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ABSTRACT The purpose of this study was to develop an open-chest animal preparation to validate the accuracy of a two-dimensional Doppler echocardiographic method for estimating pressure drops across discrete stenotic obstructions. Six mongrel dogs underwent median sternotomy and catheters were placed in the right ventricle, distal main pulmonary artery, and aorta of each. A ¼ inch umbilical tape was sewn to the posterior rim of the pulmonary artery just above the anulus and was progressively tightened to vary the degree of stenosis. Ultrasound and Doppler studies were performed with a 2.5 MHz phased-array unit with capabilities for pulsed or continuous-mode Doppler and real-time imaging. Peak systolic main pulmonary arterial flow velocities were recorded by Doppler echocardiography within the jet distal to the band from an oblique parasternal short-axis echocardiographic view and corrected for angle of incidence between the direction of Doppler sampling and the presumed direction of flow. Doppler velocities were converted to gradients with a simplification of the Bernoulli equation (gradient = 4 × maximal Doppler flow velocity²). Maximal Doppler-determined systolic pulmonary arterial velocities showed a good linear correlation with the 63 measured pressure drops (r = .95, SEE ± 36.3 cm/sec). An excellent correlation was also found between Doppler-calculated and actual pressure gradients (r = .96, SEE ± 7.26 mm Hg). Our results suggest that this Doppler method for measuring gradients across discrete stenotic obstructions may be quite accurate in clinical applications. Circulation 69, No. 6, 1177-1181, 1984.

OUR PREVIOUS WORK in children with pulmonic stenoses¹ and studies reported previously by other investigators²-⁵ have demonstrated that maximal Doppler-determined velocity measured within the jet found downstream from obstructions within the circulation can be used with a simplified form of the Bernoulli equation to predict pressure gradients.

The purpose of this study was to evaluate the accuracy of two-dimensional Doppler echocardiography for estimating pressure drops across stenotic pulmonary arterial bands in an open-chest canine preparation. In addition, the accuracy of Doppler-determined velocity in tracking changes in gradients within the same animal was also analyzed.

Methods

Surgical technique in the animal preparation. Six mongrel dogs weighing 20 to 30 kg were anesthetized with intravenous sodium pentobarbitol (30 mg/kg), intubated, and ventilated with a standard volume respirator. After a median sternotomy, the pericardium of each dog was opened and the heart was exposed. The ascending aorta and the main pulmonary artery were dissected and cleaned of fat and adventitia and an appropriately sized, precalibrated electromagnetic flow probe (Gould-Statham SP2204) was placed around the ascending aorta approximately 2 cm above the aortic valve to continuously monitor cardiac output. Catheter-tipped micromanometers (Millar) or fluid-filled catheters connected to strain-gauge transducers (Statham P23ID) were placed in the right ventricle, pulmonary artery, and aorta to record pressures continuously. Umbilical tape (¼ inch) was sewn to the posterior rim of the pulmonary artery just above the valve anulus and progressively tightened to produce varying degrees of stenosis. After each degree of constriction of the pulmonary arterial band, the animal was allowed at least 2 min to stabilize and adapt to the increased right ventricular pressure. Pulmonary arterial maximal jet ve-
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Velocity was recorded by Doppler echocardiography for each band constriction, as described below, and matched to the simultaneously measured pulmonary arterial and right ventricular pressures to allow comparison of Doppler-predicted and actual measured pressure gradients.

Ultrasound and Doppler methods. Ultrasound imaging and Doppler studies were performed with an Irex phased-array ultrasound scanner that contains a Pedof (Vingmed A/S) Doppler system capable of providing both pulsed and continuous-wave Doppler outputs (2 MHz) along with simultaneous two-dimensional echocardiographic (2.5 MHz) images. Both two-dimensional echocardiographic images and Doppler flow curves were obtained with the same transducer array, but only the central image line could be interrogated for either pulsed or continuous Doppler sampling. At a depth of 0 to 6 cm the maximal unambiguously detectable velocity in pulsed mode was 160 cm/sec; however, once located, a stenotic jet could be sampled in continuous Doppler mode with or without simultaneous imaging up to a maximum velocity of 8 m/sec (800 cm/sec). In continuous mode, no specific depth gate could be established; therefore, all velocities along the central line of sight were processed and included in the spectral velocity output.

Doppler outputs from this system were available as audio signals, as spectral outputs sampled every 20 msec with spectral analysis performed by a CHIRP Z algorithm, and as analog displays of the mean and maximal detected velocities. These analog outputs required manual gain adjustments to maximize the velocities recorded, and since this was a very subjective adjustment, only the spectral output was used in this study. Once the maximal velocities were obtained by finding the high-pitched whistling signal of the jet, a 600 Hz filter was used to minimize the contribution of the lower velocities to the spectral output. Spectra were obtained with standard gray-scale allocation selected to provide a relatively linear and almost bistable output. This allowed detection of the peak velocity even if it was not the only velocity represented within the signal. This, plus a low-reject setting in the spectrum, produced some tailing off of the spectral signal with spectral noise shown above the peak (figure 1), but this did not preclude finding the peak velocity, which was noticeably darker than the noise beyond it. The two-dimensional image and spectral Doppler outputs, with the simultaneous lead II electrocardiogram, were recorded on videotape and/or hard copy at a paper speed of 50 to 100 mm/sec (figure 1).

Ultrasound examinations were performed by lightly positioning the transducer over the right ventricular body and aiming superiorly to obtain an oblique short-axis view of the great vessels. Once the band was visualized, the sample line for continuous-mode Doppler echocardiographic examination was placed in the center of the main pulmonary artery across the band; this required the assumption that the direction of blood flow was perpendicular to the line of the imaged band. The maximal velocity was found and recorded by changing the position of the sample line within the main pulmonary artery and changing the position and angulation of the scanning plane until the highest frequency audio signals were identified and the highest maximal systolic velocity was recorded. If this maximized recording position placed the sampling line at an angle to the assumed direction of flow perpendicular to the line of the imaged band, then an angle cursor was placed on the stop-frame image. Once the angle cursor was placed, the system automatically readjusted the calibration factors by a cosine function based on the following equation:

\[
V = \frac{\Delta F \times V_s}{2F_0 \cos(\theta)}
\]

where \(\Delta F\) = Doppler frequency shift in kilohertz; \(V_s\) = the velocity of sound in blood, i.e., 1540 m/sec; \(F_0\) = the sampling frequency, i.e., 2 MHz; \(\theta\) = the angle between blood flow and Doppler sampling.

No correction was applied for the angle between Doppler sampling site and flow in the elevation or azimuthal plane (that is, the plane perpendicular to the imaged plane) since this could not be assessed with the two-dimensional system. To compensate for potential sampling-angle errors, flow velocity was maximized, as stated above, by fine positional changes of the sample volume and the transducer.

The recorded peak systolic flow velocity was converted to the transvalvular gradient with the following proposed simplified Bernoulli equation:

\[
\text{Gradient (mm Hg)} = 4 \times \text{Maximal velocity}^2 \text{ (m/sec)}
\]

The simplification of the Bernoulli relationship considers only the convective acceleration of blood passing through the stenotic orifice. It neglects flow acceleration as the valve opens and viscous friction, which is minimal in the central lumen of the jet, where the velocity profile is assumed to be flat.

Statistical analysis. Maximal velocities were measured by two observers who were unaware of the pressure readings or of each other's results. The relationship between maximal recorded Doppler-determined jet velocity and actual measured gradient was analyzed by the least squares regression method. Linear correlation was used to compare Doppler-determined gradients derived from the Bernoulli equation with the actual gradients measured with the pressure transducers. The paired t test was used to evaluate measurement repeatability and interobserver variability.

Results

A total of 63 gradients were obtained from the six experimental animals. Each animal had a minimum of eight and a maximum of 11 progressive degrees of constriction of the pulmonary artery.

Right ventricular pressures ranged from 15 to 130 mm Hg; pulmonary arterial pressures ranged from 3 to 44 mm Hg and derived right ventricular–to–pulmonary arterial pressure gradients ranged from 0 to 113 mm Hg. Ascending aortic pressures ranged from 41 to 199 mm Hg and cardiac outputs determined by the electromagnetic flowmeter on the ascending aorta ranged from 0.25 to 3.5 liters/min.

Peak jet velocities were identified by their whistling audio signals in all cases. Adequate Doppler spectral traces were recorded for all 63 gradients. Estimated sampling angles ranged from 0 to 15 degrees for 58 velocity measurements and were 15 to 20 degrees for the other five measurements. The angle-corrected peak systolic pulmonary arterial flow velocities determined by Doppler echocardiography ranged from 68 to 537 cm/sec. Interobserver variability and errors in repeatability were less than 5%.

A linear correlation was found between Doppler-determined maximal systolic pulmonary arterial jet velocities and the actual right ventricular–to–pulmonary arterial pressure gradients (\(r = .95\), SEE ± 36.3 cm/sec) (figure 2, A). Regression to a power function did
not improve the correlation coefficient or the SEE ($r = .68$, SEE $\pm 83.1$ cm/sec). Doppler-estimated gradients derived from the modified Bernoulli equation correlated well with pressure gradients obtained with the catheters ($r = .96$, SEE $\pm 7.3$ mm Hg) (figure 2, B).

To determine whether Doppler-determined velocities tracked changes in pressure gradient accurately within the same experimental animal, we analyzed the relationship between Doppler-determined peak velocities and catheter gradients in each animal separately. Figure 3 illustrates this relationship in an animal in which 11 separate pressure gradients were produced. These results are representative of those obtained in all six dogs and suggest that serial Doppler velocity determinations in the same individual can reflect changes in gradients.

Discussion

Results of our previous study and those of Hatle and others suggest that Doppler echocardiography could be used to accurately predict transvalvar gradient and to estimate the severity of stenotic lesions of the mitral, aortic, and pulmonic valves in humans. In this study we validated the accuracy of two-dimensional Doppler echocardiography for estimating pressure drops across discretely stenotic pulmonary arterial bands in a rigorously controlled open-chest canine preparation in which the velocity and pressure gradients were measured simultaneously over a wide range of values. In addition, we also determined the accuracy of the use of Doppler-determined velocities in tracking gradient changes within the same experimental subject, thereby showing the potential utility of this method for following individual patients longitudinally.

In our previous animal and clinical studies, as well as in this study, we have found that the single highest recorded Doppler-determined velocity is the one that corresponds most closely to the actual measured gradient. We hypothesize that this is the velocity obtained at the intercept angle closest to 0 degrees and, therefore, the one that most accurately represents the true gradient. Consequently, in reading our Doppler traces we search the recorded hard copy for the highest peak and do not average several velocities.

Since the flow velocity detected by Doppler echocardiography results from blood flowing through the obstruction at an instantaneous point in time, the catheter gradient used for comparison was measured from

![Figure 1. Top. An image of a pulmonary arterial band in an open-chest anesthetized dog. The view corresponds to a short axis with the right ventricular outflow tract (RVOT) wrapping around the aorta. The sampling line is placed along the RVOT, and while a sample volume (SV) is shown in continuous Doppler sampling mode in this older model ultrasound Doppler scanner, velocities all along this line of sight were in fact recorded since no depth gating was possible in continuous mode. While the line passes slightly off to the medial side of the orifice of the band, the beam width of the Doppler sampling direction allowed recordings of maximal velocity from this location. No angle correction was applied to this interrogation. Middle, Aortic, right ventricular, and pulmonary arterial pressures. Peak systolic gradient from right ventricle to pulmonary artery was measured at the time of highest right ventricular systolic pressure and compared with instantaneous pulmonary arterial pressure at the time. Bottom. The continuous-mode Doppler recording shows peak velocities of 3.7 m/sec. While the velocity signal is contaminated by noise above the peak, little difficulty was encountered finding the spectral peak velocity within the signal, as shown by the black arrow. The Doppler-Bernoulli-estimated gradient of 55 mm Hg was quite close to the actual pressure gradient at the time. The Doppler record is recorded at a paper speed of 50 cm/sec, whereas the pressure recording was obtained at 100 cm/sec. PV = position of the pulmonary valve.](http://circ.ahajournals.org/content/zm/69/6/1179/F1.large.jpg)
Doppler-determined peak velocity. Although the tracing is more likely open-chest scanning must be possible we could and regression analysis (Bland) is performed. This information demonstrates the accuracy of serial Doppler velocity determinations in reflecting gradient changes in the same individual.

FIGURE 2. A. Actual measured pressure gradient (abscissa) is compared with maximal Doppler-determined velocity (ordinate) by linear regression. The 95th percentile confidence limits for the regression relationship are shown by the dotted lines. B, Measured gradient (ordinate) is compared with Doppler-predicted gradient (abscissa) by linear regression analysis.

FIGURE 3. Statistical relationship of actual gradient (abscissa) and maximal recorded Doppler-determined velocity (ordinate) obtained in one animal in which 11 different gradients were produced. This relationship demonstrates the accuracy of serial Doppler velocity determinations in reflecting gradient changes in the same individual.

the tracing recorded at the same point in time as the Doppler-determined peak velocity. Although clinically it is more common to use peak-to-peak gradients, it must be recognized that the Doppler method provides information about instantaneous flow relationships.

In this preparation the capability of performing open-chest scanning assured us that we were as parallel as possible to the outflow tract in the elevational plane; we could both look at the position of the transducer itself and see a fairly long length of the parallel walls of the pulmonary artery above the band within the two-dimensional image. This allowed us to minimize the angle of incidence relative to the azimuthal, or elevational, plane of the jet downstream from the band. Further, since we used a symmetrical hour-glass band that could be imaged by two-dimensional echocardiography, we felt it reasonable to assume that the jet would lie perpendicular to the plane of the imaged band and therefore chose to correct for the incident angle along this plane. All were, as stated, under 20 degrees. While the cosine of 20 degrees is only 0.94, failure to correct for an angle of 24 degrees could potentially produce an error in gradient determination of up to 13% since velocity is squared in the simplified Bernoulli equation. For example, a 3 m/sec flow velocity would yield a gradient calculation of 36 mm Hg. If that 3 m/sec velocity were corrected for an angle of 20 degrees, the flow would be 3.2 m/sec and the gradient estimation 41 mm Hg, the potential error in gradient estimation being approximately 13%. If angular errors in the azimuthal plane were superimposed on seemingly small angles within the plane of imaging, these errors in angulation would be additive since the angle of incidence is within a three-dimensional space; therefore, the potential underestimation would be greater. In the pediatric clinical setting most stenoses are discrete and relatively symmetrical. In adults, however, calcific changes may produce very irregular valve orifices that would be difficult to image or for which it would be difficult to estimate the angle of the jet just from the imaging data. It is in these cases that the potential for erroneous angle calculations is greatest. The tradeoff, of course, in correcting for an inappropriately large angle is the potential for overestima-
tion of the size of the gradient, on which clinical decisions may rest. In general we believe that the key to the use of this method is to aim the ultrasound beam as parallel as possible to the vessel being imaged, thereby keeping the angles within the plane of imaging under 25 degrees, if possible, to minimize angular errors along this plane. If questions arise about the accuracy of the estimated angle, it would probably be best either not to correct, or to attempt another window to improve the line of sight on the stenosis. New methods are evolving that are capable of mapping flow in space. These may potentially provide direct visualization of the position of the jet downstream from the stenosis and make angle correction more scientifically precise and less arbitrary.

Our results in this open-chest animal preparation are optimized in that excellent lines of sight on the pulmonary artery and very good Doppler sensitivity were available, along with stable, simultaneously recorded pressures. Consequently, this preparation allowed us to confirm the capability of Doppler interrogation for quantitating maximal velocities across discrete vascular obstructions. Our study indicates the significant potential of this method for the noninvasive estimation and follow-up examination of pressure gradients across stenoses in children with heart disease.

References
Validation of a Doppler echocardiographic method for calculating severity of discrete stenotic obstructions in a canine preparation with a pulmonary arterial band.
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