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## **Noninvasive estimation of right ventricular systolic pressure by Doppler ultrasound in patients with tricuspid regurgitation**

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**ABSTRACT** We evaluated the accuracy of a noninvasive method for estimating right ventricular systolic pressures in patients with tricuspid regurgitation detected by Doppler ultrasound. Of 62 patients with clinical signs of elevated right-sided pressures, 54 (87%) had jets of tricuspid regurgitation clearly recorded by continuous-wave Doppler ultrasound. By use of the maximum velocity ( $V$ ) of the regurgitant jet, the systolic pressure gradient ( $\Delta P$ ) between right ventricle and right atrium was calculated by the modified Bernoulli equation ( $\Delta P = 4V^2$ ). Adding the transtricuspid gradient to the mean right atrial pressure (estimated clinically from the jugular veins) gave predictions of right ventricular systolic pressure that correlated well with catheterization values ( $r = .93$ ,  $SEE = 8$  mm Hg). The tricuspid gradient method provides an accurate and widely applicable method for noninvasive estimation of elevated right ventricular systolic pressures.

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A NUMBER of noninvasive methods for assessing right ventricular pressure have been developed based on physical examination results and the use of electrocardiograms, phonocardiograms, chest x-rays, and echocardiograms.<sup>1-10</sup> While these methods can discriminate mild from severe right ventricular pressure elevation, they lack sufficient sensitivity to be useful in evaluating the effects of short-term therapeutic interventions or in monitoring the clinical course of outpatients.

Recently, Skjaerpe and Hatle<sup>11</sup> demonstrated that the gradient across a regurgitant tricuspid valve can be estimated from the peak velocity of the systolic transtricuspid jet recorded by Doppler ultrasound. They concluded that prediction of right ventricular systolic pressure should be possible in patients with tricuspid regurgitation by adding the Doppler-determined transtricuspid gradient to the right atrial pressure estimated clinically. Experience in our laboratory and at other institutions has indicated that tricuspid regurgitation signals are detected by the Doppler method in a high proportion of patients with elevated right ventricular systolic pressures, even when clinical signs of tricus-

pid regurgitation are not explicit.<sup>11, 12</sup> Thus, a method for estimating right ventricular pressures based on Doppler-detected tricuspid regurgitation might have wide applicability.

The purpose of this study was to test the accuracy of the tricuspid gradient method in prospectively estimating right ventricular systolic pressures in a group of patients with Doppler-detected tricuspid regurgitation who underwent catheterization within 24 hr of their Doppler study.

### **Material and methods**

The study group consisted of 62 patients in whom elevation of right-sided pressures was suspected on the basis of results of physical examination (loud pulmonic closure sound, right ventricular lift), chest x-ray (right ventricular enlargement, prominent pulmonary vasculature), and/or two-dimensional echocardiography (right ventricular chamber enlargement, "D"-shaped left ventricle<sup>10</sup>). Fifteen of the 62 patients were diagnosed as having clinical tricuspid regurgitation on the basis of results of physical examination by the primary ward physician. Criteria used for the clinical diagnosis of tricuspid regurgitation included systolic murmur with positive Carvallo's sign, prominent jugular venous "c-v" and hepatic pulsations, and right-sided  $S_3$ . Specific criteria applied in a given case were not always stated in the medical record so we did not collate the incidence of such signs. The group included 35 male and 27 female patients with ages ranging from 16 to 90 (mean 50) years. Primary cardiac diagnoses were cardiomyopathy (29 patients), rheumatic valvular disease (15), myocardial infarction (five), nonrheumatic mitral regurgitation (three), cor pulmonale (two), aortic stenosis (one), primary pulmonary hypertension (one), congenital tricuspid regurgitation (one), anomalous pulmonary venous return (one), left atrial myxoma (one), myocar-

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ditis (one), carcinoid (one), and pulmonic stenosis (one). Predominant rhythm at the time of study was sinus in 32, atrial fibrillation in 18, sinus tachycardia in eight, paced in three, and ectopic atrial tachycardia in one.

Doppler studies were performed with a combined two-dimensional and Doppler ultrasonograph with a 2.5 MHz transducer.\* Doppler recordings were made in the continuous-wave mode to allow unambiguous measurement of high velocities. Location of the regurgitant jet was verified with the pulsed Doppler mode, which detects flow in a movable small-volume element displayed on the two-dimensional echocardiographic image.

A continuous-wave Doppler signal was accepted as representing tricuspid regurgitation if (1) the signal was recorded only when the Doppler cursor was within the boundaries of the right heart (specifically not encroaching on the region of aortic outflow), (2) the pulsed wave examination confirmed the presence of a regurgitant jet originating from the tricuspid valve and directed back into the right atrium, (3) the signal extended for at least half of systole, and (4) a characteristic high-pitched signal was produced by the audio output of the instrument. Validation of these criteria has been published elsewhere.<sup>13-15</sup> In some cases adequate recording of the regurgitant jet was obtained only with the smaller nonimaging Doppler transducer (which has the advantages of both increased maneuverability and higher signal-to-noise ratio). In these cases, identification of the signal as tricuspid regurgitation was supported by placing the nonimaging transducer in the same orientation as for the tricuspid valve recording with the two-dimensional/Doppler imaging transducer and by seeing tricuspid inflow in the same pattern as recorded with the combined probe.

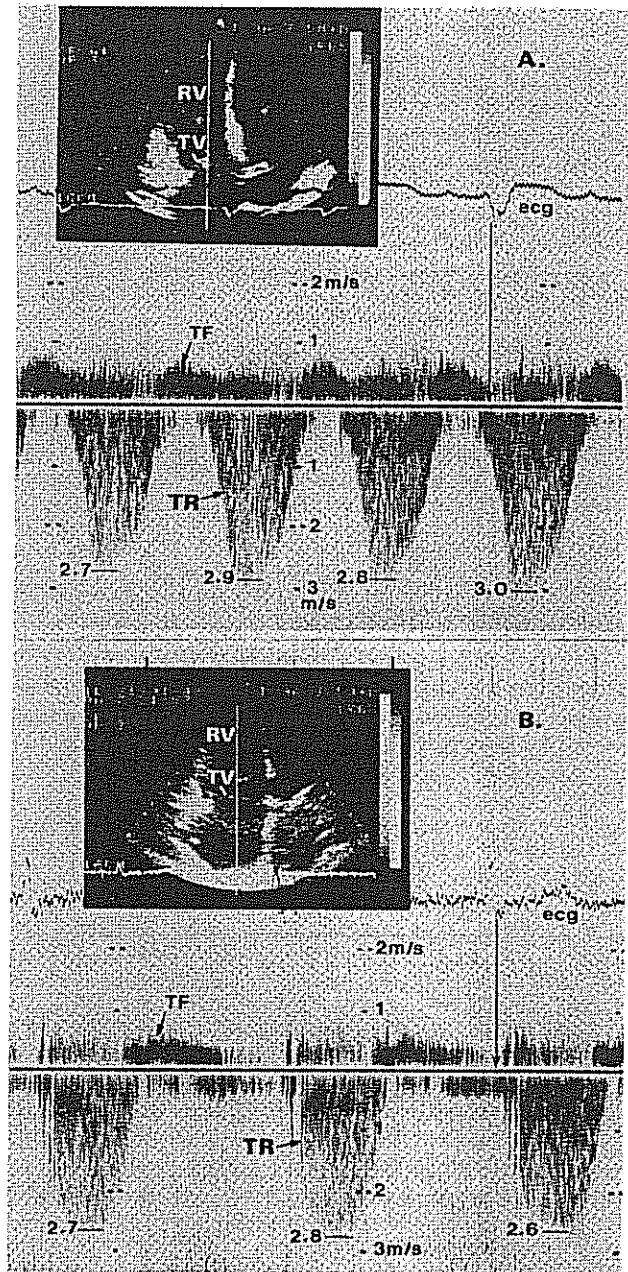
In a given patient the tricuspid regurgitation jet was sought from all available midprecordial and apical positions until a flow signal with the maximum spectral representation of high velocities was recorded. As Hatle<sup>16</sup> has emphasized, once a signal with a relatively dense high-velocity spectral representation is obtained, the angle between the ultrasound beam and the direction of flow can be assumed to be minimal. Confirmation of a narrow beam-to-flow angle was provided by the two-dimensional image showing the Doppler cursor close to the presumed direction of flow. No attempt at correction of velocities for flow angle was made in any case. In our patient group optimal transducer locations were approximately equally divided between the apical four-chamber view and a midprecordial view, with medial angulation to insonify the tricuspid valve.

The mean jugular venous pressure was measured in centimeters above the sternal angle at 45 degrees elevation of the thorax and head (higher or lower angles were required in some patients when the venous pulsations were not clear). Right atrial pressure was estimated by adding 5 cm to the jugular venous pressure measurement.<sup>17</sup> Conversion to millimeters of mercury was accomplished by dividing the right atrial pressure in centimeters by 1.3, which expresses the relative density of mercury to blood at physiologic temperatures.

The maximum velocity of regurgitant flow for a given patient was taken as the average peak velocity among those beats that produced the most complete envelopes and had the greatest representation of high velocity flows in the spectral display. For each beat analyzed, peak velocity was assigned to the highest coherent boundary on the spectral wave form (figure 1). At least 4 beats were averaged for patients in sinus rhythm, at least 8 beats for those in atrial fibrillation. Consecutive beats were analyzed only when the signal quality of all consecutive beats was optimal (less than half of the patients in our group). The transtricuspid gradient ( $\Delta P$ , in mm Hg) was approximated, with the modification of the Bernoulli equation developed and validated by Holen, Hatle, and their colleagues,<sup>20-25</sup> as follows:  $\Delta P$

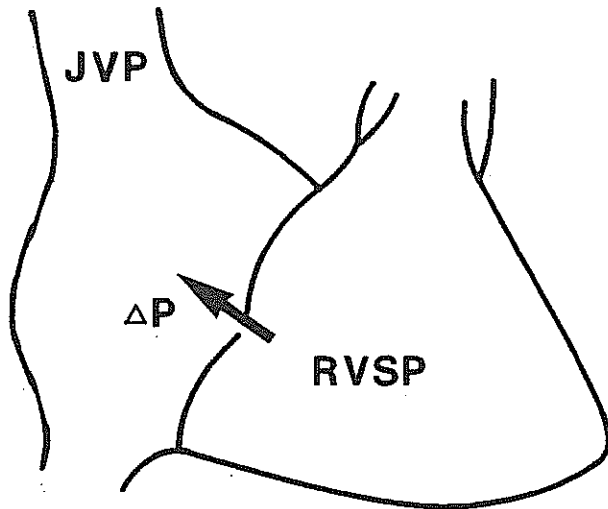
$= 4V^2$ , where V represents the average maximum velocity in meters per second (figure 1). For each patient the calculated gradient was added to the estimated right atrial pressure (figure 2) and the resulting prospective, blinded, right ventricular pressure predictions were compared with catheterization data by linear regression analysis.

The records of 25 alternately numbered patients in the series were remeasured by the original observer at another sitting and



**FIGURE 1.** Representative Doppler tricuspid regurgitation (TR) signals from a patient in sinus rhythm (A) and atrial fibrillation (B). The Doppler cursor is shown on the two-dimensional image crossing the region of the tricuspid valve (TV) orifice, parallel to the presumed direction of the jet. By convention, flow toward the transducer is displayed above the baseline (tricuspid inflow, TF). Maximum velocities in meters per second are indicated for each beat along with the calibration scale. Long arrows designate the approximate onset of mechanical systole, assigned at a point 50 msec beyond the apparent initial QRS deflection on the electrocardiogram. RV = right ventricle.

\*Irex System IIB and Exemplar; Ramsey, NJ.



$$\text{JVP} + \Delta P = \text{RVSP}$$

**FIGURE 2.** Schema for the method of estimating right ventricular systolic pressure (RVSP) from mean jugular venous pressure (JVP) and maximum transtricuspid gradient ( $\Delta P$ ). The mean JVP is approximated as the height above the sternal angle plus 5 cm. This figure is divided by 1.3 to convert centimeters of blood to millimeters of mercury. The transtricuspid gradient ( $\Delta P$ , in mm Hg) is calculated by use of the modified Bernoulli equation,  $\Delta P = 4V^2$ , where V represents the maximum velocity of the regurgitant jet in meters per second. Right ventricular systolic pressure is then estimated as the sum of the mean JVP and the transtricuspid gradient.

again by a second observer. In both cases observers were blinded to the primary results. All patients underwent catheterization within 24 hr of their Doppler study. Fourteen patients had indwelling pulmonary arterial (Swan-Ganz) catheters at the time the Doppler examination was performed. In these patients pulmonary arterial systolic pressures were recorded as a close approximation of the right ventricular systolic pressures. All 14 patients in this latter group had right ventricular pressures that differed less than 4 mm from the pulmonary arterial pressure at the time of catheter insertion. The remainder of the patients in our series had right heart pressures measured only in the catheterization laboratory by standard fluid-filled catheters and recording equipment described elsewhere.<sup>18</sup> Pressure determinations from catheterization alone and measurements of the Swan-Ganz pressure tracings were made without knowledge of the Doppler findings.

**Results**

Of the 62 patients recruited for the study on the basis of clinically suspected elevation of right-sided pressures, 56 had Doppler-detected tricuspid regurgitation (90%). Only 15 patients in this group had tricuspid regurgitation by conventional clinical criteria (25%). Full spectral profiles of the regurgitant flow signals were obtained in 54 of 56 patients (96%); in the re-

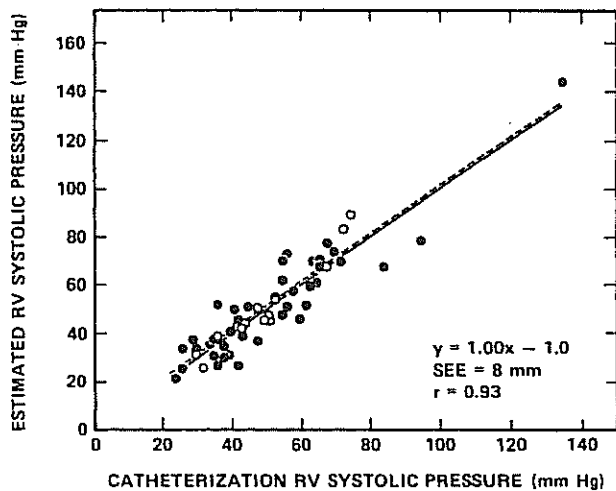
maining two poor signal-to-noise ratios with high-velocity dropout precluded determination of the maximum velocity of the regurgitant jet.

Comparison of Doppler-estimated and catheterization-measured right ventricular systolic pressures is shown in figure 3. The standard error of the estimate is 8 mm Hg and the slope and intercept of the linear regression function are not statistically different from 1.0 and zero, respectively. The correlation coefficient is high ( $r = .93$ ), in part because of one extreme data point from the patient with pulmonary stenosis. If the data from this patient is excluded from analysis, the r value decreases to .89.

**Discussion**

The results of this study confirm the previous suggestion that right ventricular systolic pressures can be predicted in patients with Doppler-detected tricuspid regurgitation by adding the calculated transtricuspid gradient to the estimated right atrial pressure. These data extend the work of Skjaerpe and Hatle,<sup>11</sup> who showed that in patients with tricuspid regurgitation the systolic transtricuspid gradient ( $\Delta P$ ) can be estimated by a modification of the Bernoulli equation,  $\Delta P = 4V^2$ , where V represents the maximum velocity recorded in the regurgitant jet. Our study demonstrates the practical application of the tricuspid gradient method in an adult population with various forms of cardiopulmonary disease.

**Sources of error.** A potentially major source of error in data acquisition in the majority of patients is the use of



**FIGURE 3.** Correlation of Doppler-predicted and catheterization-measured right ventricular systolic pressures ( $n = 54$ ). Simultaneous Swan-Ganz pressure measurements are indicated as open circles and pressures from the nonsimultaneous catheterization studies as closed circles. The regression function is plotted as a solid line that is nearly superimposed on the identity function (dashed line). RV = right ventricle.

nonsimultaneous catheterization data for correlation with Doppler-predicted pressures. No patient in this study group had significant changes in therapy or clinical status between the time of the Doppler study and catheterization, and all received oral hydration and only light sedation (5 to 10 mg oral diazepam) before catheterization. Nonetheless, drift in right-sided pressures undoubtedly occurred in some patients. When the patients studied with the use of simultaneous pulmonary pressure measurements are analyzed as a subgroup, correlation is in fact closer than for the entire group ( $r = .97$  vs  $.93$ ). However, the power of this subgroup analysis is limited by the small number of patients undergoing simultaneous pressure measurement and by the use of pulmonary arterial pressures rather than direct right ventricular pressure measurements in these patients.

A possible methodologic error arises because the precise atrial pressure at the time of peak transtricuspid flow is not clinically measurable. Jugular venous pressure in this study was taken as an estimated mean of the pulsations in the jugular vein, i.e., generally as less than the v wave. There is theoretical support for the use of a mean pressure estimate rather than the v wave in right ventricular pressure calculations. As shown in figure 4, the maximum systolic gradient between right ventricle and right atrium occurs in midsystole before the peak of the v wave. Use of a prominent v wave in the jugular venous pressure for the calculation might lead to overestimation of right ventricular systolic pressures.

The clinical estimation of right atrial pressure from the jugular venous pulse is a significant and unavoidable

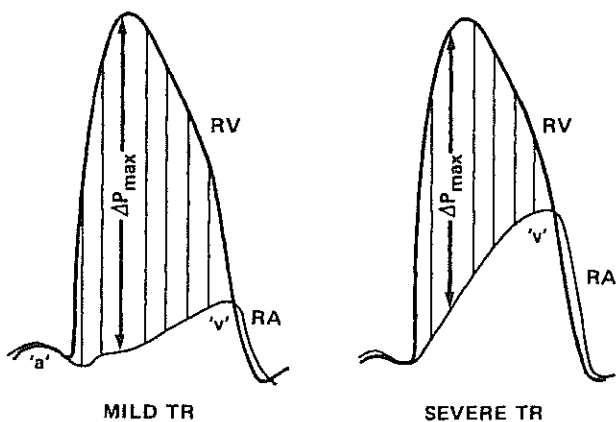


FIGURE 4. Demonstration of the maximum gradient ( $\Delta P_{max}$ ) between right ventricular (RV) and right atrial (RA) pressures.  $\Delta P_{max}$ , corresponding to the highest velocity of transtricuspid regurgitant flow, occurs before the peak v wave in the right atrial pressure. Adding the v wave pressure to the peak transtricuspid gradient would overestimate the right ventricular systolic pressure.

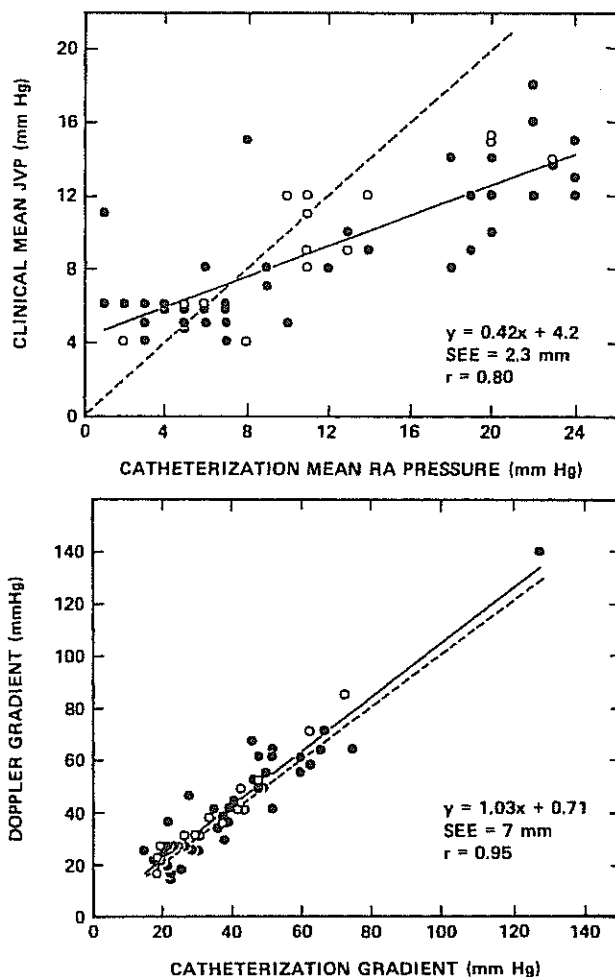


FIGURE 5. Clinical estimates of mean jugular venous pressure (*top*) and Doppler-estimated transtricuspid gradients (*bottom*) compared with catheterization values in 53 patients. One patient was excluded because right atrial pressure measurements were not recorded in the catheterization laboratory. Dashed line is the line of identity.  $\circ$  = simultaneous Swan-Ganz pressure measurements;  $\bullet$  = nonsimultaneous measurements in the catheterization laboratory; JVP = jugular venous pressure; RA = right atrial pressure.

source of error. Figure 5 shows the poor correlation between clinically estimated and catheterization-measured values for right atrial pressure, and the relatively good correlation of Doppler-estimated and catheterization-measured transtricuspid gradients. Fortunately, the estimates of right atrial pressure are generally smaller than the gradient determinations (mean 11.8 vs 38.6 mm Hg). It follows that the absolute deviations from the true right atrial pressures are correspondingly small values, so that their effect on relative error in right ventricular pressure estimations is partially diluted (compare figure 5 and figure 3).

The Doppler-determined gradients are also subject to a number of potential errors. The assumption that the beam-to-flow angle is negligible cannot be directly validated. In the present study we found that in all

cases the Doppler cursor could be placed in a position that appeared parallel to the presumed direction of flow in the plane of the echocardiographic display. Even allowing an angle deviation of 10 degrees in the unknown azimuthal or z axis, the error is minimal. The Doppler equation states that the measured velocity is underestimated by the factor  $\text{Cos}(\theta)$ , where  $\theta$  is the angle discrepancy between beam and flow. Thus, for a 10 degree angle, velocity is underestimated by only 1.5%. This percent error is approximately doubled in the gradient calculation, however, since the velocity term is squared.\*

At least as important a source of error is the assignment of the maximum velocity of the regurgitant signal. In a given patient relatively few beats may have an optimal spectral profile. Changes in signal-to-noise ratio on a beat-to-beat basis are caused by patient/transducer motion, differing cardiac cycle lengths, and respiratory variation. The possibility of a systematic error in estimation of mean gradient occurs in the latter two categories if good quality signals are recorded only at certain cycle lengths (e.g., with longer R-R intervals) or at certain phases of respiration (e.g., only during inspiration).

Even with an ideal spectral contour, assigning the maximum velocity is arbitrary to some extent. The maximum velocity contour is defined by visual inspection of the spectral display and thus is subject to observer variability. To test the extent of interobserver variability, tracings from 25 consecutive even-numbered cases were analyzed by a second investigator who was blinded to the results obtained by the first observer. The interobserver variability in calculated gradients was low, with a mean discrepancy of  $-1.8$  mm Hg and an SD of 4.9 mm Hg. The same tracings were reanalyzed by the initial observer in a blinded fashion, yielding an intraobserver mean discrepancy of  $-0.2$  mm Hg and an SD of 3.4 mm Hg.

In addition to observer variability in measurement, there is intrinsic uncertainty in the actual spectral signal introduced by the "transit time" effect, a limitation in the accuracy of Doppler velocity determinations imposed by short sampling periods.<sup>20</sup> The gradient calculation itself is an approximation based on simplifying assumptions about the characteristics of flow through the valve.<sup>21-23</sup> These assumptions have been validated in vitro<sup>21</sup> and are supported by a number of clinical series on stenotic valves.<sup>16, 21-27</sup> In practice, these technical errors in measuring velocity and calculating the gradients are probably small relative to the

biologic variables (difficulty in assessing right atrial pressure, angle of flow, and variability in signal-to-noise) discussed above.

**Utility of the method.** Our preliminary findings suggest that Doppler-detected tricuspid regurgitation is present in a high proportion of patients with elevated right-sided pressures (in significantly more patients than in whom tricuspid regurgitation is recognized clinically). Other investigators also have reported a high incidence of Doppler-detected tricuspid regurgitation in this group.<sup>11, 12</sup> The fact that tricuspid regurgitation is subclinical in most cases does not preclude use of the gradient method to estimate right ventricular systolic pressures: the calculations depend on the velocity, and not the volume, of flow. All that is required for use of the tricuspid regurgitation signal is a full spectral profile which, in our experience, is found in nearly all patients (96%) with Doppler-detected tricuspid regurgitation. We did not explore the use of contrast echocardiographic enhancement in this study, which might have provided an even higher yield of interpretable tricuspid regurgitation signals.<sup>28</sup>

Whether or not the method is sensitive enough to follow the effects of therapeutic interventions on right-sided pressures remains to be proved. Theoretically, some of the variables that lead to inaccuracy (in particular the beam angle and ambiguity in assigning the maximum velocity) may be constant errors in a given patient and thus may be less important in following changes in pressure than in predicting absolute pressures.

Finally, in this series we did not compare the tricuspid gradient method with any of the recently published Doppler techniques for estimating pulmonary arterial pressures based on the pulmonic flow velocity contours<sup>29, 30</sup> and timing of right-sided valve events.<sup>31</sup> In a given patient either the tricuspid gradient method or the pulmonic flow techniques may be preferable, depending on the quality and accessibility of the corresponding Doppler signals.

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\*As shown by Taylor expansion of the velocity-plus-error term.<sup>19</sup>

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