Assessment of Severity of Mitral Regurgitation by Measuring Regurgitant Jet Width at Its Origin With Transesophageal Doppler Color Flow Imaging

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Background. The ability of transesophageal color Doppler echocardiography to provide high-resolution images of both cardiac structure and blood flow in real time is advantageous for many clinical purposes. This study was performed to determine the utility of the regurgitant jet width at its origin measured by transesophageal Doppler color flow imaging in the assessment of severity of mitral regurgitation.

Methods and Results. Sixty-three consecutive patients with mitral regurgitation underwent transesophageal color Doppler examination, and the diameter of regurgitant jet at its origin was measured. Both right and left cardiac catheterizations were performed within 24 hours of Doppler studies, and angiographic grading of mitral regurgitation and regurgitant stroke volume were evaluated. There was a close relation between the jet diameter at its origin measured by transesophageal Doppler color flow imaging and the angiographic grade of mitral regurgitation ($r=0.86$, $p<0.001$). A jet diameter of 5.5 mm or more identified severe mitral regurgitation (grade III or IV) with a sensitivity of 92%, specificity of 92%, and positive and negative predictive values of 88% and 95%, respectively. In 31 patients with isolated mitral regurgitation, the jet diameter correlated well with the regurgitant stroke volume determined by a combined hemodynamic-angiographic method ($r=0.85$, $p<0.001$). A jet diameter of 5.5 mm or more identified a regurgitant stroke volume of 60 ml or more with a sensitivity of 88%, specificity of 93%, and positive and negative predictive values of 94% and 87%, respectively.

Conclusions. The regurgitant jet width at its origin measured by transesophageal Doppler color flow imaging provides a simple and useful method of measuring the severity of mitral regurgitation, and it may allow differentiation between mild and severe mitral regurgitation. (Circulation 1992;85:1248–1253)

Key Words • mitral regurgitation • echocardiography, transesophageal • echocardiography, Doppler • angiography

Patients with valvular regurgitation may develop left ventricular dysfunction due to a large hemodynamic overload.1,2 An accurate assessment of the severity of regurgitation is important for both medical management and optimal timing of surgical interventions in these patients.3-4 In patients with mitral regurgitation, transesophageal color Doppler echocardiography has been shown to provide high-resolution images of mitral apparatus and regurgitant flow.5-7 Both qualitative estimation and quantitative grading of the severity of mitral regurgitation by transesophageal Doppler color flow imaging have been made by mainly determining the size of the disturbed flow area in the left atrium during systole.8,9 These measurements may be inaccurate due to the difficulties in detecting the entirety of the regurgitant jet, particularly when it is highly eccentric.9,10 The flow volume crossing an orifice in a pulsatile system such as mitral regurgitation is the product of the effective orifice area and the velocity–time integral per cycle. If the velocity–time integral and the contraction coefficient of the orifice are not taken into account, the regurgitant orifice area is proportional to the regurgitant volume. Previous in vitro studies have shown that the proximal regurgitant jet width is directly related to the size of regurgitant orifice, which could be a valuable parameter for the evaluation of valvular regurgitation.10-10 A detailed examination of the relation between this measurement and the angiographic quantitation of regurgitation in patients with various degrees of mitral regurgitation has not yet been performed. The purpose of this study was to examine the clinical value of regurgitant jet diameter at its origin measured by transesophageal Doppler color flow imaging in the quantitative assessment of severity of mitral regurgitation.

Methods

Study Patients

This prospective study consisted of 63 consecutive patients with mitral regurgitation between January 1990 and March 1991. All patients underwent a transesophageal color Doppler examination within 24 hours of cardiac catheterization. There were 29 men and 34 women with a
mean age of 62±12 years (range, 25–79 years). Forty-eight patients were in sinus rhythm, and 15 had atrial fibrillation. The etiologies of mitral regurgitation were rheumatic fever in 18 patients, mitral valve prolapse in 25 (rupture of chordae tendineae in 15), ischemic heart disease in seven, dilated cardiomyopathy in five, hypertrophic cardiomyopathy in one, endocarditis in four, calcification of mitral annulus in two, and dysfunction of bioprosthetic valve in one. Thirty-eight patients had isolated mitral regurgitation, 14 had associated mitral stenosis, and 11 had concomitant aortic valve disease.

**Transesophageal Color Doppler Echocardiography**

This was performed by a single observer using a Hewlett-Packard (Sonos 500) system with a 5-MHz Doppler transducer (transverse monoplane) mounted on the end of a flexible endoscope. After local anesthesia of the back of the patient's throat (sprayed diluted lidocaine solution), patients were placed in the left lateral recumbent position. The esophageal probe was introduced, and a bite block was placed to protect the probe. Standard transesophageal views in the long axis, four and five chambers, and short axis of the left ventricle and aortic valve were then obtained for both imaging and Doppler color flow mapping. Multiple views were methodically applied to visualize the direction and configuration of the jet at the beginning of each study, and the transducer was oriented to ensure that the maximum jet diameter was obtained. For measurement of the diameter of regurgitant jet, the sector angle of imaging was set to 30°, and the gain was adjusted step-by-step to exclude signals outside of flow areas. Because the jet may widen significantly within a few millimeters distal to the regurgitant orifice, care was taken to measure the diameter of regurgitant jet at the regurgitant orifice directly on the screen using a zoom mode (Figure 1). The values of four to six proximal regurgitant jet width measurements were averaged in each patient.

To determine regurgitant jet area, a 45° color sector was used. During each examination, the transducer was panned up and down to achieve the largest jet. With the use of a software program already incorporated into the equipment, the outline of the regurgitant jet was traced manually, and the area was calculated by computerized planimetry. Because either the diameter or the size of regurgitant jet may be affected by changes in cardiac loading conditions, heart rate and systolic blood pressure were routinely recorded during each examination. Mean heart rate and systolic blood pressure were 82±9 beats per minute and 133±24 mm Hg at transesophageal color Doppler studies, which were not significantly

**FIGURE 1.** Measurement of regurgitant jet diameter by transesophageal Doppler color flow imaging using a zoom mode. Top panel: An example of a patient with mild-to-moderate mitral regurgitation. The jet diameter at its origin was 3.7 mm, and the maximum jet area was 6.1 cm². Angiography showed grade II mitral regurgitation with a regurgitant fraction of 28%. Bottom panel: An example of a patient with severe mitral regurgitation who had a jet diameter of 7.5 mm, maximum jet area of 9.4 cm², angiographic grade III mitral regurgitation, and a regurgitant fraction of 55%.
different from the values taken at cardiac catheterization (heart rate, 84±11 beats per minute; systolic blood pressure, 138±30 mm Hg; all \(p>0.05\)).

In 20 patients, the intraobserver and interobserver variabilities during repeated studies for regurgitant jet width measurement by transesophageal Doppler color flow imaging were 6.1±2.9% and 7.1±3.5%, respectively. The variability of regurgitant jet width measurement between cardiac cycles assessed in an additional 20 patients with sinus rhythm was 6.3±3.1%.

Cardiac Catheterization

Both right and left cardiac catheterizations were performed within 24 hours of the Doppler examinations. Right and left heart pressures were measured by the standard method. Forward cardiac output was determined by the thermodilution technique, and effective forward stroke volume was calculated as thermodilution cardiac output divided by heart rate. Left ventriculography was performed in a 30° right anterior oblique projection using 40 ml of contrast media injected through a 7F pigtail catheter positioned in the middle of the left ventricle. The severity of mitral regurgitation was graded visually on a scale of from I to IV following the Sellers's method\(^1\) by two independent observers who had no knowledge of the results of the transesophageal color Doppler studies. Left ventricular end-diastolic and end-systolic volumes were determined by the area-length method and corrected for magnification,\(^3\,4\) and total left ventricular stroke volume was calculated.

In 31 patients with sinus rhythm and isolated mitral regurgitation, the driving pressure of mitral regurgitation was assessed as the difference between left ventricular systolic pressure and mean pulmonary capillary wedge pressure. The regurgitant stroke volume was calculated as total left ventricular stroke volume minus effective forward stroke volume.

Statistical Analysis

Data are presented as mean±SD. Differences between data obtained in individual groups were assessed with the use of Student's \(t\) test for paired data. For continuous variable data, linear regression analysis was performed, whereas for incremental data, the Spearman correlation analysis was applied. Sensitivity, specificity, and predictive accuracy values were calculated using a standard method.\(^3\) The hemodynamic and echocardiographic variables with potential influence on severity of mitral regurgitation were examined by multivariate regression analysis. A value of \(p<0.05\) was considered significant.

Results

Jet Width and Degree of Regurgitation

A regurgitant jet was detected by transesophageal Doppler color flow imaging, and the diameter of the regurgitant jet at its origin could be measured in all patients. The contraction of the vena cava distal to the plane of the orifice was not well visualized in our patients with mitral regurgitation; thus, it appeared not to create difficulties in the jet diameter measurement. The jet diameter was closely related to angiographic grade of mitral regurgitation \((r=0.86, p<0.001)\). The correlation between jet diameter and angiographic grade was similar in 28 patients with free jets \((r=0.86)\) and in 35 patients with eccentric wall jets \((r=0.87)\). Individual values of jet diameter ranged from 1.1 to 4.3 mm (mean, 2.6±1.0 mm) for 21 patients with grade I regurgitation at angiography, from 2.2 to 7.0 mm (mean, 4.2±1.2 mm) for 17 patients with grade II, from 3.9 to 8.2 mm (mean, 6.3±1.2 mm) for 10 patients with grade III, and from 5.8 to 13.0 mm (mean, 8.6±2.2 mm) for 15 patients with grade IV. There was a significant difference in regurgitant jet width measurements among the four angiographic grades of mitral regurgitation. Although overlap existed in the values for jet diameter among individuals in each of the four grades of mitral regurgitation, this measurement nevertheless provided a good classification between mild and moderate (grades I and II) and severe mitral regurgitation (grades III and IV). Statistical analysis revealed that the jet diameter of 5.5 mm was the discriminative value. Twenty-three of 26 patients with a jet diameter of 5.5 mm or more had grade III or IV regurgitation. In contrast, 35 of 37 patients with a jet diameter of less than 5.5 mm had grade I or II regurgitation. Thus, a jet diameter of 5.5 mm or more identified severe mitral regurgitation (grade III or IV) with a sensitivity of 92%, specificity of 92%, and positive and negative predictive values of 89% and 95%, respectively (Figure 2).

Jet Width and Regurgitant Stroke Volume

In 31 patients with isolated mitral regurgitation and sinus rhythm, the diameter of regurgitant jet measured at its origin correlated well with regurgitant stroke volume determined by a combined hemodynamic-angiographic method \((r=0.85, p<0.001)\). Fifteen of 17 patients with a jet diameter of 5.5 mm or more presented a regurgitant stroke volume of 60 ml or more, whereas 13 of 14 patients with a jet diameter of less than 5.5 mm had a regurgitant stroke volume of less than 60 ml. Therefore, a jet diameter of 5.5 mm or more identified a regurgitant stroke volume of 60 ml or more with a sensitivity of 88%, specificity of 93%, and positive and negative predictive values of 94% and 87%, respectively (Figure 3).
Maximum Regurgitant Jet Area

There was a significant correlation between maximum regurgitant jet area detected by transesophageal Doppler color flow imaging and angiographic grading \((r=0.72, p<0.001)\). The mean value of maximum jet area was 2.8±2.5 cm² for 21 patients with grade I mitral regurgitation, 8.0±5.0 cm² for 17 patients with grade II, 10.3±4.1 cm² for 10 patients with grade III, and 14.1±5.3 cm² for 14 patients with grade IV. There was a significant difference in maximum jet area between mild and moderate (grades I and II) and severe (grades III and IV) mitral regurgitation \((p<0.01)\). A maximum jet area of 9.0 cm² or more predicted severe mitral regurgitation by angiography with a sensitivity of 80% and a specificity of 79% and positive and negative predictive values of 74% and 86% (Figure 4). In 31 patients with isolated mitral regurgitation and sinus rhythm, the maximum jet area also correlated with the hemodynamic regurgitant stroke volume \((r=0.55, p<0.002)\). A maximum jet area of 9.0 cm² or more identified a regurgitant stroke volume of 60 ml or more with a sensitivity of 75%, specificity of 80%, and positive and negative predictive values of 80% and 75%, respectively (Figure 5).

Driving Pressure

In 31 patients with isolated mitral regurgitation and sinus rhythm, the driving pressure, assessed as the difference between left ventricular systolic pressure and mean pulmonary capillary wedge pressure, did not correlate significantly with angiographic grade of regurgitation \((r=0.26, p>0.05)\), regurgitant jet diameter \((r=0.34, p>0.05)\), and maximum regurgitant jet area \((r=0.04, p>0.05)\) and was poorly related to regurgitant stroke volume \((r=0.38, p=0.05)\). There was no significant difference in the driving pressure measurements among the four angiographic grades. The angiographic correlation with regurgitant jet diameter with or without incorporating the driving pressure in the regression analysis was not significantly different, but the angiographic correlation was better with combined maximum regurgitant jet area and driving pressure than with maximum jet area alone (Table 1).

Discussion

Assessment of Severity of Mitral Regurgitation by Transesophageal Color Doppler Echocardiography

With the use of Doppler color flow imaging, mitral regurgitation can be characterized as an area of flow signals originating from the mitral valve orifice and moving into the left atrium during systole. Because of the great systolic pressure gradient between the left atrial and ventricular chambers, the velocity of the

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blood flow represented by these signals is high, so that resultant signals have the special mosaic appearance caused by turbulence and aliasing.10 It has been shown that the transesophageal window for color flow imaging provides evidence of mitral regurgitant flow more frequently than does the conventional transthoracic window, and Doppler regurgitant jet areas determined by transesophageal echocardiography are often larger than those by transthoracic jets using comparable scan planes.9 Previous studies that have correlated measurements from transesophageal Doppler color flow imaging with those obtained by angiography in the evaluation of the severity of mitral regurgitation have mainly used the maximum regurgitant jet area in the receiving left atrium.6,9 Yoshida et al8 have found that the use of a biplane transesophageal transducer facilitated complete visualization of both longitudinal and transverse views of the regurgitant jet. The transverse plane provided better assessment of regurgitation than the longitudinal one, and an excellent angiographic correlation was obtained with maximum jet area from the two planes. Our results are consistent with previous findings, as there was a significant correlation between regurgitant jet area from transesophageal Doppler color flow imaging and angiography grading and hemodynamic regurgitant stroke volume. However, an improved angiographic correlation was achieved with regurgitant jet width at its origin measured by transesophageal Doppler color flow imaging, and the relation was not significantly affected by the driving pressure and the eccentricity of the regurgitant jets. A jet diameter of 5.5 mm or more classified well patients with severe mitral regurgitation and identified those with a regurgitant stroke volume of 60 ml or more with high sensitivity, specificity, and predictive accuracy. This suggests that the diameter of regurgitant jet at its origin determined by transesophageal Doppler color flow imaging may be a reliable parameter to estimate the severity of mitral regurgitation. The improved correlation between jet diameter and angiographic assessment of degree of mitral regurgitation may be due to similar errors being present in both techniques.

In this study, we chose to evaluate the simple measurement of the diameter of regurgitant jet at its origin because it was difficult to detect the entire regurgitant jet and to assess accurately the regurgitant jet velocity in patients with a highly eccentric regurgitant jet.5 Furthermore, the reproducibility of regurgitant jet area measurement has been found less satisfactory.2,20 If the flow field is three-dimensional in nature, as is the case in many mitral regurgitant lesions, obtaining the spatial extent of flow in a single plane may be inadequate. Three orthogonal planes would be desirable under these circumstances.8,14,21,22 Our results show that the diameter of the regurgitant jet at its origin can be measured in patients with various degrees of mitral regurgitation using transesophageal Doppler color flow imaging, and the contraction of the vena distal to the plane of the orifice appears not to create difficulties in the jet diameter measurements. In some patients, the jet may widen significantly within a few millimeters distal to the regurgitant-orifice particularly when the orifice is small and the pressure gradient between the left atrium and the left ventricle is high. Therefore, meticulous care must be taken in the acquisition of Doppler color flow images and measurement of the proximal jet width. We found that the use of a zoom mode facilitates direct visualization of the initial portion of regurgitant jet and provides accurate measurements of jet diameter at its origin. The regurgitant orifice diameter may be measured by two-dimensional echocardiography in some patients with severe mitral regurgitation (e.g., chordal rupture), but Doppler color flow imaging was necessary to better characterize the regurgitant jet flow and to more accurately define the regurgitant jet orifice in majority of patients.

There is in vitro evidence supporting the concept that the diameter of regurgitant jet at its origin can be used to assess the severity of mitral valve leak.12-15,23 Experimental hydraulic models have shown that the amount of mitral regurgitant flow depends largely on the size of the regurgitant orifice, the pressure gradient across the mitral valve, and the compliance of the left atrium.13,23 The configuration of the flow streams at the regurgitant orifice and up to the vena contracta of the jet is complex, and the velocity profile undergoes significant changes within the contraction of the vena. The maximum velocity of the regurgitant jet, depending on the orifice shape, occurs downstream of the orifice in the vena contracta.24 At the regurgitant orifice, the jet width may be significantly less than the regurgitant orifice diameter due to the vena contracta effect, but the proximal jet width and cross-sectional area are directly related to the orifice size.13 This relation is relatively independent of flow rate and pressure gradient.13 It is apparent that the size of the regurgitant orifice is a critical variable for a mitral regurgitant jet.13,14 Measurement of the jet width at its origin as a method of assessing the severity of regurgitation may be more rational than measurement of jet area.12 Because flow is proportional to orifice area under certain loading conditions, severity of regurgitation should increase with increasing size of the regurgitant orifice.13,15,16 Proximal to the orifice, there may be little effect of postorifice flow disturbances, resulting in dispersion of flow velocities, entrained velocities, or interaction with other flow streams.12

**Limitations**

There are several potential limitations regarding the utility of proximal regurgitant jet width measured with transesophageal Doppler color flow imaging in the quantitative assessment of mitral regurgitation. In this study, each regurgitant jet width measurement was calculated by the computer in centimeters to three decimal places, which is beyond the resolution of ultrasound machine. Because the machine factors were unchanged in this study and the regurgitant jet diameters varied greatly among individual patients, the effect of the transducer beam resolution on the accuracy of regurgitant jet width determination may be minimal. In our study, the ultrasound transducer was oriented to ensure that the maximum jet diameter was obtained for each patient. The validity of regurgitant jet width at its origin determined by monoplane transesophageal Doppler color flow imaging as a measure of severity of mitral regurgitation requires the assumption that the valver orifice is relatively uniform. Morphological changes in the mitral valve resulting from pathological conditions that produce complex shapes may not con-
form to this assumption. In ellipsoid or slit-shaped orifices, significantly different measurements of regurgitant jet diameters could be found between perpendicular imaging planes. Biplane transesophageal Doppler color flow imaging may improve the accuracy. The finding of the significant changes of the regurgitant jet width measurements within a few millimeters distal to the regurgitant orifice may be an important limitation, as the mitral valve plane moves considerably. The presence of multiple regurgitant orifices may make application of this methodology difficult. There may be a systematic overestimation of the orifice size by measuring jet diameter at its origin, in part the result of the loss in lateral resolution.

Clinical Implications

The measurement of the size of the effective regurgitant orifice is an appropriate method of quantifying mitral regurgitation because it is rather independent of the loading conditions and of the left ventricular function. This prospective study has shown that the diameter of regurgitant jet at its origin determined by transesophageal color Doppler echocardiography provides a simple and useful method of measuring the quantitative assessment of the severity of mitral regurgitation. This method may be an interesting technical refinement that, despite its semi-invasiveness, can be of practical utility in some instances of the broad spectrum of anatomic varieties of mitral regurgitation, i.e., in case of eccentric jets due to flail orifice by measuring jet diameter at its origin, in part the result of the loss in lateral resolution.

Acknowledgment

We express our gratitude to Frédérique Bajus for her careful attention in the preparation of the manuscript.

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Circulation. 1992;85:1248-1253
doi: 10.1161/01.CIR.85.4.1248

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