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Intraoperative Estimation of Cardiac Output by Transesophageal Pulsed Doppler Echocardiography

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To determine whether transesophageal echocardiography could be used to estimate intraoperative cardiac output, the authors studied 35 consecutive patients undergoing cardiovascular surgery (coronary artery disease [n = 22], aortic valve disease [n = 5], mitral valve stenosis [n = 5], peripheral vascular disease [n = 3]). Two-dimensional echocardiographic and pulsed-wave Doppler signals of the pulmonary artery and mitral valve flow velocity were obtained simultaneously with thermodilution measurements of cardiac output. Cardiac output derived from pulsed Doppler imaging of pulmonary artery systolic flow velocity modestly correlated with the thermodilution-derived cardiac output (r = 0.65), but output determined from the mitral valve diastolic flow velocity did not (r = 0.24). Transesophageal echocardiography of pulmonary artery systolic flow satisfactorily detected intraoperative increases in cardiac output greater than 15% (sensitivity, 71%; specificity, 82%) but not decreases (sensitivity, 54%; specificity, 90%). Although this technique identifies increases in cardiac output greater than 15%, it does not detect decreases as accurately as those detected by thermodilution measurements. At this time, therefore, transesophageal Doppler echocardiography has significant limitations as an off-line monitor of cardiac output. (Key words: Measurement technique: pulsed Doppler; thermodilution; transesophageal echocardiography. Monitoring: cardiac output.)

TRANSESOPHAGEAL ECHOCARDIOGRAPHY is commonly used intraoperatively for detection of regional wall-motion abnormalities and ventricular volume status,[1–3] but there is little information on its use for monitoring cardiac output.[4–7] Previous studies using precordial Doppler assessment of mitral or aortic valve flow indicate that the pulsed-wave Doppler technique provides accurate estimates of cardiac output.[4–14] We prospectively compared measurements of intraoperative cardiac output derived by transesophageal echocardiographic and pulsed-wave Doppler monitoring of pulmonary artery and mitral valve flow with measurements obtained by thermodilution. We also evaluated the accuracy of transesophageal Doppler echocardiography in detecting intraoperative changes in cardiac output.

Materials and Methods

PATIENT POPULATION

With approval from our Committee on Human Research, we studied 35 consecutive patients (ages 34–77 yr) undergoing cardiac or vascular surgery while monitored by transesophageal echocardiography and pulmonary artery catheterization. The procedures performed included coronary artery bypass grafting (n = 22), aortic valve replacement (n = 5), mitral valve replacement for mitral stenosis (n = 5), abdominal aortic aneurysmectomy (n = 2), and aorta bifemoral bypass grafting (n = 1).

ANESTHETIC MANAGEMENT

Preanesthetic medication included morphine sulfate (0.1 $mg \cdot kg^{-1}$ intramuscularly [im]) and diazepam (10 mg orally [po]). Anesthesia was induced with fentanyl (30–100 $\mu g \cdot kg^{-1}$) or sufentanil (10–15 $\mu g \cdot kg^{-1}$) and maintained with isoflurane or halothane in oxygen, titrated at the discretion of the anesthesiologist. Muscle relaxants included pancuronium and/or vecuronium. After bypass, the anesthetic regimen included morphine sulfate (doses ranging up to 0.85 $mg \cdot kg^{-1}$) and diazepam (10–20 mg).

EXPERIMENTAL PROCEDURES

Transesophageal two-dimensional and pulsed Doppler echocardiography were performed with the use of commercially available transesophageal echocardiographic probes (Hewlett Packard, Inc., Andover, MA; Advanced Technology Laboratories, Inc., Bellevue, WA; Aloka [Corometrics, Inc.], Wallingford, CT). Probes were inserted after induction of anesthesia, tracheal intubation, and insertion of a pulmonary artery catheter. An observer blinded to hemodynamic data performed pulsed-wave Doppler and two-dimensional echocardiographic imaging. Doppler measurements were obtained from two-dimensional recordings of the pulmonary artery by placing the sample volume just above the level of the pulmonic valve and at the level of the mitral leaflet tips where the valve excursion was maximal. The sample volume (2 mm) was positioned where color flow indicated maximal flow velocities and where the spectral display by pulsed Doppler

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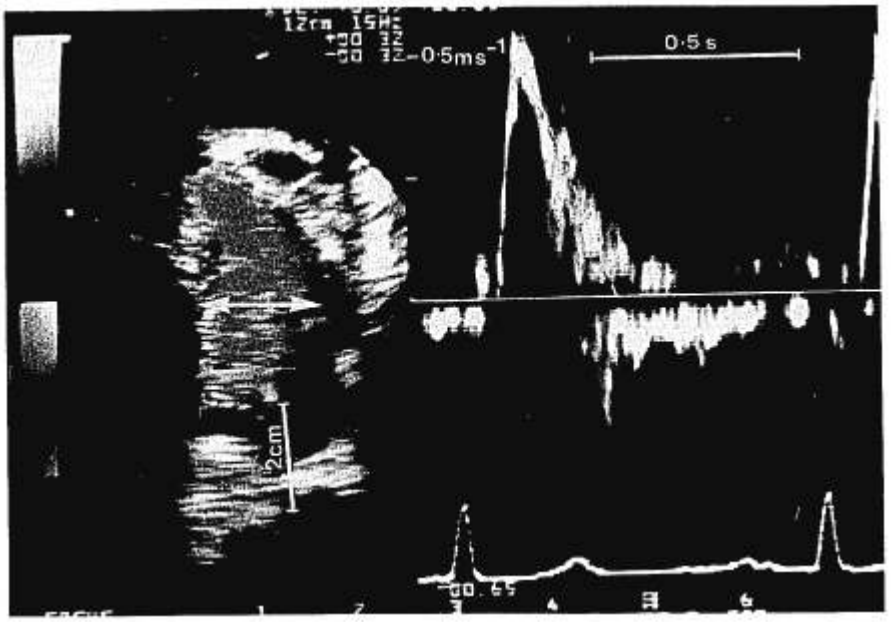

FIG. 1. Measurement of pulmonary artery diameter and velocity–time integrals. The pulmonary artery diameter was measured just above the level of the pulmonary valve, as indicated by the arrow. The velocity–time integral was measured during systole as indicated by the dashed lines.

was clearly defined (figs. 1 and 2). The Doppler recordings were taken throughout the period of measuring thermodilution cardiac output, and ventilation was not interrupted. Both thermodilution and Doppler cardiac output measurements were performed at end-expiration with the ventilator stopped, and three beats were averaged.

Invasive techniques were used to obtain measurements of arterial and pulmonary artery pressures and thermodilution cardiac output (THD-CO). Arterial pressures were continuously monitored by an arterial catheter placed in the radial artery before induction of anesthesia. Thermodilution measurements of cardiac output were obtained with the use of a balloon-tipped flotation catheter (7.5 French) that was inserted into the pulmonary artery through the right internal jugular vein either before or after induction of anesthesia and tracheal intubation. Cardiac output was determined by injecting 10 ml of normal saline at room temperature at end-expiration and using a bedside THD-CO monitor (model 9520 A, American Edwards Laboratories, Irvine, CA). Duplicate mea-

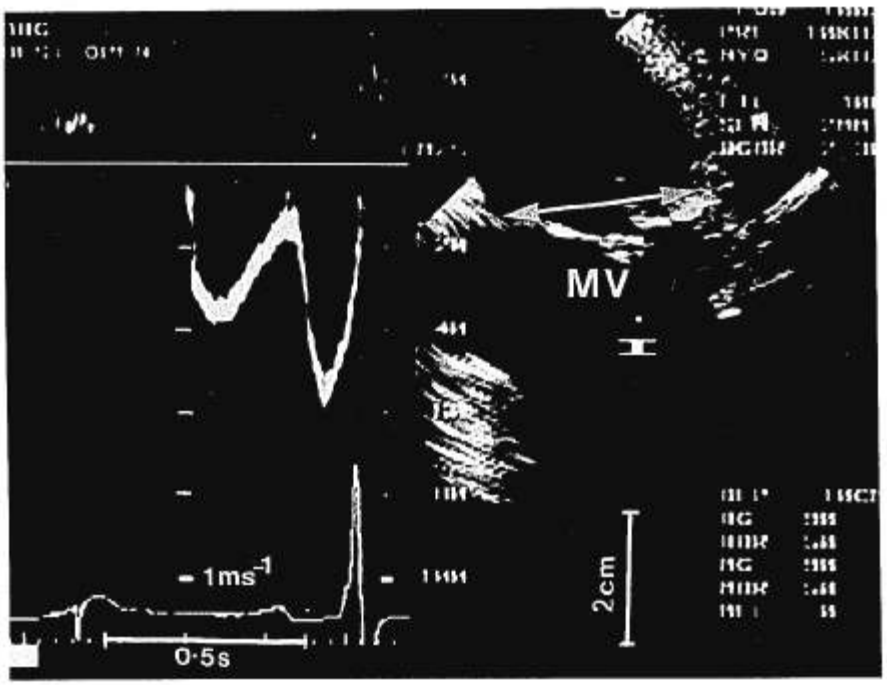

FIG. 2. Measurement of mitral inflow diameter and velocity–time integral. The mitral diameter was measured at the mitral annulus, as indicated by the arrow. The velocity–time integral of mitral inflow was measured during diastole at the mitral leaflet tips. MV = mitral valve.

surements were made in rapid succession and the results averaged. If the difference between the first two estimates of cardiac output was greater than 10%, a third measurement was made and the results averaged.

Doppler and two-dimensional echocardiographic estimates were recorded simultaneously at end-expiration by an observer blinded to the THD-CO results. Doppler recordings were then measured off-line in random order by two observers blinded to the hemodynamic data. To determine whether transesophageal pulsed-wave Doppler could accurately reflect changes in cardiac output in individual patients, we collected data during four study periods: 1) after induction of anesthesia, intubation, and insertion of the pulmonary artery catheter; 2) after pericardiectomy; 3) 15–20 min after termination of cardiopulmonary bypass when the patient was considered hemodynamically stable; and 4) after the sternum was closed. The study periods for the three patients undergoing vascular surgery were as follows: 1) after induction of anesthesia, intubation, and insertion of the pulmonary artery catheter; 2) 15 min before aortic cross-clamping; 3) approximately 15 min after removal of the cross-clamp; and 4) during closure of the incision. We obtained measurements during a total of 140 episodes in 35 consecutive patients.

Data from 99 of the 140 possible measurement episodes were analyzed. The rest were excluded from study: two for atrial fibrillation or severe dysrhythmias, 14 for technically inadequate tracings of Doppler signals, six for inadequate two-dimensional recordings of the pulmonary artery, and 14 when it was not possible to manipulate the esophageal probe. Technically inadequate Doppler tracings were defined as Doppler tracings without well-defined envelopes. Two-dimensional recordings of the pulmonary artery were considered inadequate when the arterial walls were not clearly delineated. Episodes also were excluded if thermodilution measurements of cardiac output varied more than 20% (n = 5). No patient included in the study had more than mild mitral regurgitation as determined by cardiac catheterization and color flow mapping.

Data Analysis

Echocardiographic Doppler recordings were analyzed by two observers in an order random to the sequence of acquisition. Both observers were blinded to the thermodilution results and to each other's echo analyses. The recordings were digitized off-line with the use of a phantom-calibrated computerized videotape analysis system (Cine View, Freeland Medical Division, Indianapolis, IN). To quantify cardiac output, we visually selected three consecutive cardiac cycles to measure pulmonary systolic flow velocity, mitral diastolic flow velocity, and their respective diameters. The diameters of the pulmonary artery and mitral valve annuli were measured three times and the results averaged. The pulmonary artery diameter was measured at the level of the valve by manually placing the cursors on either side of the valve during systole, and the mitral valve annulus was measured by placing the cursors at either side of the annulus during diastole, that is, at the time of end-diastole to the nearest video frame. Velocity time integrals (VTIs) of the pulmonary artery (systolic flow) and mitral valves (diastolic flow) were determined by manually tracing the mode of the flow velocities. Stroke volume (SV) was calculated as the product of the velocity-time integral and cross-sectional area (CSA). Cardiac output was calculated as the product of SV and heart rate (HR).[10] Doppler cardiac output was calculated with the following equations:

$$SV\ (ml) = VTI\ (cm) \times CSA\ (cm^2)$$

$$CO(l \cdot min^{-1} = (SV\ (ml) \times HR\ [beats\ per\ min])/1{,}000$$

Statistical Analysis

Doppler-derived cardiac outputs were correlated with THD-COs with the use of a linear regression analysis. Changes in THD-CO between the four study periods were correlated with Doppler-derived changes in output to determine the accuracy of the Doppler measurements. Sensitivity and specificity of the Doppler technique for detecting changes (increases and decreases) of cardiac output greater than 15% were calculated. The product of the VTI and HR (minute distance) was correlated with the THD-CO results to determine whether the measurement of diameter was a source of significant error in the calculation of Doppler-derived cardiac output. For each measurement episode, the difference between Doppler- and thermodilution-derived cardiac output values was compared with the mean cardiac output values for both techniques with the use of the method described by Bland and Altman.[15] Intraobserver and interobserver variability in Doppler estimates was determined by calculating the mean differences between matched pairs of measurements and by performing linear regression analysis. A value of $P \leq 0.05$ identified significant differences.

Results

Cardiac outputs derived from pulsed Doppler echocardiography of pulmonary artery flow correlated modestly ($r = 0.65$, $P \leq 0.01$) (fig. 3) with THD-CO results in a range from 1.87 to 10.9 $l \cdot min^{-1}$. Measurements obtained by pulsed Doppler imaging of mitral valve inflow did not correlate with the thermodilution results ($r = 0.24$, $P \leq 0.11$). Similarly, Doppler measurements of change in intraoperative cardiac output derived from pulmonary artery flow modestly correlated with thermodilution out-

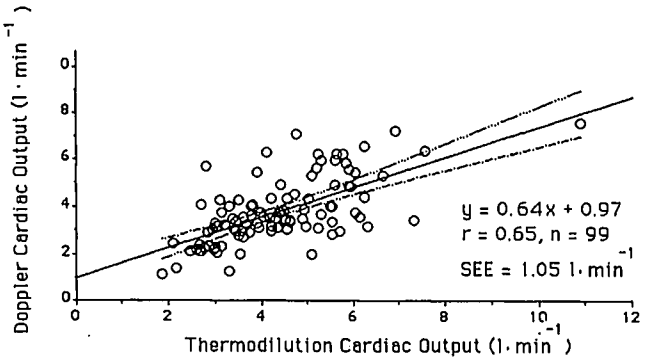

FIG. 3. Correlation of thermodilution cardiac output with cardiac output derived from pulsed Doppler imaging of pulmonary artery flow. r = correlation coefficient; n = number of episodes; SEE = standard error of the estimates.

put ($r = 0.71, P \leq 0.01$) (fig. 4), whereas changes identified by mitral valve flow did not ($r = 0.15, P \leq 0.5$).

The product of VTI and HR (minute distance) at the pulmonary artery and thermodilution measurements of output also correlated modestly ($r = 0.59, P \leq 0.01$). This correlation was similar to that between cardiac output defined by Doppler pulmonary artery flow imaging ($r = 0.65$) and thermodilution (fig. 5). The minute distance at the mitral valve correlated poorly with thermodilution measurements ($r = 0.03, P \leq 0.98$). The interobserver and intraobserver variability in Doppler estimates for all measured variables was less than 10% (table 1).Comparison of the difference between thermodilution- and pulsed Doppler-derived cardiac outputs at the pulmonary artery and the mean cardiac output from both methods showed wide limits of agreement between the two techniques (fig. 6). There must be a change of more than 2 $l \cdot min^{-1}$ to fall within two standard deviations of the mean. That is, for any given estimate of cardiac output obtained by pulsed Doppler imaging of pulmonary artery

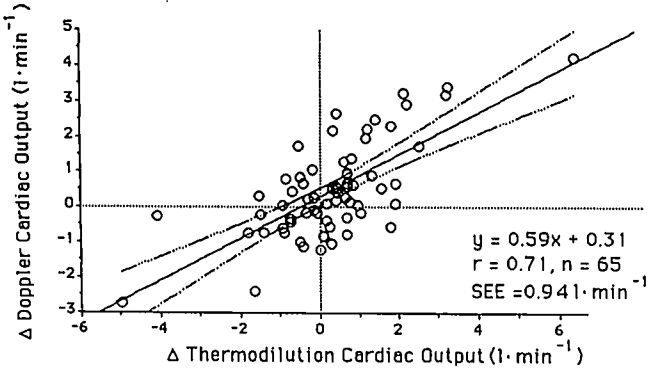

FIG. 4. Correlation of changes in thermodilution cardiac output of greater than 15% with those obtained by pulsed Doppler echocardiography at the pulmonary artery. r = correlation coefficient; n = number of episodes; SEE = standard error of the estimates.

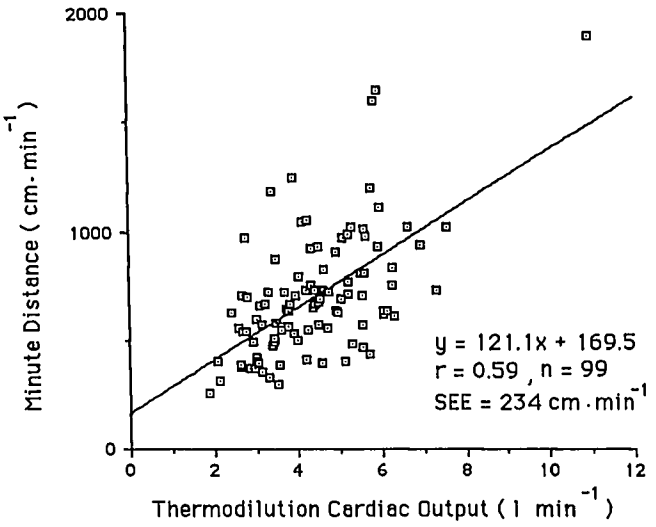

FIG. 5. Comparison of minute distance to thermodilution cardiac output at the pulmonary artery. r = correlation coefficient; n = number of episodes; SEE = standard error of the estimates.

flow, the cardiac output measured by thermodilution may fall in a range of ± 2 $l \cdot min^{-1}$ (fig. 6). The range of agreement was even greater at the mitral valve (fig. 7). If we consider thermodilution measurements of cardiac output to be the gold standard, then Doppler estimates of clinical cardiac output are rather inaccurate.

Discussion

Our results demonstrate only a modest correlation between thermodilution and transesophageal echocardiographic estimates of cardiac output derived from pulsed wave Doppler imaging of flow across the pulmonary artery but little, if any, relationship with flow across the mitral valve. These findings differ from those previously obtained from precordial imaging of the aortic and mitral valves[8–14,16–20] and other preliminary studies[4–7] of transesophageal Doppler estimates of cardiac output. Although the absolute values for pulsed wave Doppler and ther-

TABLE 1. Intra- and Interobserver Variability of Transesophageal Echocardiographic Variables*

Variable	Variability (%)	
	Intraobserver	Interobserver
Pulmonary artery diameter	2.1 (2.9)	2.1 (3.5)
Pulmonary artery velocity–time integral	1.3 (8.2)	4.2 (7.3)
Mitral valve diameter	3.4 (8.3)	0.1 (0.9)
Mitral valve velocity–time integral	5.8 (6.2)	0.1 (7.2)

* The standard deviation for each variable is indicated in parentheses.

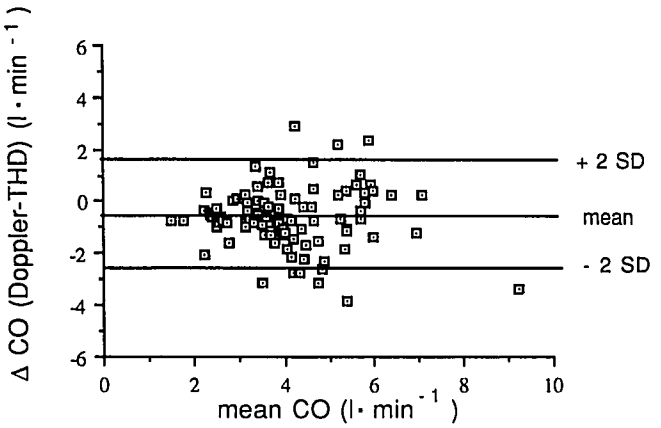

FIG. 6. Comparison of the difference in cardiac output derived by the thermodilution and Doppler techniques at the pulmonary artery to the mean cardiac output value obtained with each method.

modilution measurements of cardiac output correlated weakly (confirming the data of Elkayam *et al.*[13]), our results suggest that the transesophageal Doppler technique is fairly sensitive in detecting increases in cardiac output greater than 15% but relatively insensitive to decreases in output.

Both the thermodilution and transesophageal Doppler techniques have limitations in measuring cardiac output. It is well known that thermodilution may be relatively inaccurate.[21,22] The computation constant takes into account the catheter dead space, injection rate, and heat change in transit, but there are many other factors that could account for an intrinsic error of thermodilution of at least 10%,[21,22] including volume of injectate, change in catheter position, or inadequate temperature difference between the blood and injectate.

Doppler measurements also have inherent constraints. First, there are the assumptions that the outflow tract across the pulmonary and mitral valve annulus is circular and that the CSA is constant throughout the cardiac cycle.[12] Second, the flow velocity profile may not be flat at the sampling site or during the entire systolic portion of the cardiac cycle, which would result in overestimation of the cardiac output.[23] Third, we assumed that the Doppler sample volumes were obtained from positions exactly parallel to both the pulmonary artery and mitral valve flows at the point of maximal velocity, and that the angle between the direction of flow and the ultrasound beam was less than 5%.[23] Finally, it is assumed that the CSA does not change between cardiac output determinations and that the pulmonary artery catheter has no influence on the flow profile across the pulmonary valve.

Measurements of cardiac output derived from diastolic flow across the mitral valve depend on the site of sampling of the velocity of flow.[24] In this study population, the Doppler sample volume was placed at the mitral valve leaflet tips, whereas the diameter measurement was made at the mitral valve level. Measurement at the leaflet tips, compared with the annulus site, may result in overestimation of cardiac output. However, the measurement of flow velocity at the leaflet tips did not account for the lack of correlation we found between cardiac output values determined by thermodilution and Doppler imaging of mitral valve flow. Although our measurement of diameter at the annulus site introduced a potential source of error, eliminating this measurement by using minute distance at the pulmonary artery did not improve the results, indicating that it was not a major source of error. A plot of the difference between the mean cardiac output values of the two methods showed that, within the clinically useful range of cardiac outputs, there was considerable spread in the data points.

Intraoperative trends in cardiac output during cardiac and vascular surgery are monitored routinely with the use of pulmonary artery catheters. However, the use of pulmonary artery catheters is associated with complications such as carotid artery puncture, pneumothorax, sepsis, and emboli.[25] In contrast, transesophageal echocardiography is relatively noninvasive and currently associated with few complications. We performed this study to explore whether intraoperative cardiac output can be accurately determined with the use of transesophageal echocardiography, a method currently used to monitor intraoperative preload and possible ischemia.[1-3] Our results show that pulsed-wave Doppler transesophageal echocardiography is relatively inaccurate if thermodilution measurement is to be considered the gold standard but indicate that this Doppler technique may be useful in tracking large fluctuations in cardiac output. Specifically, pulsed Doppler echocardiographic imaging of flow across

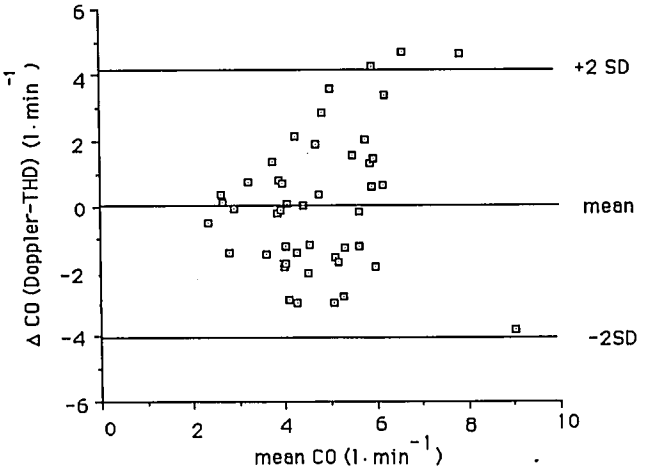

FIG. 7. Comparison of the difference in cardiac output derived by the thermodilution and Doppler techniques at the mitral valve to the mean cardiac output value obtained with each method.

the pulmonary artery (but not the mitral valve) provides a fair estimate of intraoperative cardiac output. Additionally, increases in cardiac output greater than 15% are detectable, whereas more precise estimates of change in output are not. The limitations currently inherent in the Doppler technique may affect its accuracy, limiting, for now, its usefulness as an off-line monitor of intraoperative cardiac output.

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