Assessment of Severity of Aortic Regurgitation Using the Width of the Vena Contracta
A Clinical Color Doppler Imaging Study

Christophe M. Tribouilloy, MD; Maurice Enriquez-Sarano, MD; Kent R. Bailey, PhD; James B. Seward, MD; A. Jamil Tajik, MD

Background—The width of the vena contracta (VC-W), the smallest area of regurgitant flow, reflects the degree of valvular regurgitation and is measurable by color Doppler imaging, but this method has not been validated in aortic regurgitation (AR).

Methods and Results—We prospectively examined 79 patients with isolated AR and 80 patients without regurgitation. The VC-W was measured from the long-axis parasternal view and compared with 2 simultaneous reference methods (quantitative Doppler and 2D echocardiography). In patients without regurgitation, the agreement between methods was excellent. In patients with AR, good correlations (all \( P < 0.0001 \)) were obtained between VC-W and effective regurgitant orifice (ERO) area and regurgitant volume recorded by quantitative Doppler (\( r = 0.89 \) and 0.90, respectively) and 2D echocardiographic (\( r = 0.90 \) and 0.89, respectively) methods. These correlations were similar with eccentric or central jets (all \( P > 0.60 \)). The other methods used showed good correlations of VC-W with aortographic grading of AR (n = 8, \( r = 0.82 \), \( P = 0.01 \)), with the proximal flow convergence method (n = 53, \( r = 0.85 \), \( P < 0.0001 \)), and with left ventricular end-diastolic volume (\( r = 0.81 \), \( P < 0.0001 \)). Sensitivity and specificity of VC-W \( \geq 6 \text{ mm} \) for diagnosing severe AR (ERO \( \geq 30 \text{ mm}^2 \)) were 95% and 90%, respectively.

Conclusions—For assessment of the degree of AR, VC-W shows good correlations with simultaneous quantitative measures (regardless of jet direction), shows good correlations with other methods of assessment of AR, and provides a high diagnostic value for severe AR. VC-W is a simple, reliable method that can be used clinically as part of comprehensive Doppler echocardiographic assessment of AR. (Circulation. 2000;102:558-564.)

Key Words: aorta • valves • echocardiography • regurgitation

Patients with aortic regurgitation (AR) of large degree may develop left ventricular dysfunction and heart failure due to volume overload.\(^1\) Accurate assessment of AR degree is a prerequisite to surgical decision making. Among methods available for assessing AR,\(^2,5\) color flow Doppler allows real-time visualization of the jet and is widely used for semiquantification of AR.\(^6,8\) In AR, regurgitant jet width measured by color flow Doppler correlates grossly with semiquantitative angiographic grading.\(^6,9\) However, the size of regurgitant jets depends on hemodynamic conditions,\(^10,11\) instrument settings,\(^12\) and hydrodynamic factors such as jet interaction with the receiving chamber,\(^13\) all factors affecting the diagnostic value of jet size.

Recently, considerable interest has focused on effective regurgitant orifice (ERO) area as a marker of regurgitant lesion severity,\(^2,14,15\) less dependent on hemodynamic variations than regurgitant volume (RVol) and regurgitant fraction (RF).\(^16,17\) The ERO area corresponds hydrodynamically to the area of the vena contracta (VC),\(^19\) that is, the smallest area of regurgitant flow through the valve,\(^19\) which is significantly smaller than jet size.\(^20\) In vitro studies support the concept that VC size measured by color Doppler is related directly to regurgitant orifice size.\(^21-23\) In humans, direct and exact planimetry of ERO area with color flow Doppler is not yet clinically possible,\(^8,20\) and the width of the VC (VC-W) has been proposed as a surrogate for ERO size and validated in mitral regurgitation.\(^20,24-27\) Although the measurement of VC-W using color Doppler in AR has recently been pioneered in animal studies,\(^19,28\) clinical data in large series of patients are not yet available but are warranted.\(^28\)

Therefore, we hypothesized that in AR, VC-W directly correlates with ERO area and has high diagnostic value for severe AR. To verify this hypothesis, we analyzed, in patients prospectively examined for AR of any degree, the relation between VC-W and ERO, RVol, and RF obtained simultaneously by previously validated methods.

Methods

Patient Population
Inclusion criteria were (1) isolated and pure AR of at least mild degree, as determined by standard color Doppler imaging; (2) simultaneous Doppler echocardiographic measurements, allow-
ing quantitative assessment of AR; and (3) measurement of the VC-W. Exclusion criteria were (1) more than trace associated mitral disease, (2) associated aortic stenosis with mean gradient ≥25 mm Hg, (3) inability to acquire both quantitative reference methods, and (4) multiple or diffuse AR jets.

In addition to patients with AR, 80 patients (46 male; age 57 ± 15 years) without regurgitation had Doppler echocardiographic measurements performed prospectively to assess the accuracy of stroke volume measurements.

Echocardiographic Doppler Analysis

All echocardiographic data were collected during the same examination without observed hemodynamic change.

Color Doppler Echocardiography

Color Doppler imaging was performed with standard color encoding and maximum Nyquist limit. The presence of an eccentric jet was determined by the jet direction immediately below the regurgitant orifice. The narrowest sector angle of imaging was selected to optimize the frame rate. The gain was adjusted to the maximal color gain without signal outside of flow areas. Jet width and ratio to left ventricular outflow tract (LVOT) width could be measured just below the valve, as previously described, in 66 patients.

The color Doppler images of the VC were obtained from parasternal long-axis views. Transducer position was optimized to visualize the flow convergence region and regurgitant flow proximal to, through, and distal to the aortic valve. With a zoom of the region of interest, meticulous care was taken to visualize the VC, defined as the narrowest neck of regurgitant flow immediately downstream from the flow convergence region (Figure 1). Measurement of VC-W was made in early to mid diastole before quantitative reference methods were obtained. The values of 4 measurements were averaged in each patient. In 14 patients, measurements of VC-W were repeated independently by a second observer.

Reference Methods

The ERO area and RF with both quantitative Doppler (QDop) methods were calculated with the following formula: $ERO = \frac{RVol}{RTVI}$ and $RF = \frac{RVol}{aortic stroke volume}$, where RTVI is the regurgitant time velocity integral of the AR jet obtained by continuous-wave Doppler.

For QDop, RVol was calculated as the difference between aortic and mitral stroke volumes measured with pulsed Doppler. The mitral annulus diameter was measured along multiple axes to account for possible noncircular shape. For quantitative 2D echocardiography (Q2DE), RVol was calculated as the difference between left ventricular and mitral stroke volumes.

Other Methods

Left ventricular volumes were measured at end-diastole and endsystole by the biplane method of disks. Cardiac index was measured by use of mitral stroke volume. In addition, in 8 patients, the angiographic grade of AR was obtained, and in 53, the ERO of AR was calculated by the proximal flow convergence method.

Statistical Analysis

Descriptive results were expressed as mean ± SD for continuous variables and percentages for categorical variables. Groups were compared by Student’s t test or χ² test. The VC-W was related to the ERO area, RVol, and RF with linear regression and to categorical variables by use of nonparametric regressions. Analyses were performed in the entire group and in subgroups with eccentric and
VC-W and Quantitative Regurgitant Measurements

Close correlations were found between VC-W and ERO calculated with QDop \( (r=0.90, P<0.0001, \text{SEE}=8 \text{ mm}^2) \) and Q2DE methods \( (r=0.90, P<0.0001, \text{SEE}=8 \text{ mm}^2) \) (Figure 2). When a quadratic relationship was used, the correlation coefficients were marginally improved \( (both \ r=0.92) \), with a mild decrease of the SEE \( (7 \text{ mm}^2 \) for both reference methods). Good correlations \( (all \ P<0.0001) \) were also found between VC-W and RVol and RF determined by QDop \( (r=0.89 \text{ and } 0.90, \text{SEE}=18 \text{ mL and } 7\%, \text{respectively}) \) and Q2DE \( (r=0.90 \text{ and } 0.89, \text{SEE}=18 \text{ mL and } 7\%, \text{respectively}) \) (Figures 3 and 4).

Subgroup analysis showed similar correlations between VC-W and ERO in 42 patients with eccentric jets \( (r=0.88 \text{ for both methods}, P<0.0001) \) and in 37 patients with central jets \( (r=0.91 \text{ and } 0.92, \text{respectively}; P<0.0001) \). Correlations between VC-W and RVol or RF were also similar for eccentric jets and central jets \( (all \ r>0.85, all \ P<0.0001) \). The slopes of the regressions of VC-W to the ERO, RVol, and RF were not different in eccentric and central jet groups \( (all \ P>0.60) \) (Figure 5).

VC-W and Other Methods

No significant relations were found between VC-W and ejection fraction \( (P=0.20) \) and cardiac index \( (P=0.56) \). Conversely, VC-W was related significantly to left ventricular end-systolic and end-diastolic volume index \( (r=0.65 \text{ and } r=0.81, \text{respectively}; P<0.0001) \). Also, VC-W showed sig-

**Table 1. Baseline Characteristics of 79 Patients With Aortic Regurgitation**

<table>
<thead>
<tr>
<th></th>
<th>Overall Group ( (n=79) )</th>
<th>Eccentric Jet Group ( (n=37) )</th>
<th>Central Jet Group ( (n=42) )</th>
<th>( P^* )</th>
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<tr>
<td>Age, y</td>
<td>58±18</td>
<td>52±21</td>
<td>63±14</td>
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<td>Male, %</td>
<td>57</td>
<td>68</td>
<td>48</td>
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<td>SBP, mm Hg</td>
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<td>135±20</td>
<td>146±21</td>
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<td>DBP, mm Hg</td>
<td>73±13</td>
<td>71±12</td>
<td>75±15</td>
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<td>EDVI, mL/m²</td>
<td>113±39</td>
<td>122±42</td>
<td>105±36</td>
<td>0.05</td>
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<tr>
<td>ESVI, mL/m²</td>
<td>42±22</td>
<td>47±26</td>
<td>38±18</td>
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<tr>
<td>Ejection fraction, %</td>
<td>64±8</td>
<td>63±9</td>
<td>65±8</td>
<td>0.46</td>
</tr>
<tr>
<td>Cardiac index, L/m²</td>
<td>2.8±0.6</td>
<td>3.0±0.6</td>
<td>2.6±0.5</td>
<td>0.015</td>
</tr>
<tr>
<td>Jet width, mm</td>
<td>10.0±5.1</td>
<td>10.7±5.2</td>
<td>9.1±5.0</td>
<td>0.22</td>
</tr>
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<td>Jet/LVOT width, %</td>
<td>40±18</td>
<td>41±19</td>
<td>38±17</td>
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<td>VC width, mm</td>
<td>5.1±2.2</td>
<td>5.7±2.3</td>
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<td>ERO area, mm²</td>
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<td>Doppler</td>
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<td>29±19</td>
<td>19±16</td>
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<td>2D</td>
<td>23±19</td>
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<td>19±17</td>
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<tr>
<td>RVol, mL</td>
<td></td>
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<tr>
<td>Doppler</td>
<td>52±39</td>
<td>59±37</td>
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<td>0.14</td>
</tr>
<tr>
<td>2D</td>
<td>52±40</td>
<td>60±39</td>
<td>46±40</td>
<td>0.13</td>
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<tr>
<td>RF, %</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Doppler</td>
<td>36±15</td>
<td>38±15</td>
<td>33±15</td>
<td>0.12</td>
</tr>
<tr>
<td>2D</td>
<td>35±16</td>
<td>38±16</td>
<td>33±16</td>
<td>0.15</td>
</tr>
</tbody>
</table>

SVP indicates systolic blood pressure; DBP, diastolic blood pressure; EDVI, ESVI, left ventricular end-diastolic and end-systolic volume index; PAP, pulmonary artery pressure; and 2D, 2D echocardiography.

*Comparison between eccentric jet and central jet groups.
significant correlations with aortographic grading of AR (n=8, \( r=0.82, P=0.01 \)), with jet width and jet/LVOT ratio by color flow imaging (\( r=0.82 \) and \( r=0.75 \), both \( P<0.0001 \)), and with ERO measured by the proximal flow convergence method (n=53, \( r=0.85, P<0.0001 \)).

**Diagnostic Value of VC**

With QDop and Q2DE, ERO \( \geq 30 \text{ mm}^2 \) was noted in 19 and 21 patients, RVol \( \geq 60 \text{ mL} \) in 26 and 27, and RF \( \geq 45\% \) in 29 and 27, respectively. VC-W \( \geq 6 \text{ mm} \) was present in 24 patients. The analysis of the diagnostic value for severe AR is presented in Table 2 for the QDop variables. Similar results were obtained with Q2DE. For ERO, RVol, and RF, the 6-mm threshold of VC-W offers consistently high odds ratios of severe AR with high sum of sensitivity and specificity (boldface in Table). The 5-mm threshold provides high sensitivity and negative predictive value, so that with VC-W <5 mm, the probability of missing severe AR is extremely low. The 7-mm threshold provides high specificity and positive predictive value, so that with VC-W \( \geq 7 \text{ mm} \), the probability of falsely diagnosing severe AR is extremely low.

The diagnostic value of a VC-W \( \geq 6 \text{ mm} \) is confirmed by the fact that compared with VC-W <6 mm, it was associated with lower diastolic blood pressure (65\( \pm 15 \text{ mm Hg, } P=0.0003 \)) and larger left ventricular end-diastolic diameter (64\( \pm 9 \text{ versus } 53\pm 6 \text{ mm, } P<0.0001 \)) and volume (153\( \pm 41 \text{ versus } 95\pm 23 \text{ mL/m}^2, P<0.0001 \)). The odds ratio (95\% CI) of severe left ventricular enlargement (\( \geq 120 \text{ mL/m}^2 \)) with VC-W \( \geq 6 \text{ mm} \) was 29.0 (8.0 to 109).

The areas under the receiver-operator curve for diagnosing severe AR with the thresholds noted in Table 2 for ERO, RVol, and RF were 0.98, 0.94, and 0.96 with QDop and 0.99, 0.95, and 0.99 with Q2DE, respectively. These were higher than those of jet measurements for ERO (both \( P<0.045 \)) and RVol (both \( P<0.02 \)) and tended also to be higher for RF (\( P=0.18 \) and 0.055). These differences were related to better correlations of ERO with VC-W than with jet width and jet/LVOT ratio in the 66 patients in whom all measurements were made (\( r=0.9 \) versus \( r=0.77 \) and versus \( r=0.68 \), both \( P<0.0001 \)), even when nonparametric correlations were used (both \( P<0.01 \)).

**Reproducibility of Measurements**

For the 14 patients in whom VC-W was measured by a second observer, interobserver variability was low, with highly significant correlation between observers (\( P<0.0001 \), SEE=0.6 mm) and low absolute difference between the 2 measurements (0.26\( \pm 0.15 \text{ mm} \)).

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Figure 2. Correlations between VC-W (y axis) and ERO area (x axis) calculated by quantitative 2D (left) and QDop (right) echocardiography. Continuous lines are regression lines.

Figure 3. Correlations between VC-W (y axis) and RF (x axis) calculated by quantitative 2D (left) and QDop (right) echocardiography. Continuous lines are regression lines.
In the 80 patients without regurgitation, the absolute value of the difference between aortic and mitral stroke volumes was 4.1 ± 3.1 mL and between left ventricular and mitral stroke volumes, 3.8 ± 3.6 mL. In our laboratory, the absolute interobserver variability for RF is 4.6 ± 3.3%. In AR patients, correlations between quantitative reference methods (QDop, Q2DE) and between these and the proximal flow convergence method were excellent for RVol (all \( r > 0.91 \), SEE \( < 10 \) mL) and ERO (all \( r > 0.92 \), \( \text{SEE} < 5 \) mm²).

**Discussion**

The present study shows that color Doppler measurement of VC-W (1) can be performed in large numbers of patients with variable degrees and causes of AR; (2) is closely related to the ERO, RF, and RVol in patients with eccentric or central jets; (3) is closely related to other methods of assessment of the degree of AR; and (4) has a high diagnostic value for severe AR and therefore is a simple and useful method of assessment of the severity of AR.

**Color Flow Imaging and Degree of AR**

Color flow imaging shows regurgitant flows in real time, and significant correlations between jet width and angiography have been observed. However, this approach has limitations, and as shown in Figure 1, jet spreading occurs after its exit from the regurgitant orifice and is under the influence of complex factors. The variable jet spreading or constraint may explain the relatively high variability of jet measurements and the influence on jet size of factors independent of lesion severity. Jet width, even immediately below the valve, is much larger than VC-W, as demonstrated in the present study. Even expressed as a ratio to LVOT, jet size does not carry similar physiological significance and shows a significantly poorer correlation with ERO than VC-W. Therefore, it is reasonable to examine the possibility of assessing the degree of AR by use of the more physiologically sound analysis of regurgitant flow core by measurement of VC-W, defined as the smallest color flow diameter at the junction of flow convergence region and regurgitant jet.

**Figure 4.** Correlations between color Doppler VC-W (y axis) and RVol (x axis) calculated by quantitative 2D (left) and QDop (right) echocardiography. Continuous lines are regression lines.

**Figure 5.** Correlations between VC-W (y axis) and ERO area (x axis) calculated by QDop echocardiography in eccentric jets (left) and central jets (right). Continuous lines are regression lines.
VC-W as an Index of Severity of AR
The concepts of ERO and VC have developed slowly from in vitro studies, animal experiments, and clinical series. The areas of ERO and VC are equivalent and smaller than anatomic orifice area because of blood flow contraction through the regurgitant orifice. Therefore, clinical measurement of VC size measured by color Doppler imaging was of great value for quantification of AR. To the best of our knowledge, the present study is the first large clinical series to analyze the value of VC-W measurement in AR. The present clinical data confirm recent experimental data and show that VC-W displays close correlation with independent measurements of ERO, RF, and RVol. VC-W is also strongly associated with other methods of assessment of AR, with clinical alterations due to AR, and with left ventricular enlargement. All these data confirm that in AR, measurement of VC-W, despite its simplicity, strongly reflects the degree of AR and has high diagnostic value for severe AR.

VC-W is not meant to replace ERO calculation, however, because of the notable standard error in estimating ERO from VC-W. This may be a result of measurements of the small dimension of VC-W or of potential variations in shape of the regurgitant orifice. In the future, this may be overcome by 3D reconstruction. Also, the VC-W does not carry the physiological significance of RVol and ERO. However, the major advantage of VC-W measurement in comparison with other quantitative standard is the simplicity of measurement of a highly meaningful variable, which can be obtained by use of multiple echocardiographic views. A VC-W ≥6 mm provided a good diagnostic value for severe AR, even with an eccentric jet. Values of VC-W <5 mm or >7 mm provide excellent specificity for nonsevere and severe AR. Therefore, VC-W should be included in the tools for comprehensive assessment of AR degree.

Limitations of the Study
We evaluated VC-W, although VC area may appear more attractive. Defining the entire VC area perfectly is currently impossible but may be possible in the future with 3D reconstruction. Also, lateral resolution problems of echocardiography limit area but not width measurements performed in the axial direction. In experimental studies, VC size is relatively unaffected by flow rate and driving pressure and by jet type. Recently, with the clarification of the concept of VC, pioneering animal studies using epicardial echocardiography suggested that VC size measured by color Doppler imaging was of great value for quantification of AR. To the best of our knowledge, the present study is the first large clinical series to analyze the value of VC-W measurement in AR. The present clinical data confirm recent experimental data and show that VC-W displays close correlation with independent measurements of ERO, RF, and RVol. VC-W is also strongly associated with other methods of assessment of AR, with clinical alterations due to AR, and with left ventricular enlargement. All these data confirm that in AR, measurement of VC-W, despite its simplicity, strongly reflects the degree of AR and has high diagnostic value for severe AR.

Patients with multiple or diffuse regurgitant jets were excluded, and the value of VC-W with these jets cannot be determined. This problem is of particular concern in patients with bicuspid valves, but in those who fulfilled criteria for inclusion in the present study, the correlations of VC-W with quantitative variables were highly significant (all r>0.83; P<0.0001) and not different from those with tricuspid valves (all P>0.16). Future studies of patients with multiple or diffuse jets should address the value of VC measurements in this setting.

Quantitative echocardiographic methods may be questioned, but their accuracy has been confirmed in multiple centers and used to validate the concept of the VC. Moreover, high correlations between reference methods and the new flow-convergence method and excellent results obtained in patients without regurgitation support the accuracy of these methods and confirm that the reference methods used do not represent a limitation.

The thresholds used to define severe AR are still tentative and should be confirmed in large outcome studies. However, use of

<table>
<thead>
<tr>
<th>Reference</th>
<th>VC-W Threshold, mm</th>
<th>Sensitivity, %</th>
<th>Specificity, %</th>
<th>PPV, %</th>
<th>NPV, %</th>
<th>Odds Ratio 95% CI</th>
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<td>ERO ≥30 mm², Doppler</td>
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<td>73</td>
<td>54</td>
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PPV indicates positive predictive value; NPV, negative predictive value. Boldface type shows 6.0-mm threshold of VC-W (see text).
different thresholds did not reduce the high diagnostic value of VC-W. For example, the positive and negative predictive values of a VC-W <5 mm for noneurose AR with a threshold of RVol <50 mL were 91% and 83%, respectively, and with a threshold of ERO <25 mm², 100% and 74%. Also, the predictive values of VC-W ≥6 mm for severe AR with a threshold of RF ≥50% were 63% and 98%, respectively. Therefore, the thresholds used have little bearing on the results.

Conclusions

This prospective study of patients with AR demonstrated that measurement of VC-W with color Doppler imaging can be obtained in large numbers of patients and provides a reliable assessment of AR, even with eccentric jets. Thus, VC-W can be used clinically as part of a comprehensive Doppler assessment of AR.

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References

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