Quantitative Assessment of Pulmonary Hypertension in Patients With Tricuspid Regurgitation Using Continuous Wave Doppler Ultrasound

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Doppler ultrasound examination was performed in 69 patients with a variety of cardiopulmonary disorders who were undergoing bedside right heart catheterization. Patients were classified into two groups on the basis of hemodynamic findings. Group I consisted of 20 patients whose pulmonary artery systolic pressure was less than 35 mm Hg and Group II consisted of 49 patients whose pulmonary artery systolic pressure was 35 mm Hg or greater.

Tricuspid regurgitation was detected by Doppler ultrasound in 2 of 20 Group I patients and 39 of 49 Group II patients ($p < 0.001$). Twenty-six of 27 patients with pulmonary artery systolic pressure greater than 50 mm Hg had Doppler evidence of tricuspid regurgitation. In patients with tricuspid regurgitation, continuous wave Doppler ultrasound was used to measure the velocity of the regurgitant jet, and by applying the Bernoulli equation, the peak pressure gradient between the right ventricle and right atrium was calculated. There was a close correlation between the Doppler gradient and the pulmonary artery systolic pressure measured by cardiac catheterization ($r = 0.97$, standard error of the estimate = 4.9 mm Hg). Estimating the right atrial pressure clinically and adding it to the Doppler-determined right ventricular to right atrial pressure gradient was not necessary to achieve accurate results.

These findings indicate that tricuspid regurgitation can be identified by Doppler ultrasound in a large proportion of patients with pulmonary hypertension, especially when the pulmonary artery pressure exceeds 50 mm Hg. Calculation of the right ventricular to right atrial pressure gradient in these patients provides an accurate noninvasive estimate of pulmonary artery systolic pressure.

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The diagnosis of pulmonary hypertension by noninvasive diagnostic techniques is often difficult. Echocardiography, although routinely used for this purpose, has several important limitations. These include technical difficulty in obtaining an adequate recording of the pulmonary valve, a relatively low sensitivity and an inability to provide a quantitative estimate of the pulmonary artery pressure (1,2).

Recently, several investigators (3–8) have utilized pulsed Doppler ultrasound to assess pulmonary pressure noninvasively. Doppler measurements of right ventricular isovolumic relaxation time (3), right ventricular systolic time intervals (4,5) and pulmonary artery flow velocity patterns (6–8) have shown good correlation with pulmonary artery pressure measurements obtained at cardiac catheterization.

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Continuous wave Doppler ultrasound (9), which is capable of measuring high blood flow velocities, provides another method for the noninvasive diagnosis of pulmonary hypertension. In the presence of tricuspid regurgitation, the pressure gradient between the right ventricle and right atrium during systole can be estimated by measuring the maximal velocity of the regurgitant jet and applying the Bernoulli equation (10). Addition of this pressure gradient to the right atrial pressure estimated by physical examination has been shown to provide a reliable assessment of the right ventricular systolic pressure (11), and, in the absence of a significant gradient across the pulmonary valve or right ventricular outflow tract, is equivalent to the pulmonary artery systolic pressure. The success of this technique is dependent on the presense of tricuspid regurgitation, obtaining accurate velocity measurements by Doppler ultrasound and the ability to correctly estimate right atrial pressure clinically. In critically ill patients, attempts to predict right atrial pressure on the basis of physical examination frequently yield inaccurate results (12,13). However, a linear relation between mean right atrial pressure and the degree of pulmonary hy-

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pertension has been noted by several investigators (14–16). Thus, omitting the right atrial pressure and relying solely on the right ventricular to right atrial pressure gradient might result in simplification of the technique without a loss of accuracy.

We therefore undertook this study with the following objectives: 1) to further define the ability of continuous wave Doppler ultrasound to predict the pulmonary artery systolic pressure in patients with pulmonary hypertension; 2) to determine if this could be accomplished without concomitant clinical estimation of the right atrial pressure; and 3) because tricuspid regurgitation is a prerequisite for this technique, to determine its prevalence in a series of patients with pulmonary hypertension.

Methods

Patients. Doppler ultrasound examination was performed in 69 patients undergoing bedside hemodynamic monitoring with a Swan-Ganz catheter positioned in the pulmonary artery. In 39 patients, Doppler studies and pressure measurements were recorded simultaneously. In the remaining 30 patients, the pulmonary artery pressure was measured immediately after completion of the Doppler study. Thirty-four patients were men and 35 were women ranging in age from 27 to 95 years (mean 68). The diagnoses were ischemic heart disease in 30 patients, valvular heart disease in 9, chronic obstructive pulmonary disease in 5, pneumonia in 5, congestive cardiomyopathy in 3, hypertensive heart disease in 3, connective tissue disease in 2 and tricuspid endocarditis in 1. Eleven patients had no apparent cardiac or pulmonary disease but required pulmonary artery catheterization for assessment of fluid status or because of hemodynamic instability. Fifty-nine patients had sinus rhythm, six had atrial fibrillation and four had pacemaker rhythm.

Patients were classified into two groups on the basis of the pulmonary artery systolic pressure: Group I consisted of 20 patients whose pulmonary artery systolic pressure was less than 35 mm Hg. Group II consisted of 49 patients with pulmonary hypertension, with a pulmonary artery systolic pressure of 35 mm Hg or greater.

Doppler ultrasound techniques. Ultrasound studies were performed using a commercially available phased array echocardiography system with simultaneous pulsed and continuous wave Doppler (Irex Exemplar). The system is equipped with a dual frequency transducer that operates at a carrier frequency of 3.5 MHz for the two-dimensional echocardiographic examination and 2 MHz for the simultaneous Doppler study which can be perfromed in either the pulsed or continuous mode. In the pulsed mode, localized flow disturbances along the course of the ultrasound beam can be detected, but the maximal velocity that can be measured is 1.7 m/s at depth settings up to and including 9 cm and 1.1 m/s at depth settings greater than 9 cm. When operated in the continuous mode, velocities up to 6 m/s can be measured but there is a loss of range resolution. A chirp-Z spectral analyzer that displays the full spectrum of Doppler shifts and provides both direction of flow and a quantification of blood flow velocity was used for velocity measurements. Flow velocity toward the transducer was displayed above the baseline and flow velocity away from the transducer was displayed below the baseline. An audio signal corresponding to frequency shifts along the sound beam was helpful in positioning the transducer.

The ultrasound examination was performed with the patient in the supine or left lateral decubitus position. Standard two-dimensional echocardiographic views obtained from the parasternal, apical and subcostal positions were used to image the tricuspid valve (17). Pulsed Doppler mode (Fig. 1, left) was used to detect the presence of tricuspid regurgitation by placing the sample volume in the right atrium and sweeping it back and forth behind the tricuspid valve using techniques that have been previously described (18,19). If tricuspid regurgitation was present, the system was switched to the continuous mode to measure the maximal velocity of the regurgitant jet (Fig. 1, right). This was accomplished by gradually tilting the ultrasound beam from side to side and anteroposteriorly until the highest frequency audio signals were identified and the highest maximal velocity was recorded on the spectral display. To minimize underestimation of the maximal velocity, the angle of incidence between the ultrasound beam and the direction of regurgitant flow should be as close to zero as possible. Because the direction of the regurgitant jet may vary from one patient to another, several transducer positions (parasternal, apical and subcostal) were used in an attempt to record the highest possible maximal velocity.

The pressure gradient between the right ventricle and right atrium during systole was calculated from the maximal velocity measurement by applying a modification of the Bernoulli equation (20):

$$\Delta P = 4 \times V^2,$$

where ΔP is the pressure gradient and V is the maximal velocity of the tricuspid regurgitant jet in m/s. A minimum of three beats showing the highest maximal velocities was averaged for patients having sinus rhythm and at least five beats were used if atrial fibrillation was present. The systolic pressure gradient between the right ventricle and right atrium calculated by this method was compared with the systolic pressure in the pulmonary artery measured during right heart catheterization. Doppler measurements were made without knowledge of the catheterization findings.

Hemodynamic studies. Pulmonary artery pressure was measured at end-expiration with the patient supine, using a Gould P23 ID transducer positioned at the midchest level

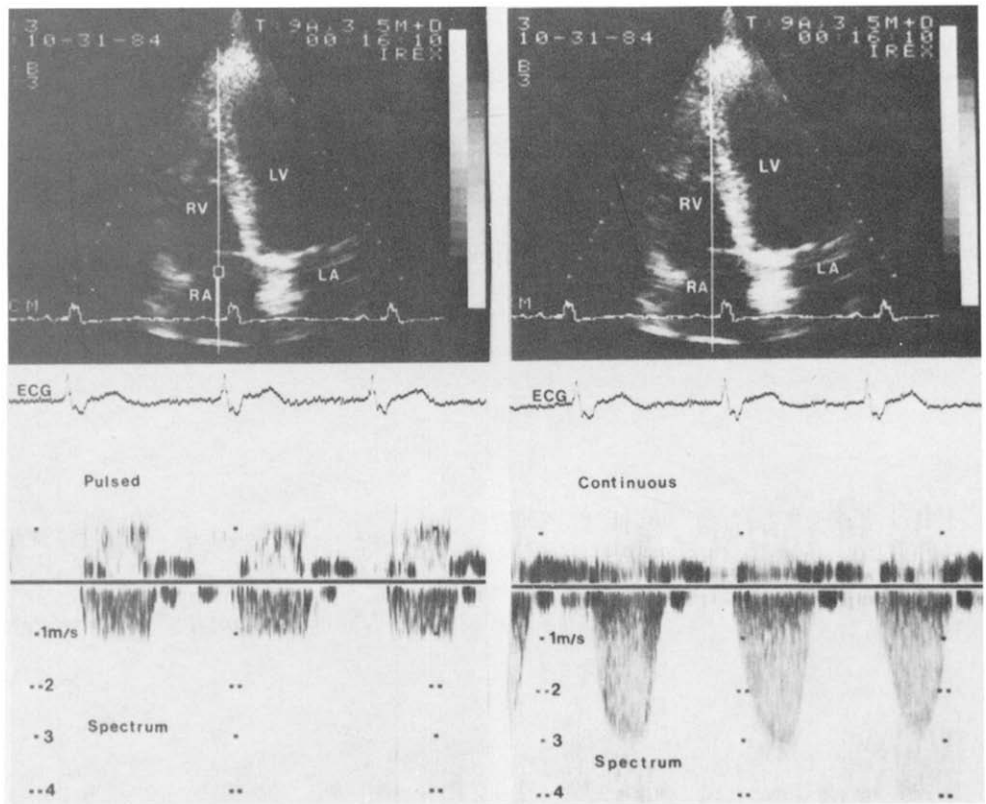


Figure 1. Two-dimensional echocardiogram and Doppler ultrasound recording obtained with the transducer at the apex. The study shown in the **left panel** was obtained using the pulsed mode. The sample volume (**box**) is placed in the right atrium (RA) to detect the presence of tricuspid regurgitation. Note that velocities greater than 1.1 m/s are cut off preventing accurate measurements. In the continuous mode (**right panel**), the spectral display shows a maximal velocity of 3.1 m/s. ECG = electrocardiogram; LA = left atrium; LV = left ventricle; RV = right ventricle.

and interfaced with an American Optical recorder. No patient was found to have a significant systolic pressure gradient between the right ventricle and the pulmonary artery.

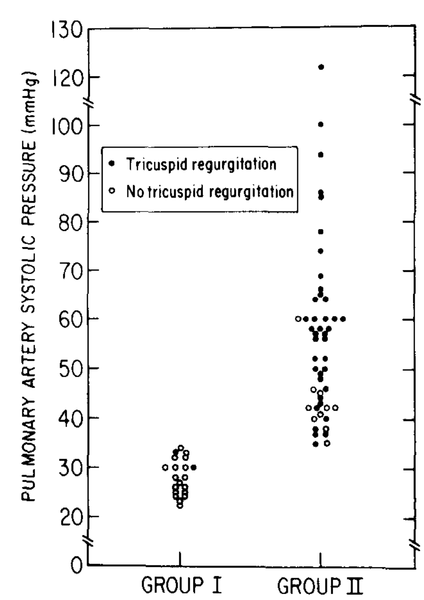
Statistical analysis. The chi-square method was used to compare the prevalence of tricuspid regurgitation in patients in Group I (normal pulmonary pressure) and Group II (pulmonary hypertension). The pressure gradient between the right ventricle and right atrium obtained by Doppler measurement and the pulmonary artery systolic pressure recorded by right heart catheterization were compared using linear regression analysis. Data are expressed as mean ± standard deviation.

Results

Catheterization findings. Pulmonary artery systolic pressure in the 69 patients ranged from 22 to 122 mm Hg (mean 48 ± 20). In the 20 patients in Group I, pulmonary artery systolic pressure ranged from 22 to 34 mm Hg (mean 28 ± 4) and in the 49 patients in Group II from 35 to 122 mm Hg (mean 56 ± 17). The distribution of pulmonary artery systolic pressures in both groups is shown in Figure 2.

Tricuspid regurgitation. Tricuspid regurgitation was detected by Doppler ultrasound in 41 (59%) of the 69 patients. Two (10%) of 20 patients in Group I had tricuspid regurgitation compared with 39 (80%) of 49 patients in Group II (chi-square = 28.5, $p < 0.001$). Figure 2 illustrates the distribution of tricuspid regurgitation in both groups of patients and its relation to the pulmonary artery systolic pressure. Tricuspid regurgitation was detected more frequently with increasing pulmonary artery pressure and was

Figure 2. Distribution of patients in Groups I and II according to pulmonary artery systolic pressure.



present in 26 of 27 patients with pulmonary artery systolic pressures above 50 mm Hg (Fig. 3).

Maximal velocity measurements. The maximal velocity of the regurgitant jet measured by continuous wave Doppler ultrasound in the 41 patients with tricuspid regurgitation ranged from 2.5 to 5.1 m/s (mean 3.4 ± 0.5). The systolic pressure gradient between the right ventricle and right atrium calculated from the maximal velocity measurements ranged from 25 to 104 mm Hg (mean 58 ± 19). A representative case is illustrated in Figure 4.

Doppler gradient versus catheterization findings. A comparison of the right ventricular to right atrial pressure gradient calculated by Doppler ultrasound with the pulmonary artery systolic pressure recorded at catheterization showed an excellent correlation (r = 0.97, standard error of the estimate = 4.9 mm Hg) (Fig. 5).

Discussion

Previous Doppler studies of pulmonary hypertension. A variety of Doppler techniques has been utilized in the noninvasive evaluation of pulmonary hypertension. These have primarily relied on pulsed rather than continuous wave Doppler recordings to obtain quantitative estimates of pulmonary artery pressures. Three types of pulsed Doppler approaches have been used. In one of these, several groups of investigators (4,5) found a good correlation between mean pulmonary artery pressure and the ratio of right ventricular preejection period to right ventricular ejection time. Using another approach, Hatle et al. (3) used the Doppler amplitude signal and phonocardiography to measure the interval from pulmonary valve closure to tricuspid valve opening. This interval was then applied to a nomogram previously described by Burstin (21) to predict pulmonary artery systolic pressure and again a good correlation was noted. Perhaps the pulsed Doppler technique most commonly used involves analysis of blood flow velocity patterns in the pulmonary artery or right ventricular outflow tract (6–8). The most consistent finding with this method has been a shortening of the interval from the onset of ejection to the time of peak flow velocity (also referred to as the acceleration time). Use of this measurement either alone or in combination with other Doppler derived intervals has proven to be reliable and correlation with pulmonary artery pressures in published studies has been quite good.

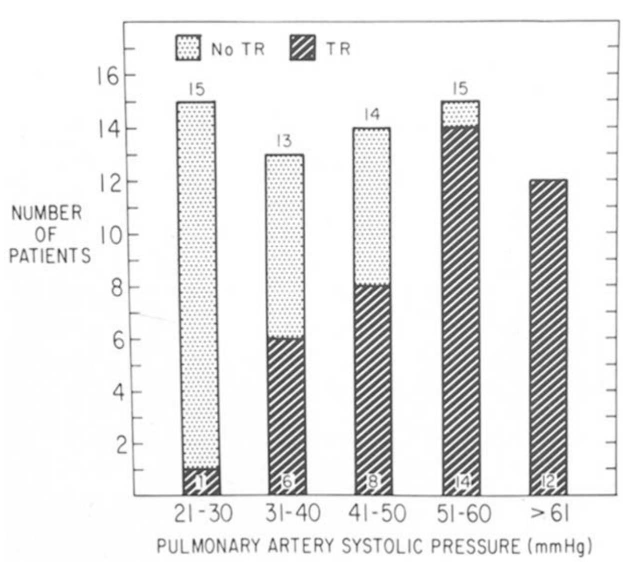


Figure 3. Relation between pulmonary artery systolic pressure and the presence of tricuspid regurgitation (TR).

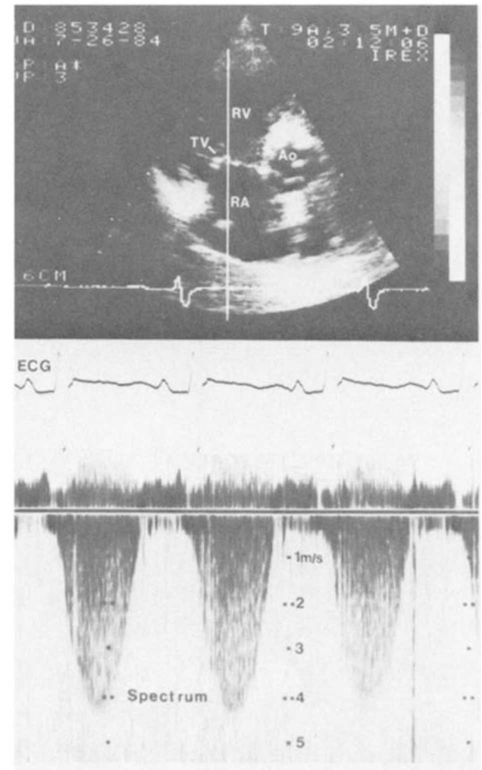


Figure 4. Two-dimensional echocardiogram and Doppler ultrasound study recorded from the left parasternal position. The Doppler ultrasound beam is directed across the tricuspid valve (TV) as indicated by the cursor. The maximal velocity of the regurgitant jet which is directed away from the transducer is 4.3 m/s and the calculated pressure gradient between the right ventricle (RV) and right atrium (RA) is 74 mm Hg. Ao = aorta; ECG = electrocardiogram.

Although these techniques are useful, they have limitations. In some patients, diagnostic right ventricular outflow tract or pulmonary artery flow velocity patterns cannot be recorded (7). In addition, many of the Doppler-derived intervals used to predict pulmonary artery pressure show an overlap between normal control subjects and patients with pulmonary hypertension (8). The method described by Hatle et al. (3) tends to be somewhat cumbersome because it requires a phonocardiogram together with the Doppler study. Finally, on the basis of the limited data currently available (11) and the results of our own study, it appears that esti-

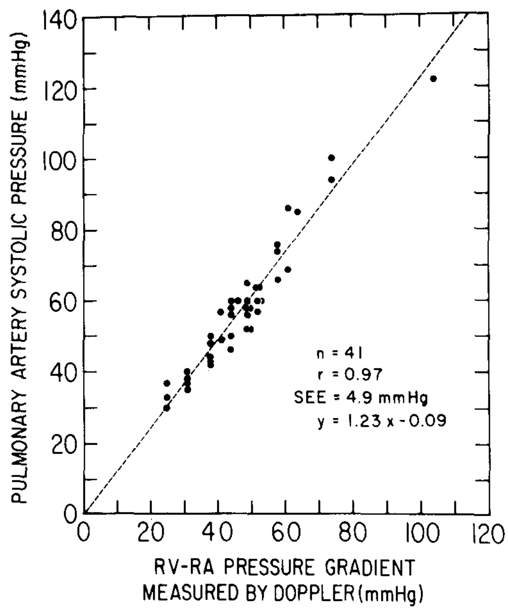


Figure 5. Right ventricular (RV) to right atrial (RA) pressure gradient measured by continuous wave Doppler ultrasound compared with pulmonary artery systolic pressure recorded at cardiac catheterization in 41 patients with tricuspid regurgitation. The correlation coefficient (r) = 0.97 and the standard error of the estimate (SEE) = 4.9 mm Hg.

mation of pulmonary artery pressure by pulsed Doppler echocardiography may be slightly less accurate than continuous wave techniques that use the right ventricular to right atrial pressure gradient to obtain this measurement. Studies comparing these techniques in the same patient population are needed to further clarify this point.

Continuous wave Doppler in pulmonary hypertension. In the present study we used continuous wave Doppler ultrasound to assess pulmonary artery systolic pressure in patients with pulmonary hypertension. Employing a method introduced by Hatle and Angelsen (10), we measured the maximal velocity of the regurgitant jet in patients with tricuspid insufficiency and, by applying the Bernoulli equation, calculated the pressure gradient between the right ventricle and right atrium. We then compared this value with the catheterization-derived pulmonary artery systolic pressure and found an extremely close correlation for a wide range of measured pulmonary artery systolic pressures. The validity of maximal velocity measurements recorded by continuous wave Doppler ultrasound in measuring pressure gradients across cardiac valves has been well established (20,22–25).

Yock and Popp (11), with the continuous wave Doppler mode, and Saal et al. (26), with the high pulse repetition frequency Doppler mode, have also used maximal velocity measurements across the tricuspid valve to compute the right ventricular to right atrial pressure gradient. They then added this gradient to the right atrial pressure derived from physical examination and obtained an estimate of the pulmonary artery systolic pressure that correlated well with the pressure measured at right heart catheterization.

The close correlation in the present study between the Doppler-derived right ventricular to right atrial pressure gradient and the measured pulmonary artery systolic pressure indicates that clinical estimation of the right atrial pressure may not be necessary to obtain reliable results. This might be explained by the fact that although right atrial pressure increases proportionately as the pulmonary artery systolic pressure increases, the right atrial pressure varies over a much narrower range of values (14–16). When the pulmonary artery pressure increases to the hypertensive range, right atrial pressure is relatively low in comparison and, thus, the right ventricular to right atrial pressure gradient will approximate pulmonary artery systolic pressure. This observation is particularly important in very ill patients in whom accurate assessment of right atrial pressure solely on clinical grounds, may be difficult. In two studies (12,13) performed on critically ill patients undergoing bedside right heart catheterization, mean right atrial pressure was correctly estimated in only 43 and 55% of patients, respectively. Furthermore, in some of these cases, there were major discrepancies between the clinically estimated pressure and the pressure measured by catheterization. Our data indicate that an accurate assessment of pulmonary artery systolic pressure may be made by continuous wave Doppler ultrasound even in the absence of the ability to clinically determine the right atrial pressure. Substituting the absolute value of the right ventricular to right atrial pressure gradient into the regression equation, pulmonary artery systolic pressure = (right ventricular to right atrial pressure gradient × 1.23) − 0.09, will yield an estimate of the pulmonary artery systolic pressure that correlated closely with the hemodynamically determined value.

Tricuspid regurgitation. Doppler ultrasound used in conjunction with two-dimensional echocardiography is probably the most reliable noninvasive technique for the detection of tricuspid regurgitation (27). It is considerably more sensitive than physical examination, especially in cases of mild or moderate severity. In a recent study, Waggoner et al. (28) found a systolic murmur compatible with tricuspid insufficiency in only 12 of 61 patients with Doppler evidence of tricuspid regurgitation. Most cases of tricuspid regurgitation are functional, resulting from dilation of the tricuspid anulus rather than intrinsic involvement of the leaflets themselves (29). Pulmonary hypertension, regardless of its etiology, is considered to be the most common cause of functional tricuspid regurgitation (30).

In the present study, tricuspid regurgitation was detected by Doppler ultrasound in only 2 of 20 patients with normal pulmonary artery pressures. One patient had tricuspid endocarditis; in the other, there was no apparent cause for the regurgitation. In contrast, tricuspid regurgitation was found in 39 of 49 patients with elevated pulmonary artery pressure.

Furthermore, when the systolic pressure in the pulmonary artery exceeded 50 mm Hg, tricuspid regurgitation was almost invariably present (26 of 27 patients). Thus, it appears that tricuspid regurgitation diagnosed by Doppler ultrasound is a useful screening test for pulmonary hypertension and that failure to detect its presence makes significant elevation of the pulmonary artery pressure highly unlikely. Other studies (18,19,28) using Doppler techniques have also noted a high prevalence rate of tricuspid regurgitation in patients with pulmonary hypertension.

Limitations of the technique. Underestimation of the pressure gradient between the right ventricle and the right atrium may occur if the ultrasound beam is not properly aligned with the tricuspid regurgitant jet. Attempts to locate the jet from multiple transducer positions together with use of the audio signal to record the highest frequency Doppler shifts will minimize this problem. The presence of a systolic gradient between the right ventricle and pulmonary artery is another potential source of error in estimating the pulmonary artery pressure. A careful physical examination and use of the Doppler technique to detect a pressure gradient between the right ventricle and pulmonary artery should permit this condition to be recognized. The absence of detectable tricuspid regurgitation in 20% of patients with pulmonary hypertension is an additional important limitation of the study, because in these patients pulmonary artery pressure could not be estimated. However, this was noted primarily in patients with mild pulmonary hypertension; when pulmonary artery pressure exceeded 50 mm Hg, tricuspid insufficiency was almost always present and the pressure could be accurately estimated.

Conclusions. Continuous wave Doppler ultrasound is extremely useful in the noninvasive assessment of pulmonary hypertension. Pulmonary artery pressures calculated by this technique appear to be accurate and correlate well with measurements obtained at cardiac catheterization. Clinical estimation of right atrial pressure is not necessary to achieve accurate results. The presence of tricuspid regurgitation is a useful screening test for the identification of patients with pulmonary hypertension especially when pulmonary artery systolic pressure exceeds 50 mm Hg. Because this technique provides a reliable quantitative assessment of pulmonary hypertension, it may be useful in patients with severe pulmonary hypertension who now require serial invasive studies to test the efficacy of drug therapy.

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