Intraoperative determination of cardiac output by transesophageal continuous wave Doppler

A new prototype transesophageal transducer with continuous-wave Doppler and pulsed Doppler capabilities was evaluated to calculate intraoperative cardiac output from the main pulmonary artery. Fifteen consecutive patients undergoing elective coronary artery bypass surgery were studied. The main pulmonary artery diameter above the pulmonic valve was measured with the single horizontal plane transesophageal transducer. The pulmonary artery cross-sectional area was calculated from its diameter using the formula: 

\[
\text{Area} = \frac{1}{4} \pi (\text{diameter})^2
\]

Continuous-wave Doppler and pulsed Doppler spectra were recorded from the main pulmonary artery and their flow velocity integrals were then multiplied by pulmonary artery area and heart rate to yield cardiac output. The main pulmonary artery diameter could not be confidently measured in 2 of 15 patients (13%). In the remaining 13 patients, Doppler cardiac output measurements were correlated with simultaneous thermodilution measurements. The closest correlation with thermodilution cardiac output was with the continuous-wave Doppler cardiac output method: 

\[
R = 0.91, \text{SEE} = 0.2 \text{ L/min}, \text{ and } y = 1.1x - 0.2 (p < 0.001).
\]

The correlation of thermodilution with pulsed Doppler cardiac output was 

\[
R = 0.83, \text{SEE} = 0.5 \text{ L/min}, \text{ and } y = 0.86x + 1.0 (p < 0.001).
\]

Transesophageal continuous-wave Doppler is a new technique that may be used in selected patients for accurate determination of intraoperative cardiac output. (Am Heart J 1992;123:171.)

John Gorcsan III, MD, Paul Diana, MD, Beth A. Ball, MS, and Brack G. Hattler, MD, PhD. Pittsburgh, Pa.

Intraoperative transesophageal echocardiography is a rapidly expanding technique to monitor left ventricular wall motion and guide surgical decisions. Cardiac output is an important measure of intraoperative left ventricular function, but the routinely used thermodilution method requires right heart catheterization. Transesophageal continuous-wave and pulsed Doppler echocardiography have been shown to accurately calculate stroke volume and cardiac output noninvasively. The proximity of the heart and great vessels to the esophagus has permitted a new window for high resolution echocardiographic imaging with minimal risk to the patient.
Fig. 1. Transesophageal two-dimensional echocardiogram of the main pulmonary artery. Ao, Aorta; PA, pulmonary artery.

Fig. 2. Transesophageal continuous-wave Doppler spectral display with the cursor aligned parallel to main pulmonary artery blood flow.

cordingly, a prototype transesophageal transducer with continuous-wave Doppler as well as pulsed Doppler capabilities was evaluated to calculate intraoperative cardiac output from the main pulmonary artery. Doppler calculations of cardiac output were evaluated by correlating results with simultaneous determinations of cardiac output by the thermodilution technique.

**METHODS**

Fifteen consecutive patients, age 62 ± 15 years (range 44 to 62 years), who were undergoing elective coronary artery bypass surgery were studied. The study protocol was approved by the Institutional Committee on Human Research. There were 10 men and 5 women. The mean left ventricular ejection fraction of the group was 42 ± 12% (range 25% to 67%) by left ventriculography. All patients were in sinus rhythm and had right heart catheterizations for determination of cardiac output by the thermodilution technique. They were all given general anesthesia and were mechanically ventilated prior to introduction of the transesophageal echo probe. No patient had significant tricuspid or pulmonic regurgitation by transesophageal color Doppler technique. No patient had pulmonic stenosis. All measurements were made at hemodynamically stable states, prior to the institution of cardiopulmonary bypass.

**Invasive cardiac output measurements.** Thermodilu-
Fig. 3. Transesophageal pulsed Doppler spectral display with the sample volume within the main pulmonary artery.

transesophageal pulsed Doppler measurement of cardiac output was performed in each patient using 10 ml of iced saline solution simultaneously with the transesophageal Doppler measurements. The mean value for cardiac output from a minimum of three measurements was used. If individual measurements were not within 10% of each other, the highest and lowest of five serial measurements were excluded and the remaining three measurements were averaged. Thermodilution measurements were made by an investigator blinded to the Doppler results.

Echocardiographic measurements. A prototype Hewlett-Packard 5 MHz single-plane imaging/5 MHz continuous-wave Doppler transducer (Hewlett-Packard Co., Medical Products Group, Andover, Mass.) was used with a Hewlett-Packard 77026A ultrasound system in each patient. The internal diameter (D) of the main pulmonary artery above the pulmonic valve was measured in systole from a transducer level that imaged the great vessels superior to the cardiac chambers (Fig. 1). The cross-sectional area (A) of the main pulmonary artery was calculated using the formula $A = \frac{1}{4} \pi D^2$, which assumes circular geometry of the vessel. The transesophageal continuous-wave Doppler cursor was then directed parallel to the blood flow within the main pulmonary artery. Slight adjustments of the position and angulation of the transesophageal probe were made to obtain a high quality Doppler spectral display (Fig. 2). Analyses of all Doppler data were carried out by an investigator blinded to the thermodilution results. The Doppler cardiac output was then calculated using the formula: 

$$\text{Cardiac output} = \frac{\text{pulmonary artery area}}{\text{flow velocity integral}} \times \text{heart rate}.$$  

Table I. Transesophageal continuous-wave Doppler cardiac output ($N = 13$)

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA area</td>
<td>3.1 ± 0.6 cm$^2$</td>
<td>(2.0-3.8 cm$^2$)</td>
</tr>
<tr>
<td>CW FVI</td>
<td>23.8 ± 4.4 cm</td>
<td>(8.6-29.9 cm)</td>
</tr>
<tr>
<td>Heart rate</td>
<td>63 ± 12/min</td>
<td>(43-83/min)</td>
</tr>
<tr>
<td>Doppler CO</td>
<td>4.6 ± 0.9 L/min</td>
<td>(2.8-5.6 L/min)</td>
</tr>
<tr>
<td>Thermo CO</td>
<td>4.8 ± 1.0 L/min</td>
<td>(2.8-6.2 L/min)</td>
</tr>
</tbody>
</table>

$CW$ FVI, Continuous-wave flow velocity integral; $CO$, cardiac output; PA, pulmonary artery; Thermo, thermodilution.

Table II. Transesophageal pulsed Doppler cardiac output ($N = 13$)

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA area</td>
<td>3.1 ± 0.6 cm$^2$</td>
<td>(2.0-3.8 cm$^2$)</td>
</tr>
<tr>
<td>PD FVI</td>
<td>21.9 ± 5.5 cm</td>
<td>(15.8-33.1 cm)</td>
</tr>
<tr>
<td>Heart rate</td>
<td>62 ± 11/min</td>
<td>(42-85/min)</td>
</tr>
<tr>
<td>Doppler CO</td>
<td>4.0 ± 1.1 L/min</td>
<td>(1.7-5.3 L/min)</td>
</tr>
<tr>
<td>Thermo CO</td>
<td>4.4 ± 1.2 L/min</td>
<td>(2.5-6.1 L/min)</td>
</tr>
</tbody>
</table>

$PD$ FVI, Pulsed Doppler flow velocity integral; other abbreviations as in Table I.

placed in the center of the main pulmonary artery above the pulmonic valve (Fig. 3). Calculation of cardiac output was then carried out in a manner similar to that for continuous-wave Doppler.

Interobserver variability was evaluated for echocardiographic and Doppler measurements in 10 randomly selected studies, with a second investigator blinded to the results of the first observer. Interobserver variability was expressed as the mean difference between observers divided by the average measurement. Interobserver variability for the pulmonary artery diameter was 5%; for the continuous-wave Doppler flow velocity integral variability was 3%; and for the pulsed Doppler flow velocity integrals variability was 4%.
Continuous-Wave Cardiac Output (L/min)

Fig. 4. Correlation of transesophageal continuous wave Doppler method of calculating cardiac output with simultaneous thermodilution cardiac output.

Statistical analysis. All data are expressed as mean values ± standard deviation. First order linear regression analysis was used to correlate transesophageal continuous-wave and pulsed Doppler cardiac output values with the thermodilution cardiac output values. Significance was determined as \( p < 0.05 \).

RESULTS

The main pulmonary artery could not be clearly imaged in 2 of the 15 patients studied (13%) because of air artifact from the left main stem bronchus. For the remaining 13 patients the mean diameter of the main pulmonary artery above the pulmonic valve was 2.0 ± 0.3 cm (range 1.6 to 2.2 cm). The calculated pulmonary artery area was 3.1 ± 0.6 cm\(^2\) (range 2.0 to 3.8 cm\(^2\)) (Table I). The mean continuous-wave flow velocity integral was 23.8 ± 4.4 cm, with a range of 8.6 to 29.9 cm. The heart rate was 63 ± 12/min (range 43 to 83/min), and the calculated continuous-wave Doppler cardiac output was 4.6 ± 0.9 L/min (range 2.8 to 5.6 L/min).

The mean pulsed wave Doppler flow velocity integral was 21.9 ± 5.5 cm (range 15.8 to 33.1 cm) (Table II). The heart rate was 62 ± 11/min (range 42 to 85/min), with a calculated pulsed wave Doppler cardiac output of 4.0 ± 1.1 L/min (range 1.7 to 5.3 L/min). The mean thermodilution cardiac output for the simultaneous continuous-wave Doppler measurements was 4.8 ± 1.0 L/min (range 2.8 to 6.2 L/min) and for the simultaneous pulsed wave Doppler measurements cardiac output was 4.4 ± 1.2 L/min (range 2.5 to 6.1 L/min). Linear regression analysis of the transesophageal continuous-wave Doppler method and thermodilution cardiac output revealed the best correlation with \( R = 0.91 \), \( \text{SEE} = 0.2 \) L/min, and \( y = 1.1x - 0.2 \), \( (p < 0.001) \) (Fig. 4). Linear regression analysis of the transesophageal pulsed Doppler method also revealed a significant, but less close correlation, with \( R = 0.83 \), \( \text{SEE} = 0.5 \) L/min, and \( y = 0.86x + 1.0 \), \( (p < 0.001) \) (Fig. 5). Cardiac output determinations by transesophageal continuous-wave Doppler were more closely correlated with thermodilution results than transesophageal pulsed wave cardiac output results.

DISCUSSION

This study demonstrates the feasibility of transesophageal echocardiography with continuous-wave Doppler for determining cardiac output, and expands the utility of transesophageal echocardiography in the intraoperative monitoring of left ventricular function. Over the past decade, numerous investigators have demonstrated the accuracy of Doppler echocardiographic techniques for the measurement of cardiac output at the aortic, mitral, tricuspid, and pulmonic levels. All techniques require the use of two-dimensional echocardiographic measurement of diameter at a particular cardiac level, which is then converted to cross-sectional area. Doppler velocity data at the same cardiac level are then integrated with respect to time for calculation of flow velocity integrals. The two-dimensional cross-sectional area is then multiplied by the Doppler flow velocity integral to determine stroke volume, which is then multiplied by heart rate to yield cardiac output.

In this study, placement of the transducer in the esophagus appeared to be an ideal location to measure blood flow in the main pulmonary artery, which is directed toward the transducer. Doppler velocity data may be underestimated if the transducer beam is not aligned directly parallel to blood flow. The esophageal location of the transducer appears to minimize this source of error. Additional advantages of this technique are a result of the close proximity of the transducer to the structures being studied for high resolution two-dimensional images and high technical quality Doppler data. The main pulmonary artery was also selected for measurement of flow because of the simplicity of shape, which was assumed to be circular. Other investigators have measured Doppler velocity at the mitral anulus level to determine flow. However, difficulties exist in accurately measuring mitral anulus area and in determining changes in mitral annular shape and size throughout diastole from transesophageal planes.7,12

Thermodilution cardiac output data were more closely correlated with simultaneous continuous-wave Doppler output values than were pulsed Dop-
pler cardiac output values. This was felt to be a result of the operator's ability to make slight adjustments and angulations of the transducer in the continuous wave Doppler mode, which produced high quality spectral Doppler data of the consistently highest velocity profiles. The technique of guiding the pulsed Doppler sample volume within the two-dimensional image of the pulmonary artery appeared to produce less consistent Doppler velocity data in this study group. Another explanation of a more suitable signal with continuous-wave Doppler is that continuous-wave is a broad-beamed signal that may avoid some of the flow problems encountered with pulsed Doppler. The transesophageal Doppler technique usually passes through the anterior half of the pulmonary artery. Thus pulsed Doppler may reflect a less suitable or a less representative signal. The exact explanation for the closer correlation of cardiac output with continuous-wave Doppler data in this study however, is not known.

A limitation of this technique lies in the ability to measure the main pulmonary artery accurately. In a small subset of patients (2 of 15), the diameter of the main pulmonary artery could not be confidently measured by the single horizontal plane transducer utilized in this study. Air from the left main stem bronchus appeared to be a source of artifact and a cause for degeneration of image quality in these patients. Previous investigators have demonstrated the two-dimensional measurement of the pulmonary artery as an important potential source of error in the determination of cardiac output by Doppler techniques. This limitation is likely to be overcome by the use of biplane transesophageal echocardiography, which has demonstrated superior imaging of the right ventricular outflow tract and proximal main pulmonary artery compared with the single-plane technique.

It has been suggested that increases in the pulmonary artery diameter during systole are a potential source of error in the Doppler cardiac output technique. However, the majority of flow occurs when the vessel is at or near its peak systolic dimension, and it appears acceptable to utilize this single systolic dimension in the calculation of cross-sectional area. Another potential limitation of this study involves the use of the thermodilution technique as the reference standard for cardiac output. There is inherent variability in the use of this technique, but the error is usually less than 10%, and this technique has been widely used as an adequate reference in previous studies. The results of Doppler cardiac output in this study are within the range of error of the thermodilution standard.

Transesophageal continuous-wave Doppler is a promising new technique that may be used in selected patients for accurate determination of cardiac output. The use of Doppler hemodynamics further extends the use of transesophageal echocardiography to monitor intraoperative cardiac function. Refinements of this technique, such as the use of biplane imaging of the main pulmonary artery, should further enhance its accuracy and clinical utility for future applications.

We thank Jillian Wszelaki for excellent secretarial assistance and Emile Morse for superb computational and statistical guidance.

REFERENCES

6. Nishimura RA, Callahan MJ, Schaff HV, Istrup DM, Miller...