

Anesthesiology
80:796-805, 1994
© 1994 American Society of Anesthesiologists, Inc.
J. B. Lippincott Company, Philadelphia

Cardiac Output by Transesophageal Echocardiography Using Continuous-wave Doppler across the Aortic Valve

Pierre-Louis Darmon, M.D.,* Zak Hillel, M.D., Ph.D.,† Allen Mogtader, M.D.,‡
Bruce Mindich, M.D.,§ Daniel Thys, M.D.¶

Background: The use of transesophageal echocardiography for the determination of cardiac output (CO) has been limited to date. We assessed the capability of aortic continuous-wave Doppler transesophageal echocardiography to determine CO (DCO) in a transgastric long-axis imaging plane of the heart by comparing DCO to thermodilution CO (TCO).

Methods: DCO was determined in 63 consecutive patients undergoing cardiac surgery. Aortic valve area was obtained from the transverse short-axis view of the valve assuming a

triangular shape for the valve orifice. Stroke volume was calculated as the product of velocity-time integral and aortic valve area: stroke volume = velocity-time integral \times aortic valve area. DCO was calculated off-line, by multiplying stroke volume with heart rate: DCO = stroke volume \times heart rate.

Results: The aortic valve orifice was easily imaged in all patients. Excellent-quality continuous-wave Doppler flow profiles were obtained in nearly all (62 of 63). A total of 109 DCO determinations were performed. Mean DCO was 4.35 ± 1.18 l \cdot min⁻¹ (range 2.02-7.42 l \cdot min⁻¹), and mean TCO was 4.41 ± 1.17 l \cdot min⁻¹ (range 2.24-8.94 l \cdot min⁻¹). Very high correlation and agreement were found between the two methods: DCO = $0.94 \times$ TCO + 0.19, $r = 0.94$, SEE (standard error of the estimate) = 0.41 l \cdot min⁻¹; 95% confidence interval = 0.06 ± 0.83 l \cdot min⁻¹. Relative changes from pre- to postbypass CO (Δ) also showed a strong correlation (Δ DCO = $0.93 \times \Delta$ TCO + 5.4%, $r = 0.82$, SEE = 17.8%). For CO changes greater than 10%, Doppler was in accordance with thermodilution in 43 of 45 measurements. DCO repeatability coefficient was 0.51 l \cdot min⁻¹.

Conclusions: Compared to thermodilution, continuous-wave Doppler measurements of blood flow velocity across the aortic valve in the transesophageal echocardiographic transgastric view allow accurate CO determination. (Key words: Heart; aortic valve; cardiac output. Measurement techniques: Doppler ultrasound. Monitoring: echocardiography.)

DETERMINATION of cardiac output (CO) by Doppler ultrasound has been reported by numerous authors. Many different approaches have been utilized and a wide range of agreement with the thermodilution method has been observed. Transesophageal echocardiography (TEE), with its highly detailed image has also been explored for the determination of CO. Using TEE and pulsed-wave Doppler, investigators have determined and compared Doppler CO (DCO) to thermodilution CO (TCO). The Doppler signals were usually sampled at the level of the pulmonary artery or mitral valve. Results of these studies have demonstrated varying degrees of accuracy.^{1-6, #, **} Discrepancies in the determination of blood flow velocity-time integral (VTI) and orifice area have been responsible for the lack of agreement between DCO and TCO.^{7,8} The purpose of the current study was to explore a new ap-

This article is accompanied by a Highlight. Please see this issue of ANESTHESIOLOGY, page 25A.

* Research Fellow, Department of Anesthesiology.

† Associate Professor, Department of Anesthesiology.

‡ Assistant Professor, Division of Cardiology, Department of Medicine.

§ Attending Surgeon, Department of Surgery.

¶ Professor and Director, Department of Anesthesiology.

Received from the Departments of Anesthesiology and Surgery and the Division of Cardiology, Department of Medicine, St. Luke's-Roosevelt Hospital Center, College of Physicians and Surgeons, Columbia University, New York, New York. Accepted for publication December 7, 1993. Supported in part by a Research Fellowship Grant from the Society of Cardiovascular Anesthesiologists (to PLD). Presented in part at the annual meeting of the Society of Cardiovascular Anesthesiologists, San Diego, California, April 27, 1993.

Address reprint requests to Dr. Hillel: Department of Anesthesiology, St. Luke's-Roosevelt Hospital Center, College of Physicians and Surgeons, Columbia University, 1111 Amsterdam Avenue, New York, New York 10025.

Ellis JE, Runyon-Hass A, Lichter JL, Keamy MF, Roizen MF: Can Doppler ultrasound, targeted by two dimensional transesophageal echocardiography, be used to measure cardiac output? (abstract). ANESTHESIOLOGY 67:A638, 1987.

** LaMantia K, Harris S, Mortimore K, Davis E, Barash PG: Transesophageal pulse-wave Doppler assessment of cardiac output (abstract). ANESTHESIOLOGY 69:A1, 1988.

CARDIAC OUTPUT BY TEE USING AORTIC VALVE DOPPLER

proach for the determination of DCO by TEE. The two particular aspects of this study are (1) the recording of Doppler signals across the aortic valve in a transgastric TEE imaging plane showing the long-axis of the left ventricle, the left ventricular outflow tract (LVOT), and the ascending aorta (fig. 1)^{6,††} and (2) the application of a new model for the determination of the effective aortic valve orifice area (AVA) in systole. As the agreement between the Fick "gold standard" and thermodilution methods for CO determination has been demonstrated to be excellent,⁹ the validity of the current method was assessed by comparison of DCO with simultaneous TCO measurements, as well as with DCO determined by a Doppler approach using a conventional circular model for the aortic valve orifice.

Materials and Methods

Patients were enrolled in the study in accordance with the guidelines of the local Institutional Review Board. Sixty three consecutive patients, scheduled for coronary artery bypass grafting or automatic cardioverter-defibrillator insertion were included. All patients were shown to be free of valvular heart disease, septal hypertrophy or intercavity defects by the preoperative evaluation and an intraoperative TEE examination. All patients were in regular heart rhythm (sinus rhythm or paced). Anesthetic technique was left to the discretion of the anesthesiologist in charge of the patient's management. Routine cardiovascular monitoring: ECG, peripheral artery cannula, pulmonary artery catheter with mixed venous oxygen saturation capability (Opticath P7110, Oxymetrix 3, Abbott Critical Care, Mountain View, CA), and a TEE probe, was implemented before surgery. Transesophageal two-dimensional and continuous-wave Doppler (CWD) echocardiography were performed using commercially available single plane or biplane 5 MHz probes (models 77040A and 77030A, Hewlett-Packard, Andover MA, and model 128 XP/10C, Acuson, Mountain View, CA).

Determination of Mean Aortic Valve Area

AVA was determined from the transverse short-axis image of the aortic valve. From the five-chamber view,

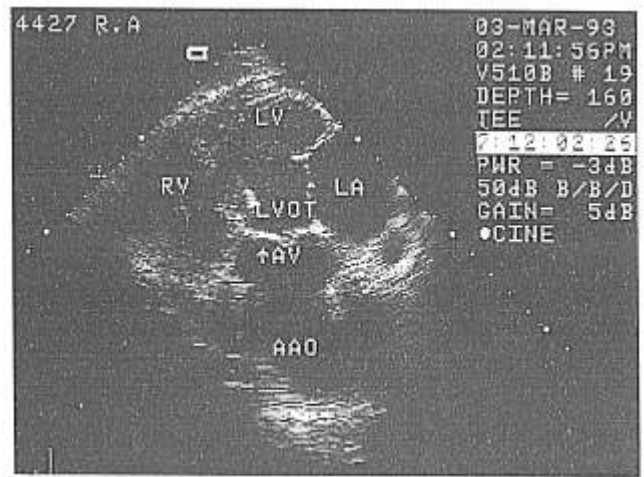


Fig. 1. Transgastric long-axis view of the heart. AAO = ascending aorta; AV = aortic valve; LA = left atrium; LV = left ventricle; LVOT = left ventricular outflow tract; RV = right ventricle.

the TEE probe was flexed to the left to visualize the aortic valve plane where the aortic attachments of the leaflet extremities are seen as fused pairs at the wall of the aortic bulb (fig. 2). Minimal depth and rotation adjustments were necessary to achieve clear imaging of the three fusion points for each pair of the three cusps. Opening of the human aortic valve has been described precisely, using a video camera on a frame-by-frame analysis, in an *in vitro* study, as an evolving triangle.¹⁰ However, at maximal valve aperture, near peak systole, we observed the aortic valve orifice as nearly circular but smaller than the aortic cross-section (fig. 2C). Early and late in systole, the valve shape could be best approximated as that of a three-legged starfish (fig. 2A). At intervening time points, near mid-systole, the aortic valve aperture closely resembled an equilateral triangle (fig. 2B). The dynamics of the aortic valve opening have been demonstrated in an animal study using radiopaque markers positioned on the aortic valve leaflets.¹¹ We assumed that the time-averaged shape of the aortic valve aperture was represented by the equilateral triangle. Therefore, the AVA was calculated as the area of an equilateral triangle, using the TEE frame in which each aortic valve cusp tip appeared as a near straight line describing one side of the triangle (fig. 2B). The length of each side of the aortic valve triangle was measured for each cusp and the three values were averaged for AVA calculation. The relation between the length of the side of the equilateral triangle and the valve area is: $AVA = 0.5 \times \cos 30^\circ \times S^2 = 0.433$

†† Gadasalli SN, Sarnoski JS, Kubota J, Schmidt DH, Gal R: Transesophageal echocardiography with a single-plane probe: Long-axis views of the heart from the apical (transgastric) approach. *Echocardiography* 9:589-596, 1992.

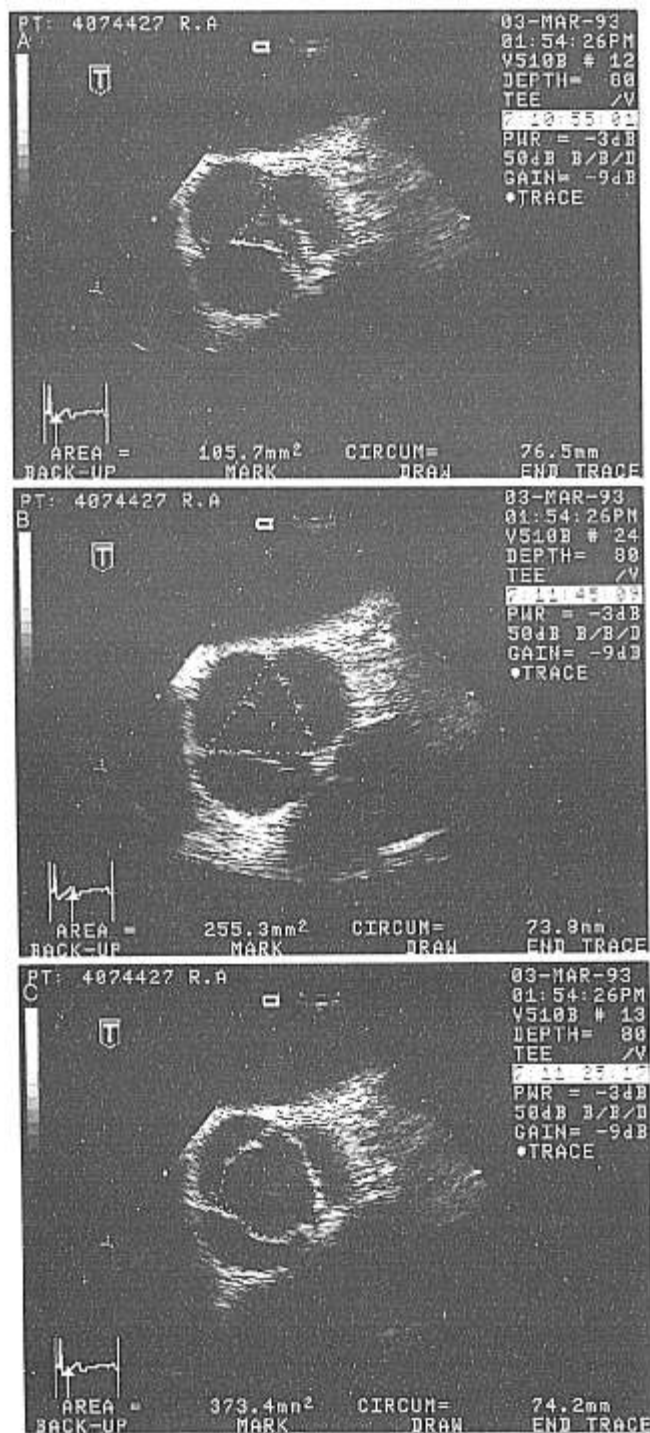


Fig. 2. Short-axis images of the aortic valve during systole. (A) Early and late systole: "three-legged starfish" shape. Circumference 76.5 mm; area 1.06 cm². (B) Approximately triangular shape observed at times other than early, peak, or late systole. Cusps appear as nearly straight lines. The leaflets' fusion points identify the corners of a triangle. Circumference 73.8 mm; area 2.55 cm². (C) Near peak systole: approximately circular shape. Circumference 74.2 mm; area 3.73 cm².

$\times S^2$, where S was the average length of the three sides. Description of the anatomic basis of this model can be found in classic textbooks.¹² Moreover, this model can also be demonstrated in a careful TEE examination using a high imaging frame rate (≈ 50 Hz).

In 22 patients, a biplane TEE probe was used. In those patients, AVA was also determined with a circular model, using the aortic valve diameter measured in the longitudinal plane image of the ascending aorta at the proximal (ventricular) level of the annulus.^{13,14} Duplicate determinations of the aortic valve diameter were performed using the inner leaflet surface to inner leaflet surface method (fig. 3), and the average value of the aortic valve diameter was used to calculate AVA: $AVA = \pi \times (\text{aortic valve diameter}/2)^2$.

Determination of Left Ventricular Stroke Volume

Left ventricular stroke-volume was determined at the aortic valve site. From the conventional transgastric mid-papillary short-axis view of the left ventricle, the TEE probe was further advanced in the stomach, fully flexed anteriorly and to the left, and slowly withdrawn until the transgastric long-axis view could be displayed.^{6,††} Minimal depth and rotation adjustments were necessary to perfect the plane in which the LVOT, the aortic valve, and the proximal ascending aorta were imaged in a nearly vertical orientation in the center of the scan sector. This image allowed alignment of the proximal aorta and the Doppler beam (fig. 1). By use of the color flow map of the LVOT and aorta, the position of the Doppler beam was more finely adjusted to coincide with the region of maximal flow velocity through the aortic valve. The largest, best-defined and most stable (over consecutive beats) aortic systolic ejection CWD spectral envelopes were selected for analysis by visual inspection. The velocity spectra were traced manually, using the leading edge method (maximal velocity), and automatically integrated over systole to yield the VTI.

Because CWD has no axial resolution but detects the highest velocities, these were assigned to the narrowest area through which blood flows along the Doppler beam. In the normal heart, the narrowest area in the path from the LVOT to the ascending aorta occurs at the aortic valve orifice. More precisely, this area appears to be at the tip of the aortic leaflets rather than at the proximal level of the annulus.⁶ Because the highest detected flow velocity originated from the aortic valve orifice, left ventricular stroke volume was obtained from the product of VTI and AVA: stroke volume = VTI \times AVA. DCO was calculated by multiplying stroke vol-

CARDIAC OUTPUT BY TEE USING AORTIC VALVE DOPPLER



Fig. 3. Longitudinal view of the aortic valve obtained with the biplane transesophageal echocardiographic probe. Diameter was measured at the hinge points using the inner leaflet surface to inner leaflet surface method.

ume with heart rate: $DCO = \text{stroke volume} \times \text{heart rate}$.

Experimental Procedures

After a routine TEE examination, the TEE probe was positioned to display the transgastric long-axis view. When cardiopulmonary bypass was required for surgery, we obtained pre- and postbypass measurements, otherwise only one evaluation per patient was performed. All measurements were obtained under stable hemodynamic conditions. TEE-based measurements were performed on freeze-frame images and were videotaped, as well as printed on hard copy. The angle subtended by the Doppler beam to a line perpendicular to the aortic valve annular plane was determined during systole by off-line measurements on hard-copy with the aid of a protractor. The CWD spectrum of flow across the aortic valve was displayed, without angle correction, until the highest well-defined velocity envelopes were imaged. Two consecutive envelope tracings (VTI-1 and VTI-2) were averaged to determine the aortic VTI. TCO determination was initiated by a second observer, blinded to the Doppler measurements, during VTI recording. For each measurement, 10 ml of normal saline were injected manually at room temperature,

and the average of triplicate measurements was used as the TCO value. If more than 10% variation was observed between the three values, two additional measurements were performed and the highest and lowest values were excluded from average calculation. Both Doppler and thermodilution measurements were performed without interruption of mechanical ventilation, and without regard to the phase of the respiratory cycle.¹⁵ For each aortic valve model, two repeat AVA determinations (AVA-1 and AVA-2) were completed as described above just after VTI and TCO recording. Calculations of DCO were carried out off-line, after the completion of data recording.

Statistical Analysis

All results are reported as mean values \pm standard deviations. DCO and TCO values were compared using simple linear regression analysis. In addition, for each pair of measurements, the difference between TCO and DCO was related to the mean value of both techniques according to the method of Bland and Altman.¹⁶ The mean bias (*i.e.*, mean difference) and the 95% confidence intervals were calculated and displayed graphically, together with the individual difference data. When cardiopulmonary bypass was required for surgery, relative changes in pre- to postbypass TCO and DCO values were calculated for each patient and were compared using simple linear regression analysis.

To examine the reproducibility of the measurements, VTI-1 and AVA-1 were used to calculate DCO-1. A different DCO-2 value was calculated from VTI-2 and AVA-2. Comparison between DCO-1 and DCO-2 was also performed by linear regression and bias analyses. Because AVA determinations were not exactly simultaneous with determinations of aortic VTI, additional comparisons between different pairs of AVA and VTI values were performed. DCO-3 was calculated by combining VTI-1 with AVA-2, and DCO-4 was obtained by associating VTI-2 with AVA-1. DCO-3 and DCO-4 were subjected to the same statistical analyses, as described above. The repeatability coefficient was calculated as two standard deviations of the differences between two repeated measurements.^{16:##}

In the patients for whom additional longitudinal biplane images were available, DCO was determined from one set of VTI values using both the triangular and circular models for the aortic valve orifice. Each of these DCO values were independently compared to the corresponding TCO using the above statistical methods.

The mean values, slopes, intercepts and the null hypothesis for r were tested using Student's t test; Fisher's

British Standards Institutions: Precision of test methods: 1. Guide for the determination and reproducibility for a standard test method. BS 5497, part 1. London, British Standards Institutions, 1979.

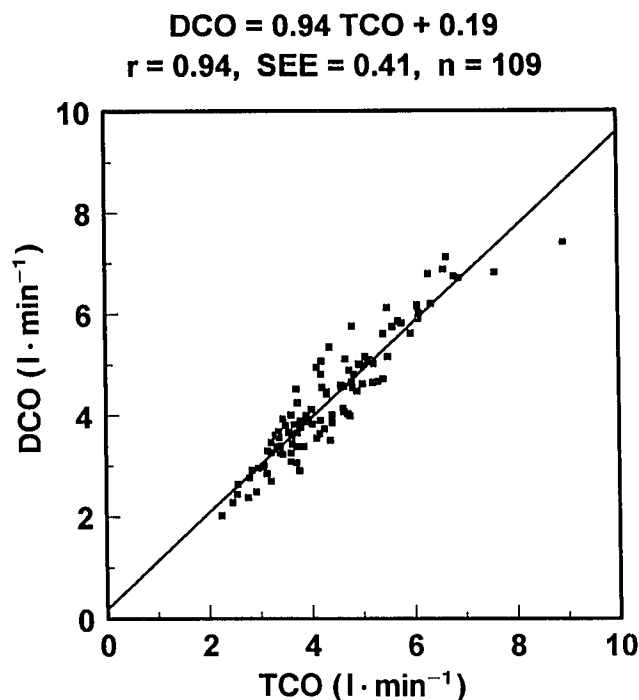


Fig. 4. Regression analysis: aortic Doppler cardiac output versus thermodilution cardiac output.

z transformation was applied to compare the correlation coefficients in the subset of 22 patients.¹⁷ Data variance results were compared using the variance ratio F test. A P value of less than 0.05 was considered significant.

Results

The transgastric long-axis view of the heart was imaged successfully in all patients. Excellent-quality CWD velocity spectra were obtained across the aortic valve in all but one patient (62 of 63, 98%). In that patient, the transgastric view was easily obtained, but the aortic CWD velocity could not be recorded because of pronounced cardiac motion. This condition, which was not associated with a high TCO value, led to loss of the aortic flow Doppler signal during systole. Satisfactory short-axis images of the aortic valve were obtained in all patients. The length of the free margin of the aortic valve cusps was 2.28 ± 0.26 cm, with a repeatability coefficient of 0.12 cm. The AVA based on the triangular shape was calculated to be 2.27 ± 0.52 cm²,

with a repeatability coefficient of 0.24 cm². The mean CWD VTI was 24.3 ± 4.9 cm, with a repeatability coefficient of 1.44 cm. The angle between the Doppler beam and the line perpendicular to the aortic valve plane was $7^\circ \pm 5^\circ$ ($\cos 7^\circ = 0.99$), with a range of 0° ($\cos 0^\circ = 1$) to 18° ($\cos 18^\circ = 0.95$). A total of 109 sets of VTI and triangular AVA measurements were obtained in the 62 patients. Although the time required to perform these measurements was not precisely recorded for each patient, once the TEE probe was inserted, DCO determinations were usually achieved within 5 min, including all imaging and measurements steps (≈ 30 s to obtain the transgastric view, ≈ 2 min to select and trace the VTI, ≈ 30 s to obtain the aortic valve short-axis, ≈ 2 min to measure the length of the aortic valve triangle, and 15 s for calculation, a total of approximately 5 min). The mean DCO was 4.35 ± 1.18 l · min⁻¹, with a range of 2.02–7.42 l · min⁻¹, and the mean TCO was 4.41 ± 1.17 l · min⁻¹, with a 2.24–8.94 range (no significant difference between the means, $P = 0.24$, or between the standard deviations, $P = 0.69$). Regression analysis (fig. 4) showed a close relationship between the two methods ($r = 0.94$, SEE (standard error of the estimate) = 0.41 l · min⁻¹) best represented by the equation: $\text{DCO} = 0.94 \times \text{TCO} + 0.19$ (Slope not statistically different from 1, $P = 0.10$; intercept not statistically different from 0, $P = 0.22$). In this analysis, more than one data point was used for some patients. When the regression analysis was repeated using a single data point for each patient, very similar results were obtained. Figure 5 displays the difference between TCO and DCO determinations for each patient, plotted against the mean CO value by the two methods. The mean bias was 0.06 l · min⁻¹ (not statistically different from 0, $P = 0.12$) and the 95% confidence interval was 0.06 ± 0.83 l · min⁻¹. Assessment of relative changes in CO between the pre- and post-bypass periods showed a good correlation between the two methods ($n = 47$, $r = 0.82$, SEE = 17.8%). The changes in CO (fig. 6) were related by the equation: $\Delta\text{DCO} = 0.93 \times \Delta\text{TCO} + 5.4\%$ (slope not statistically different from 1, $P = 0.46$; intercept not statistically different from 0, $P = 0.19$). For CO variations greater than 10%, the Doppler method was in accordance with thermodilution regarding the direction of change in 43 of 45 instances (96%). Assessment of reproducibility in DCO determinations, performed by comparing DCO-1 with DCO-2 and DCO-3 with DCO-4, is presented in table 1. The mean DCO repeatability coefficient is 0.51 l · min⁻¹.

CARDIAC OUTPUT BY TEE USING AORTIC VALVE DOPPLER

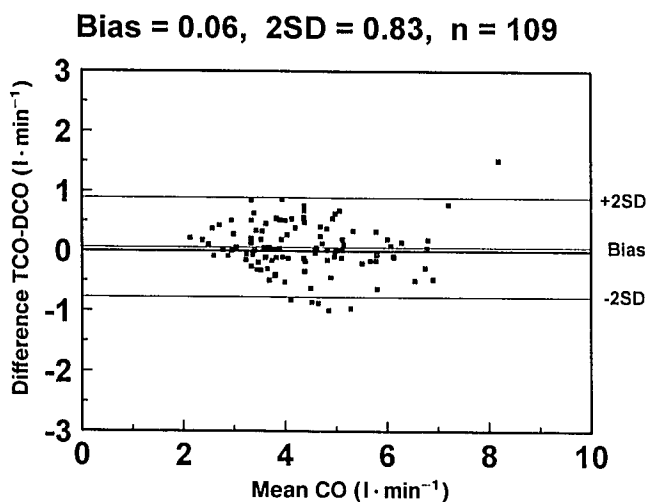


Fig. 5. Bias analysis: aortic Doppler cardiac output versus thermodilution cardiac output.

In 22 patients, the AVA calculations were based on a circular as well as a triangular model. Thirty-five sets of aortic VTI, triangular AVA and circular AVA determinations were obtained. When the triangular model was used, results of DCO and TCO comparisons (table 2) were similar to those reported for the whole population (figs. 4 and 5). When the circular model was used in the same patients, good correlation and agreement between the Doppler and thermodilution methods were also obtained (table 2). However, the analysis of the differences between TCO and DCO showed a significantly wider 95% confidence interval for the circular model when compared to the triangular model of AVA determination ($P < 0.01$).

Discussion

The findings of this investigation demonstrate that CO can be determined accurately from transesophageal CWD measurements across the aortic valve. They further demonstrate that the transgastric long axis view of the heart can be obtained in a large number of cardiac surgery patients, thus providing a plane that allows imaging of the LVOT and the proximal aorta. The results of this investigation also indicate that a triangular aortic valve orifice shape provides more accurate results than the conventional circular model for DCO determinations. To our knowledge, the findings reported here

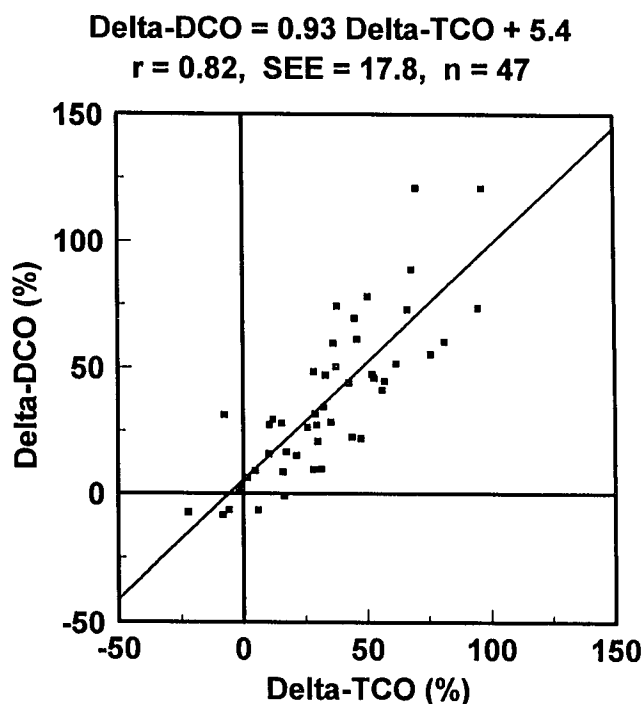


Fig. 6. Four-quadrant scattergram of relative changes in cardiac output between the pre- and postbypass periods, as assessed by aortic valve Doppler and thermodilution.

represent the first determination of CO using TEE CWD at the aortic valve site with a triangular model for the aortic valve orifice. There are several reasons why flow velocity measurements at the aortic valve site are preferred for DCO. First, the use of aortic valve velocities allows measurement of the output of the left ventricle, the cardiac chamber directly involved in supplying oxygenated blood to tissues including coronary blood

Table 1. Assessment of DCO Reproducibility

n = 109	DCO-1 vs. DCO-2	DCO-3 vs. DCO-4
Linear regression analysis		
r	0.98	0.97
SEE	0.21 l·min ⁻¹	0.29 l·min ⁻¹
Slope	0.96	0.98
Intercept	+0.21 l·min ⁻¹	+0.07 l·min ⁻¹
Bias analysis		
Mean bias	+0.03 l·min ⁻¹ *	-0.03 l·min ⁻¹ †
Repeatability coefficient	0.43 l·min ⁻¹	0.58 l·min ⁻¹

* Not statistically different from 0; $P = 0.22$.

† Not statistically different from 0; $P = 0.36$.

Table 2. Comparison of CO Results with the Two Aortic Valve Area Models

n = 35	TCO vs. DCO, Triangular AVA	TCO vs. DCO, Circular AVA	P, Triangular vs. Circular AVA
Linear regression analysis			
r	0.93	0.88	0.23
SEE	0.46 l · min ⁻¹	0.71 l · min ⁻¹	
Slope	0.96*	1.07†	0.36
Intercept	+0.11 l · min ⁻¹ ‡	-0.15 l · min ⁻¹ §	0.12
Bias analysis			
Mean bias	+0.07 l · min ⁻¹	-0.15 l · min ⁻¹ #	0.12
95% confidence interval	±0.91 l · min ⁻¹	±1.40 l · min ⁻¹	<0.01

* Not statistically different from 1; $P = 0.53$.

† Not statistically different from 1; $P = 0.49$.

‡ Not statistically different from 0; $P = 0.70$.

§ Not statistically different from 0; $P = 0.74$.

|| Not statistically different from 0; $P = 0.37$.

Not statistically different from 0; $P = 0.20$.

flow. Second, the highest cardiac blood flow velocities are usually encountered in the narrowing of the aortic valve, and thus a flatter velocity profile is present at the aortic valve by comparison with other anatomic sites.¹⁸⁻²¹ Third, the signal-to-noise ratio of the velocity spectra at the aortic valve site is superior to CWD spectra from other anatomic flow sites, thus leading to more accurate aortic CWD envelopes.⁷ Last, excellent-quality aortic CWD spectra can be obtained in a large number of patients, presumably because the transgastric long-axis cardiac imaging plane allows parallel alignment of the Doppler beam with the proximal ascending aorta blood flow direction, as attested by the small angles (less than 20°) measured between the Doppler beam and the line perpendicular to the aortic valve plane. Although the Doppler beam alignment could not be verified in the third dimension (*i.e.*, the orthogonal plane), it is reasonable to believe the alignment was also good in that plane because in the transgastric view, the ascending aorta could be imaged with parallel walls for a distance of 4-6 cm (\approx 5 cm in fig. 1), with the beginning of the arch as its extension. Because the average length of the ascending aorta in normal adults is about 5 cm,²² only slight or no foreshortening occurred.

High-resolution, detailed images of the aortic valve in the short-axis plane were consistently easy to obtain as a result of the anatomic proximity of the aortic valve and the esophagus, with only the left atrium interposed between them. The equilateral triangular model for the aortic valve orifice describes closely the anatomic and dynamic shape of the valve during systole.¹⁰⁻¹² It cor-

responds to the smallest area in the path from the LVOT to the ascending aorta where the highest velocities, accurately recorded by CWD, occur. Several factors suggest why the triangular aortic valve orifice shape is the correct model.¹² During systole, the diameter of the aorta increases by an average of 15% at a level slightly distal to the aortic annulus, thus stretching the free edges of the leaflets. In addition, part of each stroke volume fills the sinuses of Valsalva, and may help maintain the aortic valve orifice in a triangular configuration. Although anatomy texts depict the aortic valve orifice as triangular, this shape is more likely to represent a dynamic concept rather than a fixed anatomic structure.^{10,11} Theoretically, the most accurate cardiac stroke volume determinations by Doppler would involve integration of the instantaneous area-velocity product over time. Because the precise shape and aperture of the aortic valve orifice is difficult to determine instantaneously throughout systole, this approach is not practical. For this reason, the triangular AVA was used as an assumed time-averaged valve area. This area represents the value that the aortic valve orifice would have if it were abruptly opened in this shape at the beginning of systole, stayed constant during, and closed abruptly at the end of systole. Thus, this value is contained between zero (closed orifice) and the maximal value of the AVA (fully opened orifice). This explains why the AVA values in this investigation are smaller than usually reported. However, the fully opened aortic valve orifice was in the 3-4-cm² range, as shown in figure 2C (3.73 cm²). Using a high imaging frame rate,

CARDIAC OUTPUT BY TEE USING AORTIC VALVE DOPPLER

we observed the aortic valve opening and determined empirically that the equilateral triangular orifice shape could readily be substituted for the conventional circular shape assigned to the aortic valve orifice in past studies. Comparison of the two aortic valve models yielded more accurate CO results with the triangular model than with the circular one, as assessed by bias analysis. Moreover, in TEE the circular AVA model requires measurements in the longitudinal imaging plane, with a biplane probe. Biplane imaging capability may not be available in all clinical settings.

Although there was no statistical difference between pre- and postbypass measurements of triangular AVA in our patients (regression and bias analyses, data not shown), it is not recommended to use a single determination of AVA for each patient because it has been shown that aortic valve opening is proportional to flow.^{10,11} Therefore, AVA should be calculated each time a CO determination is required, with near simultaneous aortic VTI measurements.

In a recent series of 31 consecutive patients using transgastric aortic CWD, Katz *et al.* have demonstrated a good correlation between DCO and TCO, with $r = 0.91$ in 50 measurements.⁶ In this study, the AVA was considered as circular with the annulus diameter measured in the five-chamber view. However, in this view, the aortic valve is not imaged in a truly transverse cross-section. Thus, in this oblique view, the aortic walls are not perpendicular to the scan plane and a two-dimensional measurement may be inaccurate. For this reason, only the diameter obtained in the longitudinal biplane view of the ascending aorta should be considered when measuring the aortic valve annulus diameter by TEE (fig. 3).

It is nearly impossible to assess the overall reproducibility in DCO determination in the face of underlying variability in CO during the time required to produce truly independent measurements (which include probe repositioning and realignment). Therefore, to estimate the repeatability of the CO measurements, we compared pairs of DCO determinations obtained from sequential or closely timed cardiac cycles, excluding the variability due to probe repositioning and realignment. We estimate that the contribution to the overall DCO variability due to variability in probe position and alignment introduces an additional mean error of 2% (largest possible error 5%). This was based on the average angle between the Doppler beam and the line perpendicular to the plane of the aortic valve, which, for the entire study group, was shown to be $7^\circ \pm 5^\circ$,

and whose cosine of 0.99 ± 0.01 corresponds to a 1–2% error.

The aortic flow VTI could not be recorded exactly simultaneously with the aortic valve orifice image because of differences in the anatomic locations of the transducer. The AVA measurements were obtained a few seconds after VTI recordings, when no change in the patient's hemodynamic status had occurred. For this reason, we chose to duplicate the repeatability analysis by associating each of the two independent aortic VTI determinations with each of the two independently measured AVA values. We could indeed have related each VTI to the mean of the two AVA values. This, however, would have excluded the variability in AVA determination, and would have led to the assessment of the reproducibility of VTI instead of the reproducibility of DCO measurements. The independent repeatability coefficients obtained, $0.43 \text{ l} \cdot \text{min}^{-1}$ and $0.58 \text{ l} \cdot \text{min}^{-1}$ (mean = $0.51 \text{ l} \cdot \text{min}^{-1}$), are close to, or better than those previously reported using pulmonary artery blood flow and mean pulmonary artery diameter measurements in a select, nonconsecutive group of patients.²

The relative variation in TCO and DCO between the pre- and postbypass periods also demonstrated the strong correlation between the thermodilution and the Doppler methods, with only four disagreements in forty seven pairs of measurements (*i.e.*, CO changes in opposite directions). However, two of these four pairs were associated with small variations in CO. Thus, they probably were more likely due to the intramethod variability of the DCO and TCO techniques.

We believe that the methods described herein improve the accuracy of measurement of both determinants of DCO: the Doppler flow velocity spectrum and the cross-sectional flow area. This may explain why our DCO results were closer to the thermodilution determinations than in any previously reported comparison using single-plane TEE. In addition, we were able to obtain data in a nearly perfect consecutive series of patients free from aortic valve disease because it was possible to visualize the aortic valve in detail in all patients and it was also possible to obtain aortic velocity spectra in all but one patient. This high inclusion rate (98%) confirms the recent findings of Katz *et al.*⁶ (88%) and is in contrast with previous studies in which the pulmonary artery was used as the site to measure velocities. In those studies, 15–30% of patients were excluded because of poor visualization of the vessel wall.^{1–4}

Even though the Doppler method shows accurate and reproducible CO determinations, some limitations remain. First, the use of thermodilution as the reference method could be criticized based on its inherent variability.^{2,3} However, thermodilution has been widely accepted as the standard for CO determination intraoperatively and in the critical care setting.^{1-6,9,14} Second, the aortic valve Doppler technique cannot be used in patients with aortic valve disease: in aortic stenosis, the triangular model is not valid because the aortic leaflets are less compliant and the commissures are often fused in an irregular manner; in aortic insufficiency, the regurgitant flow of each diastole artificially increases the antegrade flow of the next systole thus leading to an overestimation of CO by the Doppler method. Lastly, if a subaortic obstruction is present, as in asymmetric hypertrophic cardiomyopathy, the aortic valve orifice may no longer be the smallest area in the path from the LVOT to the ascending aorta and the highest velocities measured by CWD in the transgastric long-axis view may not originate at the aortic valve orifice. Although pulsed-wave Doppler with its range-resolution capability could solve this problem, the depth of the aortic valve in the transgastric long-axis view as well as the higher transducer frequency used with TEE imaging could, because of aliasing, prevent accuracy in pulsed-Doppler velocity measurements.

We conclude that CO determined by TEE with CWD across the aortic valve is in very good agreement with TCO in anesthetized patients with regular heart rhythm and free of aortic valve disease. Because TEE is associated with a low rate of complications,^{24,25} our results suggest that this technique could be used as a clinical tool to measure and monitor CO in a less invasive manner.

References

- Muhiudeen IA, Kuecherer HF, Lee E, Cahalan MK, Schiller NB: Intraoperative estimation of cardiac output by transesophageal pulsed Doppler echocardiography. *ANESTHESIOLOGY* 74:9-14, 1991
- Savino JS, Troianos CA, Aukburg S, Weiss R, Reichel N: Measurement of pulmonary blood flow with transesophageal two-dimensional and Doppler echocardiography. *ANESTHESIOLOGY* 75:445-451, 1991
- Gorcsan J III, Diana P, Ball BA, Hattler BG: Intraoperative determination of cardiac output by transesophageal continuous-wave Doppler. *Am Heart J* 123:171-176, 1992
- Roewer N, Bednarz F, Schulte am Esch J: Continuous measurements of intracardiac and pulmonary blood flow velocities with transesophageal pulsed Doppler echocardiography: Technique and initial clinical experience. *J Cardiothorac Anesth* 1:418-428, 1987
- Hozumi T, Shakudo M, Applegate R, Shah PM: Accuracy of cardiac output estimation with biplane transesophageal echocardiography. *J Am Soc Echocardiogr* 6:62-68, 1993
- Katz WE, Gasior TA, Quinlan JJ, Gorcsan J III: Transgastric continuous-wave Doppler to determine cardiac output. *Am J Cardiol* 71:853-857, 1993
- Coats AJS: Doppler ultrasonic measurement of cardiac output: Reproducibility and validation. *Eur Heart J* 11:49-61, 1990
- Sahn DJ: Determination of cardiac output by echocardiographic Doppler methods: Relative accuracy of various sites for measurement. *J Am Coll Cardiol* 6:663-664, 1985
- Spahn DR, Schmid ER, Tornic M, Jenni R, Von Segesser L, Turina M, Baetscher A: Noninvasive versus invasive assessment of cardiac output after cardiac surgery: Clinical validation. *J Cardiothorac Anesth* 4:46-59, 1990
- Montarello JK, Perakis AC, Rosenthal E, Boyd EGCA, Yates AK, Deverall PB, Sowton E, Curry PVL: Normal and stenotic human aortic valve opening: In vitro assessment of orifice area changes with flow. *Eur Heart J* 11:484-491, 1990
- Thubrikar M, Boshier LP, Nolan SP: The mechanism of opening of the aortic valve. *J Thorac Cardiovasc Surg* 77:863-870, 1979
- Williams PL, Warwick R, Dyson M, Bannister LH: *Angiology: The heart*, Gray's Anatomy. 37th edition. Edited by Williams PL, Warwick R, Dyson M, Bannister LH. Edinburgh, Churchill-Livingstone, 1989, pp 711-712
- Stewart WJ, Jiang L, Mich R, Pandian N, Guerrero JL, Weyman AE: Variable effects of changes in flow rate through the aortic, pulmonary and mitral valves on valve area and flow velocity: Impact on quantitative Doppler flow calculations. *J Am Coll Cardiol* 6:653-662, 1985
- Dubin J, Wallerson DC, Cody RJ, Devereux RB: Comparative accuracy of Doppler echocardiographic methods for clinical stroke volume determination. *Am Heart J* 120:116-123, 1990
- Snyder JV, Powner DJ: Effects of mechanical ventilation on the measurement of cardiac output by thermodilution. *Crit Care Med* 10:677-682, 1982
- Bland JM, Altman DG: Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1:307-310, 1986
- Zar JH: Simple linear correlation: Comparing two correlation coefficients, *Biostatistical Analysis*. 2nd edition. Edited by Kurtz B. Englewood Cliffs, Prentice-Hall, 1984, pp 312-313
- Caro CG, Pedley TJ, Schroter RC, Seed WA: Flow in pipes and around objects: Flow in the intrance region, *The Mechanics of the Circulation*. Edited by Caro CG, Pedley TJ, Schroter RC, Seed WA. Oxford, Oxford University Press, 1978, pp 49-50
- Caro CG, Pedley TJ, Schroter RC, Seed WA: The systemic arteries: Flow patterns in arteries, *The Mechanics of the Circulation*. Edited by Caro CG, Pedley TJ, Schroter RC, Seed WA. Oxford, Oxford University Press, 1978, pp 312-334
- Hatle L, Angelsen B: Physics of blood flow: Viscosity, velocity profile, and turbulent flow, *Doppler Ultrasound in Cardiology*. Edited by Hatle L, Angelsen B. Philadelphia, Lea & Febiger, 1985, pp 16-22
- Skjaerpe T, Hegrenæs L, Ihlen H: Cardiac output: Aortic flow, *Doppler Ultrasound in Cardiology*. Edited by Hatle L, Angelsen B. Philadelphia, Lea & Febiger, 1985, pp 306-310
- Williams PL, Warwick R, Dyson M, Bannister LH: *Angiology: The aorta*, Gray's Anatomy. 37th edition. Edited by Williams PL, Warwick R, Dyson M, Bannister LH. Edinburgh, Churchill-Livingstone, 1989, pp 726-727

CARDIAC OUTPUT BY TEE USING AORTIC VALVE DOPPLER

23. Levett JM, Replege RL: Thermodilution cardiac output: A critical analysis and review of the literature. *J Surg Res* 27:392-404, 1979

24. Urbanowicz JH, Kernoff RS, Oppenheim G, Parnagian E, Billingham ME, Popp RL: Transesophageal echocardiography and its potential for esophageal damage. *ANESTHESIOLOGY* 72:40-43, 1990

25. Werner GD, Erbel R, Kasper W, Visser A, Engberding R, Sutherland GR, Grube E, Hanrath P, Maisch B, Dennig K, Schartl M, Kremer P, Angermann C, Iliceto S, Curtius J, Mugge A: Safety of transesophageal echocardiography: A multicenter survey of 10,419 examinations. *Circulation* 83:817-821, 1991