Measurement of Pulmonary Blood Flow with Transesophageal Two-dimensional and Doppler Echocardiography

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Transesophageal echocardiography permits measurement of the pulmonary artery diameter (two-dimensional echocardiography) and pulmonary artery blood flow velocity (pulsed-wave Doppler). These measurements considered with the heart rate allow for the determination of pulmonary artery blood flow, which is equivalent to cardiac output. This study compared the precision of transesophageal Doppler-derived cardiac output (DdCO) with the precision of thermodilution cardiac output (TdCO) and examined the agreement between DdCO and TdCO in 33 cardiac surgical patients. The proximal pulmonary artery diameter was measured in triplicate during systole and end expiration, and the local blood flow velocity was recorded on video tape. The instantaneous pulmonary artery blood flow velocity (centimeters per second) for three random cardiac beats was integrated with respect to time. DdCO was calculated as the product of the flow velocity integral (centimeters per beat), heart rate (beats per min), and the mean cross-sectional area (centimeters squared) of the main pulmonary artery. At the same time that the velocity recordings were made, three serial determinations of TdCO were made by an independent observer. Pulmonary blood flow could be measured in 25 of the 33 patients. The anatomical relationship among the esophagus, the left main stem bronchus, and the pulmonary artery did not allow adequate imaging of the pulmonary artery in 8 (24%) of the patients. A total of 45 sets of triplicate measurements were made. The range of cardiac outputs encountered was 1.7–6.6 $l \cdot min^{-1}$ by TdCO and 1.5–6.9 $l \cdot min^{-1}$ by DdCO. The 95% confidence limits for the difference between the two methods (agreement) was 0.030 ± 0.987 $l \cdot min^{-1}$. The repeatability coefficient for DdCO, using a single mean value for pulmonary artery diameter, was ± 0.588 $l \cdot min^{-1}$ and for thermodilution was ±0.947 $l \cdot min^{-1}$. Transesophageal echocardiographic analysis of axial flow velocity and flow volume in the pulmonary artery is an alternate method of measuring cardiac output that compares favorably with the thermodilution technique. (Key words: Measurement technique: Doppler ultrasonography; thermodilution; transesophageal echocardiography. Monitoring: cardiac output; pulmonary blood flow.)

THE MOST COMMON METHOD of cardiac output determination in clinical practice is the measurement of pulmonary artery blood flow by thermodilution. Transtho-racic echocardiographic determination of stroke volume and cardiac output is noninvasive but has only limited applicability as an intraoperative monitoring technique. Positioning of the probe on the precordium is not practical for many operations. Transesophageal echocardiography is used with increasing frequency in cardiac surgical patients as a qualitative technique for monitoring cardiac function and as a diagnostic technique for assessing abnormalities of cardiac and aortic anatomy. The purpose of this study was to describe and validate a method that applies transesophageal two-dimensional and pulsed-wave Doppler echocardiography to measure pulmonary blood flow. This technique would permit a quantitative echocardiographic measurement of cardiac function without additional cost or risk for those patients already monitored with transesophageal echocardiography.

Materials and Methods

The protocol was approved by the Committee on Studies Involving Human Beings of the University of Pennsylvania. Thirty-three cardiac surgical patients with regular heart rhythms were studied prospectively. Each patient was monitored with a pulmonary artery catheter and transesophageal echocardiography. Patients with moderate-to-severe pulmonic or tricuspid valve incompetence demonstrated by color flow Doppler were excluded from the study. The number of patients with these problems was not recorded.

Anesthetic management proceeded at the discretion of the attending anesthesiologist. After induction of anesthesia and tracheal intubation, a standard 5.0-MHz transesophageal echocardiography probe (Hewlett Packard, Andover, MA) was inserted into the esophagus. After the transesophageal echocardiography examination was conducted, the transesophageal probe was repositioned to yield the basal short axis view at the level of the aortic root. The main pulmonary artery was imaged near its bifurcation so that the axis of pulmonary artery blood flow was approximately parallel to the pulsed-wave Doppler signal (fig. 1). The angle ϕ created by the trunk of the pulmonary artery and the ultrasound beam was estimated off-line with a protractor. While the two-dimensional image was being viewed the position of the transesophageal probe was adjusted to obtain the maximum cross-sectional diameter of the main pulmonary artery. The maximum diameter is an echocardiographic approximation of the
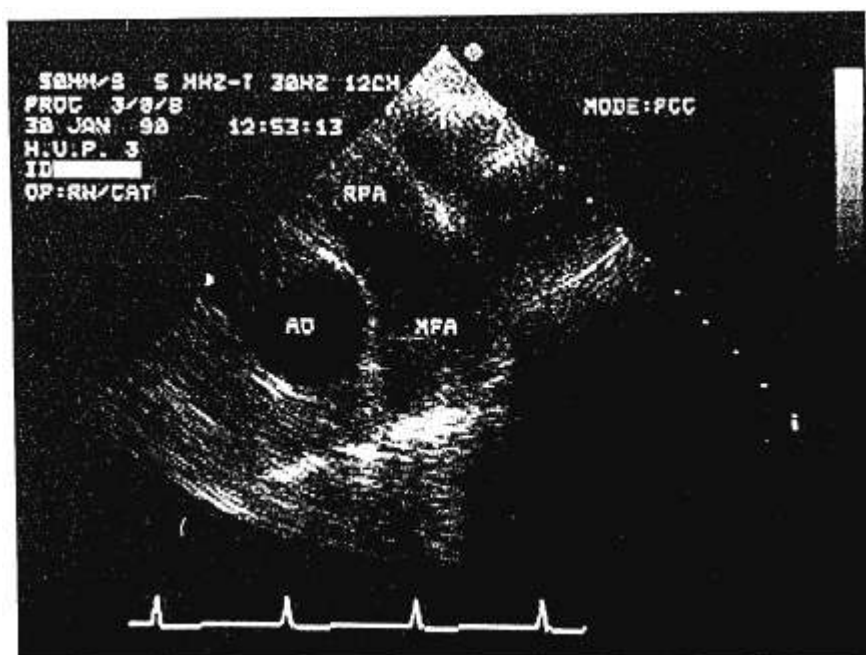
FIG. 1. Two-dimensional transesophageal echocardiogram of the main pulmonary artery (MPA) using the basal short-axis view at the level of the aortic root. RPA = right pulmonary artery; AO = aortic root. The emitted ultrasound beam is parallel to blood flow in the MPA.

pulmonary artery diameter if the pulmonary artery is a cylindrical structure. Image planes that do not traverse the center of the pulmonary artery result in a chord that is shorter than the diameter. Pulmonary artery diameter was measured in triplicate during systole and at end expiration on a stop-frame using the inner-edge method.[1]

Pulsed-wave Doppler estimations were made at the locus of maximum pulmonary artery blood flow velocity in the plane of the maximum vessel diameter. This locus was identified by inspection of the spectral display of the Doppler signal as the cursor (sample volume) was moved along the diameter of the vessel. The locus of measurement was proximal to the bifurcation and as close as possible to the pulmonic valve. The spectral display of the pulmonary blood flow velocity was recorded during end expiration on video tape (fig. 2). The flow velocity integral
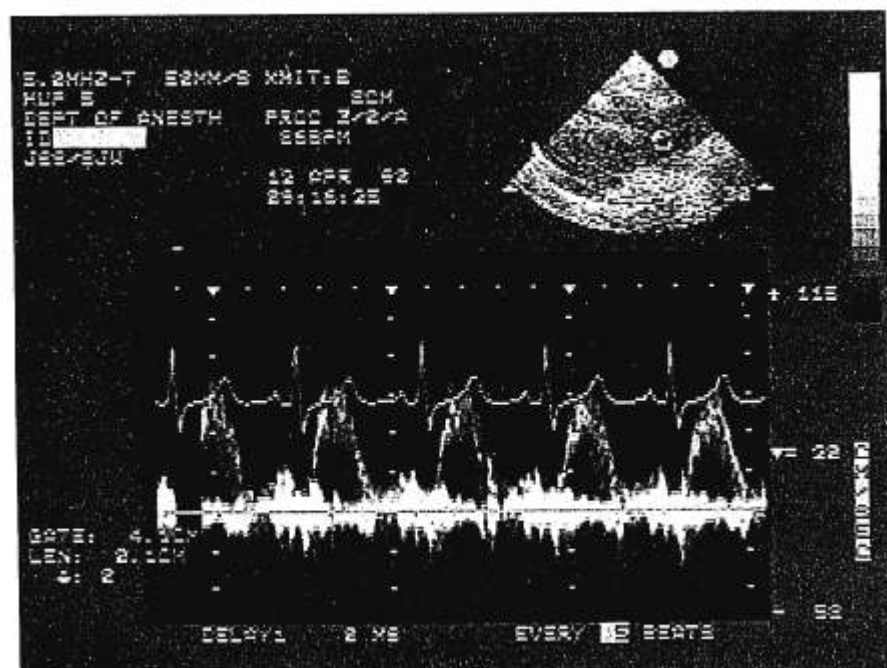

FIG. 2. Spectral display of the pulsed-wave Doppler signal with the sample volume in the main pulmonary artery.

for three random cardiac beats was determined off-line by manual planimetry of the area within the outer boundary of the spectral display (Hewlett Packard Sonos 500). The flow velocity integral represents the movement of red blood cells in the pulmonary artery during systole and has units of length. The three DdCO values were calculated by using the three flow velocity integrals and the mean of the triplicate diameter measurements (the mean cross-sectional area). Doppler-derived cardiac output (DdCO) was calculated as the product of the flow velocity integral, the mean cross-sectional area of the main pulmonary artery, and the heart rate.

Three successive thermodilution cardiac output (TdCO) measurements were made at the same time as the pulmonary blood flow velocity was recorded. TdCO measurements were made by a different investigator, masked to the echocardiography data, using a standard 7-Fr 110-cm thermodilution pulmonary artery catheter (Baxter–American Edwards), 10 ml normal saline at room temperature, and manual injection. Passive changes in injection temperature were monitored with a thermocouple secured to the surface of the injection reservoir. In an attempt to simulate our standard practice, mechanical injection devices were not used.

Cardiac output determinations were conducted after induction of anesthesia, both pre- and post-cardiopulmonary bypass, in order to obtain a range of values under a variety of conditions. Triplicate sets of measurements were assumed to be independent of each other. All measurements were made when heart rate was stable and large fluctuations in cardiac output were not expected. The mean cardiac output and the intrapatient standard deviation were calculated for the three measurements from each device.

Repeatability is the intrasubject standard deviation of replicate measurements.[2] The repeatability of each of the two methods of measuring cardiac output was assessed independently by visual inspection of a graph of the standard deviation plotted against the mean cardiac output and by calculation of the repeatability coefficient.[2] The repeatability coefficient, as defined by the British Standards Institution, is "the value below which the difference between two single test results . . . may be expected to lie with a specified probability, in the absence of other indications; the probability is 95 per cent".** Assuming that the differences follow a normal distribution, this coefficient is the product of 2.83 and the intrasample standard deviation. Variance within triplicate data sets was calculated from one-way analysis of variance. Agreement be-

tween the two independent methods for measuring cardiac output was evaluated using the approach suggested by Bland and Altman.[3] For each data point, the difference between the triplicate values measured by DdCO and TdCO and the average value of the two methods were calculated. Agreement was evaluated by inspection of the difference between mean cardiac outputs determined for each technique plotted against the average for the two techniques. The mean bias (i.e., the average difference) and the 95% confidence limits, defined as the mean bias ± two standard deviations, were calculated and indicated on the graph. To allow comparison with other investigations, linear regression was used to describe the correlation between the two techniques, although it has limited value in assessing agreement.[3] The effect of the magnitude of the cardiac output on the agreement and repeatability of the measurements was assessed by reanalyzing the data from three equal-sized cohorts of low ($\leq$ 3.1 $l \cdot min^{-1}$), moderate (3.2–4.3 $l \cdot min^{-1}$), and high ($\geq$ 4.4 $l \cdot min^{-1}$) cardiac output.

Results

Pulmonary artery blood flow could be determined in 25 of 33 patients. The mean age was 67 yr (range 40–81 yr). The mean body surface area was 1.85 m^2 (range 1.3–2.3 m^2). The mean pulmonary artery diameter was 2.4 cm (range 1.8–3.3 cm). The anatomic relationship among the esophagus, the left main stem bronchus, and the pulmonary artery did not allow adequate imaging in 8 (24%) of the patients studied. Pulsed-wave Doppler signals could be obtained in all patients in whom a pulmonary artery diameter was measurable. Angle ϕ was determined only in the 25 patients in whom a pulmonary artery diameter was measurable. The mean angle ϕ was 12° (cosine 12° = 0.98), range was 0–28° (cosine = 1 to 0.88), and the standard deviation was 7° (standard deviation of the cosine ϕ = ± 0.03). Forty-five sets of triplicate cardiac output determinations were made; mean values were 1.7–6.6 $l \cdot min^{-1}$ by thermodilution and 1.5–6.9 $l \cdot min^{-1}$ by the Doppler technique. The mean time required for an investigator to measure a pulmonary artery diameter, record the pulsed-wave Doppler signal from the pulmonary artery, and determine the flow velocity integral and manually calculate DdCO was 4 min and 58 s (range = 3 min and 12 s to 10 min and 8 s) (standard deviation = ± 1 min and 38 s).

REPEATABILITY

Plots of the standard deviation for each triplicate cardiac output measurement against the mean of the triplicate measurements are shown in figure 3A for TdCO and in figure 3B for DdCO. The calculated coefficients of repeatability were ±0.947 $l \cdot min^{-1}$ and ±0.588 $l \cdot min^{-1}$

** British Standards Institution: Precision of test methods, part 1: Guide for the determination of repeatability and reproducibility for a standard test method. BS 5497, Part 1, London, 1979.
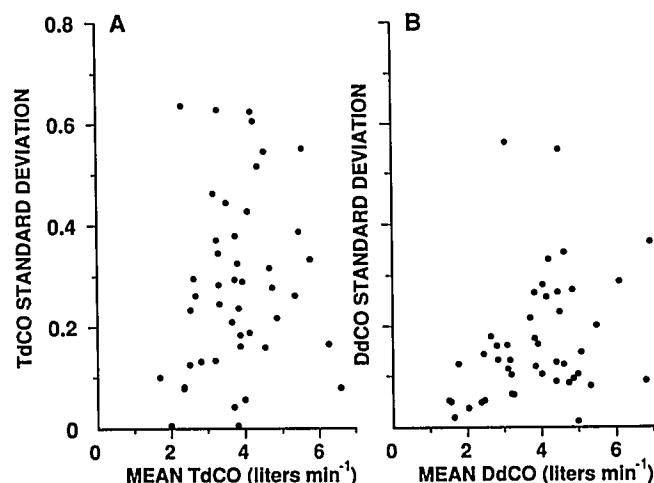
FIG. 3. Plots of the standard deviation for each triplicate cardiac output measurement *versus* the mean of the triplicate measurements.

for TdCO and DdCO respectively ($P < 0.05$). The DdCO value was based on the mean pulmonary artery diameter and excluded variance that might be expected from independent measurements of pulmonary artery diameter. By analysis of variance, the intrapatient standard deviation of the diameter measurements was ± 0.11 cm. The variances for the three cohorts of low, moderate, and high cardiac output did not differ appreciably from the overall repeatability coefficients.

AGREEMENT

A plot of the difference between paired DdCO and TdCO determinations against the mean for the two methods of determination is shown in figure 4. The mean bias (DdCO − TdCO) was 0.03 l·min⁻¹, and the 95%

confidence limits for agreement were 0.03 ± 0.987 l·min⁻¹. For no cohort of data was the agreement between the two techniques significantly less than 0.987 l·min⁻¹.

By linear regression analysis, the relationship between the two methods of determining cardiac output was found to be:

DdCO = (1.096 × TdCO) − 0.336 (fig. 5)

The correlation coefficient was 0.93 and the standard error of prediction was ±0.47 l·min⁻¹.

Discussion

Many methods of measuring intraoperative cardiac output that do not depend on an indwelling pulmonary artery catheter have been evaluated previously. Measurement of cardiac output by dye dilution, aortic pressure pulse contour, transthoracic bioimpedance, and R/T-wave ratio of the ECG have proven cumbersome, impractical, or unreliable for intraoperative use. Our data suggest that cardiac output determined by two-dimensional and Doppler echocardiography is an accurate and precise technique yielding results comparable to those obtained by thermodilution.

In individuals without intracardiac shunts or pulmonic or aortic valve incompetence, Doppler estimations of blood flow distal to the pulmonic and aortic valve are equal.[4] Because blood flow velocity in the pulmonary artery is more constant, peak blood flow velocity in the pulmonary artery is lower and is measurable by pulsed-wave Doppler.[5] Therefore, pulsed-wave Doppler measurement of pulmonary blood flow velocity is an alternative for measuring cardiac output.
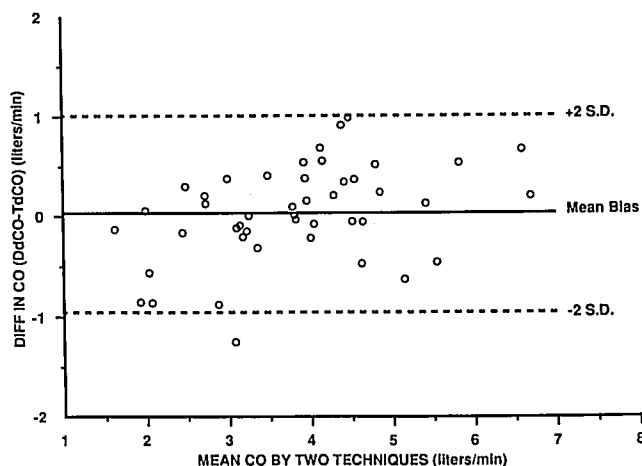

FIG. 4. Plot of the difference between paired Doppler-derived cardiac output (DdCO) and thermodilution-derived cardiac output (TdCO) determinations against the mean for the two methods.
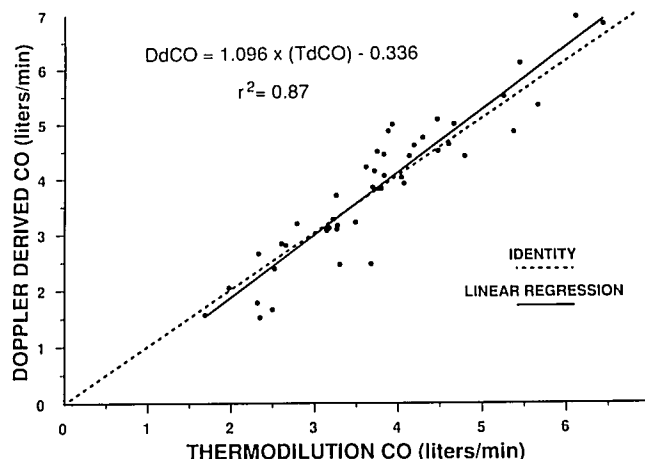

FIG. 5. Linear regression analysis depicting correlation between Doppler-derived cardiac output (DdCO) and thermodilution-derived cardiac output (TdCO) measurements.

In the current study, two-dimensional and Doppler echocardiography were combined to calculate stroke volume by multiplying the cross section of the pulmonary artery (determined by two-dimensional echocardiography) and the integral of the instantaneous flow velocity (determined by pulsed-wave Doppler) in the plane of the cross section. The calculated stroke volume by the DdCO method would equal the true stroke volume if the pulmonary artery was a cylinder with a fixed diameter, the cross-sectional velocity was constant (*i.e.*, plug flow), and the Doppler signal was perpendicular to the plane of the cross section. Implicit in our method of calculation of pulmonary blood flow is the assumption that each of the above conditions exists in our measurement system. A detailed analysis of each of these assumptions follows.

Volume flow in a cylinder is the product of the cross-sectional area and the mean velocity. The mean velocity can be calculated by spatially integrating the velocity profile over the whole cross section. However, pulsed-wave Doppler measurements of flow velocity have limited spatial information because the velocities are recorded only from a small locus (the sample volume). During plug flow, the maximum velocity is approximately equal to the spatial mean velocity. The relatively constant cross-sectional velocity permits measurement of volume flow based on pulsed-wave Doppler flow velocity and flow area. Plug flow occurs when blood accelerates through a converging flow cross section such as a ventricular outflow tract (fig. 6).[6] The assumption of plug flow may be inappropriate because the pulmonary artery is a curved structure: the blood flow velocity is expected to be greater along the concave and less along the convex border. Skewed velocity
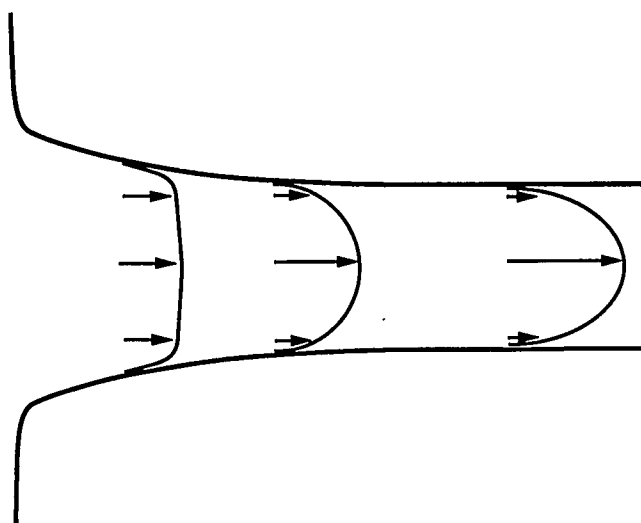

FIG. 6. Schematic illustration of the effects of a converging flow channel on the spatial velocity profile. Plug flow occurs at the site of convergence and becomes parabolic in more distal segments (redrawn from Hatle[7] with permission from Lea and Febiger).

profiles across the mitral orifice, demonstrated by two-dimensional instantaneous digital Doppler ultrasound maps, suggest that maximum flow velocity measured by pulsed-wave Doppler overestimates the mean velocity.[7] The error introduced by assuming plug flow in the proximal pulmonary artery is unknown. Flow topography based on Doppler two-dimensional flow maps requires sophisticated algorithms, is not widely used for clinical measurements, and is not available with transesophageal echocardiography. In the current study, the locus of velocity and diameter measurements was in the proximal pulmonary artery where its curvature is smallest and where flow most closely approximates plug flow. The mean bias between DdCO and TdCO, $0.030 \, 1 \cdot min^{-1}$, suggests that there was no significant tendency for DdCO to overestimate TdCO.

The measurement of pulmonary artery diameter introduces another source of error that is magnified when calculating cross-sectional area. The diameter of the pulmonary artery changes during systole. In theory one should integrate the product of the instantaneous flow velocity and the instantaneous diameter. The flow-weighted mean diameter is the value that, when multiplied by the flow velocity integral, yields the same result as the more complex integration. Because the greatest flow occurs when the diameter is maximal and videotape frame rate is slow, it was reasoned that the maximum pulmonary artery diameter during systole was a close approximation of the flow-weighted mean diameter. Maximum pulmonary artery diameter may not be constant from heart beat to heart beat. Temporally matched diameter and flow velocity measurements were not possible because the diameter could not be measured during the flow velocity determination. Because the pulmonary artery is an anterior structure, its diameter is measured in the far-field, where resolution is poorest. Furthermore, the diameter of the pulmonary artery is measured between tissue interfaces that are parallel to the ultrasound beam, and so accuracy is limited by lateral resolution.

The alignment of the Doppler signal and pulmonary blood flow was measured by the angle ϕ. The measured flow velocity is a function of the cosine ϕ, and the maximum measured flow velocity occurs when $\phi = 0$. Any deviation of the angle ϕ from zero would cause the Doppler method to underestimate pulmonary blood flow velocity. Small deviations ($\pm 20°$) in the angle ϕ do not significantly contribute to the error of the technique.

The pertinent clinical questions when a new measurement technique is compared to an old one are, "How much does the new technique differ from the established method?" and "Is the difference clinically acceptable?" A statistical approach that addresses the former is the evaluation of the difference between two techniques as a function of their mean.[3] The 95% confidence limit for

the difference between the two techniques (agreement) was 0.03 ± 0.987 l·min^{-1}. Inspection of the differences (fig. 4) suggests that the limits of agreement are not a function of the value for cardiac output within the range encountered.

In the current study, the repeatability coefficients of ± 0.947 l·min^{-1} for TdCO and ± 0.588 l·min^{-1} for DdCO suggest that transesophageal two-dimensional and Doppler echocardiography is more precise than thermodilution for the measurement of cardiac output (figs. 3A and 3B). However, the repeatability coefficient for the DdCO method did not account for error in the estimation of pulmonary artery diameter. Because diameter and flow velocity integrals cannot be measured simultaneously, the mean of three diameter measurements was used with each of the three velocity measurements to calculate DdCO. This permitted the continuous recording of the spectral display during the thermodilution measurements. Exclusion of the variance in the pulmonary artery diameter from the calculation of the repeatability of the DdCO method yields a lower value than would be obtained if the error in the diameter measurement were included. To estimate the repeatability that might be expected if independent diameters could have been measured with each flow velocity integral, we assigned one of the previously measured diameters to each of the integrals and repeated the DdCO calculation. The repeatability coefficient from this data was ± 0.960 l·min^{-1}, a value not significantly different from that for TdCO.

Repeatability of each of the two tests being compared places limits on the possible agreement between the two measurement techniques. A technique with poor repeatability (*i.e.*, one that does not agree well with itself) cannot agree well with another method. The agreement between two techniques is limited by the repeatability of the poorer of the two techniques. If DdCO were an unequivocal measurement of cardiac output, it would not have perfect agreement with TdCO because of the inherent variability in each method. Repeatability estimations in the current study suggest that the precision of TdCO and DdCO measurement limited the agreement between the two techniques. This is especially important for the cohort of low cardiac outputs, for which the repeatability of each technique and the difference between the two techniques may be greater than 50% of the mean cardiac output. Comparison of DdCO with direct measurement of pulmonary blood flow would better determine the accuracy of the DdCO measurement technique. Though no comparison of transesophageal echocardiography with electromagnetic flow probes has been reported, pulsed-wave Doppler measurements of cardiac output *via* a hand-held transducer compared favorably to measurements made by electromagnetic flow probes in open-chested dogs.[8,9]

Other investigators have attempted to measure intraoperative cardiac output using echocardiography, but with limited success.[10-12] Large mean differences between echocardiographic estimates of cardiac output and thermodilution, the need for a preoperative M-mode echocardiogram to determine aortic root diameter, frequent probe repositioning, or the inability to provide other pertinent cardiovascular data render these approaches less desirable than transesophageal echocardiography.

Muhuideen *et al.* compared transesophageal-echocardiography–derived cardiac output to thermodilution using a technique similar to that reported here, in a comparable patient population.[13] The direction of change but not the absolute value of the TdCO could be predicted. The discrepancy between the data of the current study and their data has several plausible explanations. DdCO determination may be observer-dependent, despite the reported less than 10% interobserver variability in flow velocity integral and pulmonary artery diameter measurements.[13] The inclusion–exclusion criteria in the current study may have been more restrictive. Tricuspid regurgitation increases mixing in the right atrium and ventricle and leads to a falsely high TdCO measurement. Pulmonic valve regurgitation results in a falsely high DdCO value unless the regurgitant fraction is subtracted from the Doppler-derived stroke volume. A valid noninvasive method of measuring regurgitant fraction through an incompetent valve does not exist. The current study's exclusion of patients with right-sided valvular incompetence may have improved the agreement. The broader 95% confidence limits between TdCO and DdCO reported by Muhuideen *et al.*[13] also may reflect fundamental differences in methodology. Muhuideen *et al.* measured pulmonary artery diameter at the level of the pulmonic valve, which was not always the locus of the flow velocity integral measurement. The flat velocity profile of plug flow changes downstream into a parabolic shape with a greater maximum velocity (fig. 6). Trends, but not absolute values, of cardiac output would be predicted if the Doppler and diameter measurements were determined at separate sites in the pulmonary artery.

Despite the accuracy and precision of transesophageal DdCO, it is not an ideal cardiac output monitor. In 24% of patients, the main pulmonary artery could not be adequately imaged because it was obscured by the left main stem bronchus. There was no association between the inability to image the main pulmonary artery and the body surface area of the patient, type of cardiac disease, or time of performance of the study (before or after sternotomy). Other major disadvantages of the DdCO technique include the impracticality of on-line analysis, the inability to simultaneously measure diameter and blood flow velocity, the need for operator familiarity with the

software for measurement of the flow velocity integral, and the skill required to image the pulmonary artery in long axis. Although anterior flexion of the esophageal probe does not significantly increase esophageal surface pressure, transesophageal echocardiography is not without risk.[14] Reported complications are rare but include laryngeal nerve damage, cardiac dysrhythmia, and death from esophageal perforation.[15,16] Finally, like thermodilution, DdCO measures pulmonary blood flow and right ventricular cardiac output. Therefore, DdCO measurements do not accurately estimate left ventricular cardiac output in patients with intracardiac shunts.

We conclude that transesophageal two-dimensional and pulsed-wave Doppler echocardiography permits analysis of axial flow velocity in the pulmonary artery and determination of pulmonary blood flow in most patients. Cardiac output determined by this technique compares favorably to those measured by thermodilution.

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