A Doppler echocardiographic method for calculating volume flow across the tricuspid valve: correlative laboratory and clinical studies

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ABSTRACT In this study we tested a two-dimensional Doppler echocardiographic method for measuring volume flow across the tricuspid valve. Five anesthetized, open-chest dogs had a calibrated electromagnetic flow probe placed on the ascending aorta. Volume flow across the tricuspid valve was controlled by creating a variable femoral-to-pulmonary arterial shunt. Since no standard plane provided a direct view of the tricuspid valve orifice, tricuspid flow area was estimated by calculating a fixed circular flow orifice from the maximal late diastolic diameter of the tricuspid anulus in a four-chamber view. Doppler-determined velocities across the tricuspid valve and tricuspid anulus images in the four-chamber view were obtained in inspiration and expiration. For 24 cardiac outputs (0.6 to 4.0 liters/min), inspiratory tricuspid flow determined by the Doppler method correlated minimally better (r = .90, SEE = 0.30 liter/min) than did expiratory measurements (r = .89, SEE = 0.35 liter/min) with the time-averaged systemic flow determined electromagnetically. Doppler-determined tricuspid volume flows in four-chamber and short-axis two-dimensional echocardiographic views from 10 children were then compared with values determined simultaneously by thermodilution during cardiac catheterization. In the children, Doppler-determined flows in short-axis and four-chamber views, both in inspiration and expiration, were similar; when results for the two views were averaged in inspiration and expiration, the tricuspid flows predicted by the Doppler method were highly correlated (r = .98, SEE = 0.48 liter/min) with the results of thermodilution. The two-dimensional Doppler echocardiographic method provides a means of estimating volume flow across the tricuspid valve noninvasively.


NONINVASIVE two-dimensional Doppler echocardiographic methods for calculating volume flow have achieved variable clinical accuracy mainly because of potential errors in obtaining the cross-sectional areas of flow and in estimating the angle between the direction of interrogation and the direction of flow.1–3 Our experience, even when the circulation is intact, suggests that having several sites at which to determine flow allows a cross-check that increases the accuracy of Doppler-determined flow estimates and that combining sampling sites also provides methods for calculating shunts.4,5 Available sites previously studied by Doppler techniques include the mitral valve,6 pulmonary artery and aorta, and the right ventricular flow tract.1,2,4

In this study we explored a method for measurement of volume flow across the tricuspid valve orifice by two-dimensional Doppler echocardiography in an open-chest dog preparation and in a small clinical population of children undergoing cardiac catheterization.

Methods

Surgical technique and animal preparation. Five mongrel dogs weighing 20 to 30 kg were anesthetized with sodium pentobarbital (30 mg/kg), intubated, and ventilated with a standard Harvard volume pump respirator. Tidal volume was set at 100 to 150 cc once the chest was open, and the ventilatory rate was 20 to 25/min. A median sternotomy was performed and the pericardium was opened. The ascending aorta and the main pulmonary artery were dissected and cleaned of fat and adventitia, and an appropriately sized, previously calibrated electromagnetic flow probe (Gould-Statham SP2204) was placed around the ascending aorta 2 cm above the aortic valve. Adequate contact of the cuff was verified by recording phasic aortic flow tracings.

The right femoral artery was then dissected, cannulated, and connected to a roller pump by ¾ inch tubing. The return end of

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the roller pump tubing was attached to a cannula inserted and fixed into the main pulmonary artery through a purse-string suture (figure 1). The roller pump had been previously calibrated by measuring flow rates with a stopwatch and a graduated cylinder. Ascending aortic flow was measured with the electromagnetic flowmeter reading, and left-to-right shunt volume was the measured flow through the roller pump. Systemic blood flow, calculated as systemic venous return at the tricuspid valve, was equal to ascending aortic flow determined by the electromagnetic flowmeter minus the roller pump volume.

Continuous electromagnetic flow recordings were obtained throughout the study for comparison with Doppler-determined flows. After each step-by-step change in shunt size achieved by altering pump settings, a period of 2 min was allowed to elapse after the electromagnetic flowmeter reading stabilized before any Doppler recordings were made.

Ultrasound and Doppler methods. Ultrasound imaging and Doppler studies were performed with a commercially available, range-gated, pulsed Doppler unit (Electronics for Medicine/Honeywell). The unit contains a 3.5 MHz single-element transducer mechanically swept through a 30 to 75 degree arc to achieve real-time two-dimensional echocardiographic imaging at 30 frames/sec. The scanner could be stopped along any line within the image and a Doppler sample volume could be positioned at any depth along that line. This permitted precise localization of the sample volume and determination of the angle between the direction of Doppler sampling and direction of flow within the plane of imaging. The sampling angle relative to the direction of flow within the elevational or azimuthal plane, i.e., the plane perpendicular to the plane of imaging, could not be determined; however, potential errors in sampling angle were minimized by slight changes in transducer and sample volume position until the clearest spectral display and audio signal were obtained. Small deviations from sampling exactly parallel to flow (angles of 0 or 180 degrees) were of no practical importance, since the cosine of the sampling angle would still be close to unity (see formula 1). Sample volume length was variable between 2 mm and 2 cm and was usually set at 5 mm in these studies. Sample volume width in a water tank at 6 dB was ±2 mm at 4 to 8 cm depth and was not variable. The operational mode of the scanner could be switched from real-time imaging to spatially oriented Doppler sampling in less than 0.1 sec. In Doppler mode, signals were sampled at a pulse repetition frequency of 13,000 samples/sec when the signal was obtained from a depth less than 6 cm, resulting in a maximal nonambiguously detectable velocity of ±143 cm/sec, and were sampled at a frequency of 7800 samples/sec at a depth of 6 to 12 cm, resulting in a maximal nonambiguously detectable flow velocity of 85 cm/sec at 0 degrees sampling angle. Two outputs of the Doppler frequency shift were available: an audio signal and a quantitative fast-Fourier transform spectral analysis of the Doppler shift sampled at 200 times/sec. The Doppler spectral output was converted automatically by the scanner to flow velocity (cm/sec) with the formula:

\[
\text{flow velocity} = \frac{(\text{frequency shift}) \times (\text{velocity of sound in blood})}{2 \times (\text{transmitted frequency}) \times (\cos \theta)}
\]

(1)

The sampling angle \( \theta \), i.e., the angle of incidence between direction of flow and the Doppler sample volume, was determined manually with a protractor directly from the freeze frame of the two-dimensional image that showed the sample volume position relative to the imaged cardiac structures. Correction for the angle \( \theta \) was applied manually in formula 2 rather than in formula 1 (see below).

The tricuspid valve flow area was determined from an apical four-chamber view. The diameter of the tricuspid anulus was obtained by anterior/posterior angulation of the transducer and was measured as the maximal diastolic diameter between insertion points of the septal and anterior tricuspid valve leaflets. The diameter was converted to tricuspid flow area with the equation \( \pi(D/2)^2 \). The Doppler sample volume was then placed within the right ventricular inflow tract beyond the tricuspid valve for recording of velocities. Once the optimal two-dimensional image and Doppler waveforms were obtained for inspiration or expiration, they were recorded on strip chart and/or videotape. The volume flows across the tricuspid valve were calculated by Doppler techniques as described below.
**Human population.** To evaluate the clinical usefulness of the method, 10 children (6 months to 18 years of age, mean 7.2 years) were studied at rest in the catheterization laboratory during a clinically indicated elective cardiac catheterization after standard sedation with meperidine and chlorpromazine. The patients had aortic stenosis (n = 7), aortic coarctation (n = 2), or rheumatic mitral valve disease (n = 1), and none had tricuspid valve disease and/or intracardiac shunts at atrial or ventricular level. Cardiac outputs determined by thermodilution were performed with an Edwards 9510-A system as an average of three measurements, one before and two after obtaining the Doppler data. Doppler echocardiographic flow studies and imaging of human tricuspid valves (figures 2 and 3) were performed both in four-chamber and short-axis views and were compared with the results of the thermodilution studies. The procedure for obtaining the flow data and the tricuspid orifice area in inspiration and expiration was similar to that used in the animal studies for the four-chamber recordings (figure 2). Doppler flow waveforms and maximal diastolic anulus diameter were also obtained in inspiration and expiration from short-axis views (figure 3). As in the dogs, tricuspid annular diameter was converted to flow area using the equation π(D/2)^2. A Doppler sample volume length of 1 to 2 cm was used in human studies.

**Digitizing methods: calculation of mean temporal flow.** The mean flow velocities as a function of time for the tricuspid valve were obtained by digitizing and integrating the area under three consecutive RR interval–matched Doppler flow velocity curves with a minicomputer. To accomplish this, we traced the middle of the densest portion of the gray scale spectral display of the Doppler velocity curves (this is the modal velocity shift; the velocity most frequently present in the returning signal). Flow curves were traced to zero during systole, ignoring any low velocity forward or reverse flow recorded when the tricuspid valve was closed. The minicomputer divided the velocity time integral for the 3 complete beats by the time of the 3 beats to obtain mean flow velocity across the tricuspid valve with respect to time. Calculations of volume flow across the tricuspid valve were then performed with the formula

\[
\text{flow} = \frac{\text{mean flow velocity} \times \text{tricuspid anulus area} \times 60 \text{ sec/min}}{\cos \theta}
\]

**Repeatability of the measurements.** To determine repeatability and interobserver variability, all measurements for the animal and human studies were made in duplicate by two investigators who were unaware of the simultaneous electromagnetic flowmeter readings or of each other’s results.

**Statistical analysis.** Linear correlations were used to compare Doppler-determined flows across the tricuspid valve to actual flows for both the animal and clinical data. Paired t tests were used to assess measurement repeatability and interobserver variability.

**Results**

**Animal studies.** A total of 24 values for tricuspid valve cardiac output derived from Doppler velocity information and varying from 0.6 to 4.0 liters/min, were calculated and compared with simultaneously obtained electromagnetic flowmeter–roller pump calculated systemic blood flow.

Angle-corrected peak early diastolic Doppler velocities across the tricuspid valve ranged from 35 to 83 cm/sec (all sampled at ≤6 cm depth) and were highest during late inspiration; angle-corrected transvalvular temporal mean flow velocities ranged from 6.1 to 15.3 cm/sec. Spectral width (6 dB) on these tracings varied...
from 8 to 21 cm/sec. The angle between the sampling cursor and the direction of the tricuspid flow varied from 0 to 30 degrees (mean 19 ± 2.5 [SE]).

The linear regression between Doppler-determined flows and the results obtained electromagnetically in inspiration yielded a comparable correlation coefficient to that obtained for the expiration studies (r = .90, SEE = 0.3 liter/min and r = .89, SEE = 0.35 liter/min, respectively) (figure 4). These were not statistically different.

Differences in interobserver variability and repeatability for measuring the same tracings were under 5%.

Clinical studies. Ten Doppler-derived cardiac outputs, obtained by the tricuspid valve orifice method in both four-chamber and short-axis views, were compared with simultaneously obtained thermodilution cardiac output measurements from 1.2 to 9.6 liters/min, which when indexed to the patients’ body surface area ranged from 3.6 to 9.2 liters/m²/min. For the children, Doppler-derived, angle-corrected peak ve-
locities across the tricuspid valve ranged from 38 to 80 cm/sec and were highest in early inspiration. Angle-corrected temporal mean velocities across the tricuspid valve ranged from 8.2 to 18.4 cm/sec. The angle of sampling was less than 20 degrees (mean 12.3) for all four-chamber views and less than 35 degrees (mean 17.6) for short-axis views. For this limited clinical series, volume flow results obtained from the two echocardiographic views both in inspiration and expiration were not statistically separable; therefore the mean of the four measurements was used for analysis to achieve the best sample averaging over time. When calculated as an average of the two views over the entire respiratory cycle, Doppler-determined flow across the tricuspid valve was highly correlated with the thermodilution results (r = .98, SEE = 0.43 liter/min) (figure 5). Correlation of the thermodilution- and Doppler-determined flows indexed to body surface area was also high (r = .96, SEE = 0.54 liter/m²/min). Interobserver variability and differences of results on repeated measurements by the same observer were also less than 5% for the clinical studies.

Discussion

Previous studies have indicated that range-gated two-dimensional Doppler echocardiography offers a reliable noninvasive method for measuring cardiac output by calculating cardiac flow at various locations. The present study validates the tricuspid valve as an additional sampling site for two-dimensional Doppler echocardiographic calculation of intracardiac flow.

When using the tricuspid valve, we encountered the problem of not being able to obtain a satisfactory cross-sectional image of the entire valve orifice itself as we had obtained previously for our studies of mitral valve flow. Therefore we assumed the orifice to be of circular shape and maximal in late diastole so it could be estimated from the diameter derived from a single four-chamber or short-axis view, realizing that this was an oversimplification of a complex and dynamic tricuspid valve and annulus structure. Although we did not attempt to measure diameters from subcostal short-axis views, imaging in this plane, when possible, would serve as an additional cross-check if care were taken to maximize the diastole annular diameter. Nonetheless, in spite of these assumptions and oversimplifications, our results demonstrate acceptable accuracy for this method even in the clinical setting.

In the presence of tricuspid regurgitation, the forward volume flow measured across the valve would not be total forward cardiac output since a fraction of it would actually be the regurgitant volume. Quantitation of total tricuspid forward flow, however, should still be possible with this technique and, if combined with flow measurement at another cardiac site, would allow estimation of regurgitant volume.

In the animal preparation we noted distinct differences in the Doppler-derived flow curves during inspiration and expiration in spite of the absence of negative intrathoracic pressure in the open-chest dog. These flow differences might be explained by a decrease in afterload resulting from a forced expansion of the lungs by the respirator. In these animals, the electromagnetic flowmeter and roller pump averaged inspiratory and expiratory events, but the Doppler studies recorded during inspiration had a slightly lower scatter and a closer correlation to the reference standard for systemic blood flow than those Doppler values obtained in expiration.

In our initial human studies, although velocities in general were slightly higher in inspiration (figures 2 and 3), no systematic statistical difference in calculated volume flows could be demonstrated. We believe that in the clinical setting it is probably correct to average inspiratory and expiratory flow waveforms and to use diastolic tricuspid diameters in whichever view or phase of respiration they may be most clearly imaged to derive an averaged single estimate of tricuspid flow as we did in this pilot study. The short-axis view has the advantage of allowing flow to be mea-
Averaging inspiratory and expiratory Doppler waveforms, the tricuspid valve method differs little from previously described methods and our results suggest that anulus diameter may be derived from a short-axis view, a four-chamber view, or an average of both. Thus, because it appears accurate and easy to perform and has potential applications as an alternative means for estimating cardiac output or for noninvasive calculation of shunt size, we believe this method may be an important addition to the growing body of Doppler echocardiographic methods in clinical cardiology.

Conclusion. We have explored a two-dimensional Doppler echocardiographic method for quantitating flow across the tricuspid valve. Our results in an open-chest animal preparation and pilot studies in children suggest that this method may prove useful because it uses an auxiliary site for noninvasively measuring cardiac output. It also provides a potential method that may prove useful for estimating tricuspid valve flow in patients with congenital heart lesions such as atrial septal defects, total anomalous pulmonary venous drainage, and other atrial level shunts.

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