JACC Vol. 6, No. 4
October 1985:750–6

METHODS

Continuous Wave Doppler Determination of Right Ventricular Pressure: A Simultaneous Doppler-Catheterization Study in 127 Patients

PHILIP J. CURRIE, MBBS, FRACP, JAMES B. SEWARD, MD, FACC,
KWAN-LEUNG CHAN, MD, FRCPC, DEREK A. FYFE, MD, PHD,
DONALD J. HAGLER, MD, FACC, DOUGLAS D. MAIR, MD, FACC,
GUY S. REEDER, MD, FACC, RICK A. NISHIMURA, MD, A. JAMIL TAJIK, MD, FACC

Rochester, Minnesota

Simultaneous continuous wave Doppler echocardiography and right-sided cardiac pressure measurements were performed during cardiac catheterization in 127 patients. Tricuspid regurgitation was detected by the Doppler method in 117 patients and was of adequate quality to analyze in 111 patients. Maximal systolic pressure gradient between the right ventricle and right atrium was 11 to 136 mm Hg (mean 53 ± 29) and simultaneously measured Doppler gradient was 9 to 127 mm Hg (mean 49 ± 26); for these two measurements, r = 0.96 and SEE = 7 mm Hg. Right ventricular systolic pressure was estimated by three methods from the Doppler gradient. These were 1) Doppler gradient + mean jugular venous pressure; 2) using a regression equation derived from the first 63 patients (Group 1); and 3) Doppler gradient + 10. These methods were tested on the remaining 48 patients with Doppler-analyzable tricuspid regurgitation (Group 2). The correlation between Doppler-estimated and catheter-measured right ventricular systolic pressure was similar using all three methods; however, the regression equation produced a significantly better estimate ($p < 0.05$).

Use of continuous wave Doppler blood flow velocity of tricuspid regurgitation permitted determination of the systolic pressure gradient across the tricuspid valve and the right ventricular systolic pressure. This noninvasive technique yielded information comparable with that obtained at catheterization. Approximately 80% of patients with increased and 57% with normal right ventricular pressure had analyzable Doppler tricuspid regurgitant velocities that could be used to accurately predict right ventricular systolic pressure.

(J Am Coll Cardiol 1985;6:750–6)

The ability to quantitate right ventricular systolic pressure noninvasively would facilitate diagnosis and clinical decision-making in patients with a wide spectrum of cardiac lesions. By using continuous wave Doppler echocardiography, it has been possible to determine the systolic pressure gradient from the right ventricle to the right atrium and, therefore, indirectly derive right ventricular systolic pressure (1,2).

We performed a prospective study to assess the accuracy of right ventricular systolic pressure as determined by continuous wave Doppler measurements. Since our initial communication based on 36 patients (3), simultaneous Doppler velocity measurements and right heart pressures during cardiac catheterization have been obtained in a total of 127 patients. Furthermore, three methods of estimation of right ventricular systolic pressure from the Doppler-measured gradient have been compared.

Methods

Patients. The study group consisted of 127 patients who had simultaneous Doppler and catheter pressure measurements performed during cardiac catheterization. There were 63 men and 64 women with an age range of 2 weeks to 88

From the Division of Cardiovascular Diseases and Internal Medicine and Division of Pediatric Cardiology, Mayo Clinic and Mayo Foundation, Rochester, Minnesota. Dr. Currie was supported by an Overseas Clinical Fellowship of the National Heart Foundation of Australia, Canberra, Australia. Dr. Chan was supported by the Heart and Stroke Foundation of Ontario, Toronto, Ontario, Canada. Manuscript received February 26, 1985; revised manuscript received April 19, 1985, accepted May 21, 1985.

Address for reprints: Philip Currie, MBBS, Mayo Clinic, 200 First Street, SW, Rochester, Minnesota 55905.

0735-1097/85/$3.30

years (mean 42 years); 16 patients were under the age of 2 years. Only 45 patients (35%) had tricuspid regurgitation clinically evident on physical examination. The patients were referred for cardiac catheterization for evaluation of various underlying conditions: valvular heart disease in 35 patients, pulmonary hypertension in 31, right ventricular outflow obstruction in 22, left ventricular outflow obstruction in 8, dilated cardiomyopathy in 11, constrictive pericarditis/restrictive cardiomyopathy in 8, atrial septal defect in 5 and other conditions in 7. Of the 127 patients, 50 had congenital heart disease.

The 127 patients were classified into two sequential subgroups with different entry criteria. Group 1 consisted of 63 consecutive patients who had tricuspid regurgitation detected by continuous wave Doppler examination at catheterization. Doppler examinations were performed because the patients had clinical evidence of increased right heart pressure or clinical tricuspid regurgitation. The jugular venous pressure was not consistently estimated in this group. Group 2 consisted of 64 consecutive patients whose only entry criterion was scheduled performance of right heart catheterization. A prospective clinical estimation of the mean jugular venous pressure was attempted in all Group 2 patients. This information was used to determine the frequency of continuous wave Doppler detectable tricuspid regurgitation and compare various Doppler methods of estimation of right ventricular systolic pressure.

Doppler examination technique. The Doppler examination was performed with an Irex model 3B utilizing a 2.0 MHz nonimaging transducer (Pedof, Vingmed) and occasionally a combined 2.5 MHz two-dimensional imaging/Doppler transducer. Doppler recordings of maximal velocity were obtained from apical, lower left parasternal and subcostal transducer positions. From each transducer position, the tricuspid regurgitant blood flow moved away from the transducer. The continuous wave Doppler recordings were considered optimal only after a systematic examination of each transducer position to locate a signal of highest audible frequency, maximal velocity and clearly definable spectral envelope. Optimal signals were assumed to be oriented nearly parallel to the direction of maximal regurgitant blood flow. Therefore, no correction was used to compensate for the presumed angle between the ultrasound beam and the direction of the maximal regurgitant jet.

Care was taken to differentiate tricuspid regurgitation from mitral regurgitation by transducer angulation and occasionally by the use of the two-dimensional imaging transducer. Other helpful but less consistent differentiating features were: 1) the mitral regurgitant signal generally had a higher maximal velocity (> 4 m/s) than the tricuspid regurgitant signal; 2) tricuspid diastolic flow velocity was usually lower than mitral diastolic flow velocity; 3) commonly there was a distinctive notch on the initial contour of the tricuspid regurgitant spectral envelope; and 4) the duration of the spectral envelope was longer with tricuspid regurgitation.

The Doppler estimate of systolic pressure gradient across the tricuspid valve was calculated by using the modified Bernoulli equation (4),

$$\text{Grad} = 4v^2,$$

in which grad is the pressure gradient in millimeters of mercury and v is the maximal systolic regurgitant flow velocity across the tricuspid valve in meters per second.

Interobserver variability of the maximal Doppler gradients at cardiac catheterization was assessed by three observers who had no knowledge of the patient's clinical or hemodynamic data. In addition, the continuous wave Doppler tracings were graded according to technical quality (0 = no tricuspid regurgitation signal detected, 1 = tricuspid regurgitation signal detected but inadequate for measurement, and 2 = a fair, 3 a satisfactory and 4 a good signal). In all patients, the Doppler velocity spectral profile analyzed was the one with the highest velocity and most complete envelope.

In addition to the simultaneous Doppler and catheter pressure measurements, 43 patients had tricuspid regurgitation detected by a nonsimultaneous continuous wave Doppler study within 7 days before catheterization. This was performed by a separate examiner during an outpatient comprehensive two-dimensional/Doppler echocardiographic examination, with an average of 3 days separating the two Doppler studies.

The mean jugular venous pressure (centimeters of water) was estimated in Group 2 patients immediately before cardiac catheterization by an independent cardiologist; measurements were made with the patient at a 45° angle. Pressure was calculated as the mean of the venous waveforms in centimeters vertically above the sternal angle plus 5 cm H_2O and converted to millimeters of mercury by dividing by 1.3, which expressed the relative density of mercury to blood at physiologic temperature.

Cardiac catheterization. Before catheterization, premedication was given according to the patient's age and clinical condition. Young patients were sedated with meperidine hydrochloride at 2.5 mg/kg body weight, chlorpromazine at 0.65 mg/kg and promethazine hydrochloride at 0.65 mg/kg. Adult patients were sedated with 2.5 to 15 mg of diazepam given intravenously.

Fluid-filled end-hole catheters (5F to 8F) connected to strain gauge pressure transducers (Gould P231d) were used for pressure recordings. The systolic pressure gradient across the tricuspid valve was measured by catheter withdrawal from the right ventricle to the right atrium in 83 patients (65%). To measure the maximal systolic gradient between the right ventricle and right atrium, the right ventricular pressure waveforms immediately before pullback were traced and superimposed over the right atrial waveforms imme-

diately after catheter withdrawal. Tracings were aligned for electrocardiographic R waves and respiratory fluctuation. In 44 patients (35%), two catheters were used for simultaneous recording of right ventricular and right atrial pressures.

The right ventricular systolic pressure, maximal systolic right ventricle-right atrium pressure gradient and right atrial pressure at maximal gradient were determined at end-expiration. All pressures were recorded on a calibrated multichannel direct-writing polygraph and separately, using a direct current coupler, on the calibrated Irex 7 inch (17.8 cm) strip chart recorder with the simultaneous Doppler spectral display and the electrocardiogram (Fig. 1). Simultaneous beat to beat comparisons of Doppler signals and catheter pressure measurements were made for correlation and estimation of the right ventricular systolic pressure.

Cardiac output was measured in 119 of the 127 patients during catheterization by a dye-dilution technique or, in the case of patients with an intracardiac shunt, by the Fick method. In the latter, the pulmonary flow was calculated.

Statistical analysis. Data were expressed as mean values ± SD. Doppler and pressure gradients were correlated by linear regression using a least squares method.

The effects of clinically detected tricuspid regurgitation, cardiac index and quality of Doppler spectral envelope on the accuracy of determination of systolic tricuspid pressure gradient were assessed by comparing the differences between the maximal catheter gradient with the Doppler-estimated gradient. The accuracy of the three methods of right ventricular systolic pressure estimation was assessed by comparing the differences between the catheter-measured and Doppler-estimated right ventricular pressures using a one-way analysis of variance and the Neuman-Keuls multiple range test.

Results

Doppler recordings. Tricuspid regurgitation was detected by continuous wave Doppler recording in all 63 patients in Group 1 by definition using the selection criteria, and in 54 (84%) of the 64 patients in Group 2. The quality of Doppler recordings, graded by the independent observers, was good in 38 patients (32%), satisfactory in 51 (44%), and fair in 22 (19%) and inadequate for velocity measurement in 6 (5%). All patients in Group 1 had tricuspid regurgitation velocities of analyzable quality for Doppler gradient estimation, but the incidence of analyzable velocities was 48 (75%) of 64 patients in Group 2. In the 50 of the 64 patients in Group 2 with elevated right ventricular pressure (> 35 mm Hg), there were 45 (90%) with detectable and 40 (80%) with analyzable velocities of Doppler tricuspid regurgitation. In the 14 patients with a normal right ventricular pressure (≤ 35 mm Hg), 9 (64%) had a detectable and 8 (57%) had analyzable Doppler velocities.

In the 111 patients with analyzable Doppler tricuspid regurgitation spectral profiles, the maximal velocity ranged from 1.5 to 5.6 m/s (mean 3.4 ± 0.9). The transducer position producing the highest velocity in these patients was apical in 65 patients (59%), lower left parasternal in 42 (38%) and subcostal in 4 (3%).

The interobserver variability of the maximal Doppler velocities and gradient measured by the three blinded observers was acceptable. The average coefficient of variation of the velocities was 2.8% (range 0 to 18) and of the gradients was 5.4% (range 0 to 35).

Figure 1. Simultaneous Doppler and catheter pressure tracings. **A**, Catheter withdrawal from right ventricle (RV) to right atrium (RA). Right ventricular systolic pressure was 117 mm Hg and maximal systolic right ventricular-right atrial gradient was 104 mm Hg. The corresponding Doppler envelope had a maximal velocity of 5.0 m/s; maximal Doppler gradient was 100 mm Hg. **B**, Simultaneous Doppler and right ventricular and right atrial tracings. The patient was in atrial fibrillation; the fourth beat was chosen for analysis. The right ventricular (RV) systolic pressure was 87 mm Hg and the maximal catheter right ventricular-right atrial gradient was 64 mm Hg. The maximal Doppler velocity was 4.1 m/s and the maximal Doppler gradient was 66 mm Hg. Note the excellent beat to beat correlation between the Doppler and catheter maximal pressure gradients.

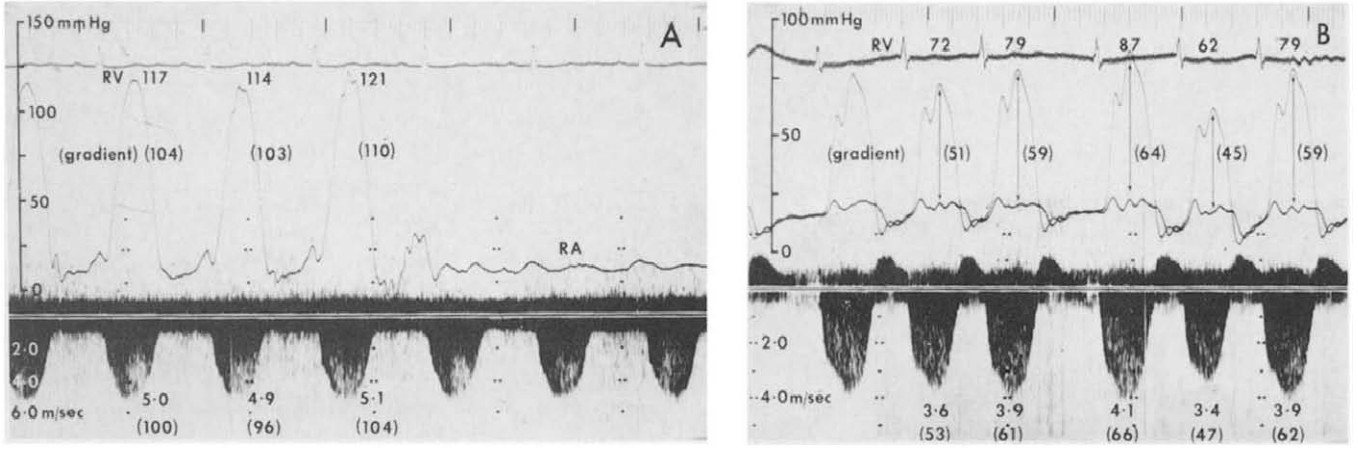

Figure 1. Simultaneous Doppler and catheter pressure tracings.

Correlation of right ventricular and right atrial pressures. The right ventricular systolic pressure by catheter measurement ranged from 24 to 158 mm Hg (mean 67 ± 30). The right atrial pressure, measured at the maximal systolic pressure gradient, ranged from 0 to 44 mm Hg (mean 14 ± 8). There was a poor correlation between these pressures (r = 0.31). No significant correlation (r = 0.10) between the right atrial pressure and the Doppler gradient was found. Therefore, catheter-measured right atrial pressure could not be accurately predicted from the Doppler gradient or measured right ventricular pressure.

Simultaneous Doppler-catheter pressure gradient measurements. The Doppler-derived maximal gradient ranged from 9 to 127 mm Hg (mean 49 ± 26) and the maximal catheter gradient ranged from 11 to 136 mm Hg (mean 53 ± 29). The correlation of Doppler gradient with maximal catheter pressure gradient was high with a coefficient of 0.96 and SEE of 7 mm Hg (Fig. 2).

Effect of cardiac index, Doppler quality and clinical tricuspid regurgitation. The cardiac index ranged from 1.2 to 11.9 liters/min per m^2 (mean 3.1 ± 1.7). There was no significant effect of Doppler quality, level of cardiac index or presence of clinical tricuspid regurgitation on accuracy of Doppler gradient measurement.

Nonsimultaneous (outpatient) versus simultaneous Doppler-catheter measurements. In the 43 patients with two Doppler studies, the outpatient Doppler velocities ranged from 1.7 to 5.5 m/s (mean 3.3 ± 0.9) and the Doppler velocities at the time of cardiac catheterization in these patients were 2.0 to 5.0 m/s (mean 3.4 ± 0.8). The outpatient maximal Doppler gradient ranged from 12 to 120 mm Hg (mean 48 ± 26) and Doppler gradient at catheterization ranged from 16 to 100 mm Hg (mean 49 ± 23). These values were not significantly different. In these 43 patients, the correlation of the outpatient Doppler gradient with the maximal catheter gradient (r = 0.87, SEE = 12 mm Hg) was less than the simultaneous Doppler-catheter correlation (r = 0.97, SEE = 6 mm Hg).

Doppler estimation of right ventricular pressure. The systolic pressure gradient across the tricuspid valve equals the difference between the right ventricular and right atrial systolic pressures. Therefore, the right ventricular systolic pressure can be estimated if the pressure gradient and right atrial systolic pressure are known. Three methods of right ventricular systolic pressure estimation, using the Doppler gradient, were tested on the patients in Group 2. In the first method, a clinical estimate of right atrial pressure was made from the mean jugular venous pressure, and the formula used to estimate right ventricular systolic pressure (2) was: Doppler gradient + mean jugular venous pressure (mm Hg).

In the second method, a linear regression equation derived from the 63 patients in Group 1 was applied to estimate the right ventricular systolic pressure from the Doppler gradient.

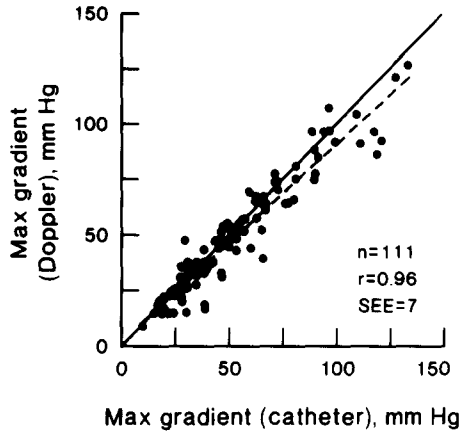

Figure 2. Correlation of simultaneous Doppler and right ventricular-right atrial maximal (Max) systolic pressure gradient in the 111 patients with analyzable tricuspid regurgitant Doppler velocity. The **dotted line** is the regression line and the **solid line** is the line of identity. The regression equation is: Doppler gradient = 2.2 + 0.88 × catheter gradient.

The third method assumed a constant right atrial pressure of 10 mm Hg irrespective of right ventricular pressure (5). The formula used was: Doppler gradient + 10 (mm Hg).

The accuracy of these three methods was compared with the catheter-measured right ventricular systolic pressure in the patients in Group 2 who had both analyzable Doppler tricuspid regurgitation and jugular venous pressure estimation.

1. Doppler gradient + mean jugular venous pressure. In Group 2, there were 55 of the 64 patients who had clinical estimates of mean jugular venous pressure. Seven of the remaining nine patients were 2 years of age or less, causing jugular venous pressure estimation to be impractical; technical reasons prevented clinical estimate of jugular venous pressure in the remaining two patients. The mean jugular venous pressure ranged from 3.8 to 17 mm Hg (mean 7 ± 3) and catheter-measured right atrial pressure at maximal systolic gradient ranged from 2 to 29 mm Hg (mean 10 ± 6). There was poor correlation between the clinically estimated and catheter-measured right atrial pressure (r = 0.58, SEE = 5 mm Hg).

There were 41 patients in Group 2 with both analyzable tricuspid regurgitation by Doppler recording and estimated jugular venous pressure. The estimated right ventricular pressure ranged from 20 to 93 mm Hg (mean 45 ± 17) and the catheter-measured right ventricular pressure ranged from 26 to 133 mm Hg (mean 54 ± 21). There was close correlation (r = 0.90, SEE = 8 mm Hg) with a mean difference of 9 ± 9 mm Hg between these measurements (Fig. 3A).

2. Regression equation. Regression equations were derived from the 63 patients in Group 1 on the basis of whether the right atrial pressure was high or low. This was done because of the marked variability of the right atrial pressure. The patients were classified into two subgroups according

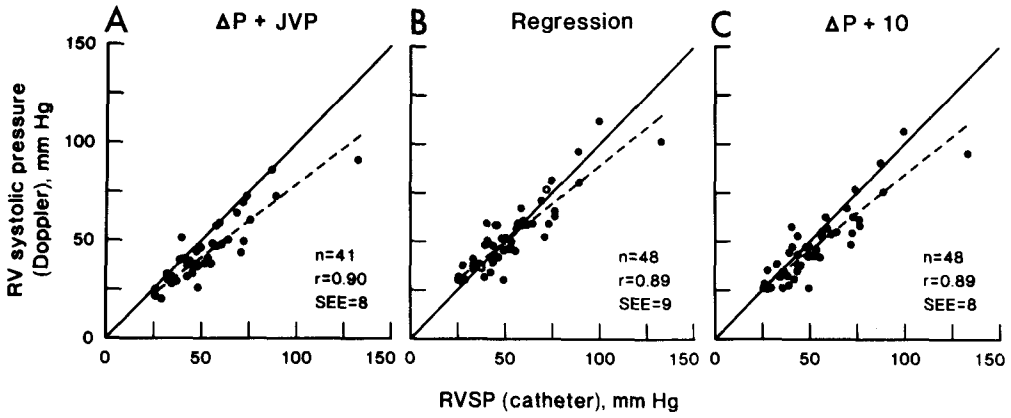

Figure 3. Doppler-estimated versus catheter-measured pressures. **A**, Estimated right ventricular systolic pressure (Doppler gradient (ΔP) + jugular venous pressure [JVP]) versus catheter right ventricular systolic pressure (RVSP) in 41 patients from Group 2. The **dotted line** is the regression line and the **solid line** is the line of identity. **B**, Estimated right ventricular systolic pressure (RV) (using the regressions derived from the 63 patients in Group 1) versus the catheter right ventricular systolic pressure (RVSP) in 48 patients from Group 2. The **closed circles** are estimates using the low regression (patients with jugular venous pressure [JVP] ≤ 20 cm H_2O) and the **open circles** represent the other two patients in whom the high regression was used (jugular venous pressure > 20 cm H_2O). **C**, Estimated right ventricular systolic pressure (Doppler gradient [ΔP] + 10 mm Hg) versus the catheter right ventricular systolic pressure in the 48 patients from Group 2.

to whether the right atrial pressure was 15 mm Hg or less (n = 31) or greater than 15 mm Hg (n = 32) (equivalent to mean jugular venous pressure > 20 cm H_2O), as it was judged that jugular venous pressure greater than 20 cm should usually be obvious at the bedside. The derived regression equations were: RA ≤ 15 mm Hg:RVSP = 14 + Doppler gradient (r = 0.96, SEE = 8) and RA > 15 mm Hg:RVSP = 20 + 1.1 × Doppler gradient (r = 0.94, SEE = 12), where RA = right atrial pressure and RVSP = right ventricular systolic pressure.

In the 48 patients of Group 2 with analyzable Doppler tricuspid regurgitation, the appropriate regression equation was chosen to derive the right ventricular systolic pressure according to whether the jugular venous pressure was less or greater than 20 cm H_2O. In the small children with unmeasurable jugular venous pressure, it was assumed to be 15 mm Hg or less. The estimated right ventricular pressure ranged from 30 to 113 mm Hg (mean 53 ± 19) and the catheter-measured right ventricular pressure ranged from 26 to 133 mm Hg (mean 54 ± 21). Thee was close correlation (r = 0.89, SEE = 9 mm Hg) and a mean difference of 1 ± 10 mm Hg between these measurements (Fig. 3B).

The regression equation for the entire 111 patients with analyzable Doppler tricuspid regurgitation was very similar to that of RA ≤ 15 mm Hg:RVSP = 14 + 1.1 × Doppler gradient.

3. Doppler gradient + 10. Using this formula, the estimated right ventricular pressure ranged from 26 to 107 mm Hg (mean 48 ± 19) and the catheter-measured right ventricular pressure ranged from 26 to 133 mm Hg (mean 54 ± 21). There was close correlation (r = 0.89, SEE = 8 mm Hg) and with a mean difference of 5 ± 10 mm Hg between these measurements (Fig. 3C).

Although all three methods of right ventricular pressure estimation had similar correlation with catheter-measured pressure, the regression equation method was significantly more accurate than the other methods as demonstrated by the significantly lower difference between the Doppler-estimated and catheter-measured right ventricular pressure ($p < 0.05$).

Despite close correlation between the maximal catheter pressure gradient and the Doppler gradient, there were disparities between the Doppler-estimated right ventricular systolic pressure and the catheter right ventricular pressure. These disparities were related to the unpredictable variability of the right atrial pressure, which unfortunately was not completely overcome by clinical estimation of the right atrial pressure in each patient. Some patients with similar

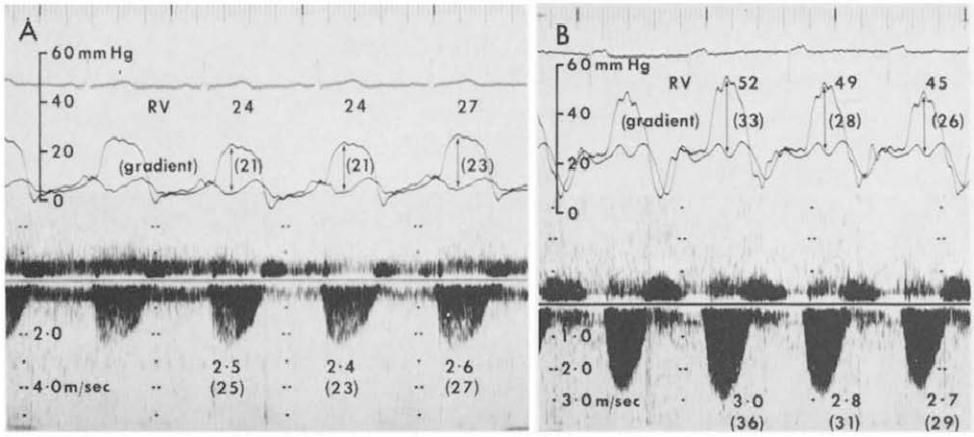

Figure 4. Effect of right atrial pressure estimation on the prediction of right ventricular (RV) systolic pressure is demonstrated by these simultaneous Doppler and catheter pressure recordings in patients with similar maximal systolic pressure gradients. **A**, Patient with an atrial septal defect with a maximal gradient of 21 mm Hg but with a low right atrial pressure. **B**, Patient with constrictive pericarditis with a markedly increased right atrial pressure leading to higher right ventricular systolic pressure despite a comparable maximal Doppler gradient.

Doppler velocities had markedly different values for right atrial pressure and, therefore, quite different values for right ventricular systolic pressure (Fig. 4).

Discussion

Correlation between catheter-measured and Doppler-estimated pressures and gradients. This study documents that the maximal right ventricular to right atrial systolic pressure gradient can be estimated accurately from the maximal Doppler velocity of the tricuspid regurgitant jet. Doppler measurements of tricuspid regurgitation accurately predicted right ventricular systolic pressure in patients with a wide spectrum of both acquired and congenital heart disease, different clinical degrees of severity of tricuspid regurgitation and a wide range of right ventricular systolic pressures. The validity of using the modified Bernoulli equation to estimate an intracardiac pressure gradient from regurgitant blood flow in this clinical situation has also been confirmed.

There were discrepancies between the Doppler and catheter pressure gradients in individual patients. A potential cause of underestimation of pressure gradient by Doppler recording is the failure to obtain a zero or small angle of incidence between the ultrasound beam and maximal regurgitant jet (4). To minimize this potential source of error, it is essential to perform a systematic examination from multiple transducer positions even when a high quality Doppler signal is recorded from a single position. An important consideration in a correlative study is the accuracy of the reference standard, that is, the catheter pressure measurements. Inherent artifacts occasionally associated with fluid-filled catheter systems (under- or overdamped) may lead to discrepancies in pressure recordings which may be incorrectly attributed to inaccuracies of Doppler estimation.

Skjaerpe and Hatle (1) reported good correlation between catheter right ventricle-right atrium pressure gradient and the Doppler gradient in 28 patients with Doppler-detectable tricuspid regurgitation. However, the Doppler and catheter pressure gradient measurements were nonsimultaneous in 21 of their 28 patients. In addition, they did not attempt to predict, by any method, the right ventricular pressure from the Doppler gradient. Yock and Popp (2) also found that the Doppler method could accurately estimate the systolic tricuspid pressure gradient in patients with Doppler-analyzable tricuspid regurgitation. They estimated the right ventricular systolic pressure from the Doppler gradient and clinically estimated mean jugular venous pressure and showed good correlation with catheter-measured right ventricular systolic pressure. However, simultaneous Doppler and catheter pressure measurements were performed in only 14 of 62 patients in their study.

Our study extends the findings of the previous studies by reporting data from a large number of patients of all ages, including neonates, with a much broader spectrum of both acquired and congenital heart disease. In addition, these patients had a wider range of maximal Doppler gradients and right ventricular and right atrial pressures.

Nonsimultaneous versus simultaneous Doppler-catheter correlation. Another important feature of our study was that the Doppler-catheter measurements were simultaneous with the inclusion of a large number of simultaneous dual catheter measurements permitting beat to beat Doppler-catheter pressure comparisons. Our study allowed comparison of simultaneous Doppler and catheter pressure measurements with the nonsimultaneous outpatient Doppler measurements in the 43 patients with two Doppler studies. Variations between nonsimultaneous and simultaneous correlations were partly related to the time elapsed between studies, differences in hemodynamic state and inability to make beat to beat correlations with the nonsimultaneous measurements.

To accurately demonstrate the close beat to beat correlation of Doppler and catheter pressure measurements, it is essential that these be recorded together (Fig. 1B). However, the Doppler and catheter pressure recordings were

measured at separate times to avoid potential measurement bias.

Right ventricular pressure estimation. Three potential methods of right ventricular pressure estimation from the Doppler gradient were compared in our study. No other study has compared these various Doppler methods. Three Doppler methods proved relatively accurate in estimating right ventricular systolic pressure; however, the most accurate method was provided by the regression equations. Inaccurate estimation in individual patients appears to be mostly due to variability in prediction of right atrial pressure. Use of a clinical estimate of right atrial pressure would seem to be a logical approach to overcome this variability. However, despite careful measurement of jugular venous pressure, there was poor correlation of the clinically estimated and catheter-measured right atrial pressure. Accurate measurement is especially difficult in small children, obese patients and patients with markedly increased pressures. To overcome the limitations of precise jugular venous pressure estimation, which included inability to estimate venous pressure in infants and small children, regression equations were derived to broadly categorize patients into high (> 20 cm H_2O) and low (≤ 20 cm) right atrial pressure groups. Small children were then assumed to have normal to low right atrial pressure (≤ 20 cm H_2O). This allowed consideration of individual variation in right atrial pressure. A limitation of any such method is the tendency for slight overestimation of lower right ventricular systolic pressure.

Only 2 of the 41 patients in Group 2 with analyzable tricuspid regurgitation had a mean jugular venous pressure greater than 20 cm H_2O. This leads to small differences between the Doppler gradient + 10 and regression equation methods. Despite this, we believe that the regression equation methods (Doppler gradient + 14 for normal to low jugular venous pressure and 1.1 × Doppler gradient + 20 for high jugular venous pressure) are preferable to the method of Doppler gradient + 10. The Doppler gradient + jugular venous pressure and regression equation methods are comparable. In situations where mean jugular venous pressure cannot be clinically determined, the regression equation method is a suitable alternative.

Doppler detection of tricuspid regurgitation. This study also determined the frequency of detection of tricuspid regurgitation by continuous wave Doppler recording in Group 2 patients. We found that 54 (84%) of the 64 patients had Doppler-detectable tricuspid regurgitation, and in 48 (75%) the recording was of sufficient quality to permit pressure gradient estimation. The incidence of detection of analyzable Doppler tricuspid regurgitation was higher in patients with increased right ventricular systolic pressure (> 35 mm Hg) and 80% compared with 57% in those with 35 mm Hg or less. Yock and Popp (2) found that continuous wave Doppler recording detected tricuspid regurgitation in 56 (90%) of 62 patients with clinically suspected increased right ventricular pressure and in 19 (95%) of 20 normal adults (6). Waggoner et al. (7) found that in patients with increased right ventricular pressure (> 35 mm Hg) approximately 71% had Doppler-detectable tricuspid regurgitation. These studies indicate that tricuspid regurgitation is detected by Doppler recording in a high percentage of patients even without clinical tricuspid regurgitation or increased right ventricular pressure. The variation of incidence between studies is related to differences in patient selection and technique.

Summary. Doppler estimation of right ventricular pressure is an important addition to noninvasive cardiac evaluation. In patients without right ventricular outflow obstruction, the estimated right ventricular pressure also predicts the pulmonary artery systolic pressure. On the basis of this simultaneous Doppler-catheter correlative study in a large group of patients, we suggest that continuous wave Doppler is an accurate noninvasive technique for the estimation of right ventricular systolic pressure in patients with a wide spectrum of cardiac lesions. The cardiologist can now accurately assess right ventricular systolic pressure in a high proportion of patients at the bedside noninvasively. The clinical implications and impact of this development are far reaching.

We thank Elizabeth Dunnett for help with manuscript preparation. We also thank the staff of the catheterization and echocardiography laboratories for their assistance.

References

1. Skjaerpe T, Hatle L. Diagnoses and assessment of tricuspid regurgitation by Doppler ultrasound. In: Rijsterborgh H, ed. Echocardiology. Boston: Martinus Nijoff, 1981:299–304.
2. Yock PG, Popp RL. Noninvasive estimation of right ventricular systolic pressure by Doppler ultrasound in patients with tricuspid incompetence. Circulation 1984;70:657–62.
3. Currie PJ, Fyfe DA, Seward JB, et al. Noninvasive right ventricular pressure determination with continuous wave Doppler: simultaneous Doppler-catheterization correlation (abstr). Circulation 1984:70(suppl II):II-116.
4. Hatle L, Angelsen B. Doppler Ultrasound in Cardiology: Physical Principles and Clinical Applications. Philadelphia: Lea & Febiger, 1982:23.
5. Tei C, Kisanuki A, Arima S, et al. Non-invasive assessment of right ventricular pressure in patients with tricuspid regurgitation by continuous wave Doppler echocardiogram (abstr). Circulation 1984;70(suppl II):II-116.
6. Yock PG, Schnittger I; Popp RL. Is continuous wave Doppler too sensitive in diagnosing pathologic valvular regurgitation? (abstr). Circulation 1984;70(suppl II):II-381.
7. Waggoner AD, Quinones MA, Young JB, et al. Pulsed Doppler echocardiographic detection of right-sided valve regurgitation: experimental results and clinical significance. Am J Cardiol 1981;47:279–86.