Three-Dimensional Echocardiographic Planimetry of Maximal Regurgitant Orifice Area in Myxomatous Mitral Regurgitation: Intraoperative Comparison With Proximal Flow Convergence

CHRISTIAN S. BREBRUDA, MD,* BRIAN P. GRIFFIN, MD, FACC, MIN PU, MD, LEONARDO RODRIGUEZ, MD, DELOS M. COSGROVE, MD, JAMES D. THOMAS, MD, FACC
Cleveland, Ohio

Background. Regurgitant orifice area (ROA) is an important measure of the severity of mitral regurgitation (MR) that up to now has been calculated from hemodynamic data rather than measured directly. We hypothesized that improved spatial resolution of the mitral valve (MV) with three-dimensional (3D) echo might allow accurate planimetry of ROA.

Methods. We reconstructed the MV using 3D echo with 3° rotational acquisitions (TomTec) using a transesophageal (TEE) multiplane probe in 15 patients undergoing MV repair (age 59 ± 11 years). One observer reconstructed the prolapsing mitral leaflet in a left atrial plane parallel to the ROA and planimetered the two-dimensional (2D) projection of the maximal ROA. A second observer, blinded to the results of the first, calculated maximal ROA using the proximal convergence method defined as maximal flow rate \(2\pi r^2 v_a\), where \(r\) is the radius of a color alias contour with velocity \(v_a\) divided by regurgitant peak velocity (obtained by continuous wave [CW] Doppler) and corrected as necessary for proximal flow constraint.

Results. Maximal ROA was 0.79 ± 0.39 (mean ± SD) cm\(^2\) by 3D and 0.86 ± 0.42 cm\(^2\) by proximal convergence (p = NS). Maximal ROA by 3D echo (y) was highly correlated with the corresponding flow measurement (x) (\(y = 0.87x + 0.03, r = 0.95, p < 0.001\)) with close agreement seen \((\Delta ROA (y - x) = 0.07 ± 0.12 \text{ cm}^2)\).

Conclusions. 3D echo imaging of the MV allows direct visualization and planimetry of the ROA in patients with severe MR with good agreement to flow-based maximal convergence measurements.

©1998 by the American College of Cardiology

The mitral valve (MV) apparatus has a complex three-dimensional (3D) structure, especially in the presence of myxomatous degeneration with leaflet prolapse or flail. Although excellent images of the MV are obtainable by two-dimensional (2D) echocardiography (1), a full appreciation of the 3D morphology is often lacking.

The regurgitant orifice area (ROA) is a fundamental measure of valvular incompetence, which may be used to follow the regurgitant severity over time. ROA may be measured using Doppler echocardiographic examination of the proximal convergence zone (2), the difference in flow across regurgitant and nonregurgitant valves (3), and direct measurement of the jet vena contracta (4), but these techniques are time consuming, technically demanding, and affected by the geometry of the regurgitant flow field and by machine factors, limiting utilization in the clinical setting. Ideally, ROA would be measured directly similar to the orifice area of stenotic valves, but 2D echocardiographic definition of ROA is difficult because of the complex geometry involved. This is unfortunate because an integrated assessment of mitral morphology and regurgitant severity is used in deciding the repairability of the MV and the appropriate timing of surgery (5–7).

Three-dimensional echocardiography is an evolving technology (8) that can improve on 2D echo in the depiction of MV pathology (9,10). We have recently used intraoperative 3D reconstruction of the MV to better characterize the location and extent of leaflet prolapse (11), suggesting that the improved spatial orientation and resolution of 3D echo would allow direct planimetry of ROA. The purposes of this study therefore were: (1) to quantify the ‘anatomical’ size of the maximal ROA by 3D echo, comparing the size with that measured by Doppler techniques; and (2) to determine whether the area and volume of prolapsing tissue measured by 3D echo correlates with the severity of mitral regurgitation.
Methods

Patient selection. We studied 15 patients (32–75 years, mean 59±11 years, nine men and six women) with myxoma-
tous MV prolapse or leaflet flail with severe mitral regurgita-
tion (MR) undergoing MV repair. The patients were selected 
at random based on the logistics of the intraoperative eco-
chocardiography schedule, with typically one patient per day being 
studied. Patients were not excluded on the basis of image 
quality, although patients in atrial fibrillation were excluded 
because of difficulties in 3D reconstruction. All patients un-
derwent a preoperative transthoracic echo and an intraopera-
tive transesophageal echocardiography (TEE) pre- and post-
cardiac bypass. The prebypass intraoperative exam preceded 
the 3D acquisition and was recorded on 0.5 in. VHS video tape 
by an experienced independent clinician with complete inter-
rogation of the MV apparatus.

Three-dimensional echocardiography and reconstruction. 
Three-dimensional TEE was performed in conjunction with 
the preoperative exam, utilizing a 5-MHz phased-array multi-
plane probe (12), interfaced with a Hewlett-Packard Sonos 
1500 (77035A) or 2500 (M2406A) (Andover, MA), equipped 
with investigational 3D acquisition software. Electrocardio-
graphic gating was obtained from the Hewlett-Packard system 
and recalibrated using the 5-cm reference scale on the 3D image. 
The proximal convergence method. The proximal convergence 
method was optimized by baseline shifting the color Doppler 
aliasing velocity to between 34 and 69 cm/s or ±10% to 15% of 
peak mitral velocity. The radial distance (r) between the first 
aliasing contour (red/blue interface) and the center of the 
regurgitant orifice was measured at the time of the largest

Abbreviations and Acronyms

2D = Two-dimensional
3D = Three-dimensional
CW = Continuous wave
MR = Mitral regurgitation
MV = Mitral valve
ROA = Regurgitant orifice area
RSV = Regurgitant stroke volume
TEE = Transesophageal echocardiography
convergence image. For patients with nonflail mitral leaflets, the orifice was assumed to be at the plane passing through the tips of the mitral leaflets; for flail mitral leaflets, the orifice was assumed to lie in the plane of the nonflail leaflet. Maximal instantaneous regurgitant flow \( (Q_{\text{max}}) \) was calculated as \( Q_{\text{max}} = 2\pi r^2 v_a \), where \( r \) is the maximal distance to the contour of velocity \( v_a \), with a hemispheric contour assumed. The regurgitant orifice area was obtained by dividing maximal flow by the peak regurgitant velocity \( (v_p) \) obtained by continuous-wave (CW) Doppler: \( \text{ROA} = Q_{\text{max}}/v_p \). Regurgitant stroke volume \( (\text{RSV}) \) was obtained by multiplying ROA by the velocity–time integral of CW regurgitant velocity \( (\text{VTI}_{\text{CW}}) \): \( \text{RSV} = \text{ROA} \times \text{VTI}_{\text{CW}}/v_p \). If the proximal flow field was distorted by wall contact in any transesophageal plane, the geometric convergence angle \( (\alpha) \) was determined and corrected. ROA \( (c\text{ROA}) \) and RSV \( (c\text{RSV}) \) were calculated as \( c\text{ROA} = \text{ROA} \times \alpha/180 \) and \( c\text{RSV} = \text{RSV} \times \alpha/180 \) as validated previously (15).

**Statistical analysis.** All values are expressed as mean ± SE. For the validation of 3D echo, planimetered ROA was compared with proximal convergence ROA by linear regression and analysis of agreement to give the bias and scatter in the measurements. Doppler RSV and ROA as well as the 3D estimation of the severity of prolapse by prolapse area and volume were compared with 3D ROA using linear regression.

**Interobserver and intr observer variability.** In 10 patients selected randomly, the proximal flow convergence and 3D echo planimetry were obtained independently by two observers. Intraobserver variability was also calculated by repeating measurements 1 month after the initial measurement.

**Results**

Table 1 lists the demographic and clinical characteristics of the patients. Salient features include male dominance (60%) and relative lack of symptomatology.

**Imaging of the regurgitant orifice.** Under optimal conditions, the 3D ROA quantification took ~15 min to complete, with 3 to 4 min for image acquisition, 8 to 10 min for processing and reconstruction of the image, and 2 to 3 min for recalibration and planimetry of the ROA. In three patients, electrocautery from adjacent surgical suites interfered with image quality and slowed acquisition, but the regurgitant orifice could be successfully reconstructed in all patients.

Figure 1 shows a 3D echo reconstruction of the MV at the level of the mitral annulus. The regurgitant orifice is viewed with a posterior projection from a position in the anterior left atrium, showing deep prolapse and partial flail of the middle scallop of the posterior mitral leaflet. Figure 2 shows an example of an eccentric proximal flow convergence zone with wall constraint.

**Echocardiographic findings.** Table 2 summarizes the findings from the clinical intraoperative echo studies. Cases were divided approximately equally between leaflet flail and pure prolapse, with the expected posterior leaflet predominance.

---

**Table 1. Demographic and Clinical Data of the Patient Population**

<table>
<thead>
<tr>
<th>Continuous Variables</th>
<th>Mean ± SD</th>
<th>(Minimum and Maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>59.1 ± 11.2</td>
<td>(32-75)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.8 ± 10.2</td>
<td>(157-189)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>75.9 ± 14.2</td>
<td>(53.7-109)</td>
</tr>
<tr>
<td>Systolic BP (mm Hg)</td>
<td>125 ± 13</td>
<td>(104-148)</td>
</tr>
<tr>
<td>Diastolic BP (mm Hg)</td>
<td>71 ± 11</td>
<td>(50-86)</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>84 ± 7</td>
<td>(76-100)</td>
</tr>
<tr>
<td>Onset of murmur (years)</td>
<td>9.4 ± 7.2</td>
<td>(0-60)</td>
</tr>
<tr>
<td>Ejection fraction (%)</td>
<td>59 ± 8</td>
<td>(40-70)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Categorical Variables</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>9 men</td>
<td>60</td>
</tr>
<tr>
<td>Hypertension</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Congestive heart failure</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>CHF class I</td>
<td>8</td>
<td>53</td>
</tr>
<tr>
<td>CHF class II</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>CHF class III</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Dyspnea</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>Palpitations</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>Chest pain</td>
<td>3</td>
<td>20</td>
</tr>
</tbody>
</table>

(BP) blood pressure; (CHF) congestive heart failure (grading based on New York Heart Association).

The left ventricular ejection fraction was normal in most cases, although it ranged as low as 40%.

**Measurements of the regurgitant orifice area.** The proximal convergence zone was well visualized in all cases. Because of the preponderance of posterior prolapse and flail pathology, all but one of these zones were constrained by the adjacent posterior wall, requiring correction of the ROA by the constraining angle \( \alpha \). Maximal ROA by 3D echo \( (y) \) was 0.79 ± 0.39 cm\(^2\) (mean and SD, range 0.37 to 1.97 cm\(^2\)) and 0.86 ± 0.42 cm\(^2\) (range 0.31 to 1.63 cm\(^2\)) by proximal convergence \( (x) \). Regression analysis demonstrated excellent correlation and...
agreement: $y = 0.87x + 0.03$, $r = 0.95$, $p < 0.001$, $\Delta\text{ROA} (y - x) = -0.07 \pm 0.13 \text{cm}^2$ (mean $\pm$ SD), with a range of $-0.31$ to $0.14 \text{cm}^2$ (Fig. 3). Figure 4 shows the difference between ROA planimetered by 3D echo and calculated by proximal convergence plotted against the mean of these measurements.

**Correlation of ROA with area and volume of prolapse.** The area ($x$) and volume ($y$) of prolapse, each quantified by 3D echo, were closely correlated with $r = 0.79$, $p < 0.001$, $y = 0.91x + 0.39$. Three-dimensional area of prolapse correlated slightly better with the 3D ROA ($r = 0.58$, $p < 0.04$) than with calculated ROA by proximal convergence ($r = 0.43$, $p = \text{NS}$), although wide scatter was seen in the relationship. Three-dimensional prolapse volume correlated neither with 3D nor flow ROA (see Table 3).

**Reproducibility.** The intraobserver and intraobserver variability averaged $1.1 \pm 11\%$ (mean difference $\pm$ SD) for radius measurement, $6.7 \pm 11\%$ (mean difference $\pm$ SD) for convergence angle measurement and $1 \pm 10\%$ (mean difference $\pm$ SD) for 3D ROA planimetry, $1.3 \pm 12\%$ for area and $1.2 \pm 8\%$ volume of 3D mitral valve prolapse.

**Discussion**

This study demonstrates that MV ROA planimetry is feasible with 3D echocardiography even in patients with severely distorted valvular geometries resulting from leaflet flail. ROA measured by 3D echo correlated well with that calculated by the proximal convergence method.

**Quantification of mitral regurgitation.** Despite the importance of accurate quantitation of mitral regurgitation (MR) for surgical timing and assessing medical therapy, semiquantitative methods such as contrast ventriculography (15) and visual assessment of color Doppler regurgitant jet size (17) and morphology (18) within the left atrium are mostly used to characterize MR in the routine clinical setting. Although quantitative angiography (19) and 2D Doppler methods (20) are well validated and considered reference standards, they are technically demanding and not used routinely. Semiquantitative methods are easy to use but grade regurgitant severity on a simple linear scale from 1 to 4. Extremes of regurgitant severity are easily differentiated, but the classification of moderate lesions is difficult, especially because these tech-

![Figure 2](image_url) Flail posterior leaflet (transesophageal view) demonstrating proximal flow convergence with wall constraint because of the proximetry of the posterior wall. To adjust for the predictable overestimation due to this geometric distortion, regurgitant flow rate and orifice area are adjusted by $\alpha/180$. LA = left atrium; LV = left ventricle.

![Figure 3](image_url) Regression analysis relating effective ROA calculated by flow convergence and planimetered regurgitant orifice area by 3D echocardiography. ($r = 0.95; p < 0.001; y = 0.87x + 0.03; \text{standard error of estimate (SEE)} = 0.125.$)
Dilatation (26). In myxomatous MV disease, however, the cases of incomplete MV closure due to severe left ventricular systolic define the area of malcoaptation and ROA, typically in measure of regurgitant severity, but 2D echo can only occasionally a method to measure ROA as a flow-independent planimetry of the stenotic aortic valve (25). Planimetry is thus a method have limited its use in practice.

Convergence method. The proximal convergence method has been proposed as a simple quantitative method, requiring only a single acoustic window. Regurgitant flow is measured directly and can be combined with CW Doppler estimate of peak regurgitant velocity to predict ROA. It is generally based on an assumed hemispherical contour shape (2), although prior experimental studies have shown this to be incorrect near the regurgitant orifice (21) or when the proximal flow is constrained by surrounding structures (15,22). Although formulas have been proposed to overcome the overestimation because of proximal constraint (15); in practice only one-dimensional corrections have been applied (as in this study), rather than the more valid 3D adjustment (23). This and other technical difficulties in performing the proximal convergence method have limited its use in practice.

Three-dimensional echo planimetry. Planimetry is an established method for stenotic orifices, especially in mitral stenosis (24). More recently, multiplane TEE has allowed direct planimetry of the stenotic aortic valve (25). Planimetry is thus potentially a method to measure ROA as a flow-independent measure of regurgitant severity, but 2D echo can only occasionally define the area of malcoaptation and ROA, typically in cases of incomplete MV closure due to severe left ventricular dilatation (26). In myxomatous MV disease, however, the ROA occurs in planes not readily imaged by conventional 2D imaging, necessitating 3D imaging.

Several approaches have been described for 3D echo, not all of them applicable to planimetry of the ROA. Levine and coworkers have used acoustic and electromagnetic localizing devices to position randomly acquired 2D echo planes in 3D space (8). Manual segmentation is required to identify endocardial borders and other structures from which volumes and areas may be calculated. Although good accuracy has been reported for LV volume (27–30) and ventricular septal defect size (31), the inhomogeneous sampling of this technique would make characterization of the mitral regurgitant orifice difficult. In contrast, the TomTec device adopts a structured data acquisition strategy from a single echocardiographic window to yield a nearly isotropic data set. Such a structured approach can be a linear or fan-like sweep or a rotational acquisition from either the transthoracic or (as done here) TEE approach, which is especially effective for reconstructing the MV, as it is in the near field of the TEE probe, allowing it to be densely sampled by the rotating 3D plane. At a 5-cm depth, the edges of successive 3° sector scans are <2 mm apart, becoming progressively closer as one moves toward the center of the imaging field (where the ROA usually fell). A potential problem is the misregistration of planes when patient or probe movement occurs during the acquisition, a problem exacerbated when arrhythmia or artifact from electrocautery prolongs the acquisition.

Finally, an instrument that performs 3D echo in real time has recently been developed (31). Using 16:1 parallel processing and a 2D-phased array crystal, it is capable of generating 3D data sets consisting of 64 scan lines and 64 scan planes at 20 to 40 Hz. Although very promising—and likely the long-term approach to 3D echo—this device cannot yet be used with TEE, and the resolution from the chest wall is likely to be inferior (pending technical improvements) to the approach used in this study.

Limitations. We demonstrated that the MV ROA may be imaged and measured by 3D echocardiography, even in patients with distorted MV geometry. One limitation is the lack of a true reference standard for regurgitant severity, especially as the 3D and Doppler methods used in this study measured slightly different entities. Three-dimensional planimetry defines the anatomical ROA, whereas the proximal convergence method should yield the narrowest flow stream (vena contracta), which is smaller than the anatomic orifice by the coefficient of contraction (generally 0.8 to 0.9). Thus, it may be surprising that planimetered areas were slightly smaller than the flow areas. Although this likely relates in large part to measurement noise in both data sets, there may be some systematic overestimation of the flow areas because of incomplete adjustment for flow constraint. The previously validated one-dimensional angle adjustment corrects ~80% of the overestimation; in the future, 3D echo may be used to more fully correct for this complex geometric constraint. Another potential source of error is that 3D ROA was based on a planar projection of the largest apparent orifice but might have

Table 3. Correlations among Three-Dimensional Area of Prolapse, 3D Volume of Prolapse Compared to ROA by Convergence Method, and 3D Echo Planimetry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter</th>
<th>r</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D area</td>
<td>3D ROA</td>
<td>0.58</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>3D area</td>
<td>ROA_{pc}</td>
<td>0.43</td>
<td>NS</td>
</tr>
<tr>
<td>3D volume</td>
<td>3D ROA</td>
<td>0.25</td>
<td>NS</td>
</tr>
<tr>
<td>3D volume</td>
<td>ROA_{pc}</td>
<td>0.14</td>
<td>NS</td>
</tr>
<tr>
<td>3D volume</td>
<td>3D area</td>
<td>0.79</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

ROA_{pc} = calculated regurgitant orifice area using the proximal flow convergence method; area = prolapse area; volume = prolapse volume.
missed additional areas in other planes. Additionally it is possible that ROA may be underestimated (if beam width artifact thickens the mitral leaflets) or overestimated (if the thin mitral leaflets are not captured in the surfacing algorithm, resulting in drop-out). Artifact from electrocautery is a major problem, sometimes seen even from an adjacent operating room. Atrial fibrillation can significantly prolong 3D reconstruction (although no patients in the current study were in this rhythm) but may be less important with real-time 3D imaging. These results should thus only be considered applicable to patients in sinus rhythm. To minimize the effects of dynamic changes in ROA between the two techniques (33,34), we compared maximal rather than mean values.

Conclusions. In this study we have demonstrated that it is feasible to perform quantitative 3D echocardiography for measurement of the mitral ROA in the intraoperative setting. We further showed that 3D ROA agrees closely with that derived by the flow-based proximal convergence method. As 3D acquisition and analysis become faster, quantitative applications such as this should become more common.

We thank Sheila Wallace for assistance with the manuscript and Paula Shalling for assistance with the illustrations.

References

7. Schiller NB, Foster E, Redberg RF. Transesophageal echocardiography in the evaluation of mitral regurgitation. The twenty four signs of severe mitral regurgitation. Cardiol Clin 1993;11:399–408.