice (20).

Tricuspid regurgitation (TR) is a common echocardiographic finding, whether due to intrinsic valve abnormalities (1) or to functional regurgitation with a structurally normal valve (2,3). Tricuspid regurgitation, even functional, may lead to increased long-term morbidity and mortality (3,4) and can persist even after surgical correction of the primary left-sided lesion (5–7). Therefore, with improvements in surgical methods and results of tricuspid repair, more liberal surgical indications have been recommended in patients with marked TR (8,9). Consequently, there is a renewed emphasis on determining, simply but reliably, the severity of TR for clinical decision making (2).

For the assessment of TR severity, invasive methods have major limitations and pitfalls, well recognized in the catheterization laboratory (10,11), and have never been reference methods (12). Noninvasive quantitation of TR remains a challenge. Color-flow imaging is useful to recognize small jets (2,13), but the assessment of larger TR jets has important limitations (14). Systolic flow reversal in the vena cava and hepatic veins is a useful sign of severe TR (15–17) but is not quantitative and does not provide a full description of the entire spectrum of TR. Calculation of the tricuspid regurgitant orifice area by the flow convergence method (18,19) is appealing but time consuming and requires multiple measurements. Therefore, the subjective visual assessment of TR often remains the only method used in routine clinical practice (20).

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Consequently, we hypothesized that the VCW measured by color Doppler allows specific determination of the degree of TR in a clinical setting, and we prospectively examined, in a large series of patients, the relation of VCW with ERO simultaneously calculated by the proximal flow convergence
method (PISA) and with the presence of systolic flow reversal in the hepatic vein.

METHODS

Patient population. The inclusion criteria for the present study were:
1) presence of TR of at least mild degree, as determined by standard color-flow Doppler imaging,
2) the presence of sinus rhythm or regular rhythm in paced patients,
3) quantitative Doppler assessment of the severity of TR with PISA method,
4) Doppler analysis of the hepatic venous flow pattern, and
5) evaluation of the VCW of TR.

Exclusion criteria included:
1) presence with color-flow Doppler imaging of more than one tricuspid regurgitant jet,
2) inability to acquire the reference methods, and
3) atrial fibrillation.

The presence of clinical signs of severe TR, in particular a pulsatile liver, was noted independently by the patient’s attending physician.

Doppler echocardiography. The studies were performed with 2.5-MHz transducers and were recorded on Umatic tapes for off-line review and analysis. All patients had a complete two-dimensional and Doppler echocardiographic study using multiple windows during the same examination. The mechanism of the TR was determined based on the analysis of the right ventricle, tricuspid annulus, subvalvular apparatus and valve leaflets. Organic regurgitation was related to intrinsic abnormalities of the tricuspid valve, and functional regurgitation was characterized by normal valves and enlarged annulus.

Color-flow Doppler imaging was obtained with the standard color encoding system with the patient in the left lateral decubitus position from the apical views and the parasternal right ventricular inflow view. The presence or the absence of an eccentric TR jet was determined on the basis of the direction of the jet immediately below the regurgitant orifice (14).

VCW. The color Doppler images of the vena contracta were obtained from an apical view (Fig. 1). The narrowest sector angle of imaging was selected to optimize the imaging frame rate. The low velocity cutoff ranged from 8 to 16 cm/s. A tissue priority algorithm was used. The gain was adjusted step by step to obtain the maximal color gain level that did not introduce signal outside of flow areas (21). The position of the transducer was modified to optimize visualization of the flow convergence region and the regurgitant flow proximal and distal to the tricuspid valve. The aliasing velocity ranged from 46 to 96 cm/s. By using a zoom of the region of interest, considerable care was taken to visualize the vena contracta, defined as the narrowest neck of the regurgitant flow just distal to the flow convergence region (Fig. 1). Measurement of the VCW was made in mid-systole by an observer unaware of the clinical examination, the results of PISA and the hepatic venous flow pattern. The values of measurements of four consecutive cardiac cycles were averaged in each patient. In 17 patients randomly selected, measurements of the VCW were repeated independently by a second observer for determining interobserver variability.

PISA method. Theorietic background for the PISA method has been described previously (18,34,35). After downshifting of the color baseline, the radius (r) of the flow convergence is measured and the corresponding aliasing velocity (Vr) is noted. Two corrections for local and geometric factors, as previously validated in TR (19,36,37), were systematically applied. First, the ratio (V/[V – Vr]) of the peak tricuspid regurgitant velocity from continuous-wave Doppler, was calculated to avoid underestimation of flow rate (38) due to a flattening of the isovelocity shells close to the orifice. Second, the ratio alpha/180 was calculated, where alpha is the angle of the systolic inverted tricuspid valve funnel, to account for the shape of the tricuspid valve. By combining these two corrections, mid-systolic instantaneous regurgitant flow (RFlow) was calculated as:

\[ R_{\text{flow}} = \left( 2\pi \times r^2 \times V_r \right) \times \left( \frac{V}{V - V_r} \right) \times \left( \frac{\alpha}{180} \right) \]
The ERO area was then calculated as:

\[
\text{ERO} = \frac{R\text{Flow}}{V}
\]

Practically, color Doppler images of the proximal flow convergence of TR were obtained from an apical or parasternal view using a zoom of the region of interest. The position of the transducer was modified to minimize the angle between the centerline of the flow convergence and the ultrasound beam. The color-flow velocity scale was maximized and the baseline shifted downward until the flow convergence region was clearly visualized. The Nyquist velocities selected ranged from 11 to 43 cm/s (mean, 24 ± 7 cm/s). Radial distance r between the first aliasing (red/blue interface) and the center of the tricuspid orifice was measured along the centerline of the flow convergence region in midsystole. Angle alpha was measured with a protractor from a printout of the tricuspid valve image from the same apical view.

**Other signs of TR.** The jet area by color Doppler was measured with a sector allowing visualization of the entire right atrium (RA). The images were reviewed frame by frame, and planimetry of the maximal aliasing area of the regurgitant jet was performed. The ratio of the maximal jet area to the RA area measured on the same image was also calculated.

Hepatic venous flow was recorded from the subcostal view with pulsed Doppler (17) with the patients supine.

**Severe TR.** The patients were classified objectively as having severe TR if they had either clinical signs of severe TR with pulsatile liver, systolic flow reversal in the hepatic veins by Doppler (15) or an ERO ≥40 mm² (18), and the number of criteria present was noted. A classification as “visually marked TR” based on a large size of jet and RA and on reversal in hepatic veins was also obtained.

**Statistical analysis.** Descriptive results were expressed as mean value ± SD for continuous variables and as percentages for categorical variables. Groups were compared with t test or chi-square. Color Doppler width of the vena contracta was related to the ERO area obtained by the PISA method with linear regression in the entire group and in subgroups of patients with eccentric jets and those with noneccentric jets. Comparison of regressions between these two subgroups was performed using analysis of covariance. The relation to categorical variables was assessed by Spearman rank-order correlation. The optimal threshold of the VCW to classify patients with and those without severe TR was determined by testing the whole range of VCW by increments of 0.5 mm. The sensitivity, specificity and positive and negative values for each threshold were calculated. The receiver operating characteristic (ROC) curve was also calculated for the diagnosis of severe TR for the VCW, the jet area and the jet/right atrium ratio, and the areas were compared using the paired t test. Statistical significance was accepted for p < 0.05.

**RESULTS**

**Patients.** We examined 80 eligible patients, and the VCW could not be measured in nine (11%). Therefore, the study included 71 patients (age, 62 ± 15 years; 24 men and 47 women) with TR fulfilling the eligibility criteria. Sixty-six patients were in normal sinus rhythm, and five had regular paced rhythm. Tricuspid regurgitation was of organic cause in 10 patients (rheumatic in 4, prolapse in 3, endocarditis in 1, carcinoid in 2) and functional in 61 (due to left heart disease in 30, to chronic obstructive pulmonary disease in 21 and to miscellaneous diseases in 10). Pulmonary hypertension with systolic pulmonary artery pressure ≥50 mm Hg was noted in 43 patients. Severe TR was observed in 26 patients, and the diagnosis was based on one criterion in 2 patients, on two criteria in 22 patients and on three criteria in 2 patients. The baseline characteristics of the overall population and of the patients with and those without severe TR are reported in Table 1.

**VCW of TR.** The mean VCW was 6.1 ± 3.4 mm (range, 1.5 to 20.5 mm). A good correlation was found between the VCW measured with color-flow Doppler imaging and the ERO area calculated with the PISA method (r = 0.90, SEE = 0.17 cm², p < 0.0001) (Fig. 2). This correlation between VCW and ERO was comparable in 12 patients with eccentric jets (r = 0.93, p < 0.0001) and 59 with noneccentric jets (r = 0.90, p < 0.0001), and the slopes of these two regressions were not significantly different by analysis of covariance (p = 0.69). The VCW showed significant, although less tight, correlations with regurgitant flow (r = 0.85, p < 0.0001) and regurgitant volume (r = 0.77, p < 0.0001). The VCW was closely related to the presence or absence of reversal flow in the hepatic vein (r = 0.79, p < 0.0001) (Fig. 3). The correlations between VCW and jet area or the ratio of jet area to RA area were weaker (r = 0.62 and 0.60, respectively) although significant (both p < 0.0001). The VCW also showed significant correlation with RA size (area, r = 0.46, p < 0.0001). Therefore, the correlations of VCW with the diagnosis of visually marked TR (n = 30) based on these criteria were significant but modest (r = 0.69, p < 0.0001). Indeed, visually marked TR showed higher correlation to RA pressure (r = 0.56) and weaker correlation to ERO (r = 0.70) than VCW (both p < 0.05).

The VCW was measurable in 71 of 80 consecutive patients (89%) in whom it was attempted. The reproducibility of VCW was excellent. In 17 patients randomly selected, measurement of VCW by a second observer showed low interobserver variability, with highly significant regression (r > 0.90, p < 0.0001), a low standard error of the estimate of the VCW (0.59 mm) and a low mean absolute difference between observers (0.46 ± 0.42 mm).

**Diagnostic value of VCW for severe TR.** The baseline characteristics of patients with and those without severe TR are listed in Table 1. In the 26 patients with severe TR, compared with those without severe TR, regurgitant flow,
regurgitant volume and RA area were all larger, confirming the appropriateness of the diagnosis of severe TR. In severe TR, the VCW was larger (9.7 ± 3.0 mm vs. 4.3 ± 1.7 mm, p, 0.0001), but the maximal jet area and jet-to-RA area ratio were also significantly higher (both p, 0.0001). Comparison of the association with the degree of TR between VCW and jet measurements showed that correlations were stronger with VCW. There were significant but weak correlations between the maximal jet area or the ratio of jet to RA area and the ERO (r = 0.54, p < 0.0001 and r = 0.52, p < 0.0001, respectively) but with large scatter (both standard error of the estimate = 0.33 cm²) among patients (Fig. 4). The comparison of correlations showed that the correlation between ERO and VCW was significantly stronger than those between ERO and jet area or jet-to-RA area ratio (both p < 0.01). For the diagnosis of severe TR, the area under the ROC curve regarding the VCW was excellent (0.98) and was significantly better than those obtained with jet area (0.88, p = 0.017) and for the jet-to-RA area ratio (0.85, p = 0.01) (Fig. 5).

The various thresholds of VCW for identifying patients with severe TR are reported in Table 2, with their respective diagnostic values. All except 1 of the 19 patients with a VCW > 7.5 mm had severe TR, and none of the 40 patients with a VCW < 6 mm had severe TR. The threshold of 6.5 mm showed the lowest difference and a high sum of sensitivity and specificity.

**DISCUSSION**

The results of this prospective study show that measurement of the VCW using color-flow Doppler: 1) can be reproducibly performed in patients with various degrees and causes of TR; 2) shows close association to the ERO, even in patients with eccentric jets; and 3) identifies, with high sensitivity and specificity and better than jet size, patients with severe TR and, thus, is a useful tool for assessing severity of TR.

**Assessment of TR.** The degree of TR has been underscored as an important determinant of outcome (3,4), and liberal surgical indications in patients with marked TR have

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**Table 1.** Baseline Characteristics of the Entire Population and of Patients With or Without Severe Tricuspid Regurgitation

<table>
<thead>
<tr>
<th></th>
<th>Overall (n = 45)</th>
<th>Severe TR (n = 26)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>62 ± 12</td>
<td>62 ± 15</td>
<td>0.78</td>
</tr>
<tr>
<td>Male (%)</td>
<td>34</td>
<td>22</td>
<td>0.006</td>
</tr>
<tr>
<td>SBP (mm Hg)</td>
<td>130 ± 25</td>
<td>129 ± 25</td>
<td>0.62</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>76 ± 13</td>
<td>74 ± 13</td>
<td>0.14</td>
</tr>
<tr>
<td>Stroke volume (mL)</td>
<td>61 ± 22</td>
<td>63 ± 23</td>
<td>0.36</td>
</tr>
<tr>
<td>Cardiac index (L/m²)</td>
<td>2.6 ± 0.8</td>
<td>2.6 ± 0.8</td>
<td>0.40</td>
</tr>
<tr>
<td>S-PAP (mm Hg)</td>
<td>62 ± 25</td>
<td>68 ± 27</td>
<td>0.007</td>
</tr>
<tr>
<td>LV ejection fraction (%)</td>
<td>55 ± 16</td>
<td>56 ± 14</td>
<td>0.50</td>
</tr>
<tr>
<td>Right atrial area (cm²)</td>
<td>27 ± 10</td>
<td>25 ± 10</td>
<td>0.009</td>
</tr>
<tr>
<td>Jet area (cm²)</td>
<td>7.2 ± 6.2</td>
<td>4.8 ± 4.7</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Jet/right atrial area (%)</td>
<td>25 ± 16</td>
<td>19 ± 12</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Vena contracta width (mm)</td>
<td>6.1 ± 3.4</td>
<td>4.2 ± 1.6</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Regurgitant flow (mL/s)</td>
<td>125 ± 100</td>
<td>67 ± 33</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>ERO (mm²)</td>
<td>42 ± 38</td>
<td>19 ± 9</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Rvol (mL/beat)</td>
<td>35 ± 24</td>
<td>22 ± 11</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>

ERO = effective regurgitant orifice area; LV = left ventricle; RVol = regurgitant volume; SBP = systolic blood pressure; S-PAP = systolic pulmonary artery pressure.
been recommended (8,9). The color Doppler jet size is widely used for assessment of the degree of TR but has important limitations. The jet area has been reported to correlate with angiographic grading (2,13) and quantitative Doppler echocardiographic methods (14). However, regurgitant jet area, even corrected for the receiving chamber size, is strongly limited by its dependence on hemodynamic conditions (27), instrument settings (26) and jet interaction with the receiving chamber (39). Accordingly, mediocre correlations between jet size and TR severity were noted in previous studies (14,20,40) and in this study. Severe TR causes systolic flow reversal in the vena cava and hepatic vein, but this interesting approach remains qualitative (15–17) and does not allow assessment of the full range of TR. Conversely, the PISA method is quantitative (18) but is not widely used in clinical practice because a time-consuming angle correction is required (19). Therefore, a simple but quantitative method such as the vena contracta may have an important clinical role in the assessment of TR.

**VCW as an index of severity of TR.** The vena contracta area corresponds to the ERO area, that is, the hemodynamic regurgitant area, which is smaller than the anatomical regurgitant area due to the contraction of flow as it accelerates through the regurgitant orifice. Experimental studies have suggested that the vena contracta area provides unique information with regard to severity of the regurgitation because it is a direct measure of the ERO area (23,32) and is relatively unaffected by flow rate and driving pressure within the clinical range (27,29). Other factors, such as instrument settings, that influence mainly the regurgitant jet area do not significantly affect VCW (29,41).

Previous in vivo studies have supported the idea that color-flow Doppler imaging of VCW is a useful and simple index for quantifying mitral regurgitation (21,22,32,42) and aortic regurgitation (23,24). Three-dimensional imaging has confirmed that VC area measures the mitral ERO (43). Proximal TR jet size was measured in a pilot study (33). It is uncertain whether proximal jet size is identical to VCW because the vena contracta measurement requires recognizing the three components of regurgitant flow, that is, the flow convergence, the turbulent jet and, in-between these two components, the narrow neck of the vena contracta. Nevertheless, these data were promising but included a small number of patients and few with severe regurgitation (33). To the best of our knowledge, this study is the first to analyze, in TR, the relation between the measurement of the VCW with an independent measure of ERO area and the pattern of hepatic flow in a large series of patients with various degrees of severity of TR.

In this series, the VCW showed a close correlation with the ERO area, even in the presence of an eccentric regurgitant jet, and significantly better than the jet area or ratio of jet to RA area. Furthermore, the VCW also showed significant correlations with the hepatic venous flow pattern, regurgitant flow and volume and the RA area. Therefore, the simple measurement of the VCW closely reflects the degree of TR.

Regarding the diagnostic value for severe TR, the ROC curve area shows that VCW is an excellent index of severe TR. Comparison of areas under the ROC curves showed that the diagnostic value of VCW is superior to that of jet area or jet to RA area ratio. Also VCW correlates better with ERO than the visual judgment of TR degree, which is influenced by RA pressure. The statistical analysis showed that the threshold of 6.5 mm has the lowest difference between sensitivity and specificity and the second highest sum of sensitivity and specificity and, therefore, is identified as the single best value to diagnose severe TR. A threshold

<table>
<thead>
<tr>
<th>Threshold Value of VCW (mm)</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>PPV (%)</th>
<th>NPV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>100.0</td>
<td>88.9</td>
<td>83.9</td>
<td>100.0</td>
</tr>
<tr>
<td>6.5</td>
<td>88.5</td>
<td>93.3</td>
<td>88.5</td>
<td>93.3</td>
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<tr>
<td>7</td>
<td>84.6</td>
<td>95.6</td>
<td>91.7</td>
<td>91.5</td>
</tr>
<tr>
<td>7.5</td>
<td>80.8</td>
<td>97.8</td>
<td>95.5</td>
<td>89.8</td>
</tr>
<tr>
<td>8</td>
<td>69.2</td>
<td>97.8</td>
<td>94.7</td>
<td>84.6</td>
</tr>
</tbody>
</table>

NPV = negative predictive value; PPV = positive predictive value; VCW = vena contracta width.
of 7.5 or 8 mm prioritized the specificity and positive predictive value, whereas a threshold of 6.0 mm prioritized the sensitivity and negative predictive value.

Therefore, the VCW is a quantitative index of severity of TR, simple to obtain, closely reflecting important physiologic variables such as the ERO and with high diagnostic value for severe TR. The VCW can be used in combination with other methods, such as hepatic venous flow, in routine practice for noninvasive assessment of TR or with the PISA method when comprehensive physiologic quantitation of TR is considered warranted.

Study limitations. A limitation of studies on TR is the lack of an established reference method. Angiographic grading is widely recognized to have considerable variability and possible errors (10,12). Visual, “expert” judgment on TR is influenced by the RA pressure. Despite encouraging results for research purposes (18,19), Doppler calculation of tricuspid and pulmonic stroke volumes and TR regurgitant volume has major limitations (36). The PISA method used in this study, despite possible limitations and pitfalls (38,44–48), has been validated (18) and confirmed by independent investigators (40). Confined flow convergence was not observed and, as previously recommended for TR (18,19), corrections that account for flattening of the isovelocity (38) and for the nonplanarity of the structure surrounding the orifice (37) were systematically applied. Finally, the PISA method was combined with clinical assessment and hepatic venous flow to define severe TR.

Although the VCW correlated well with the ERO area, it cannot be used to calculate precisely the ERO area, as shown by the distribution of values, probably because the tricuspid regurgitant orifice shape is unknown. Currently, it is impossible to image the entire area of the vena contracta, but future studies using three-dimensional reconstruction of the flow convergence (45) and vena contracta region could overcome this geometric limitation (43). Furthermore, future studies are needed to assess the VC in unselected large numbers of patients from all subsets, in particular with eccentric jets.

The accuracy of color-flow measurements is highly dependent on the resolution of the imaging system (28,29). This is particularly important when the lateral resolution of ultrasound is used. To optimize measurement of the VCW, it is essential to observe all three components of the regurgitant flow (flow convergence, VC, jet) by optimizing transducer position and to maximize color Doppler frame rate. With this approach, good reproducibility of VCW was observed.

This study did not attempt sequential measurements of the VCW during systole and, thus, did not address the issue of variability of the width during the regurgitant phase. Although it has been suggested that the ERO area in TR is fairly constant throughout systole (18), future studies addressing this point are warranted.

Conclusions. Direct measurement of the VCW is a new and promising method for assessing the degree of TR. This study has shown that the measurement of the VCW of TR is a simple, reproducible, quantitative measurement that provides high diagnostic value for severe TR and can be used in routine clinical practice.

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