1. Role of Two-dimensional Echocardiography

Evaluation of the RV outflow tract and pulmonary valve by 2D echocardiography is possible from the parasternal and sub-costal views. Identification of anatomic abnormalities associated with PR, such as abnormalities of cusp number (quadricuspid or bicuspid valves), motion (doming or prolapse) or structure (hypoplasia, dysplasia or absence of the pulmonary valve) may help define the mechanism of regurgitation and yield clues to its severity. Visualization of the entire pulmonary valve is more difficult than the mitral, aortic and tricuspid valves. However, dilatation of the pulmonary artery, frequently observed in pulmonary hypertension, allows easier visualization of the valve. Inability to fully visualize the pulmonary valve may limit the quantitation of pulmonary regurgitation. Lastly, evaluation of the size and function of the RV in the absence of pulmonary hypertension provides an indirect indicator to the significance of PR and adaptation of the RV to the volume overload state.

2. Doppler Methods

a. Color flow Doppler. Color Doppler flow mapping is the most widely used method to identify PR. A diastolic jet in the RV outflow tract, beginning at the line of leaflet coaptation and directed toward the right ventricle is diagnostic of PR (Figure 8). Although color Doppler is ideally suited to determine the jet size and spatial orientation, many of the factors used to evaluate the severity of regurgitation (jet size, extent and duration) will be determined by a combination of the regurgitant volume and the driving pressure (gradient between the pulmonary artery and the RV). Regurgitant jets seen in normal pulmonary valves, considered a variation of normal, are usually very small, 'spindle-shaped' and originate centrally from the pulmonary leaflet coaptation site (Figure 8).[91] Initial studies attempted to quantify pulmonary regurgitation by measuring jet length.[91] Jets $<$ 10 mm in length were trivial while larger jets were associated with heart disease. However, jet length is highly dependent on the driving pressure gradient between the pulmonary artery and the RV, and is therefore not a reliable index of severity. Assessing the entire jet area by planimetry should, theoretically, fare better than the jet length alone. Planimetered jet areas, indexed for body surface area, correlated well with PR severity compared to angiography. However, a high degree of variability and overlap among different grades of regurgitation was observed.[92] In cases of severe pulmonary regurgitation, the full extent of the regurgitant jet may not be appreciated from the parasternal position; subcostal imaging may be necessary to fully appreciate its full extent.

Although not systematically validated for the pulmonary valve, the vena contracta width is probably a more accurate method to evaluate the severity of PR by color Doppler, similar to other regurgitant lesions. Some investigators have used the PR jet width in the serial assessment of pulmonary homografts, but standards for pulmonary vena contracta width have not been established.[93] It is important to note that in cases of severe PR, where equalization of diastolic pulmonary artery and RV pressures occurs early in diastole, the color jet area can be brief and misleading at first glance. In this case, the large width of the vena contracta and findings by PW and CW Doppler (see below) alert the observer to the severity of regurgitation (Figure 8).

b. Continuous wave Doppler. CW Doppler is frequently used to measure the end-diastolic velocity of PR and thus estimate pulmonary artery end-diastolic pressure. However, there is no clinically accepted method of quantifying pulmonary regurgitation using CW Doppler. Similar to AR, the density of the CW signal provides a qualitative measure of regurgitation.[51] A rapid deceleration rate, while consistent

Table 10 Echocardiographic and Doppler parameters used in grading pulmonary regurgitation severity

Parameter	Mild	Moderate	Severe
Pulmonic valve	Normal	Normal or abnormal	Abnormal
RV size	Normal*	Normal or dilated	Dilated
Jet size by color Doppler§	Thin (usually < 10 mm in length) with a narrow origin	Intermediate	Usually large, with a wide origin; May be brief in duration
Jet density and deceleration rate –CW†	Soft; Slow deceleration	Dense; variable deceleration	Dense; steep deceleration, early termination of diastolic flow
Pulmonic systolic flow compared to systemic flow –PWᵠ	Slightly increased	Intermediate	Greatly increased

CW, Continuous wave Doppler; *PR*, pulmonic regurgitation; *PW*, pulsed wave Doppler; *RA*, right atrium; *RF*, regurgitant fraction; *RV*, right ventricle.
* Unless there are other reasons for RV enlargement. Normal 2D measurements from the apical 4-chamber view; RV medio-lateral end-diastolic dimension ≤ 4.3 cm, RV end-diastolic area ≤ 35.5 cm^2(89).
** Exception: acute PR
§ At a Nyquist limit of 50-60 cm/s.
ᵠ Cut-off values for regurgitant volume and fraction are not well validated.
† Steep deceleration is not specific for severe PR.

with more severe regurgitation, is influenced by several factors including RV diastolic properties and filling pressures. In severe PR, a rapid equalization of RV and pulmonary artery pressures can occur before the end of diastole. Thus, an intense signal of "to and fro" flow in the shape of a "sine wave", with termination of flow in mid to late diastole can be seen (Figure 8). This finding however, is not specific for severe PR, as early and rapid equilibration of diastolic pressures is also seen in patients with low pulmonary artery end-diastolic pressure and/or elevated RV diastolic pressure (eg. RV infarction). However the intensity of the PR signal, color Doppler characteristics of the jet and pulmonic flow quantitation in the RV outflow tract by PW Doppler help differentiate these entities.

c. Pulsed Doppler. In the evaluation of PR, pulsed Doppler interrogation of velocity can be useful at the level of the pulmonic annulus and in the pulmonary artery.[94-96] If the velocity of the PR jet is not aliased by PW Doppler, its contour and timing can be evaluated similar to CW Doppler (above), with identical implications.[97]

Pulsed Doppler assessment of the forward and reverse flows in the pulmonary artery has been used to calculate regurgitant volume and regurgitant fraction.[95,96] If the diameter of the pulmonary artery is assumed to be constant, then the ratio of the reverse to forward velocity time integral can be used to estimate the percent of regurgitant flow.[95] Although differences in regurgitation fraction were observed among groups with various severity of PR, a considerable overlap was seen and standards for pulmonary artery regurgitant fraction have not been established.[96] Furthermore, this method is not valid in patients with pulmonic stenosis because of post-stenotic turbulent flow.

As previously discussed, pulsed Doppler can be used to calculate stroke volume at different annular sites. The pulmonic annulus however, is probably the most difficult site to measure because of its poor visualization and the changing size of the RV outflow tract during the cardiac cycle. It is recommended to measure the pulmonic annulus during early ejection (2-3 frames after the R wave on the ECG), just below the pulmonic valve.[98,99] Although not validated for quantitation of PR, flows at the pulmonic annulus can be compared to other sites to derive quantitative parameters of regurgitation (regurgitant volume and fraction). Clinically, this is feasible provided that particular attention is taken to image well the area of the pulmonic annulus and thus minimize errors of its measurement.