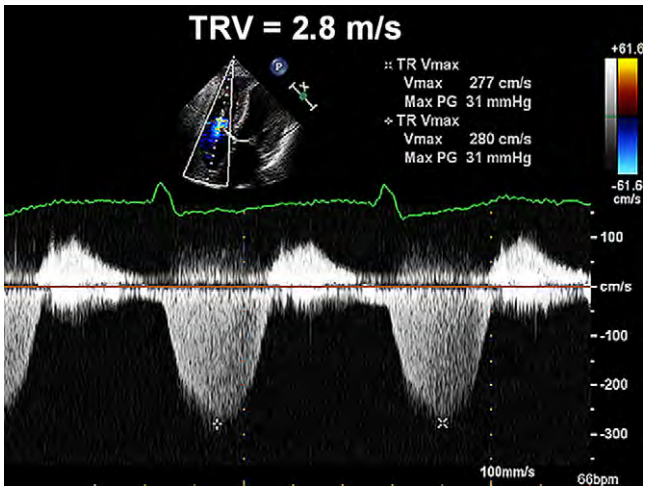

Figure 11 Doppler echocardiographic determination of systolic pulmonary artery pressure (SPAP). Spectral continuous-wave Doppler signal of tricuspid regurgitation corresponding to the right ventricular (RV)–right atrial (RA) pressure gradient. SPAP was calculated as the sum of the estimated RA pressure (RAP) and the peak pressure gradient between the peak right ventricle and the right atrium, as estimated by application of the modified Bernoulli equation to peak velocity represented by the tricuspid regurgitation Doppler signal. In this example, SPAP is estimated at 31 + central venous pressure, or 34 mm Hg, if RAP is assumed to be 3 mm Hg. Adapted with permission from *J Am Soc Echocardiogr*.[52]

HEMODYNAMIC ASSESSMENT OF THE RIGHT VENTRICLE AND PULMONARY CIRCULATION

A. Systolic Pulmonary Artery Pressure

SPAP can be estimated using TR velocity, and PADP can be estimated from the end-diastolic pulmonary regurgitation velocity. Mean PA pressure can be estimated by the PA acceleration time (AT) or derived from the systolic and diastolic pressures.

RVSP can be reliably determined from peak TR jet velocity, using the simplified Bernoulli equation and combining this value with an estimate of the RA pressure: RVSP = $4(V)^2$ + RA pressure, where V is the peak velocity (in meters per second) of the tricuspid valve regurgitant jet, and RA pressure is estimated from IVC diameter and respiratory changes as described above. In the absence of a gradient of across the pulmonic valve or RVOT, SPAP is equal to RVSP. In cases in which RVSP is elevated, obstruction at the level of the RVOT or pulmonic valve should be excluded, especially in patients with congenital heart disease or post-pulmonic valve surgery. The simplified Bernoulli equation may occasionally underestimate the RV-RA gradient because of its neglect of the inertial component of the complete Bernoulli equation. Because velocity measurements are angle dependent, it is recommended to gather TR signals from several windows and to use the signal with the highest velocity.

Technically adequate signals with well-defined borders can be obtained in the majority of patients. It is recommended that Doppler sweep speeds of 100 mm/s be used for all tracings. If the signal is weak, it may be enhanced with agitated saline or blood-saline contrast, but it is important to avoid overestimation of the spectral envelope by ensuring that only the well-defined, dense spectral profile is measured. This is important both with and without contrast (Figure 12).

The normal cutoff value for invasively measured mean PA pressure is 25 mmHg. In the echocardiography laboratory, SPAP is more commonly measured and reported. Normal resting values are usually defined as a peak TR gradient of ≤2.8 to 2.9 m/s or a peak systolic pressure of 35 or 36 mm Hg, assuming an RA pressure of 3 to 5 mm Hg.[73] This value may increase with age and increasing body surface area and this should be considered when estimations are at the upper limits of normal.[74,75] The most recent American College of Cardiology Foundation and American Heart Association expert consensus document on PH recommends further evaluation of patients with dyspnea with estimated RVSP > 40 mm Hg.[76] Some cardiologists who care for patients with congenital heart disease will consider SPAP greater than two thirds of the systemic blood pressure as indicative of severe PH.

Determination of SPAP by the sum of peak RV-RA gradient and RA pressure has been established as a reliable method since the publication by Yock and Popp[77] in 1984 and has been proven by other studies,[78] but additional studies have questioned the accuracy of

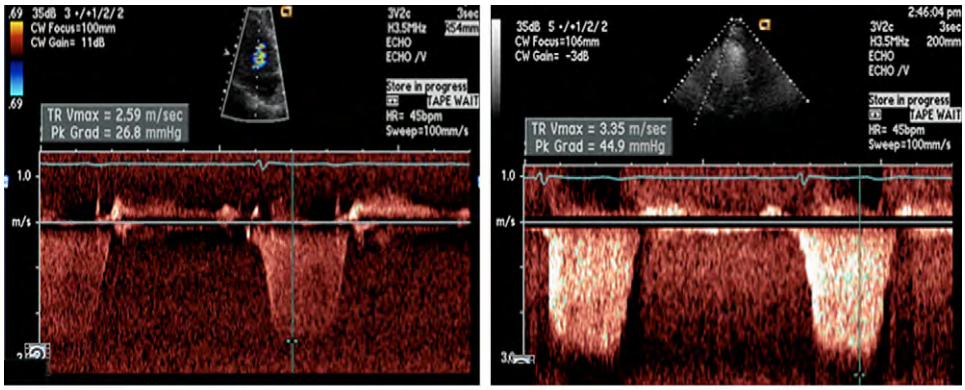

Figure 12 **(A)** Tricuspid regurgitation signal that is not contrast enhanced and correctly measured at the peak velocity. **(B)** After contrast enhancement, the clear envelope has been obscured by noise, and the reader erroneously estimated a gradient several points higher. As this example shows, it is critical that only well-defined borders be used for velocity measurement, as slight errors are magnified by the second-order relationship between velocity and derived pressure.

this relationship, particularly at higher PA pressures.[79,80] In patients with very severe TR, the Doppler envelope may be cut off because of an early equalization of RV and RA pressures, and the simplified Bernoulli equation may underestimate the RV-RA gradient.

B. PA Diastolic Pressure

PADP can be estimated from the velocity of the end-diastolic pulmonary regurgitant jet using the modified Bernoulli equation: [PADP = 4 × (end-diastolic pulmonary regurgitant velocity)^2 + RA pressure].

C. Mean PA Pressure

Once systolic and diastolic pressures are known, mean pressure may be estimated by the standard formula mean PA pressure = 1/3(SPAP) + 2/3(PADP). Mean PA pressure may also be estimated by using pulmonary AT measured by pulsed Doppler of the pulmonary artery in systole, whereby mean PA pressure = 79 (0.45 × AT).[81] The same group also found that in patients with ATs < 120 ms, the formula for mean PA pressure is 90 (0.62 × AT) performed better.[82] Generally, the shorter the AT (measured from the onset of the Q wave on electrocardiography to the onset of peak pulmonary flow velocity), the higher the PVR and hence the PA pressure, provided the heart rate is in the normal range of 60 to <100 beats/mins. The mean PA pressure can also be estimated as 4 × (early PR velocity)^2 + estimated RA pressure.[83] An additional recently described method adds estimated RA pressure to the velocity-time integral of the TR jet to calculate a mean systolic pressure. This method has been validated by right heart catheterization and provides a value closer to one derived hemodynamically than the empirical methods.[84,85] Whenever possible, it is helpful to use several methods to calculate mean pressure so that the internal consistency of the data can be challenged and confirmed.

Recommendations: Pulmonary hemodynamics are feasible in a majority of subjects using a variety of validated methods.[86] SPAP should be estimated and reported in all subjects with reliable tricuspid regurgitant jets. The recommended method is by TR velocity, using the simplified Bernoulli equation, adding an estimate of RA pressure as detailed above. In patients with PA hypertension or heart failure, an estimate of PADP from either the mean gradient of the TR jet or from the pulmonary regurgitant jet should be reported. If the estimated SPAP is >35 to 40 mm Hg, stronger scrutiny may be warranted to determine if PH is present, factoring in other clinical information.