Intraoperative Determination of Cardiac Output Using Multiplane Transesophageal Echocardiography
A Comparison to Thermodilution

Albert C. Perrino, Jr., M.D.,* Stephen N. Harris, M.D.,* Martha A. Luther, M.P.H.†

Background: Limitations in the imaging views that can be obtained with transesophageal echocardiography (TEE) have hindered development of a widely adopted Doppler method for cardiac output (CO) monitoring. The authors evaluated a CO technique that combines steerable continuous-wave Doppler with the imaging capabilities of two-dimensional multiplane TEE.

Methods: From the transverse plane transgastric, short-axis view of the left ventricle, the imaging array was rotated to view the left ventricular outflow tract (LVOT) and ascending aorta. Steerable continuous-wave Doppler was subsequently used to measure aortic blood flow velocities. Aortic valve area was determined using a triangular orifice model. Matched thermodilution and Doppler CO measurements were obtained serially during surgery.

Results: The left ventricular outflow tract was imaged in 32 of 33 patients (97%). Data analysis reveal a mean difference between techniques of −0.01 L/min, and a standard deviation of the differences of 0.56 L/min. Multiple regression showed a correlation of r = 0.98 between intrasubject changes in CO. Multiplane TEE correctly tracked the direction of 37 of 38 serial changes in thermodilution CO but with a modest 14% underestimation of the magnitude of these changes.

Conclusions: These results indicate that multiplane TEE can provide an alternative method for the intraoperative measurement of CO. The ability of the rotatable imaging array to align with the left ventricular outflow tract and the need for only minimal adjustments in probe position advance the utility of intraoperative TEE. (Key words: Cardiac output; Doppler ultrasonography; echocardiography; measurement techniques.)

SERIAL determinations of cardiac output (CO) are used widely to diagnose and guide treatment of cardiovascular disorders. Although multiple approaches to CO monitoring by Doppler ultrasound have been explored, a widely adopted method for clinical practice has not evolved. Shortcomings of Doppler ultrasound methods arise from errors associated with measurement of the blood flow velocity and the cross-sectional area of the flow stream. Transesophageal echocardiography (TEE), by providing high-fidelity, two-dimensional imaging and stable probe position, is ideally suited to reduce these errors in Doppler CO monitoring. However, TEE approaches to CO measurement have been hampered by limitations in imaging views. In contrast to transthoracic and epicardial echocardiographic techniques, in which an ultrasound probe can be positioned around the thorax to obtain the best view for CO measurements, TEE probe manipulations are restricted within the confines of the esophagus and stomach. As a result of the lack of probe mobility, alignment of the Doppler beam with blood flow necessitates complex and technically difficult probe manipulations. Consequently, adequate imaging is not easily obtained in a significant percentage of patients.

Multiplane technology greatly expands the imaging capabilities of TEE. Controlled by a switch located on the control handle, a motor drive rotates the transducer array to provide omnidirectional imaging around the center of the ultrasonic sector. The ability to steer the imaging plane with multiplane TEE provides new perspectives for visualizing the aortic valve and for determining aortic blood flow velocity. We evaluated a CO technique that, by combining continuous-wave (CW) Doppler with the imaging capabilities of two-dimen-
sional multiplane TEE, aims to minimize the limitations associated with other Doppler CO approaches. This investigation was designed to assess the agreement and trending capability of serial intraoperative multiplane TEE CO measurements to matched thermodilution CO measurements.

Methods

After institutional review board approval of the study protocol, patients scheduled for either cardiac or non-cardiac surgery necessitating pulmonary artery catheter monitoring at the Veterans Affairs Connecticut Health Care System were interviewed by a member of the research team for inclusion in the study. Patients with either a preoperative history or intraoperative TEE evidence of cardiac valvular disease, aortic aneurysm, intracavity defects, septal hypertrophy, or dysrhythmias were excluded. Informed consent was obtained before inclusion in the study. Anesthetic management was at the discretion of the anesthesiology care team. After induction of general anesthesia and tracheal intubation, a 5-MHz multiplane TEE probe (Hewlett-Packard, Andover, MA) was inserted and a routine echocardiographic evaluation was performed.

Measurement of Mean Aortic Valve Area

The transesophageal probe was positioned to obtain a basal short-axis view of the aortic valve. The multiplane imaging angle was then adjusted (40–60°) to align the imaging plane with the cross-sectional plane of the aortic valve (fig. 1). Aortic valve area (AoVA) was planimetered using the triangular model proposed by Darmon et al.8,9 This method assumes that the time-averaged AoVA during systole is best approximated as the triangular orifice occurring during mid systole. Using the TEE frame in which each aortic valve cusp appeared as a nearly straight line describing one side of the triangle, the AoVA was planimetered using the analysis package of the Sonos 1500 (Hewlett-Packard). The AoVA was measured from two consecutive cardiac cycles. The mean of these initial AoVA measurements was used for all subsequent Doppler CO calculations.

Determination of Aortic Blood Flow Velocity

To obtain measurements of aortic blood flow, the transesophageal ultrasound probe was positioned to obtain a transverse plane, transgastric short-axis view of the left ventricle at the mid-papillary level. By rotating the imaging array to approximately 120°, the left ventricular outflow tract (LVOT) and ascending aorta are imaged lying parallel to the ultrasound beam (figs. 2 and 3). This 120° transgastric, LVOT view was optimized through minor adjustments in the probe position, including anteroflexion and rotation. Aortic blood flow velocities were measured by a CW Doppler beam focused at the level of the aortic valve. Doppler signals were judged to be optimized when the greatest amplitude and clarity of the spectral waveform was achieved through adjustment of the beam position and gain settings. At suspended end expiration, two consecutive velocity waveforms were recorded and then measured by planimetry during operation to generate the velocity time integral (VTI). We traced the high-velocity envelope of the Doppler spectra, which best reflects the blood flow velocity across the aortic valve.10 The average of the two VTI measurements was used to calculate
Doppler CO. No correction was applied to adjust for the angle of incidence between the ultrasound beam and aortic blood flow. Ultrasound measurements were performed by an investigator blinded to thermodilution data. Doppler CO was calculated off-line as the product of VTI, AoVA, and heart rate.

During VT1 recording, thermodilution CO measurements were obtained at end expiration by the patient’s anesthesiologist using 10 ml injectate at room temperature and a calibrated computer (Marquette Electronics, Milwaukee, WI), which provided a real-time display of the thermodilution washout curve. The anesthesiologist was blinded to the Doppler measurements but not to two-dimensional echocardiographic images. Three thermodilution CO measurements with < 15% variation, largest to smallest, were obtained. If one of the CO values varied by more than ± 15% from the others, an additional CO measurement was obtained. If three of the four values were not within ± 15%, the set of CO values was discarded and a new set of triplicate CO measurements was obtained. The average of the three thermodilution CO measurements was used for comparison to Doppler measurements. Matched thermodilution and Doppler CO measurements were obtained during a period of hemodynamic stability without electrosurgery at four specific epochs during a surgical procedure. For cardiac procedures, data were collected after induction, after sternotomy, before aortic cannulation, and after separation of the patient from cardiopulmonary bypass when the chest was closed. For vascular procedures, data were collected after induction, before vessel cross-clamping, during vessel grafting or anastomosis, and during chest closure. For general abdominal and pelvic procedures, data were collected after induction, before resection, after resection, and during wound closure.

Statistical Methods
Bias analysis,11 with calculation of the mean difference and SD of the differences, was used to assess the agreement between the CO values of each technique. The range of ± 2 SD of the differences estimates the 95% level of agreement between the two techniques. Paired Student’s t tests were used to compare the mean differ-
ence with zero. Because multiple measurements were made in each patient studied, regression analysis was performed by calculation of the weighted correlation between the mean Doppler CO and the mean thermodilution CO of each patient.\(^\text{12}\)

To evaluate the ability of multiplane TEE to track directional changes in CO (trending capability), multiple regressions using analysis of covariance were performed.\(^\text{13}\) Separately, we evaluated the ability of the Doppler approach to detect large changes in thermodilution CO, those > 1 L/min, in the study population as a whole.

As a measure of the intraobserver variability in AoVA and VT1 measurements, the mean percentage error (± SD) was calculated as the absolute difference between the first and second determinations divided by the mean of the two observed values.

**Results**

Thirty-four patients agreed to participate in and were enrolled in the study. One patient was excluded during operation based on the finding of restricted motion of the aortic valve leaflets and Doppler findings of mild aortic stenosis and aortic insufficiency. In 32 of 33 patients, 120\(^\circ\) transgastric, IVOT views were obtained using an imaging angle of 118\(^\circ\) (SD ± 15\(^\circ\)). This view was not visualized adequately in a patient undergoing repeat coronary artery bypass grafting. The study population was predominantly elderly (mean age, 67 yr ± 8 yr) with coexisting cardiac disease. A history of previous myocardial infarction was present in 17 of 32 (53%) patients, and left ventricular ejection fraction was < 35% in 8 of 32 (25%) and was between 35% and 50% in 14 of 32 (44%) patients. Coronary artery bypass grafting was performed in 25 of 32 (78%) patients, and the remaining 7 of 32 (22%) underwent major vascular or other noncardiac surgical procedures. Pulmonary artery catheter and echocardiographic monitoring were present for 116 epochs, and matched data were obtained in 110 (95%) epochs. Data were not collected in some cases because of patient death, insertion of an intraaortic balloon pump, patient care demands on the clinical care team, or hemodynamic instability. None of these
instances were related to an inability to obtain echocardiographic images.

Figure 4 shows a Bland-Altman plot of the data from the 110 matched Doppler and thermodilution CO measurements. Thermodilution values ranged from 1.7 to 9.8 l/min (mean, 4.6 l/min), and Doppler values ranged from 2.2 to 9.8 l/min (mean, 4.6 l/min). Bias analysis revealed no systematic error in Doppler estimates (mean difference, -0.01 l/min; P = not significant) and a SD of the differences of 0.56 l/min. Regression analysis of the mean CO values from each patient (n = 32) produced a weighted correlation coefficient, r = 0.91 (P < 0.01).

Multiple regression analysis, evaluating the within-subject variation in Doppler CO to that of thermodilution CO, produced a correlation coefficient of r = 0.98 (P < 0.001). Serial changes in thermodilution CO > 1 l/min and the associated Doppler data are displayed in a four-quadrant plot (fig. 5). The Doppler method was in accord with thermodilution regarding the direction of change in CO of 37 of 38 instances (97%). Although the Doppler technique tracked the direction of serial changes in CO, on a percentage basis, serial changes in Doppler CO averaged 86% of the magnitude of the matched changes in thermodilution CO.

To assess the reliability of multiplane TEE to provide a CW beam aligned near parallel to blood flow, the two-dimensional echocardiograms of the first 20 study patients were analyzed off-line to measure the angle of incidence between the CW ultrasound beam and a line perpendicular to the aortic valve plane. In 71 of 76 measurements (93%), the angle subtended resulted in a cosine θ > 0.95. Because this measurement does not provide information of the imaging angle in the orthogonal plane, the length of the imaged aorta was measured. In 72 of 76 (95%) measurements, the distal aorta was visible with parallel walls for a distance of > 4 cm.

Both AoVA and VTI measurements showed little variation between their first and second determinations. The mean percentage errors (±SD) for measurements of VTI and AoVA were 2 ± 1.5% and 1.4 ± 1.3%, respectively.

Discussion

Our results support multiplane TEE as an alternative and readily obtained method for intraoperative measurement of CO during operation. The agreement between this method and thermodilution is on par with comparisons of thermodilution to electromagnetic flowmeters, invasive Doppler devices, and other TEE approaches.6,8,14-19 Table I summarizes results from previous intraoperative studies that evaluated data concerning alternative approaches to Doppler CO. Perhaps more important in assessing the clinical usefulness of the Doppler technique is its ability to track serial changes in CO throughout a procedure. Intrasubject changes in CO show a correlation of r = 0.98. Serial changes in CO > 1 l/min were tracked correctly in 37 of 38 instances by the Doppler approach, but the technique produced a modest 14% underestimation of the magnitude of these changes.

The success of multiplane TEE CO monitoring in this study can be attributed to several factors. The 120° transgastric LVOT view was easily obtained in 32 of 35 patients and repeatedly enabled the CW beam to be aligned near parallel to aortic blood flow at the level of the aortic valve during the surgical procedure. This provided high-fidelity Doppler measurements at an optimal location. The truncation of the LV outflow tract accelerates blood velocities during systole to create a nearly uniform blood flow velocity profile across the aortic valve.10 This minimizes errors that can result from

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Table 1. Intraoperative Comparisons of Doppler Echocardiography to Thermodilution

<table>
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<th>Study</th>
<th>Doppler Approach</th>
<th>Success Rate</th>
<th>Difference between Techniques</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Mean (L/min)</td>
</tr>
<tr>
<td>Savino et al.</td>
<td>Pulmonary artery</td>
<td>25/33 (76%)</td>
<td>0.0</td>
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<tr>
<td>Muhuudeen et al</td>
<td>Pulmonary artery</td>
<td></td>
<td>-</td>
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<tr>
<td>Darmon et al.</td>
<td>Aortic (transgastric long axis)</td>
<td>62/63 (98%)</td>
<td>0.1</td>
</tr>
<tr>
<td>Ryan et al.</td>
<td>Mitral valve</td>
<td>12/12 (100%)</td>
<td>-0.9</td>
</tr>
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sampling only more distal locations, such as the aortic arch, where skewed, parabolic flow profiles are present. In addition, the cross-sectional area of this site is less affected by alterations in blood pressure than that of the more elastic distal aorta and pulmonary artery.\(^6\)\(^20\)

The 120° transgastric LVOT view provides important advantages as a clinical method. This multipane TEE view is obtained from the same probe position that anaesthesiologists most commonly rely on for intraoperative TEE monitoring. From the standard transverse plane, transgastric short-axis view of the left ventricle, the imaging angle is adjusted through an operator-controlled electronic switch to bring the LVOT into view. Minimal adjustments in probe position are needed. Consequently, from a single probe location the anaesthesiologist can monitor left ventricular regional and global wall motion using the short-axis view and electronically switch to monitor CO. Although we did not precisely monitor the time necessary to rotate the imaging plane, to measure aortic flow velocities, and to calculate CO, our experience is that this process is typically accomplished in 2 or 3 min.

Alternative approaches for intraoperative CO assessment using monoplane TEE can also provide strong agreement with thermodilution (table 1). These techniques, however, necessitate substantial probe manipulation, are technically challenging, and are not successful in a significant percentage of patients.\(^6\)\(^8\)\(^21\)\(^22\) Transesophageal echocardiography-guided CO measurements based on flow in the main pulmonary artery necessitate that the probe be withdrawn to the esophagus to image the basal short-axis view and be anterolateral to align the Doppler beam with blood flow. Technical difficulties with this approach include interference from air in the left main stem bronchus, resulting in poor image quality, low Doppler signal-to-noise ratios, and artifact. In an intraoperative study of pulmonary artery blood flow, adequate imaging could not be obtained in 24% of patients.\(^6\) In addition, the maximally flexed probe tip lying within the esophagus can lead to high contract pressure and cannot be recommended for prolonged CO monitoring.\(^23\) Consequently, the pulmonary blood flow technique has not been evaluated as a means to monitor changes in CO.

Another alternative approach to Doppler CO measurement uses the transgastric, apical view to assess aortic blood flow. Studies support that this view positions the Doppler beam near parallel to aortic flow.\(^24\) A shortcoming of this approach is that it necessitates that the TEE probe be positioned at the transgastric, mid-papillary position to be advanced, fully flexed anteriorly, shifted leftward, and then slowly withdrawn until the transgastric apical long-axis view is imaged. Obtaining this view is technically challenging and cannot be achieved in as many as 12% of patients.\(^21\) In addition to not needing this degree of probe manipulations, the 120° transgastric LVOT view also positions the transducer closer to the LVOT than does the transgastric apical view. This creates more favorable signal-to-noise ratios, which lead to CW Doppler spectra of excellent quality. All of these approaches have the limitation of not measuring the beam alignment in three dimensions, and consequently, there is potential for Doppler flow measurements to underestimate flow velocities.

Multipane TEE is also well suited to assess AoVA.\(^7\)\(^25\) Cross-sectional images of the aortic valve are readily obtained by multipane TEE because of the ability to adjust the imaging plane 40–60° to image a true short axis of the aortic valve. The measurement of AoVA in this investigation was based on the triangular model proposed by Darmon et al.\(^8\) This method is advantageous for theoretical and practical reasons. Because the aortic valve orifice varies during systole, an ideal method would be to calculate the instantaneous cross-sectional area of the aortic valve throughout systole. Because a real-time, automated technique to measure instantaneous AoVA is not available clinically, most approaches rely on a single AoVA estimate to approximate the time- and flow-averaged AoVA during systole. The triangular model of the aortic valve orifice is supported.
by angiographic and anatomic studies.\textsuperscript{24,26} A clinical trial using monoplane TEE and the transgastric apical view showed a closer agreement between Doppler and thermodilution CO measurements when AoVA was based on a triangular, rather than a circular, model.\textsuperscript{18} We achieved a high degree of repeatability with the AoVA measurement technique. We attribute this, in part, to planimetricing a triangular orifice rather than tracing the valve leaflets at peak systole. The leaflet positions vary rapidly throughout systole, and reliance on a single video frame (frame rate, 30/s) from systole can result in significant differences in beat-to-beat valve area. The mid-systolic triangular model permitted rapid and repeatable AoVA measurements.

Limitations of our study design include the use of thermodilution as the reference standard. This technique is susceptible to error but remains the clinical standard for determining CO.\textsuperscript{27-29} Our study protocol relied on a one-time measurement of AoVA obtained at the start of each case. This approach greatly simplifies the procedure for determining Doppler CO because the repeated probe manipulations and manual tracings that are needed to remeasure AoVA are avoided. Alterations in AoVA resulting from changes in blood flow are a potential limitation of this approach. The extent of changes in AoVA with changes in blood flow are not fully understood. Recently, investigators showed that acute changes in stroke volume do not result in significant alterations in the AoVA in patients with aortic stenosis.\textsuperscript{30} An in vitro study of cadaveric human aortic valves without aortic stenosis showed a 5-15\% change in maximal AoVA with a 2 l/min change in flow rate. The flow rate effect on mean AoVA has not been described. Our trending analysis, which showed the Doppler technique to correctly assess the direction of serial changes in CO but to modestly underestimate the magnitude by 14\% may suggest that changes in flow rate alter mean AoVA. The validity of using a single AoVA measurement during extremes of flow warrants further evaluation. Additional limitations to the Doppler method are inaccuracies related to measurements of aortic flow velocities. Doppler flow measurements are susceptible to underestimation of blood velocities caused by misalignment of the Doppler beam to blood flow because two-dimensional Doppler does not provide the operator with visualization of the Doppler beam axis orientation in three dimensions. Sclerosis of the aortic valve leaflets or other causes that restrict motion of the valve leaflets result in an irregularly shaped valve orifice, and the triangular model will not be accurate. The flow velocity profile may also be distorted secondary to the diseased aortic valve and invalidate the necessity of uniform laminar flow.

In conclusion, our results show that multiplane TEE provides an alternative method for CO determination. The rotatable imaging array facilitates measurement of aortic blood flow velocity and AoVA. By necessitating minimal adjustment in probe position from the transgastric short-axis view commonly monitored by anesthesiologists, the technique advances the intraoperative usefulness of TEE.

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