Intraoperative Validation of Mitral Inflow Determination by Transesophageal Echocardiography: Comparison of Single-Plane, Biplane and Thermodilution Techniques

MIN PU, MD, BRIAN P. GRIFFIN, MD, PIETER M. VANDERVOORT, MD, DOMINIC Y. LEUNG, MBBS, MRCP, DELOS M. COSGROVE II1, MD, JAMES D. THOMAS, MD, FACC

Cleveland, Ohio

Objectives. This study investigated the accuracy of mitral inflow quantification using biplane transesophageal echocardiography.

Background. Mitral stroke volume can be reliably quantified by transthoracic Doppler echocardiography, but previous studies involving monoplane transesophageal echocardiography have yielded mixed results.

Methods. Thirty patients without mitral regurgitation were prospectively examined immediately before cardiovascular surgery. Mitral annulus diameter was measured in the transverse (d1) and longitudinal views (d2) by biplane transesophageal echocardiography. Assuming an elliptic shape, the annular area was calculated as πd1d2/4; area was also calculated from single-plane data assuming a circular annular shape as πd1²/4. The time-velocity integral of mitral annular Doppler velocity was then multiplied by annular area to yield stroke volume. These data were compared with simultaneous thermodilution measurements by linear regression.

Results. Good correlations were observed between thermodilution (x) and Doppler (y) measurements of stroke volume (SV) (r = 0.86, p < 0.01, ΔSV [y-x] = 2.64 ± 9.86 ml for single four-chamber view; r = 0.77, p < 0.01, ΔSV = 1.82 ± 12.59 ml for two-chamber view; r = 0.94, p < 0.001, ΔSV = 1.78 ± 5.90 ml for biplane measurements) with similar data for cardiac output (r = 0.82, r = 0.74 and r = 0.92, respectively). The biplane measurements were most accurate and had less variability in individual patients (p < 0.05). This finding was supported by a numerical model that demonstrated (for an ellipse of eccentricity 1.5:1) that even maximal misalignment of biplane diameters yielded only 8% area overestimation, whereas single-plane calculations assuming a circular shape produced a variation in area of 225%.

Conclusions. This study validates the accuracy of measurements of mitral inflow using biplane transesophageal echocardiography with potential application for quantification of valvular regurgitation in the operating room. The results are further generalizable, indicating that orthogonal biplane measurements are both necessary and sufficient to ensure accuracy in area calculation for any elliptic structure.

(J Am Coll Cardiol 1995;26:1047-53)

Accurate determination of mitral inflow (stroke volume and cardiac output) is useful in the evaluation of left ventricular function and quantification of valvular regurgitation. Transthoracic Doppler echocardiography has been extensively studied and shown to be a reliable method of measuring mitral inflow (1-4), particularly in recent validation of flow through the mitral annulus (5). However, this method is impractical in the operating room and in critically ill patients receiving mechanical ventilation.

Transesophageal echocardiography provides an alternative method to evaluate transmural flow (6,7). This has raised interest in the assessment of left ventricular function by quantitative Doppler transesophageal echocardiography. Recently some investigators (8,9) have reported good correlation between thermodilution and single-plane transesophageal echocardiographic measurement of cardiac output interrogating the left ventricular outflow tract or aorta. However, this method is of limited use because the deep transgastric view of the left ventricular outflow tract cannot be obtained in a significant minority of patients and, further, may be unreliable when patients have aortic stenosis or insufficiency. Alternatively, cardiac output might be measured using mitral inflow, but previous studies (10,11) have shown significant error in mitral inflow measurements using monoplane transesophageal echocardiography, with correlations with thermodilution ranging from 0.03 to 0.73. Therefore, quantitative Doppler transesophageal echocardiography has not been widely used in determination of mitral inflow.

Biplane transesophageal echocardiography allows the acquisition of orthogonal views of the mitral annulus (12) and may yield more accurate calculation of mitral annulus area.
One study (13) of 14 patients demonstrated more accurate stroke volume calculations with biplane measurements than with single-plane data. This encouraged us to undertake a larger study to determine 1) the applicability and accuracy of quantitative Doppler biplane transesophageal echocardiography in measuring mitral stroke volume, and 2) the existence of potentially correctable pitfalls. The study was supplemented with a numerical model to compare single-plane and biplane area estimations of elliptic structures.

**Methods**

**Study patients.** We prospectively studied 30 patients in sinus rhythm undergoing cardiac surgery who had neither mitral nor tricuspid regurgitation (Table 1).

**Echocardiographic examination.** A biplane or multiplane transesophageal echocardiographic probe (Sonos 1500, Hewlett-Packard, Acuson 128 XP) was inserted into the patient’s esophagus. To obtain forward flow through the mitral annulus, careful two-dimensional interrogation of the annulus was performed in the four-chamber (transverse, 0°) and two-chamber (longitudinal, 90°) projections at the midesophageal position (Fig. 1, A and B). The pulsed Doppler sample volume was placed at the center of the annulus in the four-chamber view, and Doppler spectra were recorded at a speed of 100 mm/s (Fig. 1C). All echocardiographic data were stored on 0.5-in. videotape. Biplane transesophageal echocardiography was simultaneously performed with thermomil dilution before bypass cannulation.

**Thermomil dilution data.** A Swan–Ganz catheter was inserted into the pulmonary artery as part of the routine intraoperative monitoring for all patients. Special care was taken to ensure that cardiac output obtained by thermomil dilution was simultaneous with the acquisition of the echocardiographic data. Cardiac output was obtained from the average of at least three consecutive thermomil dilution measurements differing by <15% from each other. Stroke volume was calculated by dividing cardiac output by heart rate.

**Data analysis.** Diameters of mitral annulus (inner edge) were measured at the base of the leaflets at the time of

### Table 1. Thermomil dilution and Transesophageal Echocardiographic Measurements in 30 Patients

<table>
<thead>
<tr>
<th>Pt No./Gender</th>
<th>Age (yr)</th>
<th>Dx</th>
<th>Thermodilution CO (liters/min)</th>
<th>Four-Chamber TEE</th>
<th>Two-Chamber TEE</th>
<th>Biplane TEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/M</td>
<td>68</td>
<td>CAD</td>
<td>4.87</td>
<td>4.22</td>
<td>5.62</td>
<td>4.87</td>
</tr>
<tr>
<td>2/F</td>
<td>74</td>
<td>CAD</td>
<td>2.48</td>
<td>2.76</td>
<td>2.07</td>
<td>2.39</td>
</tr>
<tr>
<td>3/M</td>
<td>46</td>
<td>CAD</td>
<td>4.47</td>
<td>4.65</td>
<td>3.14</td>
<td>3.82</td>
</tr>
<tr>
<td>4/M</td>
<td>51</td>
<td>AI</td>
<td>4.87</td>
<td>5.18</td>
<td>5.25</td>
<td>5.21</td>
</tr>
<tr>
<td>5/M</td>
<td>49</td>
<td>AS</td>
<td>3.90</td>
<td>4.25</td>
<td>3.92</td>
<td>4.08</td>
</tr>
<tr>
<td>6/F</td>
<td>59</td>
<td>AS</td>
<td>4.00</td>
<td>3.32</td>
<td>5.46</td>
<td>4.26</td>
</tr>
<tr>
<td>7/F</td>
<td>67</td>
<td>AA</td>
<td>3.20</td>
<td>3.76</td>
<td>2.94</td>
<td>3.33</td>
</tr>
<tr>
<td>8/M</td>
<td>61</td>
<td>AS</td>
<td>3.90</td>
<td>2.78</td>
<td>5.56</td>
<td>3.93</td>
</tr>
<tr>
<td>9/M</td>
<td>72</td>
<td>AS</td>
<td>3.17</td>
<td>2.83</td>
<td>3.19</td>
<td>3.00</td>
</tr>
<tr>
<td>10/M</td>
<td>65</td>
<td>AS</td>
<td>3.87</td>
<td>4.32</td>
<td>3.21</td>
<td>3.72</td>
</tr>
<tr>
<td>11/M</td>
<td>72</td>
<td>CAD</td>
<td>4.60</td>
<td>5.36</td>
<td>5.13</td>
<td>5.24</td>
</tr>
<tr>
<td>12/F</td>
<td>66</td>
<td>AS</td>
<td>4.20</td>
<td>4.23</td>
<td>3.98</td>
<td>4.10</td>
</tr>
<tr>
<td>13/M</td>
<td>26</td>
<td>AS</td>
<td>4.25</td>
<td>6.71</td>
<td>5.36</td>
<td>6.00</td>
</tr>
<tr>
<td>14/M</td>
<td>75</td>
<td>AS</td>
<td>5.47</td>
<td>5.83</td>
<td>5.12</td>
<td>5.46</td>
</tr>
<tr>
<td>15/F</td>
<td>82</td>
<td>CAD,AP</td>
<td>3.33</td>
<td>2.74</td>
<td>3.53</td>
<td>3.11</td>
</tr>
<tr>
<td>16/M</td>
<td>44</td>
<td>AI</td>
<td>6.17</td>
<td>6.80</td>
<td>7.43</td>
<td>7.11</td>
</tr>
<tr>
<td>17/F</td>
<td>65</td>
<td>AP</td>
<td>3.27</td>
<td>3.52</td>
<td>3.54</td>
<td>3.53</td>
</tr>
<tr>
<td>18/M</td>
<td>27</td>
<td>AI</td>
<td>5.56</td>
<td>8.80</td>
<td>4.07</td>
<td>5.98</td>
</tr>
<tr>
<td>19/M</td>
<td>52</td>
<td>CAD</td>
<td>4.06</td>
<td>4.30</td>
<td>4.09</td>
<td>4.20</td>
</tr>
<tr>
<td>20/F</td>
<td>67</td>
<td>AS</td>
<td>2.83</td>
<td>2.78</td>
<td>3.80</td>
<td>3.25</td>
</tr>
<tr>
<td>21/M</td>
<td>71</td>
<td>AS</td>
<td>4.10</td>
<td>4.39</td>
<td>3.81</td>
<td>4.09</td>
</tr>
<tr>
<td>22/M</td>
<td>53</td>
<td>AS</td>
<td>6.57</td>
<td>6.60</td>
<td>7.04</td>
<td>6.81</td>
</tr>
<tr>
<td>23/M</td>
<td>49</td>
<td>AI</td>
<td>5.03</td>
<td>4.52</td>
<td>4.98</td>
<td>4.75</td>
</tr>
<tr>
<td>24/M</td>
<td>41</td>
<td>AP</td>
<td>3.30</td>
<td>2.82</td>
<td>5.29</td>
<td>3.86</td>
</tr>
<tr>
<td>25/M</td>
<td>78</td>
<td>CAD</td>
<td>4.23</td>
<td>4.82</td>
<td>3.57</td>
<td>4.15</td>
</tr>
<tr>
<td>26/F</td>
<td>27</td>
<td>AS</td>
<td>2.57</td>
<td>3.03</td>
<td>3.17</td>
<td>3.10</td>
</tr>
<tr>
<td>27/M</td>
<td>66</td>
<td>AI</td>
<td>4.50</td>
<td>4.88</td>
<td>4.58</td>
<td>4.73</td>
</tr>
<tr>
<td>28/M</td>
<td>60</td>
<td>AS</td>
<td>4.70</td>
<td>5.61</td>
<td>4.17</td>
<td>4.84</td>
</tr>
<tr>
<td>29/M</td>
<td>41</td>
<td>AI</td>
<td>5.20</td>
<td>5.07</td>
<td>5.39</td>
<td>5.23</td>
</tr>
<tr>
<td>30/M</td>
<td>65</td>
<td>CAD</td>
<td>4.43</td>
<td>4.44</td>
<td>3.78</td>
<td>4.10</td>
</tr>
</tbody>
</table>

AA = aortic aneurysm; AI = aortic insufficiency; AP = aortic prosthesis; AS = aortic stenosis; CAD = coronary artery disease; CO = cardiac output; Dx = diagnosis; F = female; M = male; Pt = patient; TEE = transesophageal echocardiography.
maximal mitral valvular opening in the four- (d₁) and two-
chamber (d₂) views (Fig. 1). The Doppler mitral inflow spectral
display was digitized on the brightest line to obtain mitral
inflow velocity, which was integrated to yield the velocity–time
integral. At least three measurements of each variable were
averaged. Cross-sectional areas of the mitral annulus were
calculated in two ways: 1) assumption of a circular shape of the
mitral annulus (MA_c), and 2) assumption of an elliptic shape of
the mitral annulus (MA_e) as follows:

\[
MA_c = \pi d_1^2/4, \quad [1] \\
MA_e = \pi d_2^2/4, \quad [2] \\
MA_e = \pi d_1 d_2/4. \quad [3]
\]

Equations 1 and 2 yield estimates of mitral annular area using
the four- and two-chamber view diameters, respectively, and
assuming a circular annular shape. Equation 3 uses both
measurements and assumes an elliptic shape. Mitral stroke
volume was obtained by multiplying mitral annular area by
Doppler mitral inflow velocity–time integral. Cardiac output
was calculated by multiplying mitral stroke volume by heart
rate. Doppler calculations were performed without knowledge
of the thermodilution data.

Reproducibility of measurement. To test the reliability of
the measurements, we randomly selected 12 patients in whom
mitral annulus diameters, stroke volume and cardiac output by
Doppler transesophageal echocardiography were indepen-
dently measured by two different observers (interobserver
variability). Intraobserver variability was also assessed by re-
peating these measurements 3 weeks after the initial measure-
ments.

Statistical analysis. All results are expressed as mean
value ± SD. Mitral stroke volume and cardiac output calcu-
lated by Doppler transesophageal echocardiography were
compared with that obtained by thermodilution by linear
regression analysis and analysis of agreement (14). Differences
in stroke volume (ΔSV) and cardiac output (ΔCO) between
Doppler and thermodilution estimates were obtained. Signifi-
cance was determined as p < 0.05. The relative accuracy of
cardiac output and mitral stroke volume measurements be-
tween the four- and two-chamber and biplane transesophageal
echocardiographic calculations were compared using the Stu-
dent t test with the signed error (difference in bias) and
squared error (difference in scatter). Correlation coefficients
were compared after Fisher z transformation.

Mathematic modeling of annular area determination. To
help interpret the results of the study, we developed a math-
ematical model for area determination of an elliptic structure.
This model was used to compare the accuracy of single-plane
versus biplane estimations of annular area, particularly when
the measured diameters did not align with the major and minor
axes of the ellipse. The model was constructed as follows. For
an ellipse with unit-length minor half-axis directed along the y
axis and major half-axis of length e, the true area is \( e\pi \). The
boundary can be described parametrically by \( \theta \) measured
counterclockwise from the x axis as \((x,y) = (e \cos \theta, \sin \theta)\). For

---

**Figure 1.** Illustrations of quantitative Doppler transesophageal me-
asurement technique. A, Measurement of mitral annulus diameter in
the transverse plane. B, Measurement of the mitral annulus diameter
in the longitudinal plane. C, Pulsed Doppler measurement of mitral
inflow.
a misalignment of angle $\theta$, the measured “major” half-axis will be given by $(e^2 \cos^2 \theta + \sin^2 \theta)^{1/2}$, whereas the “minor” half-axis will be $(e^2 \sin^2 \theta + \cos^2 \theta)^{1/2}$. The calculated area $A(e, \theta)$ using biplane measurements is given for eccentricity $e$ and misalignment $\theta$ by

$$A(e, \theta) = \pi[(e^4 + 1) \cos^2 \theta + e^2 \sin^2 \theta]^{1/2},$$

which was compared with the true area $e \pi$. In contrast, if only one measurement is taken and circular shape is assumed, the calculated single-plane area (again misaligned with the major axis by $\theta$) is

$$A(e, \theta) = \pi(e^2 \cos^2 \theta + \sin^2 \theta).$$

For eccentricities of $e = 1.2, 1.5$ and $2.0$, the maximal error in area (normalized to the true area) was calculated, along with the range in calculated areas from largest to smallest.

**Results**

**Feasibility of recording and measuring mitral annulus.** In all patients mitral annular diameters and mitral inflow pulsed Doppler spectra were successfully recorded with biplane or multiplane transesophageal echocardiography. Diameters of the mitral annulus in the four-chamber view ranged from 2.06 to 3.84 cm (mean $\pm SD$ 3.01 $\pm 0.55$) and from 2.23 to 3.65 cm (mean 2.97 $\pm 0.42$) in the two-chamber view. Mean mitral annulus area calculated from the four-chamber view was $7.32 \pm 2.65$ cm$^2$; that from the two-chamber view was $7.05 \pm 2.05$ cm$^2$ (p > 0.05). The annular eccentricity (ratio of four- and two-chamber annular diameters) ranged from 0.71 to 1.47 (mean 1.02 $\pm 0.15$).

**Correlation between single-plane calculations of cardiac output and thermodilution.** Figures 2 and 3 illustrate the correlation between thermodilution stroke volume and mitral stroke volume calculated by the Doppler transesophageal technique assuming a circular annular shape using the transverse echocardiographic (Fig. 2) and longitudinal planes (Fig. 3). Mean stroke volume by thermodilution was 62.3 $\pm 17.1$ ml, which was not significantly different from single-plane calculations from the four- (65.4 $\pm 19.1$ ml) and two-chamber views (64.6 $\pm 19.3$ ml). There was good correlation between thermodilution (x) and Doppler (y) estimates of stroke volume (SV) for the four-chamber single-plane estimation ($y = 0.92x + 6.43$, $r = 0.94$, p < 0.001, $\Delta SV = 1.78 \pm 5.90$ ml; accuracy of cardiac output measurements was similarly excellent: $y = 1.04x - 0.002$, $r = 0.92$, p < 0.001, $\Delta CO = 0.17 \pm 0.14$ liter/min). Overall, the stroke volumes (SV = 64.3 $\pm 16.8$ ml) measured using biplane estimates of mitral annular area were not significantly different from either single-plane measurements or thermodilution, but the correlation between Doppler and thermodilution was improved compared with single-plane measurements. This correlation coefficient (0.94) was better than that for the four-chamber single-plane estimate ($r = 0.86$, p = 0.12) and significantly better than the two-chamber estimate ($r = 0.77$, p < 0.05). In addition,
although there was no systematic bias in the measurement errors among the three methods, the scatter for the biplane estimates of stroke volume was less than that obtained with the four-chamber estimate \( (p = 0.13) \) or, especially significantly, with the two-chamber estimate \( (p = 0.01) \).

**Interobserver and intraobserver variability.** The intraobserver variabilities of measurement of stroke volume and cardiac output by biplane transesophageal echocardiography were \( 2.36 \pm 9.26\% \) and \( 2.43 \pm 9.87\% \), respectively. Interobserver variabilities of determining stroke volume and cardiac output were \( 4.50 \pm 8.01\% \) and \( 6.28 \pm 8.89\% \), respectively.

**Numerical modeling of annular area calculation.** Figure 5 shows the results of the numerical modeling for an annular eccentricity of \( e = 1.5 \). For single-plane measurements, the calculated area varies by \( 225\% \), from \( 150\% \) of true area when the measured diameter was along the major axis, to \( 66.7\% \), when it was measured along the minor axis. In marked contrast, when orthogonal biplane measurements were used to calculate the area, the maximal error was only an \( 8\% \) overestimation, even when the measured diameters were completely misaligned with the ellipse axes. Table 2 shows data from all eccentricities studied. For single-plane measurements, the calculated area ranged from \( 1/e \) to \( e \) times the true area, but the error in biplane estimation was an order of magnitude less.

**Discussion**

Transesophageal echocardiography has seen widespread application in recent years. Although initial reports focused on the unique anatomic and pathologic detail available with this modality \( (6,7) \), there is a desire to use this approach to derive quantitative data, such as cardiac output, ejection fraction and regurgitant orifice area. Integral to measurements such as these is accurate estimation of the forward stroke volume through the mitral valve, a technique that has been well validated in several transthoracic Doppler studies \( (1–5) \). Relatively little data exist validating this approach by transesophageal echocardiography, prompting the current analysis. In the present intraoperative study, we showed that accurate estimates of stroke volume can be obtained by interrogation of the mitral annulus and that biplane imaging affords greater accuracy than single-plane estimation of the mitral annular area using either the transverse or longitudinal imaging plane. This second point illustrates the importance of the noncircular shape of the mitral annulus.

**Mitral annular shape.** The elliptic shape of the mitral annulus has been well demonstrated by autopsy \( (15) \) and two-dimensional echocardiography \( (16,17) \). Gutgesell et al.

![Figure 4](image_url)  
**Figure 4.** Correlation of mitral inflow stroke volume (SV) between thermodilution and transesophageal echocardiography (TEE) using biplane measurements. Symbols as in Figure 2.

![Figure 5](image_url)  
**Figure 5.** Numerical simulation of elliptic area calculations for misaligned measured axes, showing the dramatic difference in accuracy between biplane and monoplane measurements. The simulated annular shape is shown at the top of the figure with an eccentricity of 1.5:1.

<table>
<thead>
<tr>
<th>Eccentricity</th>
<th>Single-Plane Calculations</th>
<th>Biplane Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
</tr>
<tr>
<td>1.2:1</td>
<td>1.7 ± 13.0%</td>
<td>−17 to +20%</td>
</tr>
<tr>
<td>1.5:1</td>
<td>8.3 ± 29.6%</td>
<td>−33 to +50%</td>
</tr>
<tr>
<td>2.0:1</td>
<td>25.0 ± 53.3%</td>
<td>−50 to +100%</td>
</tr>
</tbody>
</table>

Eccentricity = ratio of major to minor axis diameter; Mean ± SD = mean error in annular area with standard deviation averaged for axis misalignment from 0° to 180°; Range = lowest and highest area error with axis misalignment; Ratio = ratio of highest to lowest area estimate.
reported the anteroposterior and mediolateral measurements of the mitral annulus in 19 patients using two-dimensional transthoracic echocardiography with autopsy confirmation. In 12 patients, the mediolateral dimension was greater, but in 3 the anteroposterior dimension was greater and in 4 the two dimensions were the same. By echocardiography, the diastolic shape of the mitral annulus was generally elliptic with the anteroposterior dimension 15% less on average than the lateral dimension. Vijayaraghavan et al. (16) showed that mitral annulus area calculated assuming a circular shape using a single four-chamber transthoracic diameter was systematically overestimated but that using two orthogonal planes gave excellent agreement with results obtained using six planes.

**Accuracy of biplane transesophageal estimates of mitral annular area.** In the current study, we did not specifically seek the maximal and minimal annular diameters in the hope that our results would be applicable to biplane transesophageal echocardiography rather than restricted to multipane probes. Concern might thus be raised about the accuracy of these area estimates, when major and minor axes of the ellipse were not obtained but rather standardized to the left ventricular four- and two-chamber views. To address this concern, we performed a numerical simulation using arbitrarily oriented (but orthogonal) diameter measurements of an elliptic structure for various ratios of major to minor axis diameters. As shown in Figure 5 and Table 2, biplane area estimation was quite accurate, even when the measured diameters were maximally misaligned with the major and minor axes. In contrast, when a single diameter was used, assuming circularity, variation in the calculated area was noted to be proportional to the square of the eccentricity, depending on the precise orientation of the measured diameter (from 1/e to e times the true area). Thus, it is clear that precise alignment of major and minor axis measurements is far less important than the use of any two orthogonal measurements. Although future investigations of specific alignment of measured diameters to the major and minor axes using multipane transesophageal echocardiography may be of value, it is unlikely that they will significantly improve the accuracy and correlation observed here. Additionally, this model suggests that two orthogonal measurements are both necessary and sufficient to yield accurate area calculations for elliptically shaped structures, with additional diameters adding relatively little to the accuracy of the area estimate.

Our own data have shown that mitral annulus shape and orientation vary in individual patients. Overall there was no significant difference in diameter or calculated area using measurements from the four- or two-chamber views, suggesting that the true major and minor axes lie between the standard biplane views. In general, the major axis appeared to align with the mediolateral orientation of the mitral valve (~45° by multipane imaging), with the minor axis oriented across the anteroposterior aspect of the valve (~135° by multipane). The clinical observations and numerical modeling results are entirely consistent with an experimental canine study of Ascah et al. (18) in which various technical approaches were tested for quantifying mitral valve flow, with an electromagnetic flow probe providing an absolute standard. That study observed overestimation of flow when the mediolateral annular diameter was used in isolation, underestimation of flow when the anteroposterior diameter was used, and the highest correlation and accuracy when both diameters were combined in an elliptic model of the annulus.

**Previous studies.** Some previous transthoracic studies have suggested that transmirtal flow may be overestimated by Doppler echocardiography. In addition to the need for accurate estimation of mitral annular area, improper Doppler sample volume positioning will also adversely impact mitral stroke flow calculations. A sample volume displaced apically from the mitral annulus will lead to overestimation of mitral inflow (2,3,19), which may in part explain the variable transesophageal results reported from different laboratories (10,11). Meticulous technique is needed, as is extensive experience with the method, shown by Sarano et al. (5) with improved accuracy following an initial learning curve.

The results of the current study are entirely consistent with a previous report (13) of biplane transesophageal echocardiographic estimation of transmirtal stroke volume. In the study by Hozumi et al. (13), biplane estimation of stroke volume correlated better with thermodilution measurements (r = 0.93) than with either transverse or longitudinal single-plane estimations (r = 0.81 and 0.85, respectively) and were superior to previous reports of monoplane calculations (10,11).

**Clinical implications.** Accurate determination of mitral inflow by transesophageal echocardiography is potentially important both in routine clinical care and in quantitative research. Although two-dimensional transesophageal imaging provides useful information about ventricular size, contractility and segmental wall motion abnormalities, the full extent of the left ventricle can often not be visualized from either the basal imaging window or transgastrically, limiting our ability to calculate stroke volume and cardiac output from ventricular systolic and diastolic volumes. Recent studies (8,9) have shown that transgastric Doppler echocardiography can be used to measure cardiac output through the left ventricular outflow tract, but such views are difficult to obtain in some patients. It may further be limited in the presence of aortic stenosis or regurgitation. In contrast, the mitral annular approach used in the present study appears to be very widely applicable. Indeed, no patient considered for inclusion in the present series was rejected because of technically inadequate annular imaging or Doppler measurements. Rather, more patients were rejected for the presence of tricuspid regurgitation because the thermodilution method is known to underestimate cardiac output in these conditions (20). Although biplane imaging of the annulus clearly conferred an advantage in accuracy to mitral stroke volume measurements, reasonable accuracy was obtained with single-plane estimates, particularly using the transverse imaging plane (r = 0.86), the orientation available on
contemporary monoplane transesophageal echocardiographic probes.

An important application for transesophageal measurements of transmitral stroke volume is in estimating regurgitant volume and orifice area, particularly in the operating room, where on-line quantification of regurgitant severity may be necessary in assessing the need for valve repair or replacement and in documenting the success of valve repair. For example, by subtracting net forward stroke volume by thermodilution from mitral annular stroke volume, mitral regurgitant volume can be obtained; mitral regurgitant orifice area is then easily obtained by dividing the mitral regurgitant volume by the time-velocity integral of the mitral regurgitant velocity defined by continuous wave Doppler (21). Similarly, by combining mitral stroke volume with aortic stroke volume determined by left ventricular outflow tract and aorta (8,9), estimates of mitral or atrial regurgitant indices (but not both) may be obtained (25).

Study limitations. The thermodilution method is not an ideal reference standard for cardiac output (22), but it has been widely used both clinically and as a reference standard in previous investigations. In the current study we excluded patients with atrial fibrillation and more than mild tricuspid regurgitation to have maximal confidence in the thermodilution measurements. Similarly, we excluded patients with severe mitral annular calcification and mitral stenosis because these would be likely to distort both annular area calculations and the assumption of a flat profile crossing the annulus. Such patients may require separate validation. Because in the operating room, cardiac load and inotropic state may change in a short period, care was taken to ensure that the thermodilution and mitral flow data were recorded simultaneously for comparison.

Conclusions. By combining two orthogonal measurements of mitral annular diameter with pulsed Doppler measurement of flow velocity at this level, we showed biplane transesophageal echocardiography to be an accurate and reliable method to measure transmitral flow (stroke volume and cardiac output) in the clinical setting of the operating room. Potential applications include intraoperative monitoring of left ventricular function and on-line quantification of valvular regurgitation.

We thank members of the Department of Cardiothoracic Anesthesia for their assistance in collecting thermodilution cardiac output measurements.

References