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Superiority of Two-Dimensional Measurement of Aortic Vessel Diameter in Doppler Echocardiographic Estimates of Left Ventricular Stroke Volume

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Attempts to measure left ventricular stroke volume utilizing the Doppler aortic flow method have found varying correlations between invasive thermodilution and noninvasive Doppler methods. Because stroke volume is the product of the Doppler flow velocity integral (that is, the area under the flow velocity curve) and the cross-sectional area of the vessel through which blood flows, both variables are potential sources of error. Previous studies have shown that the Doppler flow velocity integral can be measured with acceptable reproducibility in the ascending aorta. Consequently, in this study an attempt was made to determine empirically the optimal method for measuring aortic diameter and area. The diameter of the ascending aorta was measured utilizing four M-mode and seven two-dimensional echocardiographic conventions. Doppler aortic flow velocity patterns were recorded with a 2.25 MHz M-mode echocardiographic transducer from the suprasternal notch by mapping the ascending aorta until aortic peak flow velocity was recorded.

In 19 adult patients undergoing cardiac catheterization for clinical indications, Doppler stroke volume estimates utilizing the various echocardiographic conventions for measuring aortic root diameter and area were compared with simultaneous measurements of stroke volume by the thermodilution technique. The best correlation ($r = 0.87$) with thermodilution stroke volume was obtained by estimating aortic area from the two-dimensional parasternal long-axis images with the aortic dimension measured distal to the aortic sinuses from the inner to inner wall. The data were related by the equation:

Thermodilution stroke volume = (0.73) × (two-dimensional Doppler stroke volume) + 17 cc.

M-mode echographic measurements of aortic diameter resulted in Doppler estimates of left ventricular stroke volume that correlated poorly ($r < 0.3$) with thermodilution estimates.

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Attempts to reliably measure stroke volume from the aorta utilizing Doppler echocardiography have met with varying success (1–11). Because stroke volume is the product of the Doppler flow velocity integral (that is, the area under the flow velocity curve) and the cross-sectional area of the vessel through which blood is flowing, both variables are potential sources of error (12–16). We have previously shown (14,15) that the Doppler flow velocity integral in the ascending aorta can be measured reproducibly with mean intraobserver, interobserver and day to day variabilities of less than 5% in normal subjects. Various echocardiographic approaches for estimating the diameter and cross-sectional area of the ascending aorta have been reported (1–11). These methods have resulted in differing degrees of success in estimating left ventricular stroke volume and cardiac output by the Doppler technique. In this study, we attempted to determine the optimal method for measuring the diameter and cross-sectional area of the ascending aorta and estimating left ventricular stroke volume in adults.

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Methods

Patients. Our study group consisted of 19 adult patients with known or suspected heart disease who were referred for cardiac catheterization; there were 13 men and 6 women. None of the patients had aortic valve disease or intracardiac shunts. In addition, none of the patients had arrhythmias other than an occasional premature beat during the time of the study; Doppler data from premature and post-premature beats were not analyzed. In addition to our 19 study patients, 11 potential study patients were excluded because Doppler aortic flow tracings recorded on the day before catheterization were technically inadequate for analysis. Five of these 11 patients had aortic valve disease which resulted in marked systolic spectral dispersion (turbulence) in the aortic flow recordings and precluded measuring an aortic flow velocity integral. Three patients whose Doppler aortic flow recordings did not demonstrate excessive spectral dispersion were excluded because the Doppler signals were of insufficient quality to estimate the flow velocity integral. Finally, three patients were excluded because the images obtained of the ascending aorta were not of sufficient quality to make reliable diameter measurements in more than one view.

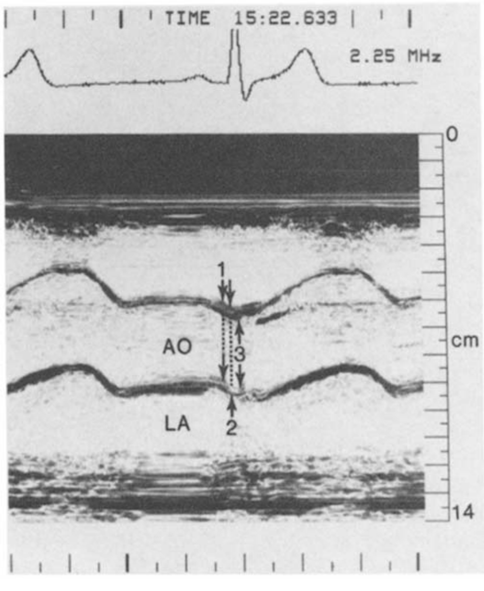
Doppler echocardiographic studies. On the day before cardiac catheterization each patient underwent Doppler echocardiography utilizing a spectrum analyzer-based pulsed Doppler velocimeter interfaced with a mechanical sector scanner (Ultra Imager, Biosound, Inc.) The sample volume used in this study approximated a cylinder 15 mm in axial length and 4 mm in diameter. Pulsed Doppler ascending aortic flow velocity recordings were obtained from the suprasternal notch by a "mapping" technique previously described (17–19). Specifically, the Doppler instrument controls were adjusted such that the beginning of the sample volume was moved stepwise in 1 cm increments from a depth of 3 to 9 cm from the suprasternal notch. Minor angulations of the transducer were made until the maximal ascending aortic blood flow velocity was obtained at each sample volume depth. The flow signal used to determine the aortic flow velocity integral was that which demonstrated the greatest peak aortic flow velocity. Implicit in this "mapping" technique is the assumption that when the greatest peak flow velocity is detected, the sample volume is parallel or near parallel to the blood flow stream. It has been shown that if the angle between the ultrasound beam and the long axis of blood flow is less than 20°, the error introduced into the Doppler measurement of peak flow velocity is less than 6% (cosine function) (20).

M-mode and two-dimensional echocardiography. In addition to the Doppler flow studies performed in the ascending aorta, M-mode and two-dimensional echocardiograms were obtained in each patient. Aortic root diameter was measured from the M-mode echocardiogram at the level at which the aortic valve leaflets were seen. Aortic diameter measurements were made at the onset of the QRS complex utilizing three different methods: leading edge to leading edge, leading edge to trailing edge (or outer to outer) and trailing edge to leading edge (or inner to inner) (Fig. 1). In addition, the maximal systolic aortic diameter was also measured using leading edge methods.

The diameter of the ascending aorta was measured from the two-dimensional echocardiograms at two levels in the parasternal long-axis view: 1) at the level of the tips of the aortic leaflets, and 2) approximately 2 cm distal to this level, which was distal to the aortic sinuses (Fig. 2). At each level, measurements of aortic diameter were made at the onset of systole utilizing 1) leading edge to leading edge, 2) outer edge to outer edge, and 3) inner edge to inner edge methods. Thus, a total of six aortic root measurements were made from the parasternal long-axis view. An attempt was made to make these aortic diameter measurements during early to mid systole using frame by frame analysis of the video recording of the two-dimensional echocardiogram.

The aortic root was also measured from the parasternal short-axis view at the level of the aortic leaflets. In five patients whose entire aortic root could be visualized in short-axis cross section, the inner area of the aortic root was measured by planimeter and the resulting value was used in the calculation of stroke volume. In seven patients whose entire circular cross section could not be visualized, the most representative diameter measured from the inner to inner edge was utilized to calculate the cross-sectional area of the aorta. In the other seven patients, the ascending aorta

Figure 1. M-mode echocardiogram at the level of the aortic valve leaflets depicting the three different conventions for measuring aortic (AO) root diameter: 1) leading edge to leading edge, 2) leading edge to trailing edge (outer to outer), and 3) trailing edge to leading edge (inner to inner). LA = left atrium.



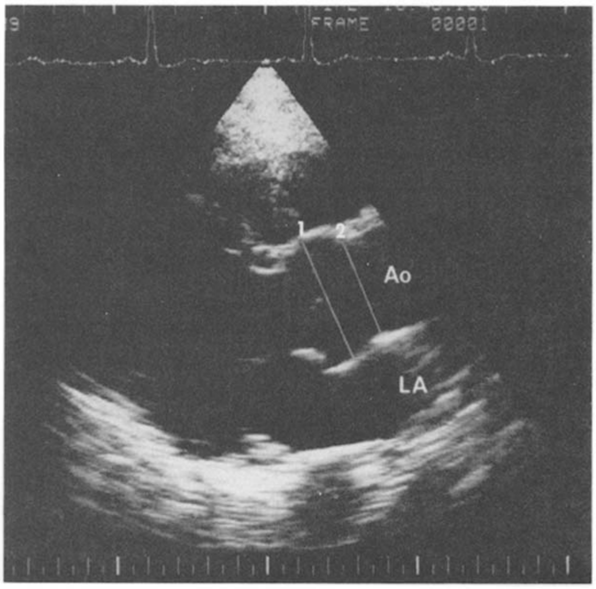


Figure 2. Two-dimensional parasternal long-axis echocardiogram illustrating methods for measuring aortic (Ao) root diameter: 1) at the level of the aortic leaflets, and 2) approximately 2 cm distal to this level, that is, distal to the aortic sinuses. At both levels, measurements were made utilizing leading edge to leading edge, outer edge to outer edge and inner edge to inner edge methods. LA = left atrium.

was suboptimally recorded (in two) or not recorded (in five) in the short-axis view.

The Doppler, M-mode and two-dimensional echocardiographic studies were performed on the day before the scheduled cardiac catheterization to identify patients with acceptable quality ultrasound tracings for inclusion in our study. In addition, the images obtained at this study were used to make the measurements of the ascending aortic diameter area as just outlined.

Cardiac catheterization. Left and right heart catheterization was performed for standard clinical indications in all 19 patients. Stroke volume was determined using the thermodilution technique with the average of six thermodilution measurements used to determine stroke volume. The stroke volume range in our patients was 24 to 111 cc (or ml). Doppler ascending aortic flow velocity recordings were obtained from the suprasternal notch simultaneously with the thermodilution measurements. Experience obtained in locating the Doppler sample volume in each patient on the day before catheterization resulted in the Doppler study requiring no more than 15 minutes during the catheterization procedure.

Stroke volume calculations. Figure 3 depicts a normal aortic flow velocity tracing and demonstrates measurement of the flow velocity integral, or area under the aortic flow velocity curve, by two methods: planimetry and mathematical approximation. The area of the flow velocity integral can be obtained by planimetry as a line drawn through the midportion of the darkest area of the systolic flow spectrum (curved dashed white line, Fig. 3) continuing through the zero flow line. The components of the flow velocity integral include the peak flow velocity, measured in cm/s on the vertical axis, and the ejection time, measured in seconds or milliseconds on the horizontal axis. If the units of peak flow velocity (cm/s) are multiplied by the units of ejection time (seconds), the units of flow velocity integral (expressed in centimeters) are obtained. Because planimetry of the flow velocity integral may be time consuming in the absence of computer assistance, we used a simplified mathematical approximation for determining the flow velocity integral as reported previously (17):

$$\text{FVI plan} = 1.14\,(0.5\ \text{PFV} \times \text{ET}) + 0.3\ \text{cm},$$

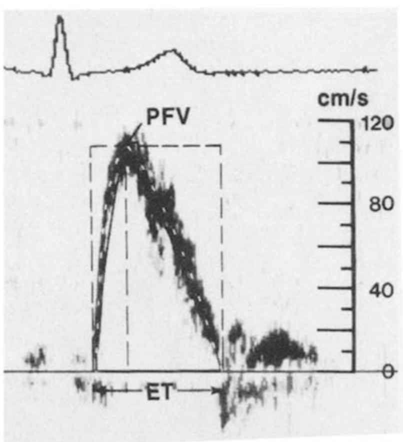
where FVI plan = the flow velocity integral obtained by planimetry, PFV = peak flow velocity and ET = ejection time. The correlation coefficient between the mathematical approximation and the planimetrically determined flow velocity integral was 0.97. Doppler stroke volume was then estimated by the following formula:

$$\text{SV} = \pi(\text{D}/2)^2\,[1.14\,(0.5 \times \text{PFV} \times \text{ET}) + 0.3],$$

where D/2 = one-half the aortic diameter.

Statistical calculations. Comparisons between thermodilution stroke volume and stroke volume determined by each of the Doppler ultrasound methods were performed

Figure 3. Normal aortic flow velocity tracing and the methods for measuring by planimetry and approximating mathematically the aortic flow velocity integral, or area under the flow velocity curve. A **white dashed line** drawn through the midpoint of the darkest portion of the flow velocity spectrum, when connected by the zero flow line (baseline) corresponding to ejection time (ET), outlines the planimetrically measured flow velocity integral. Planimetrically measured flow velocity integral (FVI plan in cm) is mathematically related to peak flow velocity (PFV in cm/s) on the **vertical axis** and ejection time (ET in seconds) on the **horizontal axis** by the following equation: FVI plan = 1.14 (0.5 PFV × ET) + 0.3 cm. See text for details.



using linear regression analysis (21). In addition, we performed a mathematical analysis of the probability of obtaining a specific correlation coefficient between the Doppler and thermodilution methods of estimating cardiac output when certain assumptions were made regarding the variability in measurements of thermodilution stroke volume (cardiac output), Doppler aortic flow velocity integral and aortic root diameter (see Appendix).

Results

Adequacy of measurements. Images of the aortic root in the parasternal long-axis views were of sufficient quality in all 19 patients to make aortic diameter measurements utilizing all four M-mode and six two-dimensional parasternal long-axis conventions. However, images of the aortic root were available in the parasternal short-axis view for measurement of aortic diameter in only 12 patients. Parasternal short-axis images of the aortic root were of suboptimal quality in two patients and were not attempted in five patients.

Doppler-thermodilution stroke volume correlations. Table 1 lists the correlation coefficients for the comparisons between Doppler and thermodilution stroke volumes for each of the best M-mode and two-dimensional parasternal long-axis and short-axis echocardiographic conventions for estimating aortic root diameter and area. The best correlation between Doppler and thermodilution stroke volume was obtained when the aortic diameter was measured from the two-dimensional parasternal long-axis view distal to the aortic sinuses using the inner edge to inner edge method (Fig. 4). This measurement convention yielded a correlation coefficient of $r = 0.87$ ($p < 0.001$) and the following regression equation:

$$SV\ (TD) = 0.73 \times SV\ (DOP) + 17\ cc,$$

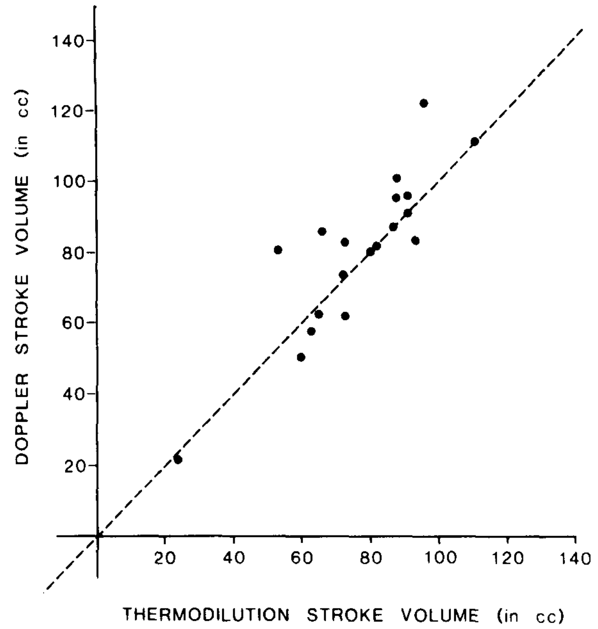


Figure 4. Comparison of data in 19 patients for thermodilution stroke volume (**horizontal axis**) and Doppler stroke volume (**vertical axis**) utilizing the best measurement convention for aortic root diameter, namely, measuring the inner to inner aortic dimension from the parasternal long-axis image distal to the aortic sinuses. Standard error of the estimate = 9.1 cc.

where SV(TD) = stroke volume in cubic centimeters by thermodilution and SV(DOP) = stroke volume by Doppler method in cubic centimeters. The standard error of the estimate was 9.1 cc.

All four M-mode echocardiographic methods for measuring the aortic diameter yielded poor correlations between Doppler and thermodilution stroke volume estimates (range $r = 0.20$ to 0.29, $p =$ NS). The leading edge methods for measuring the M-mode aortic root diameter at the onset of the QRS complex and at its maximum during systole yielded

Table 1. Comparison of Thermodilution and Doppler Aortic Flow Methods in Estimating Stroke Volume*

Aortic Root Measurement Convention	No. of Patients	Correlation	Significance
M-mode			
Leading edge to leading edge	19	r = 0.29	p = NS
Two-dimensional parasternal long axis			
Aortic leaflets			
Leading edge to leading edge	19	r = 0.49	p < 0.05
Distal to sinuses			
Inner edge to inner edge	19	r = 0.87	p < 0.001
Two dimensional parasternal short axis			
Inner edge to inner edge	12	r < 0.1	p = NS

*Correlation coefficients shown for M-mode and two-dimensional aortic measurement conventions resulting in the best correlations between Doppler and thermodilution stroke volumes.

correlation coefficients of only r = 0.28 and r = 0.29, respectively.

Discussion

Previous studies. There have been a number of attempts to estimate stroke volume and cardiac output utilizing the Doppler technique in animal models and in human adults and children (1–11). Colocousis et al. (1) found a correlation coefficient of r = 0.95 when comparing continuous wave Doppler flow with thermodilution measurements of stroke volume in closed chest dogs. More recently, Fisher et al. (7) showed in an open chest dog model that Doppler technique estimates of cardiac output derived from flow velocity recordings in the ascending and descending aorta correlate extremely well (r = 0.98 to 0.99) with values obtained by a roller pump over a range of cardiac outputs from 0.75 to 5 liters/min. In this laminar flow model, there was no difference between the predictive accuracy of any of the sampling sites in the ascending and descending aorta.

Various studies have demonstrated a very good correlation between the Doppler method and invasive estimates of cardiac output in children. Alverson et al. (4) recorded Doppler ascending aortic flow velocity from the suprasternal notch and aortic internal diameter in 33 neonates and children and found a good correlation (r = 0.98) between Doppler and invasive estimates of cardiac output. Goldberg et al. (5) also obtained a good correlation (r = 0.94) between 20 Doppler determinations of cardiac output (10 from aortic and 10 from pulmonary artery flow tracings) and simultaneous invasively measured cardiac outputs.

In a study of adult patients undergoing cardiac catheterization, Magnin et al. (2) used combined pulsed Doppler/two-dimensional echocardiography to estimate cardiac output. Two-dimensional echocardiography was used to determine aortic vessel diameter. A cursor superimposed on the precordial two-dimensional image of the aorta was used to locate the range and angle of the Doppler sample. In 11 patients whose Fick (invasive) cardiac output was compared with Doppler-calculated output, a correlation of r = 0.83 was obtained. The Doppler method consistently underestimated cardiac output as determined by the Fick method. One problem with this study was the fact that the Fick and Doppler estimates of cardiac output were not obtained simultaneously. In addition, Doppler cardiac output determinations varied considerably when different transducer locations and angles were used in the same patient.

More recently, Huntsman et al. (6) estimated cardiac output in adult patients using a continuous wave Doppler instrument to record flow velocity signals in the ascending aorta from a transducer placed in the suprasternal notch. Using an A-mode echocardiographic recording technique, these investigators imaged the aortic root at a level that was generally above the aortic sinuses. After an initial learning curve, in a second study involving 110 observations in 45 patients, they achieved an excellent correlation (r = 0.94) between Doppler and thermodilution cardiac output, with a line of regression falling near the line of identity. Using the same Doppler technique, Chandraratna et al. (3) and Nishimura et al. (8) obtained similar results.

On the other hand, in preliminary reports Waters et al. (10,11) noted various limitations in using Doppler aortic flow velocity recordings to estimate cardiac output in adults in the intensive care unit and cardiac catheterization laboratory. Their correlation between Doppler and thermodilution stroke volumes using both the pulsed and continuous wave Doppler techniques was disappointing (r = 0.32). They concluded that problems inherent in the methods used to determine cardiac output from the suprasternal Doppler aortic flow velocity technique were caused not only by errors in measurement of aortic cross-sectional area, but also by errors in flow velocity measurement.

Because of the controversy about whether stroke volume (and cardiac output) can be reliably estimated from Doppler aortic flow velocity recordings in adults, we attempted in this study to determine empirically the best method for estimating aortic diameter and area for use in the calculation of Doppler stroke volume. We had previously shown (15) in a study of 10 normal subjects that flow velocity integral could be measured with an intraobserver variability of 3.2 ± 2.9% (mean ± SD), an interobserver variability of 5.4 ± 3.4% and a day to day variability of 3.8 ± 3.1%. In addition, in a series of 14 patients with congestive heart failure undergoing 18 trials of vasodilator therapy, we had previously shown (17) that the percent change in aortic flow velocity integral correlated well with the percent change in thermodilution stroke volume (r = 0.88). Because of this study and the fact that other investigators (20,22–24) have also shown a good correlation between percent change in flow velocity integral and percent change in stroke volume, it seemed logical to assume that a major potential source of error in Doppler technique estimates of stroke volume and cardiac output was variability in the measurement of aortic root diameter—especially because the diameter measurement is squared in the stroke volume equation.

Present study. Our data indicate that the best method for measuring aortic root diameter is the parasternal long-axis view with measurement of the inner to inner edge diameter of the aortic root distal to the aortic leaflets and sinuses of Valsalva. This method was superior to any of the other two-dimensional and M-mode echocardiographic estimates of aortic root diameter evaluated.

The finding that the aortic root diameter was best measured distal to the aortic sinuses is not surprising because in this study, the Doppler sample volume was probably above the aortic sinuses when the peak ascending aortic flow velocities used for analysis were recorded. Although a nonimaging technique was used to record aortic flow velocity, the sample volume at which peak flow velocity was recorded was generally 2 to 3 cm higher than the level of the Doppler aortic leaflet closure transient. It is notable that our M-mode echocardiographic measurements of aortic root diameter were not made in the same area as the M-mode aortic measurements made by Huntsman et al. (6). The latter investigators imaged the aortic root distal to the aortic valve leaflets at a level similar to where we obtained our best estimates of aortic root diameter by two-dimensional echocardiography. No attempt was made in our study to measure the aortic root above the level of the sinuses using a two-dimensionally directed M-mode cursor because of the difficulty in aligning the cursor perpendicular to the walls of the aorta. Measuring an oblique aortic diameter would result in an overestimation of the area of volume flow.

Potential errors. *Accuracy of recording blood flow velocity patterns.* There are a number of potential errors in estimating cardiac output using Doppler aortic flow tracings and echocardiographic estimates of aortic root diameter or area. One group of potential errors relates to the accuracy of recording Doppler blood flow velocity patterns. First, the angle of incidence between the ultrasound beam and the long axis of blood flow needs to be considered. In this study, we attempted to minimize this angle of incidence by using our mapping technique to record the peak flow velocity. Although we did not use imaging to determine the angle (in the two visualized dimensions), it is likely that we maintained an angle of 20° or less, which would introduce an error of 6% or less into our Doppler estimate of flow velocity (a cosine function of the angle).

Second, if flow velocity profiles vary across the width of a vessel, a central sample volume may not accurately reflect the mean velocity across the vessel. However, studies in animals (25,26) have shown that in the ascending aorta there is a relatively blunt flow velocity profile; therefore, placing the sample volume somewhere within the flow velocity stream should result in recording a representative mean Doppler flow velocity.

Third, errors could be introduced into the calculation by obtaining blood flow velocity signals from a branch of the aorta rather than the ascending aorta. We attempted to minimize this possibility by a stepwise recording of the peak aortic flow velocity and by a knowledge of the range of sample depths at which aortic flow velocity recordings were generally recorded. Our sample volume location was further verified by a comparison with the distance from the suprasternal notch to the aortic root as approximated from two-dimensional echocardiography. Fourth, Doppler method estimates of stroke volume do not take into account coronary blood flow, which originates proximal to the level of measurement of aortic diameter and Doppler flow velocity (27).

Measurements of aortic root diameter and area. A second set of potential errors relates to the measurement of aortic root diameter and area. Inappropriately "high" or "low" gain settings might result in either an underestimation or an overestimation in measurements of aortic root diameter and area and, therefore, stroke volume. Thus, it is important that gain settings be adjusted to yield accurate dimensional measurements as calibrated against a known test object. Furthermore, the cross-sectional area of the aorta would be expected theoretically to change to some degree during the cardiac cycle, depending on such characteristics as pressure, flow and the elasticity of the aorta (28). Using a strain gauge caliper and pressure transducer technique in 10 patients undergoing cardiac surgery, Greenfield and Patel (28) previously demonstrated a maximal change during systole of 5.4 ± 1.8% in mean aortic diameter and of 11% (range 5.4 to 16.8) in mean aortic area. In our study, aortic root diameter measured by M-mode echocardiography demonstrated a similar increase (4.9 ± 3.4%) from the time of onset of the QRS complex to mid-systole. Although we attempted to estimate aortic cross-sectional area during early to mid-systole, we did not estimate a mean systolic aortic cross-sectional area. However, because our two-dimensional measurements of aortic diameter were made during early to mid-systole, the fact that we did not use a true mean systolic aortic area measurement probably introduced an error of less than 5% into our Doppler estimates of stroke volume.

Reproducibility of thermodilution and Doppler stroke volume measurements. Another source of potential errors is that related to the reproducibility of making both thermodilution and Doppler stroke volume measurements. To investigate the range of correlation coefficients that might be expected when comparing thermodilution and Doppler stroke volumes, we mathematically evaluated the probability of obtaining a given correlation coefficient between thermodilution stroke volume/cardiac output and Doppler stroke volume/cardiac output given known measurement reproducibility. Our analysis was based on data drawn from previously reported measurement variability in thermodilution stroke volume, Doppler flow velocity integral and M-mode echocardiographic aortic root diameter (Appendix). Ganz et al. (29) previously documented a mean variability of 4% in serial measurements of thermodilution stroke volume made in the same patient. We also used data obtained from a previous study (15) of reproducibility in measuring aortic flow velocity integral which had revealed an interobserver variability in this measurement of 5.4 ± 3.4%. Finally, we used data from a previous report (16) which indicated a 9% mean interobserver variability in measuring aortic root diameter by M-mode echocardiography.

When these data on measurement variability were entered into a mathematical model, it was possible to simulate 100 times the conditions found in the present study, that is, 19 paired observations for stroke volume. When this was done, we found that assuming the two techniques measured the same phenomenon (actual correlation of $r = 1.0$), the most likely correlation coefficient was $r = 0.91$. The most likely correlation coefficient utilizing 100 paired observations (for Doppler and thermodilution cardiac output) simulated 400 times was $r = 0.92$. Therefore, the best correlation ($r = 0.87$) obtained in this study, that is, using the aortic diameter measured distal to the aortic sinuses on the parasternal long-axis view, appears reasonable when related to information already known about measurement reproducibility. Nonetheless, the regression equation derived for the relation between Doppler and thermodilution estimates of stroke volume needs to be further validated prospectively in a larger series of patients before it can have widespread clinical application.

Turbulent aortic flow and inadequate flow tracings or aortic root images. Currently, the aortic flow velocity technique cannot be used to estimate stroke volume in patients with aortic valve disease who demonstrate turbulent aortic flow in the flow velocity recording. This limitation occurred in 5 of the 30 patients we initially evaluated for inclusion in this study. Furthermore, inadequate flow tracings or aortic root images occurred in six additional patients who had to be excluded from our study. Waters et al. (11) noted in their preliminary study that 34% of the patients they attempted to evaluate had inadequate Doppler flow or echocardiographic recordings for estimation of Doppler stroke volume. Consequently, recent attempts to use Doppler flow velocity recordings from the mitral valve orifice, mitral anulus, tricuspid anulus, left ventricular outflow tract and pulmonary artery have been encouraging as alternative methods to aortic flow velocity methods for estimating stroke volume and cardiac output (5,30–34). An accurate Doppler mitral flow method for estimating stroke volume and cardiac output would be useful in patients who do not have mitral valve disease or intracardiac shunts, but have turbulent aortic flow velocity recordings or images of the aorta inadequate for measurement of aortic diameter. Furthermore, flow velocity recordings in the pulmonary artery have recently been shown to be useful with or without concomitant aortic flow velocity recordings in estimating pulmonary to systemic flow ratios in patients with intracardiac shunts, for example, from atrial septal defects (32,33). It seems likely that Doppler flow recordings from various sites in the heart and great vessels will prove useful in the noninvasive estimation of stroke volume and cardiac output.

Conclusions. We have found two-dimensional echocardiography to be preferable to M-mode echocardiography for estimating aortic area when calculating stroke volume by the Doppler aortic flow method. Our best correlation with thermodilution stroke volume was obtained by measuring the aortic diameter from parasternal long-axis images distal to the aortic sinuses from the inner to inner wall. When compared with a mathematical model used to simulate the expected correlation between Doppler and thermodilution estimates of stroke volume given published measurement variabilities for the two techniques, our correlation of $r = 0.87$ was in the expected range. M-mode echographic measurements of aortic diameter at the level of the aortic leaflets did not result in reliable estimates of left ventricular stroke volume.

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Appendix

This appendix describes the assumptions and mathematical steps involved in our simulated comparisons between Doppler and thermodilution stroke volume calculations.

We employed a two-stage simulation. First, the actual flow velocity integral (FVI) and aortic diameter (D) were simulated according to the following protocol: Flow velocity integral was assumed 1) to be normally distributed with a mean value of 15 cm, and 2) to vary such that flow velocity integral would fall within a range of 5 to 25 cm 95% of the time. Similarly, aortic diameter was assumed to be normally distributed with a mean of 30 mm and to vary over a range such that it would fall within 23 to 37 mm 95% of the time. From these simulated values for FVI and D, stroke volume (SV) was computed by the following formula: $SV = FVI \times \pi(D/2)^2$. In the simulations of errors in measurement to follow, this value is used as the simulated "actual" cardiac output for both methods of measurement. Thus, we say that the actual correlation between the two measurement techniques, before the random errors are applied, is one. In this manner 100 subjects were independently simulated.

The second stage of the simulation involved considering errors due to measurement. From previous reports, the mean values for percent measurement variability (that is, the average difference between two measurements for a given variable) were found to be in the following ranges: 1) thermodilution stroke volume, 4% (28); 2) flow velocity integral, 4% (15); and 3) aortic diameter, 9% (16). Now the measured value for any one of the three variables was assumed to be normally distributed with the mean equal to the actual value simulated in the first stage and variance $= (1/4)\pi E^2$, where E is equal to the actual value multiplied by the appropriate percent variability previously given.

This variance $(\sigma)^2$ is derived in the following manner, interpreting the average difference between two measurements as follows: Let X_1 and X_2 be two independent measurements of flow velocity integral, for example. Then X_i are normally distributed with mean X_0 and variance σ^2, where X_0 is the actual value of flow velocity integral simulated in the first stage. We can derive the formula for the expectation (average) of the difference as follows:

$$E(|X_1 - X_2|) = \frac{2}{\sqrt{\pi}}\sigma = 0.4X_o,$$

where | | means "absolute value of." Thus, the variance, $\sigma^2 = (1/4)\pi\,(0.04X_o)^2$.

For each simulated subject, three independent measurement errors were simulated giving measured flow velocity integral, measured aortic diameter and measured thermodilution stroke volume. From measured flow velocity integral and aortic diameter, measured Doppler stroke volume was computed. As a result, for each of 100 subjects we simulated measurements for both methods: Doppler stroke volume and thermodilution stroke volume. The correlation coefficient (r) of Doppler stroke volume and thermodilution stroke volume on these 100 samples was obtained. This process (both stages of simulation) was repeated 400 times and r was computed for each of the 400 simulations of sample size 100. These r values were examined and seemed to fall in an approximately normal distribution with mean and standard deviation of 0.92 ± 0.017. None of the 400 observed r values was as high as 0.96. Assuming an actual correlation of r = 1.0, the probability of obtaining an r value as high as 0.955 was 2/400, given the previous assumptions regarding measurement variability.

Correlations between simulated Doppler stroke volume and thermodilution stroke volume were also obtained on 100 data sets containing 19 pairs of observations each. This model was designed to approximate the number of patients in our current investigation. For the 100 r values obtained, we found a mean and standard deviation of 0.91 ± 0.041. There was a 12/100 probability of obtaining an r value less than 0.86, assuming an actual correlation of r = 1.0.

Consequently, if correlation coefficients greater than 0.9 between Doppler and invasive estimates of stroke volume are to be obtained, investigators will need to attain a significant reduction in the measurement variabilities for the component variables (Doppler flow velocity integral, aortic diameter/area and thermodilution stroke volume).

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